MARTIN PECK (EDITOR)

Modern Concrete Construction

MANUAL

STRUCTURAL DESIGN
MATERIAL PROPERTIES
SUSTAINABILITY

Edition DETAIL

Institut für internationale Architektur-Dokumentation · Munich

MARTIN PECK (EDITOR)

Modern Concrete Construction MANUAL

STRUCTURAL DESIGN
MATERIAL PROPERTIES
SUSTAINABILITY

Authors

Dipl.-Ing. Martin Peck (Editor)
BetonMarketing Süd GmbH, Munich

Prof. Dr.-Ing. Christoph Dauberschmidt,
Prof. Dipl.-Ing. Arthur Wolfrum
Munich University of Applied Sciences

Prof. Dr.-Ing. Stephan Engelsmann,
Prof. Dr.-Ing. Stefan Peters,
Dr.-Ing. Valerie Spalding,
Dipl.-Ing. Franz Forstlechner
Engelsmann Peters GmbH, Stuttgart State Academy of Arts and Design,
Graz Technical University

Prof. Dipl.-Ing. Ulrike Förschler
Rosenheim University of Applied Sciences

Dipl.-Ing. Torsten Förster
German Cement Works Association (VDZ), Berlin

Prof. Dr.-Ing. Peter Lieblang
Cologne University of Applied Sciences

Prof. Dipl.-Ing. Tobias Wallisser
Stuttgart State Academy of Arts and Design

Editorial services

Editing, copy-editing:
Steffi Lenzen (Project Manager);
Eva Schönbrunner, Melanie Weber

Editorial assistants:
Carola Jacob-Ritz, Florian Köhler; Jana Rackwitz

Drawings:
Dejanira Ornellas Bitterer, Ralph Donhauser,
Marion Griese, Martin Hämmel, Emese M. Köszegi

Translation into English and Copy editing:
Christina McKenna, Matthew Griffon, Matt Haycocks
Keiki Communication, Berlin

Proofreading:
Stefan Widdess, Berlin

Cover:
Cathrin Huber, Munich

Production & layout:
Simone Soesters

Reproduction:
Martin Härtl OHG Repro und Publishing, Munich

Printing and binding:
Kösel GmbH & Co. KG, Altusried-Krugzell

Publisher:
Institut für internationale Architektur-Dokumentation
GmbH & Co. KG, Munich
www.detail.de

ISBN: 978-3-95553-205-5 (Print)
ISBN: 978-3-95553-206-2 (E-Book)
ISBN: 978-3-95553-207-9 (Bundle)

Bibliographic information published by the German National Library. The German National Library lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

This book is also available in a German language edition
(ISBN 978-3-920034-95-9)

MIX
Paper from
responsible sources
FSC® C013736
www.fsc.org

Contents

Foreword

Concrete is a remarkable building material, but despite its widespread presence, it is frequently an inconspicuous part of our built environment, often hidden in structures, foundations and similar parts of buildings. Sometimes, however, it stands out in an architectural structure that makes use of its material properties, is highlighted in smooth exposed concrete or deliberately roughened surfaces, plays with structures, or transforms seemingly unbuildable visions into reality.

"Concrete is everywhere", is the usual brief aphoristic or prosaic lament heard when thoughts turn to the "architectural sins" of the recent past. Yet concrete as a material does not dictate any particular application. It has its own material properties but no inherent form or texture – on the contrary: concrete harbours a wealth of potential that should be used.
Concrete also polarises people like no other building material because for all its unobtrusiveness, it is too often present and is too ubiquitous to be overlooked or ignored. Its importance to all the world's societies and national economies makes it essential to their development and prosperity. What concrete means at the global level quickly becomes clear if we try to imagine our built environment without it: Technically and economically, it is almost impossible to substitute for an equivalent material. Today's concrete construction methods are the product of a constantly continuing and mutually interdependent development of the construction material and construction methods, a development unparalleled for any other material in construction.

The education of civil engineers concentrates mainly on concrete construction techniques and technology. Architecture students, in contrast, as well as studying the structural basics, tend to focus more on the material's haptic and sensory side. The approaches differ for disciplinary and historic reasons, and despite all the change evident in both types of education, they will probably not change much in the foreseeable future.

The different approaches of the two types of professional education to the same topic highlight the need for more interdisciplinary cooperation and communication using a simple, universal technical language and terminology. The range of specialist literature available to architects on building with concrete is, however, relatively small, which makes it difficult to find advice for solving current challenges and for training and education purposes.
This work is designed to be a compendium, which, in its selection of content and style of presentation, opens up and explains current concrete construction techniques and technology, mainly to architects, clearly and with a comprehensible breadth of expertise.

The use of concrete and other cement-bonded building materials has expanded greatly in recent decades, so it would be impossible to provide a complete overview of the potential of concrete construction techniques within the limits of this book. Instead, this work focuses on presenting the fundamentals of the main aspects and applications of concrete construction and their technical, formal and regulatory backgrounds.

The "Concrete Construction Manual" by Kind-Barkauskas, Kauhsen, Polónyi and Brandt (2001/2009) has an established position in the Edition DETAIL "Atlas of Construction" series. After a detailed introduction on the material's history, the focus is on a comprehensive section on the basics of classic civil engineering and fundamental structures.
The "Modern Concrete Construction Manual" emphasises both continuing quality and renewed content in the face of changing demands on architects. With a view to the current requirements made on architecture and planning, the book concentrates more on building construction and the related possibilities in designing with concrete and especially on its haptic and sensory properties, which tend to be less important in civil engineering. There is also a focus on current topics such as energy efficiency, sustainability and restoration and renovation of concrete and steel reinforced concrete buildings.

The division of planning work between architects and structural planners results in interfaces and interactions that demand a good level of interdisciplinary detailed knowledge on both sides. The chapter on "Designing structures with structural concrete" deals with this area of planning, explaining general design and safety principles. The possibilities of digital aids and tools in the current – and perhaps future – status of software development and applications have a potential that is yet to be exploited.

The chapter on "Thermal building physics and energy efficiency" seeks to extensively describe the constantly growing demands on the energy efficiency of our buildings. Concrete has inherent potential in this area due to its fluid-plastic placing and the useful heat storage capacity of hardened concrete, which seems to have enormous development potential. In coming years, the national and international regulatory situation governing the energy efficiency requirements on buildings and structures will certainly change greatly because the global challenges that make them necessary require urgent political action and appropriate development. Energy-efficient construction will increasingly become an elementary planning measure and influence the appearance and design of buildings accordingly, leaving architects facing new and particular challenges.

As well as energy efficiency, attention to and an assessment of sustainability aspects und criteria plays a major role in planning, building and in the operation and use of buildings. There are currently almost no binding laws or regulations for expert planners and/or any governing concrete construction, although there have also been developments in this area. Building materials manufacturers are now called upon to provide an objective and comparable database on their products. It is also foreseeable that verifying the energy efficiency and sustainability of buildings will soon become an obligatory part of planning. Part C of this book deals with this topic as far as is possible and appropriate given today's state of knowledge.

The detailed examples section created by the DETAIL editorial team is characterised by the diversity of the purposes of the buildings, which come from various countries with correspondingly different architectural and structural approaches: ranging from a mountain hut in the Laternser Valley to the MAXXI Museum in Rome, and from a house in Zurich to Barcelona's City of Justice. All the selected projects highlight concrete's ability to influence design and suggest ways of using this classic construction material in a modern context.

This book's content is the result of committed work by various recognised experts in individual areas of civil engineering, architecture and interior design. Our cordial thanks go to the authors, contributors and everyone who, in various ways, helped make this publication a success. All the contributors are pleased to know that readers will find the book useful and helpful in their everyday work and ongoing individual training and education.

Martin Peck, July 2013

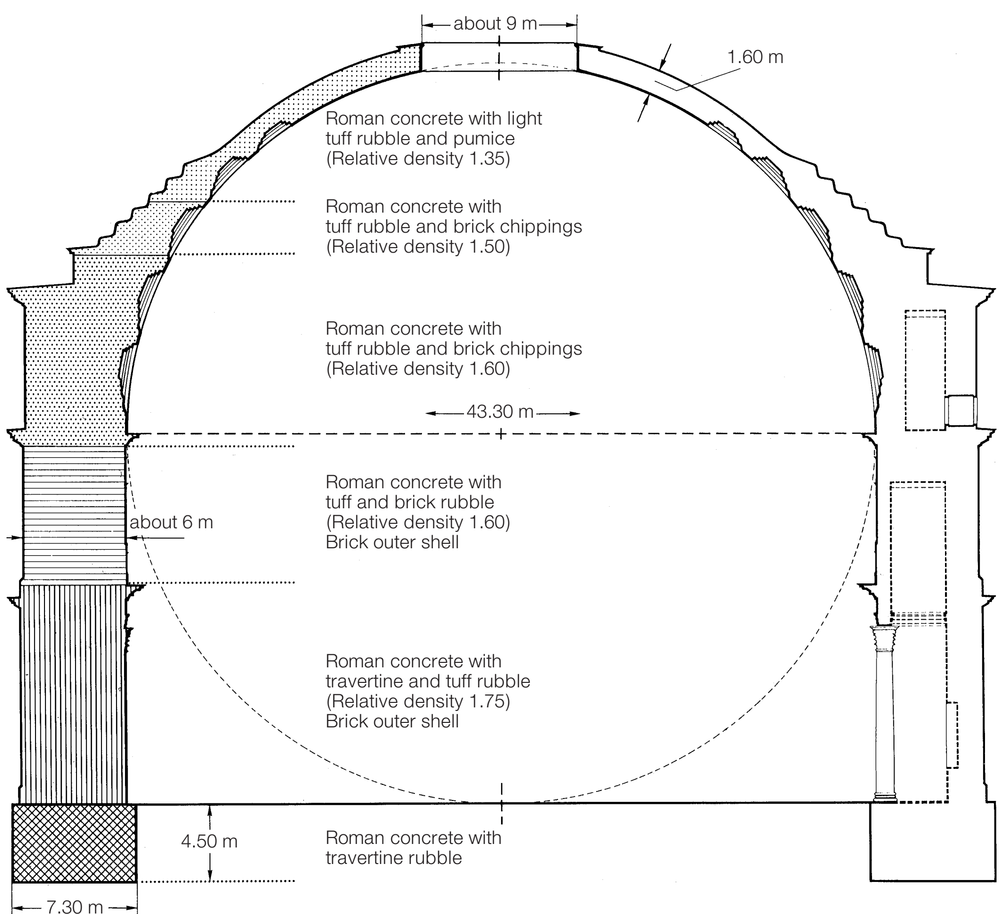
On the stage of architecture

Torsten Förster

A 1

Concrete is a character actor, or rather, it has become one. Once an invisible stagehand, silently ensuring the smooth progress of performances in the background, it has matured, grown older and gradually taken its place on centre stage. The stage of architecture is a large one and has grown larger. New experimental forms make their appearances, but concrete still plays a major role, not always, but often. Sometimes it is its centuries of experience that are sought after, sometimes its dramatic abilities. It can impress with its brilliance, dominate or eccentrically exaggerate a performance. Concrete can however also be "miscast". Critics may condemn or praise it, but they rarely ignore it. Concrete only remains unmentioned when it is supposed to. That decision lies with the "director". Concrete is compliant. Despite its many glittering appearances, it's still a silent, reliable helper. It supports, separates and protects, invisible, humble and silent, if that's what the architect wants.

Like the history of construction, the history of the theatre is as old as humanity. Stone Age people held theatrical performances, portraying their world and the major events of their lives. The Greek word "théatron" (acting, theatre) is derived from "theaomai"



A 2

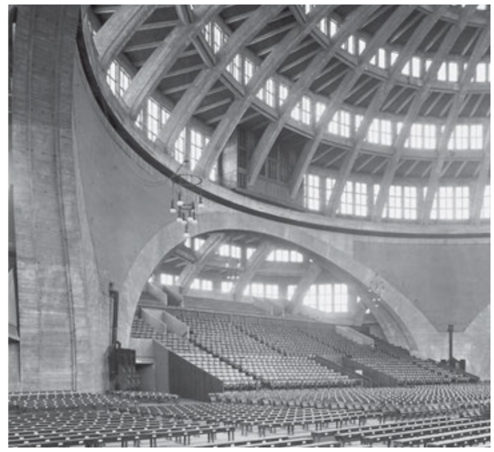
(to look at). Theatre holds up a mirror to the world. But doesn't the way in which architecture is now sometimes received have a great deal to do with simply looking? Don't images dominate the world of architecture? Is the dome of the Reichstag, shown in the background of reporting on elections, an image of architecture or a symbol of democracy? If the symbolic predominates here, what about the images of buildings by Zaha Hadid, Frank O. Gehry or Herzog & de Meuron that are so celebrated in the media? Does this looking complement the real building, or is it the other way around, the built structure reflecting a previously desired representative reality? The ancient Greek words "archi-" (head) and "tékton" (master builder) are the essential roots of the word "architecture". A builder creates a built environment and characterises what architecture is or could be in the etymological sense. Architecture's essence is defined by the profession and personality of the master builder. A person who builds creates his world, or so language, which remains the record of our cultural development, suggests.

We will go on to discuss the relationships of creation and permanence and their effects and meanings, but first, back to concrete. The Pantheon in Rome was completed under the emperor Hadrian in 125 A.D. (Fig. A 1), in the heyday of ancient Roman theatre. This is often described as the birth of concrete architecture. Here, concrete is still invisible, hidden like a silent servant in a dome whose span remained unsurpassed for more than 1,700 years. Only in 1911–1913 did the architect Max Berg build the Centennial Hall in Wroclaw with a bigger dome, 65 metres in diameter (Fig. A 3). The Pantheon's dome, at just over 43 metres, is smaller, but it would be wrong to describe the building as modest. Its space, light and atmosphere still captivate visitors. It also fascinates engineers who investigate its construction. The Roman master builders reduced its lateral shear force with a material "trick". The higher it rises towards its apex, the lighter the dome becomes. This was made possible by varying the ingredients of its mortar and concrete (Fig. A 2). At its base, brick rubble was used as aggregate for the binding mortar in the space between the dome's inner and outer shells. Above this lighter tuff and above that even lighter pumice was used. Empty clay pots were also built into it to reduce its weight even further. The Pantheon's dome construction anticipated a major trend in the way we use concrete today: precise adaptation of the construction material's properties to specific requirements. Only a material with variable components can do this. Concrete's desired physical properties can now be extremely precisely specified and implemented. Research is so advanced that different requirements can be met by one structural component, one made of functionally graded concrete, for example. Its properties can be continuously adjusted in all three spatial directions within one structural component and adapted to localised requirements. This can be done by varying the material's porosity, using different proportions of ingredients or functionally graded concrete [1], for example. Research is also being carried out into more efficiently adapting the forms of structural components to make use of the distribution of forces and a further property that only concrete offers: free formability. Examples of such components are shape-optimised supports, folded support structures, ultra-light hollow profiles, filigree rods and the like. [2] Such research aims to make more efficient use of resources, save on materials and improve components' properties. If all this can be combined with good architecture, Modernity will one day follow in the great tradition of the Roman master builders, using concrete to create great architecture.

Concrete architecture

Research into concrete's material aspects has been going on since time immemorial and its technical application has been continuously further developed, with increasing dynamism in recent decades. Much has been set in motion and become reality on building sites. Architects and civil engineers have made major contributions to its progress. Implementing their ideas and visions increases knowledge and gives rise to new capabilities.

So what is concrete architecture? Can architecture be based on one specific material? Use of a material cannot be equated with a building's essence, its significance, look and appearance. It is neither right nor fair of a builder to impose responsibility for all this on one building material. A material may be inspiring or make a planned form possible, but good architecture is even more than that. Architecture is a total experience, it's not just about material, yet there is architecture in which concrete plays a major role – including in design: concrete architecture. Concrete allows architects to create something more than the overall result of a structure. Many things contribute to this process, especially creativity. So what drives creativity? An invention is rarely an end in itself. It is usually constraints and necessities, such as budget limits, a shortage of time, misunderstanding of a task or a particular site that result in unconventional solutions. Shortages of materials can also inspire designers to produce unforeseen new solutions. Creativity may also emerge beyond constraints, due to a desire for something new and distinctive, including in architecture. Out of creativity originality sometimes develops, in a positive and in a negative sense. Really good new solutions are usually based on attempts to solve real problems, such as how to build a 43.30 metre self-supporting dome without modern steel, one like the Pantheon in Rome.



A 3

A 1 Concrete dome structure, the Pantheon, Rome (I) 125 A.D.
A 2 Pantheon, sectional view showing the various kinds of concrete used
A 3 Reinforced concrete dome structure, Centennial Hall, Wroclaw (PL) 1913, Max Berg

Concrete and vision

Planning and building is based on a projected future. It could also be called vision. Every building is "visionary architecture" until it's completed. The word "visionary" has positive connotations, even though it describes something that is not viable, or at least not yet viable. Drawings, pictures, sketches, charts, descriptions and models are the tools of the architect and planner. The construction of the Pantheon in Rome, Chartres Cathedral and Le Corbusier's church in Ronchamp was based on concrete plans. Yet what is not built, the visionary, also shapes the history of architecture: we need only think of the plan for St. Galler abbey or Mies van der Rohe's drawings of high-rise buildings for Friedrichstrasse in Berlin. The Bauhaus movement also left behind mainly words, drawings and pictures. Powerful and visionary ideas can change the world.

Whatever posterity makes of major ideas, they often start small. In 1867, a French gardener, Joseph Monier, applied for a patent for "ferrous concrete", which he had developed out of iron and concrete to make plant tubs with. This perhaps banal form and usage was the beginning of the revolutionary invention of reinforced concrete, out of which today's steel-reinforced concrete developed. It improved concrete's performance enormously and made it possible


a


b A 4

to build with it economically and quickly for the long term. In 1890 François Hennebique built the first concrete houses based on Monier's invention. The material was incorporated into architecture, the architecture of surfaces, outward forms and meanings, as a construction material, a material of many faces and a "character actor", playing itself. Its haptic, surface and manufacturing process became design features, especially in the works of architects like Tadao Ando who celebrate exposed concrete. Robert Maillart, Pierre Luigi Nervi (Fig. A 4), Luigi Snozzi, Santiago Calatrava and many other architects and engineers should also be mentioned here because they have all developed visions, drafted plans and all built with concrete. Concrete is not a material for standard feasibility studies, rather an amenable helper in implementing ideas.
So is concrete architecture visionary? Of course not per se. Only an idea or its implementation can be visionary. Yet this material can contribute to the creation of visionary architecture, provide inspiration, be a catalyst and make undreamed of possibilities a reality. Concrete has proven that it is just such a material. So why is concrete so diverse, adaptable and conformable?

Concretes

When the Pantheon was built, and right up into the 1950s, when the engineer Fritz Leonhardt was building bridges over the Rhine, concrete was a simple three-compound mixture of cement, water and aggregate. Cement reacts with water, solidifies, hardens and binds the aggregate in the mixture into hard, durable concrete, a kind of artificial stone. Mixing concrete is now far more complicated. It consists of six main ingredients: cement, aggregate, water, additives, admixtures and air (see "Basic materials", p. 26ff.). Usually only concrete technologists have specialist knowledge of the differences between individual materials, their interactions and the material properties associated with them. Their knowledge includes an understanding of the ways in which

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Africa	Production [mill. t]	70.4	76.9	79.0	87.4	92.4	105.9	117.0	125.4	132.3	145.9
	Consumption [mill. t]	81.1	90.0	90.5	98.8	103.1	115.2	123.7	134.3	143.0	160.9
America	Production [mill. t]	220.7	218.1	216.8	218.0	229.4	243.2	255.1	262.0	257.2	228.3
	Consumption [mill. t]	235.7	235.6	230.5	232.6	244.4	261.1	273.8	270.3	261.2	232.0
Asia	Production [mill. t]	1,038.0	1,110.4	1,208.0	1,360.1	1,485.3	1,601.5	1,810.0	1,966.0	2,030.0	2,303.0
	Consumption [mill. t]	1,014.4	1,089.0	1,187.0	1,340.7	1,465.6	1,574.7	1,773.4	1,935.9	2,002.3	2,266.5
Europe	Production [mill. t]	278.1	268.9	271.5	279.9	292.8	305.1	326.4	335.3	318.5	269.4
	Consumption [mill. t]	268.6	260.0	265.2	272.4	285.1	295.7	320.1	326.4	305.2	255.3
World (total)	Production [mill. t]	1,661.6	1,726.1	1,839.8	2,017.0	2,181.9	2,344.8	2,608.0	2,797.7	2,841.5	3,033.1
	Consumption [mill. t]	1,653.0	1,725.2	1,835.8	2,014.2	2,178.7	2,333.7	2,588.2	2,778.8	2,824.0	3,004.7

A 5

varying and modifying these components can create the new, specific and precise processing and usage properties that are desired and required for a specific task. Cement still always reacts to water, forms cement paste, then hardens, but with a wider range of components available, many more diverse construction possibilities have developed.
Concrete additives now have a major influence on concrete's workability, setting behaviour, hardening and durability. Although it makes up a relatively small proportion of concrete's overall mixture (no more than 5 % of it is permitted in the cement mass) it precisely effects the desired changes especially in wet concrete, but also in set concrete. Whether it's a concrete plasticiser, flow agent, catalyst, retardant agent or sealant etc., concrete additives are now present on almost every building site.
Other concrete additives such as coloured pigments, fibres or fine mineral materials, also influence concrete's properties. These are a common component of modern concrete mixes and complement the classic ingredients of cement and aggregate. Then there is the question of air in concrete. Compacting on the building site expels air incorporated into the mixture, but some air always remains and may be deliberately left in the mix. More air can be added to concrete by adding air entraining agents, increasing the set concrete's resistance to anti-free and de-icing agents, which can be important in ensuring that structural components are durable.
For architects and most engineers this is specialist knowledge. The various kinds of concrete can serve as a guide: steel-reinforced concrete, shotcrete, spun concrete, wet mix aggregate, flowing concrete, exposed concrete, vacuum concrete, lightweight concrete, normal concrete, heavy concrete, prestressed concrete, tamped concrete, textile concrete, high-performance concrete, refractory concrete and many more. Concrete is no longer a clear and simple building material; it is a high-performance material and extremely specialised. Only one rule always applies: different mixtures will produce different concretes, depending on precisely what is needed.

Concrete and responsibility

One new aspect of architectural criticism and reporting on building with concrete in recent years is that it no longer focuses solely on a structure's look, the impression it creates and its potential uses. Building with concrete is now associated with society's global issues, especially with the efficient use of energy and resources. Concrete and its economic potential constantly accompanied burgeoning humanity through the 20th century and still does, although concrete was initially not well received in architecture. Talking about building with concrete seemed to put the speaker under pressure to justify it and prove that "the sins of architecture" were not down to just one building material. For a long time, the debate on building with concrete was characterised by a "Yes, but…". "Yes", because the use of concrete was vital in building infrastructure, housing and work spaces on a massive scale. As a modern building material, concrete shaped the aesthetic of many of these buildings within the framework of the zeitgeist of modernity, industrialisation and globalisation. But the zeitgeist changed and changed quickly and concrete buildings were built which, seen with the benefit of hindsight, are no longer aesthetically and functionally adequate, which prevented urbanity from developing or were rigid urban development structures that stood in the way of a desirable flexibility.
Yet concrete can do far more than fit in with a certain zeitgeist: an attentive review of construction in recent years leaves no doubt of that. Building with concrete is now more diverse than ever, sustainable, rooted in both regional traditions and in the global mainstream. But no architect would ever use concrete just to prove that the material can do more than is usually ascribed to it. Concrete is not a statement. Concrete is a building material with its own properties and character.
Yet something new has crept into debates on architecture in recent years. Buildings need resources, first to build them, and then far more resources in their use over years and decades. How buildings are built makes a major contribution to how our future will be. What is new is that this line of thought no longer involves just functional and aesthetic issues, but also very concretely focuses on the fundamentals of life in future. Construction materials have become increasingly valuable so their use should be well thought out in advance and this especially applies to concrete.

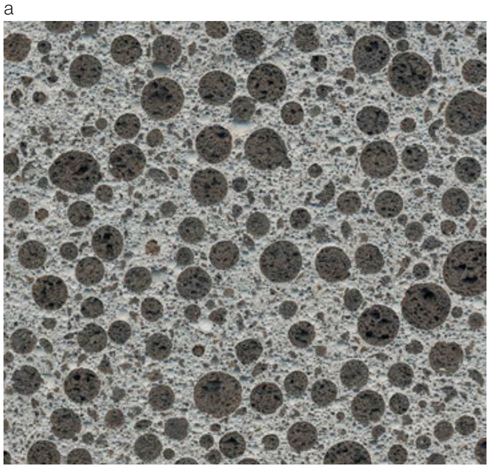
About 1,000 kWh of energy is required to produce one tonne of burnt cement clinker from limestone and clay. The resulting cement powder can be made into 3–4 m^3 of concrete. Concrete consumption corresponds with growth in the world's population and the development of national economies (Fig. A 5). It's therefore no coincidence that China uses more than half the cement produced worldwide, due among other things to that country's still growing population. At 1,000 kg/year per capita, China is the world's biggest consumer of cement [3]. Germany consumed about 310 kg of cement per capita over the same period, so about a third of that figure. The reasons for this are many, but we should be aware that concrete should be used carefully. Its economic advantages of availability, efficiency and price contribute to our prosperity, securing the foundations of modern economies in the long term. It is up to architects, planners and developers to use it responsibly. Its use should be well planned, necessary and enduring. Construction invariably uses up resources, but if it also creates the future, then buildings should be able to be used by many future generations.

A 4 Palazzetto dello Sport, Rome (I) 1957, Pier Luigi Nervi
a Reticular vault structure
b Interior view of the ribbed roof structure
A 5 Cement production and consumption trend from 2000 to 2009 by comparison

A 6

A 6 House built of insulating concrete, Chur (CH) 2003, Patrick Gartmann
A 7 Infra-light concrete house, Berlin (D) 2007, ARGE Bonnen + Schlaich
a Garden facade
b Use of foamed clay spheres as aggregate in concrete
A 8 High-performance concrete, Weinberghaus, near Wörrstadt (D) 2011, TU Kaiserslautern – Dirk Bayer, Bernd Meyerspeer, Christian Kohlmeyer, Jürgen Schnell; Design: Christoph Perka
a Construction of prefabricated concrete components with adhered plug-in connectors
b Isometric structural principle
c Exterior view
d View from the interior

a



b A 7

Concrete and sustainability

The world's population is growing, generation by generation. According to a UN prognosis issued in 2011, around 9.3 billion people will live on Earth by 2050 [4], 2.3 billion more than today. Each person fits into society, into life, work, family, friends, culture, sport, travel and whatever an individual lifestyle may focus on. Buildings are almost always needed to protect people and their possessions and goods from the environment and to make many of these activities possible in the first place. To this must be added the ubiquitous exchange of goods, all of which increases the need for built structures.

What is built, how and with which materials may depend on the material available: stone and wooden houses in the Alps, thatched roofs on the North Sea coast and bamboo huts in the tropics. Not every material is available everywhere. Limestone however, is found on all continents and in all climate zones. Its wide-spread deposits formed in prehistoric times from organisms living in the ancient oceans. For two and a half billion years, the shells of fossil microorganisms, snails, shellfish, sponges and calcareous algae and bacteria, were deposited in huge layers, initially in the form of lime sludge. The sludge solidified, was transformed and is now an important raw material. Limestone, mined and processed, can be used as natural stone, but it is more often processed into burnt lime and cement. We should be aware of how closely connected this process is with the development of humanity and its civilisations. The development of available resources and their uses is an important chapter in the history of civilisation. Perhaps someone noticed by chance that burning limestone produced lime, which made it possible to make mortar, which could be used to lay bricks. Archaeologists have found evidence showing that burnt lime has been used as a binding agent for at least 5,600 years [5]. Clay and mud has been used for around 10,000 years [6]. Bricks have been produced in large quantities for a good 3,000 years, providing "stones" for mortaring in regions that had no stone. Limestone has been burnt in an industrial process to make cement clinker for about 200 years. It can then be ground together with gypsum and anhydrite to make cement, forming the basis for producing freely formable concrete from sand and gravel, which is available everywhere, and give the concrete the required properties. Based on limestone, concrete has become the universal building material of industrialisation and modernity all over the world.

Availability and low costs are economic, comprehensible and rational criteria against which every individual decision and economic tendency is measured, but people are now aware that their activities also influence apparently immutable factors such as the climate and our natural living conditions. This also applies to construction and the materials it requires. Processing limestone ($CaCO_3$) into cement (which is about 58–66 % calcium oxide – CaO) releases carbon dioxide, which is present in limestone's chemical compounds and was derived by prehistoric organisms from the atmosphere. This too, is a legacy of the past. The use of cement must therefore be as long-term as possible. Debate, including architectural debate, will continue to focus on using raw materials sparingly. The word "sustainability" has found its way into the speeches of politicians, into talk shows and advertising, yet economy, responsibility and the conservation of resources are nothing new and certainly not for the traditional building material of concrete. We need only think of the construction of the Pantheon in Rome, which was based on guidelines still very current today: optimising the use of materials while maximising their technical performance.

Neither today's regulatory standards nor developers' attitudes assume that modern concrete structures will be used for two thousand years. On the contrary, we now discuss the subsequent use of structural components and materials in architecture when structures are first created. Reusing and converting existing buildings is rightly becoming increasingly important. Behind these debates is awareness that our primary raw materials sources are limited. Careful use of resources should be a matter of course for the sake of coming generations. It is also rational to return pre-used materials to the materials cycle and that also goes for concrete. When concrete buildings or support structures are dismantled, about 90 % of the demolition material is now used in new structures (see "Recycling and recycled materials in concrete construction", p. 121ff.). Experts are still arguing about how far more infrastructure and buildings can be built with less material. This is just one of the challenges facing burgeoning humanity.

Concrete and heat

There is currently much discussion on the efficient use of resources and on issues around "life cycles" in construction, but concrete action, even in small projects, will help advance the overall debate. One example of such a project is a small house by the architect Patrick Gartmann in Chur (Fig. A 6). The building, constructed monolithically in concrete, has done more to develop energy efficient construction than many a symposium, especially through its construction and use of a new kind of concrete. Depending on their structural requirements and necessary insulation values, the walls and ceilings were made of either normal or construction insulating concrete, and the thickness of the exterior components varied from 45 to 65 cm. Of central importance in implementing this concept was an insulating concrete that the architect developed in cooperation with two firms. Foamed clay replaced gravel as an aggregate and sand was replaced with foamed glass. The foamed glass spheres and foamed clay are insulating and light. Their spherical form ensures that the concrete has good flow characteristics and is designed to prevent undesirable chemical reactions occurring in it. This solution enabled Patrick Gartmann to not only create his vision of a reduced house planned around the arrangement of rooms and on views, it also launched a series of research and experiments on other monolithic, insulated buildings.

More experimental buildings have been built in recent years, including an infra-lightweight concrete house by Clemens Bonnen and Amanda Schlaich in Berlin (Fig. A 7). Its special concrete was developed at the Institut für Massivbau (Chair of Conceptual and Structural Design) at the Technische Universität Berlin and is characterised by low thermal conductivity and relatively high compressive strength for lightweight concrete. As well as foamed clay spheres as an aggregate, an air-entraining agent was included, so that with a relative density of less than 800 kg/m^3, the concrete has a thermal conductivity of λ = 0,181 W/mK. Using conventional steel reinforcement here would have reduced the heat insulation values, so only a fibreglass rod crack reinforcement was used, which does not detract from the thermal insulation achieved by the infra-lightweight concrete in the monolithic structural components, which were made on site.

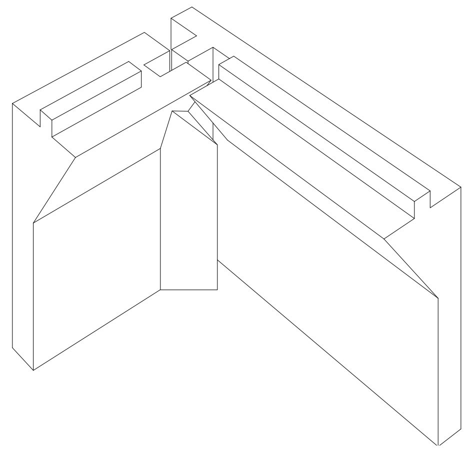
Concrete and heat (or cooling) are the focus of many current projects, including some that are not experiments. As a solid building material, concrete, like all stone, can store heat for a relatively long time. Concrete core activation has now been used in many office and residential buildings and the systems and solutions offered are being permanently optimised, modernised and made more flexible. The use of concrete as a storage medium is now a standard element of construction, although further innovation is required. As well as regulating the temperatures of rooms, concrete can potentially store thermal energy, even temporarily. The Institute of Technical Thermodynamics at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt) in Stuttgart is carrying out research in this area and has used concrete as a storage medium in a pilot project. Storing energy will be a key factor in more efficiently using renewable energies in future. As well as its ability to serve as a thermal storage medium, concrete's high cost-efficiency comes into play here. Storing heat in concrete is cost-effective and economical, if only in pilot plants at the moment. The technology has yet to make the leap into architecture. Creative architects and developers willing to experiment are called for here – inventors. The debate will then develop of its own accord.

Ultra high performance concrete

In combining iron and concrete, Monier had found an ideal combination of the outstanding properties of two building materials: the high compressive strength of concrete almost perfectly complements the high tensile strength of iron or steel. It did however mean that concrete now faced at least two of the problems inherent in metals: corrosion and a comparatively high sensitivity to temperature, in fires for example. To protect the steel in concrete from these adverse effects of physics, the minimum covering, i.e. the distance between a concrete surface and the steel inside it, is usually 3 cm. The thickness of this protective layer is however the total material thickness of the walls, ceiling and floor of the Weinberghaus at Wörrstadt near Kaiserslautern (Fig. A 8). Prefabricated Ultra High Performance Concrete (UHPC) concrete structural components were connected at the edges with preformed notches and slots. All the Weinberghaus components were joined on site using a moisture-resistant UHPC-based mineral mortar with quartz powder. The use of high-strength, self-compacting fine-grained concrete (with a maximum particle size of 2 mm) made it possible to reduce the thickness of the prefabricated concrete components to this extreme extent. It has a compressive strength of at least 100 N/mm^2 and, due to micro-reinforcing steel mesh matting, an adaptable bending tensile strength of at least 25 N/mm^2. The pressure-resistant concrete therefore required a supplementary building material.

Precision, accuracy of fit, optimisation of connections and an extremely reduced use of materials were among the project's design strategies, although it still took the academic framework of the Technische Universität Kaiserslautern and cooperation between researchers and design teachers to get the Weinberghaus built. Ultra high performance concrete is by no means standard on German building sites. Its high compressive strength of over 150 up to 250 N/mm^2 is not yet covered by European or German regulations. These values have been achieved in ongoing research projects and in initial applications on building sites by very densely packing together fine aggregates with a particle size of less than 0.125 mm (cement, microsilica, quartz powder etc.). Here too, the complex compositions of the concrete's ingredients positively and precisely influence its properties. The Weinberghaus, with its smooth surfaces and delicate appearance, is a successful built experiment. There remains only the task of transferring its construction ideas to other projects.

a



b

c

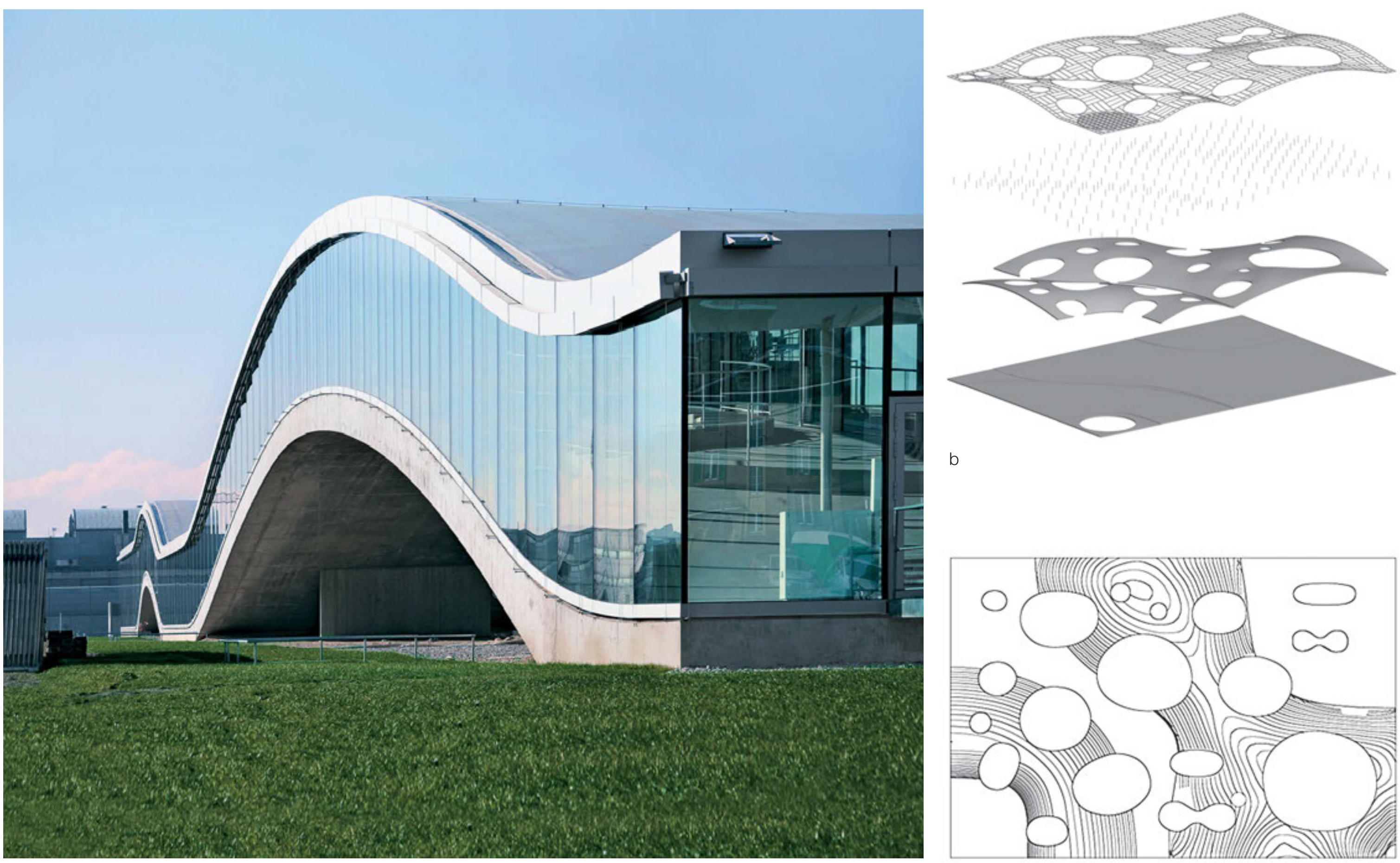
d

A 8

A 9

Concrete and reinforcement

A reinforced concrete building's "skeleton" is made of steel. Even the 3 cm slabs of the Weinberghaus are supported by steel mesh matting, although on an entirely different scale. Very filigree framework, micro-reinforcement, is replacing conventional reinforcement with steel rods and mats. The strategic approach behind its use aims to reduce size and materials. Completely new and unusual materials are also now being used so that their properties can be combined with the possibilities of concrete. One example is textiles. Concrete containing textile fibres is now scarcely inferior to ordinary concrete in its technical properties. The idea is to replace steel, which is liable to corrode, and increase concrete's low tensile strength by supporting it with a complementary form of reinforcement. Complex artificial textile fibres are usually used to do this. Research is also being carried out into fine-grained concretes containing polymers, glass and other kinds of fibres. The idea behind this fibre-reinforced concrete is to radically minimise the (required) "skeleton" of a concrete structural component in the sense of supporting "bones" and dissipate it into the material itself as a network of smaller bones, so to speak. This decentralises the structure's essential tensile strength. High-performance fibres can provide this complement and allow for filigree, thin-walled and geometrically very complicated cross sections. There have already been some examples of practical implementation that would seem to hold promise for other architectural tasks. Applications have so far been limited to strengthening and repairing the facades of existing buildings or in some experimental buildings, but experience is being gained, research carried out, and methods are developed for the future. Here too, the goal is to create thin structural components that will save on resources but still deliver high performance.

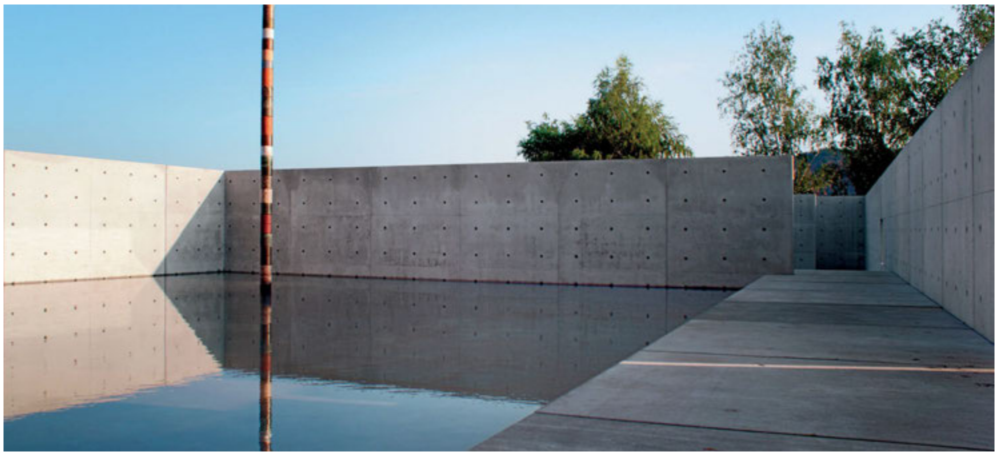


a

b

c

A 10



A 11

A 12

Concrete and free formability

Curving like the hills of the moraine landscape around the building, situated on the northern bank of Lake Geneva, a landscape, a sculpture and a place for learning, research and a meeting place all in one: as interesting as the composition of the free, flowing space of the Rolex Learning Center in Lausanne is, the support structure of this 166 metre long and 121 metre wide building is no less fascinating (Figs. A 9 and A 10). The geometry of the undulating elements of its support structure is determined by the curvature of a smaller and a larger concrete shell, which form most of the basic floor slab and rest on the roof of its underground garage. Architectural artistry and an ingenious feat of engineering were combined here to create the underground garage roof and the form of the shells. The strength of the concrete underground garage roof was further increased by prestressing. It now serves as the horizontal abutment for the shells that form the arching floor of the Learning Center, transferring its vertical loads through the basement floor walls into the foundations. Its architects developed the basic form of the curved surfaces during the planning process. In parallel, engineers from Bollinger + Grohmann planned a model based on the cambered surface of the designed shells. This cambered form also anticipated the shells' planned long-term deformation to most closely approximate the geometry the architects wanted the building to have in its deformed final state. The geometry generated then served as a basis for the project's execution planning and implementation. One precondition for it was a freely formable concrete with specifically manipulable structural properties. It would not have been possible to cast such a monolithic curved surface with any other material.

This project's construction ties in with a major chapter in the story of concrete architecture: shell construction. From about 1900, thin-walled concrete dome shells gradually began to replace brick-built domes, especially after 1945. Buildings by the Spanish civil engineer and architect Eduardo Torroja and Félix Candela were pioneers in this area. Frei Otto, one of Germany's most influential 20th century architects, also explored concrete's possibilities in his structures. By combining various materials, he developed high-performance composite membrane and concrete structures and concrete grid shells. Thin shell structures however, usually make complicated demands on structural physics, geometry and materials, which makes planning and building them more complex and costly. Yet they offer an opportunity to build design ideas that would be otherwise impossible to build. Beyond the tradition of shell construction, this also applies to the work of the Spanish architect Santiago Calatrava: his bridges, railways and high-rise buildings would have been inconceivable without compliant and freely formable concrete.

Concrete and surfaces

People live through stories. Stories are told about buildings and by buildings and they speak to us of the cultures, fashions and affectations of those who built them. For the storytellers among architects, formable and essentially ahistorical concrete is as tempting as a sheet of blank paper is to an author. Every kind of story imaginable can be "told" and then eternalised with concrete.

The surface of set concrete results from its manufacturing process. Whether we mean to or not, we find out something about the formwork material used: whether it was rough or smooth, old or new. We can see where it might have cracked or whether a leaf strayed onto an unforeseen spot. Perhaps we can also see whether the day the concrete was poured was too hot or too cold for perfect work. Tadao Ando celebrates pristine exposed concrete, which speaks less about chance and more about its disciplined and controlled manufacturing process, in Germany most recently in the Stone Sculpture Museum in Bad Münster am Stein (Fig. A 11). The surface's evenness and geometric play of joints and anchor holes highlights the space and light in Ando's works. Concrete is the perfect building material for this, not only because it can be freely formed, but because it is poured, so it can be used to make everything from monolithic structural components up to entire buildings. This fascinates not only Tadao Ando; many contemporary architects pursue the idea of a "building cast in a single piece" in their works.

A 9 Rolex Learning Center, Lausanne (CH) 2010, SANAA Kazuyo Sejima, Ryue Nishizawa
A 10 Rolex Learning Center
- a Free tensioned concrete shells with supporting arches form the building's floors.
- b Support structure: roof over the basement floor, shells, steel roof
- c Contour model, concept, design phase

A 11 Exposed concrete with six binding holes equally distributed across each formwork panel, Stone Sculpture Museum (Steinskulpturenmuseum), Bad Münster am Stein (D) 2010, Tadao Ando
A 12 Printed exposed concrete facade (photo concrete), Bibliothek für Forstwirtschaft, Eberswalde (D) 1999, Herzog & de Meuron (in cooperation with photo artist Thomas Ruff)

A 13

This freedom to design surfaces by reproducing details has led to concrete being used in a series of projects in recent years. In many cases, only concrete has made it possible to build some design ideas at all. Just as computers now offer authors a wealth of possibilities and aids, in the design of text and idea generation, concrete provides architectural "storytelling" with an enormous range of possibilities. Polyurethane elastomeric structure matrices for example, mean that any conceivable surface structure can now be poured in concrete. Photo concrete uses various processes to inscribe pictures permanently onto a concrete surface, making it possible to interpret images in an iconographic way. One prominent example of this is the facade of the library at Eberswalde University for Sustainable Development by Herzog & de Meuron, which was designed by the photographic artist Thomas Ruff (Fig. A 12, p. 17).

Self-compacting concrete's very fluid consistency makes it possible to create a much wider range of forms with techniques ranging from pouring it into filigree formwork systems through to using it to mould pre-existing structural components. One poetic and romantic example of this is AFF Architekten's translation of a wooden ski hut in the Erzgebirge Mountains into a robust and seemingly archaic concrete structure (Fig. A 14). Coupled with its recreation of the old hut's floor plan (motivated in part by building regulations), concrete makes the preceding building's appearance, haptic and patina tangible, unshakeable and legible – architecture as a teller of tales.

Concrete and colour

Daylight is made up of the light of various colours on the spectrum. A rainbow makes red, orange, yellow, green, blue, indigo and violet visible, but not grey. Grey emerges somewhere between black and white. Concrete is grey because cement as a binding agent is grey. This fine powder gets its colour from the burnt cement clinker and gypsum or anhydrite, which are ground up together. As a result of the firing processes, cement clinker is almost black. Gypsum and anhydrite are very light, almost white. Depending on regional availability, sand (white, yellow, brown, red), aggregates (often grey, but also black, coloured or glittering) and water may also be added to grey cement. Coloured pigments, special glass, metal or organic aggregate materials can also be added. Concrete is a mixture of materials, so its colour depends on its ingredients. Despite cement's grey, concrete can be any colour and can be used accordingly in architecture. Here too, it all depends on the architect's will and intentions. Stephan Braunfels envisaged his "Band des Bundes" series of government office buildings along the River Spree in Berlin in white concrete, although his plan was not carried out. Valerio Olgiati wanted a red colour reminiscent of earth, for his Atelierhaus (studio house) in the Swiss village of Scharans (Fig. A 13). The Kunstmuseum Liechtenstein in Vaduz by Morger, Degelo and Kerez features black-green basalt concrete.

More interesting than decisions on the colour of a concrete surface is the way in which light, its surroundings and age can change perceptions of its colour. This also applies to a cabin made of massive logs, which not only ages, but radiates a different inviting atmosphere depending on the time of the day and year. It's especially true of glass buildings, where the intention often seems to be to negate the structure's materiality and reflect its surroundings. Concrete's solidity means that it cannot be a mirror; it is not smooth, not shiny, not perfect enough. It reveals its character in the play of light and shadow, in the differences between the glittering light of midday and warm evening sun. Built and formed, concrete is far from characterless or featureless. The form, significance and perception of architecture can find ideal expression in concrete. Visitors to the Bruder Klaus field chapel in Wachendorf by Peter Zumthor feel this (Fig. A 15), if not while walking through the fields to the chapel, then as soon as they step inside it and are safe within its tamped concrete walls, touched by

a

b

c

A 14


a


b


c

A 15

the black walls' "orchestra of light" in its dark interior, which sharpens the perception of light, smell and sound: here, architecture is palpable.

Concrete and nature

Humanity builds as protection from nature and to live in harmony with nature. As antagonistic as that sounds, it precisely describes both the intention and dilemma of many architects. Buildings change nature and influence it, but sometimes architects succeed in harmoniously combining the contradictory. One example of this is architect Antón García-Abril's small holiday house on the Galician coast of northern Spain (Fig. A 16).
A close relationship to the place and an experimental construction process formed the basis for this project. First, a shallow pit was dug in the forest, then a wall was erected along its edges. Ready-mixed concrete was poured into the pit, then bales of straw were stacked up and covered with plastic foil to prevent the liquid concrete from penetrating the light straw to form what would be the interior. The future house was then concreted. Before the concrete set, the architects scattered loose earth over it to enhance the natural, apparently "revealed" character of the "stone". The architects cut openings with a stone saw out of the cube in three places. Within a year, the calf from the neighbouring farm had eaten the straw on the inside. The texture of the cleaned and sandblasted interior walls is now a reminder of those bales of straw. Its purist interior design complements the rough look of its shell, creating an atmosphere of safety, shelter and well-being. In this form, concrete has again become what its ingredients were: part of nature. This small house on the coast is self-sufficient, yet it can't help showing off, just a little. Nature and the sea are the real "stars" here, but this house is a gem. García-Abril chose a material that is centuries old and yet modern. Concrete protects its inhabitants against the wind, sun, cold, rain and perhaps even from the sea. Wishes and ideas have become abiding reality.

Notes:
[1] Herrmann, M.; Sobek, W.: Functionally graded concrete: Research on building sustainably with concrete, Betonwerk und Fertigteil-Technik, 78 (2012), 2, pp. 16–18
[2] Research project SPP 1542 »Leicht Bauen mit Beton« (Lightweight concrete structures) carried out with the participation of various universities: http://spp1542.tu-dresden.de/programm/universitaeten (As at 01/04/2014)
[3] The Global Cement Report, Eighth Edition
[4] United Nations, Department of Economic and Social Affairs, Population Division (2011). World Population Prospects: The 2010 Revision CD ROM Edition.
[5] Scheidecker, Fritz (ed.): Aus der Geschichte der Bautechnik. Grundlagen Band 1. Basel 1994, p. 69
[6] http://de.wikipedia.org/wiki/Ton_(Bodenart) (As at 14/01/2013)

A 13 Coloured exposed concrete, Ateliertheater Bardill, Scharans (CH) 2007, Valerio Olgiati
A 14 Hut in the Erzgebirge Mountains (D) 2010, AFF Architekten
a Casting of the original wooden facade with self-compacting concrete
b An extra glitter effect was created by adding a phonolite grit aggregate
c Interior exposed concrete walls
A 15 Bruder Klaus field chapel near Wachendorf (D) 2007, Peter Zumthor
a Exterior view
b Tamped concrete layers mark individual work sections
c Soot-blackened interior
A 16 Holiday house on the Costa da Morte (E) 2010, Ensamble Studio, Antón García-Abril
a The building fits into the landscape like a rock.
b All the openings were cut into the walls with a stone saw.
c Smooth, grey fibre cement furniture contrasts with the walls' rough surfaces


a


b


c

A 16


W129.
W129.

Building material and products

Martin Peck

B 1.1

Throughout the 20th and early 21st century, concrete has been the main material used in construction, shaping recent "Baukultur" or building culture in Central Europe as almost no other building material has. Before the development of modern concrete construction, masonry predominated in building with mineral construction materials. Masonry structures have been built for about 8,000 years. Despite this construction method's long history, it is still mainly used today to build load-bearing structural components that can absorb only compressive loads. The building of ceilings, beams and framework structural elements was limited to classic vaulted structures, which use a lot of materials and are complex and costly to build. The introduction and development of modern concrete and reinforced concrete construction in the past 150 years meant that structural components and complex support structures could be built with another mineral construction material. In spite of their relative slenderness, such structures can absorb compressive forces as well as high tensile and bending loads in the long term, significantly expanding the potential of support structures, which has lent architecture a vital impetus. Slender roof structures with the types of spans usually found in building construction can of course also be built of steel or wood, but reinforced concrete and the construction method it represents have some crucial technical and economic advantages over these building materials (such as fire resistance), which is why concrete has become so well-established in building all over the world.

What is concrete?

Construction with hydraulic binding agents has a history going back more than 2,000 years old. The Romans built with hydraulically hardening binding agents made of lime and volcanic ash (puzzolan) whose hardening reaction was basically like that of today's cement. At this time too, concrete (which Marcus Vitruvius Pollio [Vitruvius], the Roman architect, engineer and architectural theoretician of the 1st century B. C. and others documented under the name "opus caementitium") contained locally-available natural stone to save on expensive binding agents, or hollow clay vessels were used to reduce a structure's weight. The best-known historic concrete structure of this period is the Pantheon in Rome (approx. 125 A. D., Fig. B 1.2). Its hemispherical dome with an inner diameter of around 43 m – a size that was only even nearly achieved again in the Renaissance – was the world's largest dome for over 1,000 years and still marks a high point in the development of architecture and construction. The Pantheon was one of the first buildings to be planned and built with great creativity and experience in all its structural, construction operations and building material details.
Construction with "opus caementitium" spread all over the Roman world. Buildings built with this material or their ruins remain wherever its basic materials were available. After this early boom in building with hydraulic construction materials, most knowledge of these techniques was lost in subsequent centuries. Only when the first forms of cement were developed in the late 18th century did the beginnings of modern concrete construction become discernible. Iron and steel was already widely used at this time, so it was logical to combine steel's tensile strength with lighter concrete's compressive strength. The invention of reinforced concrete, a composite building material, has been ascribed to a French gardener, Joseph Monier (1823–1906), who for structural reasons added steel wire to the concrete he produced. In the 19th and early 20th centuries, research and study was carried out on structural engineering and the technology of concrete until researchers succeeded in accurately controlling the properties of hardened concrete, in particular its compressive strength, by using different mixtures, and in mathematically representing the structural properties of reinforced concrete support structures. Large reinforced concrete buildings were then built in hitherto unimaginably short times and with constantly improving techniques and quality. Architects were inspired by these construction methods and their new range of constructive possibilities and responded with an outburst of creativity.

B 1.1 The main constituents of concrete are cement, water, and gravel or sand
B 1.2 Pantheon, Rome (I) about 125 A. D.

By the end of the 1920s, concrete and steel-reinforced concrete construction had become an integral part of global "building culture". Concrete is generally defined as a material that sets when water is added to it and even under water and once set, retains its technical properties. This mundane definition of hydraulic hardening highlights its similarity to other binding agents, with a similar hardening reaction that is also created by mixing dry mineral ingredients, such as gypsum mortar and lime mortar, with water. At the same time, concrete differs from these materials in its durability and resistance to moisture.
Concrete is composed mainly of cement, water and graded aggregates (gravel, sand) (Fig. B 1.1). Commercially available cement consists of natural earths (limestone and marl clay), which are burnt together at around 1,400 °C and then ground up with other ingredients. The cement in the concrete hardens together with most of the added water. The cement, water and sand mixes with the aggregate, producing a plastic to liquid mortar that encloses the coarser aggregate and can carry it in its flow. In terms of volume, ordinary building concrete is made up of about 13 % cement, 7.5 % water, and almost 80 % natural aggregates.

Concrete – a standardised building material

The increasing "Europeanisation" of regulations on concrete and reinforced concrete construction since 2000 has produced a constantly evolving system of European and national building regulations. Although fewer profound changes are now being made, keeping an overview of the current status of the various construction standards often overwhelms even experts. Given the different standards' increasingly short validity periods, it makes little sense to describe the regulations in detail at this point. Instead, their main regulations and regulatory and safety principles, which form the basis of national and European standards and are probably more durable than sometimes short-term regulatory situations, will be presented and explained below. Reference must however be made to specific standards in describing the main statutory building regulations that set concrete construction standards and their relevance in planning and construction.

Building regulatory background

The construction of load-bearing concrete and reinforced concrete structural components is subject to strict statutory building regulations in Germany and in most European countries. These are generally part of public building legislation and in Germany are laid down at the Länder (state) level in state building regulations (Landesbauordnungen) and have the force of law. The main elements of the building regulations governing concrete construction are the various national and European calculation and design standards and regulations on concrete manufacture and on executing and monitoring construction work. For calculating and designing concrete support structures these are,

- EN 1992-1-1, Euro code 2 "Design of concrete structures – Part 1-1: General rules and rules for buildings" in conjunction with national application rules

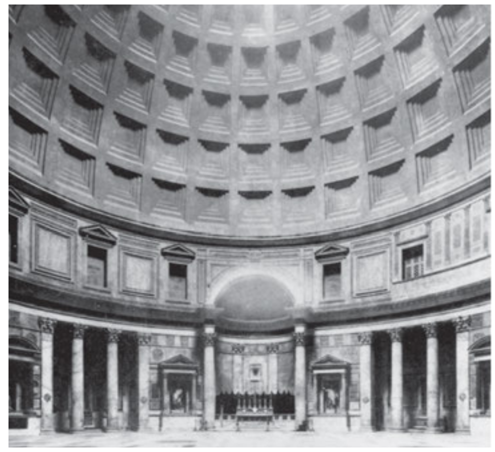
on the manufacture and monitoring of concrete,

- DIN EN 206-1 "Concrete – Part 1: Specification, performance, production and conformity"
- in conjunction with DIN 1045-2 "Concrete, reinforced and pre-stressed concrete structures – Part 2: Concrete – Specification, performance, production and conformity – application rules for DIN EN 206-1"

on the execution of structures and monitoring of concrete on the building site.

- DIN EN 13670 "Execution of concrete structures"
- in conjunction with DIN 1045-3 "Plain, reinforced, and pre-stressed concrete structures – Part 3: Execution of structures – application rules for DIN EN 13670"

These standards form a consistent national safety system.
Since the regulations on load-bearing concrete and reinforced concrete structures have the force of law, their application is mandatory in Germany. They do not have to be separately stipulated in a planning or building contract, but they cannot be excluded.
The main regulations mentioned above are however just the core of the building inspection safety system. They are based on a series of other materials, testing and construction performance standards. Concrete's basic materials, its composition and properties, and the testing and verification of these properties are also standardised and their use is authorised in building authority regulations and individual regulations. There is also a series of subsidiary regulations, such as the guidelines of the German Committee for Reinforced Concrete (Deutscher Ausschuss für Stahlbeton – DAfStB), which usefully more precisely define and supplement the main standards on certain types of building or applications of concrete, such as the DAfStB guideline on "Waterproof concrete structures" (see " Water-impermeable concrete structures", p. 43f.). These regulations have the character and structure of a standard, but have not been adopted by the building authorities and are therefore mainly relevant for the purposes of civil law (contract law).
The national regulations on calculating and designing a concrete or reinforced concrete support structure are based on the various effects of each individual element in the support structure (live loads, dead weight etc.). Appropriately exceeding the verified and designed resistance of structural components will ensure that the specified national safety standard is reached.



B 1.2

Structural planning must include verification of load-bearing capacity and serviceability limit states and a calculation of durability. The verification conditions of serviceability impose high demands on the statical properties of a structural component, because a concrete slab that is to bear only assumed loads may show considerable deformations (sagging, cracks) in the limit state of this structural behaviour, so it will not be serviceable, not only in the normative, but also in the general sense. Proof of the serviceability of floor slabs for example, is therefore limited to precisely these criteria: maximum sag, maximum crack formation and an even distribution of permissible cracks throughout the structure.
In practice, a structural planner must know whether a structural component or a building falls under the scope of building regulations statutes. The main regulations are often the only concrete construction regulations for many applications and there is largely no alternative to them, so they are also usually applied to structural elements that are not subject to legally applicable building regulations standards in the planning and manufacturing of industrial building and underground garage floor slabs that do not have a statical structural function for reasons to do with civil liability.

Calculating durability

Since only sufficiently robust construction ensures a support structure's safety in the long term, the durability of a concrete or steel-reinforced concrete structure is also part of its design. The principle of effect and resistance applies here. All corrosive, damaging environmental influences on a concrete or reinforced concrete structural component during the period of its use count as effects for the purposes of durability. Robustness is ensured by taking appropriate structural or concrete technology measures.
Current standards do not specify verifiable proofs for calculating durability; instead, the usual natural and some frequent anthropogenic corrosive environmental influences are classi-

fied and directly assigned to the component's resistance as structural and concrete technology measures. Based on experience of the durability of concrete and steel-reinforced concrete structural components, their resistance is calculated for a minimum service life of 50 years. This assumption is realistic even in the face of powerful corrosive impacts, because concrete structures designed and built in accordance with earlier regulations and with lower safety standards have been observed to have usually much longer service lives than was planned for.
The structural planner takes the first step in calculating durability, appropriately assessing the corrosive environmental conditions affecting a structural component over the course of its usage to the best of his knowledge. These impacts are classified for planning purposes in a system of "exposure classes", which realistically represent corrosive attack situations. From the exposure classes are derived a series of criteria for action under the provisions of DIN EN 206-1 and DIN 1045-2, which must be taken into account in designing a support structure and manufacturing and processing concrete for a structural component (Fig. B 1.5).
The standards deal mainly with natural environmental conditions. Some anthropogenic effects are also taken into account because they will of necessity or at least frequently occur in certain types of structures or structural components. These include the impact of de-icing salts, wastewater, salt water and swimming pool water and increased mechanical loads on a concrete surface caused by wheeled or tracked vehicles and goods storage.
Potential corrosive attacks are categorised according to their type and intensity, so the exposure class system is easily identified. Each class is represented by numbers and letters that stand for a certain category of corrosive attack, by frost or chemically attacking elements in ambient groundwater, for example. The class is designated by two capital letters beginning with an "X" for "exposure class". This is followed by the first letter of the English term for the type of attack. The following number expresses the attack's expected intensity. This class system realistically categorises the effects on concrete and steel-reinforced concrete structural components that are relevant to their durability and enables their resistance to expected corrosive influences to be economically designed (Fig. B 1.3). DIN 1045-2 contains examples of structural components to make it easier for structural planners to classify them correctly.

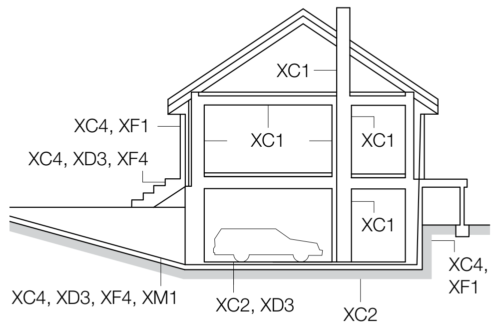
Selecting and allocating exposure classes is always the first step in designing a concrete or steel-reinforced concrete structural component. Since the exposure class also prescribes minimum compressive strength, a concrete structural component cannot be properly designed without prior categorisation (Fig. B 1.4).
Durability calculations for structures in which usage or operational conditions cause corrosive influences on concrete structural components can only be carried out in rare and clear-cut individual cases with the system of normative exposure classes. Such buildings include chemical and galvanic plants, chemical storage buildings and biogas facilities. Corrosive operational conditions must always be taken into account as a specialist part of planning. Identifying such impacts and their effects takes specialist expertise, the participation of the developer, and/or the involvement of an expert. The durability of reinforced concrete structures takes both materials, the concrete and the steel reinforcement, into account. Protection of the steel reinforcement embedded in the concrete from corrosion can only be ensured by the thickness and quality of the protective concrete layer (concrete covering). Steel reinforcement must be completely encased by a thick cement matrix. DIN EN 206-1 and DIN 1045-2 therefore only deal with structurally dense normal, lightweight and heavy concretes.

Regulations on and requirements of construction operations

While structural planning always regards a structure or structural component as "complete", with all the desired properties of the hardened concrete and reinforcement it contains, the demands on the properties of fresh concrete (unset concrete) are solely oriented towards construction operations requirements. The constructing company decides on these when the concrete is ordered, based on the construction schedule and site conditions (transport, reinforcement density and formwork geometry). The most important properties of fresh concrete for construction operations purposes are:

- the concrete's consistency, its fluidity or deformability and suitability for the placing situation and method chosen and which may be necessary in assessing the concrete's pressure on the formwork and speed of concreting,
- the hardening rate as a value indicating the expected stripping times in the prevailing temperature conditions,
- the maximum particle size of aggregates, which depends on the concrete coverage and maximum reinforcement density, so can often only be defined immediately before concreting begins.

Planning documents for formwork and reinforcement based on the calculation of properties are given to the constructing firm as construction specifications. Planners must also provide information on the exposure class and applicable compressive strength class for each concrete component as parameters for the concrete. Depending on the exposure class, the specifications for manufacturing the concrete will include the following:



B 1.3

Compressive strength class	$f_{ck, cyl}$ [N/mm²]	$f_{ck, cube}$ [N/mm²]	Concrete type
C8/10	8	10	
C12/15	12	15	
C16/20[1)]	16	20	
C20/25[1)]	20	25	
C25/30[1)]	25	30	Normal and heavy concrete
C30/37[1)]	30	37	
C35/45[1)]	35	45	
C40/50	40	50	
C45/55	45	55	
C50/60	50	60	
C55/67	55	67	
C60/75	60	75	
C70/85	70	85	High-performance concrete
C80/95	80	95	
C90/105[2)]	90	105	
C100/115[2)]	100	115	

$f_{ck, cyl}$: characteristic strength of cylinders, diameter 150 mm, length 300 mm, age 28 days, mounted according to DIN EN 12390-2
$f_{ck, cube}$: characteristic strength of cubes, edge length 150 mm, age 28 days, mounted according to DIN EN 12390-2
1) Concretes usually used in buildings
2) General approval or authorisation from building regulatory authorities in individual cases required

B 1.4

B 1.3 The usual exposure class combinations affecting the concrete components of a building.
B 1.4 Minimum compressive strength classes for normal, heavy and for high-performance concretes
B 1.5 Types of attack and exposure classes in accordance with DIN EN 206-1

Attack type	Component	Situation		Example of structural component	Exposure class	Minimum compressive strength class
No risk of attack or corrosion (Structural component without reinforcement or embedded metal in an environment that does not attack the concrete)						
		No attack		Structural component without reinforcement, in soil, not impacted by frost, chemical attack or wear and tear; Interior structural component without reinforcement	X0	C12/15
Reinforcement corrosion (only to be taken into account for structural components containing reinforcement or embedded metal)						
Through carbonising	Structural components with reinforcement or embedded metal that are exposed to air and/or moisture	Dry or constantly wet		Structural components in interiors, including damp rooms in housing, structural components under water	XC1	C16/20
		Wet, rarely dry		Parts of water tanks, founding structural components	XC2	C16/20
		Moderate moisture		Structural components exposed to frequent ingress of air from outside, open halls, commercially or publicly used damp rooms, indoor swimming pools, livestock sheds	XC3	C20/25
		Alternately wet and dry		Exterior structural components exposed to direct rainfall	XC4	C25/30
By chloride (apart from sea water)	Structural components with reinforcement or embedded metal that are exposed to water containing chloride	Moderate moisture		Structural components exposed to sprayed or splashed water in circulatory areas, individual garages	XD1	C30/37
		Wet, rarely dry		Structural components in saltwater swimming pools, in industrial facilities and structural components exposed to process media containing chloride	XD2	C35/45
		Alternately wet and dry		Structural components exposed to sprayed or splashed water in circulatory areas, reinforced road surfaces, park decks	XD3	C35/45
By chloride from sea water	Structural components with reinforcement or embedded metal that are exposed to sea water salty air	Salty air, no direct contact with sea water		Exterior structural components in coastal areas	XS1	C30/37
		Under sea water		Structural components constantly under sea water	XS2	C35/45
		Tidal areas, areas exposed to sprayed or splashed water		Quay walls	XS3	C35/45
Concrete corrosion (To be taken Into account for all concrete and reinforced concrete structural components)						
From frost	Structural components subject to significant freeze-thaw cycle attack	Moderate water saturation	No de-icing salts	Exterior structural components	XF1	C25/30
			De-icing salts	Structures with circulatory areas exposed to sprayed or splashed water containing de-icing salts, if not in XF4	XF2	C35/45 C25/30 (LP)
		High levels of water saturation	Without de-icing salts	Open water tanks, structures between high and low fresh-water levels	XF3	C35/45 C25/30 (LP)
			De-icing salts	Circulatory areas that are treated with de-icing salts, mainly horizontal surfaces in the area of splash water containing de-icing salts, scraper trackways of sewage treatment plants, structures between high and low sea water levels	XF4	C30/37 (LP)
By chemical attack	Structural components exposed to chemical attack from soils, groundwater, waste water or sea water under DIN EN 1045-2 (Table 2)	Weak chemical attack		Sewage treatment plant tanks, liquid manure tanks in agriculture	XA1	C25/30
		Moderate chemical attack		Structural components in contact with sea water or soils that attack concrete	XA2	C35/45
		Powerful chemical attack		Cooling towers with flue gas discharge systems, structural components in contact with powerfully chemically attacking waters, silage silos and feed troughs in agriculture	XA3	C35/45
By wear and tear	Structural components subject to considerable mechanical stress loads on their surfaces	Moderate wear and tear		Load-bearing or bracing industrial floors subject to stress loads from vehicles with pneumatic tyres	XM1	C30/37
		Strong wear and tear		Load-bearing or bracing industrial floors subject to stress loads from vehicles with pneumatic or solid rubber tyres	XM2	C30/37 [1)] C35/45
		Very strong wear and tear		Load-bearing or bracing industrial floors subject to stress loads from elastomer, steel roller or tracked vehicles, Structures in water contaminated with rubble (e. g. stilling basins)	XM3	C35/45

[1)] Surface treatment required

B 1.5

Object	Inspection class 1	Inspection class 2[1)]	Inspection class 3[1)]
Strength class for normal and heavy concrete according to DIN EN 206-1:2001-07 and DIN 1045-2:2008-08	≤ C25/30[2)]	≥ C30/37 and ≤ C50/60	≥ C55/67
Strength class for lightweight concrete according to DIN EN 206-1:2001-07 and DIN 1045-2:2008-08 in the relative density classes D1.0 to D1.4 D1.6 to D2.0	 Not applicable ≤ LC25/28	 ≤ LC25/28 LC30/33 and LC35/38	 ≥ LC30/33 ≥ LC40/44
Exposure class under DIN 1045-2:2008-08	X0, XC, XF1	XS, XD, XA, XM[3)], XF2, XF3, XF4	–
Special properties of concrete	–	• Concrete for water-impermeable structures (e.g. “white tanks”)[4)] • Underwater concrete • Concrete for high temperatures, T ≤ 250 °C • Radiation protection concrete (outside nuclear power plant construction) • DAfStb guidelines must be applied in special applications (e.g. to retarded concrete, concrete construction dealing with water-polluting substances).	–

[1)] Additional self-inspection requirements under Section 2; inspection by a certified inspection agency under Section 3
[2)] Prestressed concrete in the strength class C25/30 falls into Inspection Class 2;
[3)] Does not apply to ordinary industrial floors;
[4)] Concrete with high water impermeability can be classified in Inspection Class 1 if the structure is only temporarily exposed to standing seepage water and nothing to the contrary is stipulated in the project description.

B 1.6

- minimum cement content
- maximum water-cement ratio (w/c), i.e. the proportion of water to cement
- restrictions in terms of the types of cement that can be used
- restrictions in terms of the use of additives (fly ash)
- possibly separate specifications for aggregates
- possible use of micro-pores of air to increase frost resistance

The concrete manufacturer or ready-mix concrete plant then produces a concrete mix based on the properties of the fresh and hardened concrete specified and demonstrates in initial tests that the required properties of the fresh and hardened concrete have been reliably achieved. In practice, every ready-mix concrete plant keeps a list of concrete types proven for use in which almost all the usual combinations of exposure classes and compressive strength classes are listed and directly deliverable. After initial testing of the manufactured and delivered types of concrete and its basic materials (cement, aggregates, mixing water), the concrete manufacturer carries out an internal production check, which involves constant testing of the fresh and hardened concrete properties of the manufactured concrete and regular performance tests of technical equipment. The applicable standards also formulate requirements on the equipment and staffing of the plant's own internal concrete technology testing unit.
To crosscheck the concrete plant's own internal production checks, the constructing company is also required to test and monitor the concrete during placement on the building site. The extent, type and intensity of the monitoring of the concrete and its placement that the construction company is required to carry out is divided into three inspection classes. Their classification is based on the exposure classes of the respective construction materials, the concrete's compressive strength and some other criteria (Fig. B 1.6).
Concrete structural components in Inspection Class 1 only require active testing or sampling if there are any anomalies. For concrete work meeting the criteria of Inspection Class 2 and Inspection Class 3, the constructing company must provide a testing unit equipped with the appropriate staff and test equipment or commission inspection by an external testing agency. DIN EN 13 670 and DIN 1045-3 prescribe detailed tests on fresh concrete and regular sampling to verify the compressive strength of the placed concrete. Inspections must be documented in writing. The building site must also be registered with a certified testing agency that regularly checks the inspection documents and tests results and after construction is completed confirms the proper performance of inspection, assuming this to have been the case.

Basic materials

In Europe an overarching system of standards, often with national adaptations (application regulations), apply to concrete's basic materials. Materials standards therefore mainly specify the technical properties for one or more specific applications of a material. National application regulations generally require the concrete's basic material to conform to the relevant material standards but they can also regulate or even exclude the national use of some materials.

DIN EN 206-1 regulates the use of basic materials in concrete at the European level and covers basic regulations that are precisely defined, extended or limited in national application regulations in individual countries. Germany's application regulation is DIN 1045-2. Both standards must however be applied, which is complicated in practice. DIN technical report 100, “Concrete”, summarises their contents so that users do not have to laboriously compile and double-check what the valid regulations are from the two sets of regulations.

Cement

Cement is made of naturally occurring mineral raw materials extracted from quarries.

Manufacture, standardisation and material characteristics
The basic mineral materials of cement are limestone and marl clay, whose geological composition makes them suitable for its manufacture. There are deposits of these minerals in almost all regions in Europe, although they vary in composition and formation. These natural deposits contain iron oxide, which produces cement's grey colour. Limestone consists mainly of calcium carbonate ($CaCO_3$) and this is a main component in the raw materials mix. The preparation of the raw material is vital to cement's quality and uniformity. Because its raw materials are extracted from natural deposits, the content of its individual mineral elements varies. The raw material's composition is constantly checked and adjusted if necessary during the extraction and mixing process. The mixture should have a calcium carbonate content of at least 76 – 78 %. Proportions of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) must also be precisely maintained.
To manufacture cement, the raw materials are heated in a kiln to about 1,400 °C, producing Portland cement clinker. The word “clinker” is a traditional description from an earlier manufacturing process in which the mass was taken out of the kiln and the “clinking” hard, brick-like pieces were ground in a cement mill. Today's manufacturing produces an end product of the

burning process through the sintering of minerals and their conveyance through a rotary kiln in the form of compact grey nodules up to the size of an apple with a pronounced mineral hardness (Fig. B 1.7).
Portland cement is made by grinding clinker and adding about 5 % gypsum or anhydrite ($CaSO_4$) to control hardening. With recent government policy seeking to reduce industrial CO_2 emissions, the manufacture of pure Portland cement (standard designation CEM I) has declined steeply in the past ten years. Carbon dioxide is produced in clinker manufacture on the one hand by the firing required to create the necessary heat for the process. Since cement manufacture began, the proportion of CO_2 it produces has been more than halved by optimising processes and it is constantly being further optimised. On the other hand, the deacidification of limestone also produces CO_2. The calcium carbonate ($CaCO_3$) that the stone contains decomposes in the burning process into calcium oxide (CaO) and CO_2. This breaking down of limestone is indispensable in cement production and the resulting amounts of CO_2 produced cannot be reduced. To reduce CO_2 emissions, other key ingredients, such as ground slag sand, powdered limestone, hard coal fly ash or oil shale are added to Portland cement clinker, which produces standard CEM II or CEM III type cements with lower specific CO_2 emissions.

B 1.7

B 1.6 Inspection classes for concrete
B 1.7 Cement clinker
B 1.8 Various types of cement and their composition

Cements – types and compositions (under DIN EN 197-1 or for special cements DIN EN 14216)

Main cement types	Name (cement type)	Abbreviation	Main constituents [M.-%][1, 2]									
			Portland cement clinker	Slag sand	Silica fume	Puzzolan		Fly ash		Burnt shale	Limestone[5]	
						natural	naturally tempered	siliceous	calcareous			
			K	S	D[3]	P	Q[4]	V	W	T	L	LL
CEM I	Portland cement	CEM I	95 ... 100	–	–	–	–	–	–	–	–	–
CEM II	Portland blast furnace cement	CEM II/A–S	80 ... 94	6 ... 20	–	–	–	–	–	–	–	–
		CEM II/B–S	65 ... 79	21 ... 35	–	–	–	–	–	–	–	–
	Portland silica fume cement	CEM II/A–D	90 ... 94	–	6 ... 10	–	–	–	–	–	–	–
Portland composite cements	Portland puzzolan cement	CEM II/A–P	80 ... 94	–	–	6 ... 20	–	–	–	–	–	–
		CEM II/B–P	65 ... 79	–	–	21 ... 35	–	–	–	–	–	–
		CEM II/A–Q	80 ... 94	–	–	–	6 ... 20	–	–	–	–	–
		CEM II/B–Q	65 ... 79	–	–	–	21 ... 35	–	–	–	–	–
	Portland fly ash cement	CEM II/A–V	80 ... 94	–	–	–	–	6 ... 20	–	–	–	–
		CEM II/B–V	65 ... 79	–	–	–	–	21 ... 35	–	–	–	–
		CEM II/A–W	80 ... 94	–	–	–	–	–	6 ... 20	–	–	–
		CEM II/B–W	65 ... 79	–	–	–	–	–	21 ... 35	–	–	–
	Portland burnt shale cement	CEM II/A–T	80 ... 94	–	–	–	–	–	–	6 ... 20	–	–
		CEM II/B–T	65 ... 79	–	–	–	–	–	–	21 ... 35	–	–
	Portland limestone cement	CEM II/A–L	80 ... 94	–	–	–	–	–	–	–	6 ... 20	–
		CEM II/B–L	65 ... 79	–	–	–	–	–	–	–	21 ... 35	–
		CEM II/A–LL	80 ... 94	–	–	–	–	–	–	–	–	6 ... 20
		CEM II/B–LL	65 ... 79	–	–	–	–	–	–	–	–	21 ... 35
	Portland composite cement[6]	CEM II/A–M	80 ... 88	12 ... 20								
		CEM II/B–M	65 ... 79	21 ... 35								
CEM III or VLH III	Blast furnace cement	CEM III/A	35 ... 64	36 ... 65	–	–	–	–	–	–	–	–
		CEM III/B VLH III/B	20 ... 34	66 ... 80	–	–	–	–	–	–	–	–
		CEM III/C VLH III/C	5 ... 19	81 ... 95	–	–	–	–	–	–	–	–
CEM IV or VLH IV	Puzzolan cement[6]	CEM IV/A VLH IV/A	65 ... 89	–	11 ... 35					–	–	–
		CEM IV/B VLH IV/B	45 ... 64	–	36 ... 55					–	–	–
CEM V or VLH V	Composite cement[6]	CEM V/A VLH V/A	40 ... 64	18 ... 30	–	18 ... 30			–	–	–	–
		CEM V/B VLH V/B	20 ... 38	31 ... 49	–	31 ... 49			–	–	–	–

[1] The figures provided refer to the sum of main and subsidiary constituents (without calcium sulphate and cement admixtures).
[2] Additional subsidiary constituents up to 5 M.% possible, e.g. one (or more) main constituent(s), if they are not a main constituent of the cement
[3] The proportion of silica fume is restricted to 10 M.%.
[4] e.g. Phonolite
[5] Total content of organic carbons (TOC) ≤ 0,50 M.% (L) or ≤ 0,20 M.% (LL)
[6] In CEM II/A-M, CEM II/B-M, CEM IV and CEM V cements, other constituents must be specified as well as Portland cement clinker, e.g. CEM II/A-M (S-V-L) 32,5 R. Analogous information for special cements VLH required.

B 1.8

Strength class	Compressive strength [N/mm^2]			
	Initial strength		Normal strength	
	2 days	7 days	28 days	
32.5 L[1]	–	≥ 12		
32.5 N	–	≥ 16	≥ 32.5	≤ 52.5
32.5 R	≥ 10	–		
42.5 L[1]	–	≥ 16		
42.5 N	≥ 10	–	≥ 42.5	≤ 62.5
42.5 R	≥ 20	–		
52.5 L[1]	≥ 10	–		
52.5 N	≥ 20	–	≥ 52.5	–
52.5 R	≥ 30	–		

[1] Only for CEM III cements

B 1.9

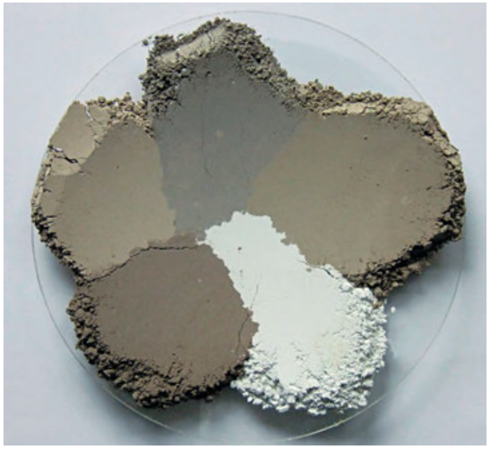
B 1.9 Strength classes of normal cements
B 1.10 Facade made of prefabricated elements with a strong contrast to the white cement around the windows, administration building, Berlin (D) 2012, BarkowLeibinger
B 1.11 Comparing the colours of various cements using the glass plate method
B 1.12 Standard grading curve as specified in DIN 1045-2 for an aggregate with a largest particle size of 16 mm, Curve A = coarse, Curve B = normal, Curve C = sand-rich (pumped concrete, exposed concrete)
B 1.13 Particle compositions in various standard grading curves, largest particle size 32 mm

B 1.10

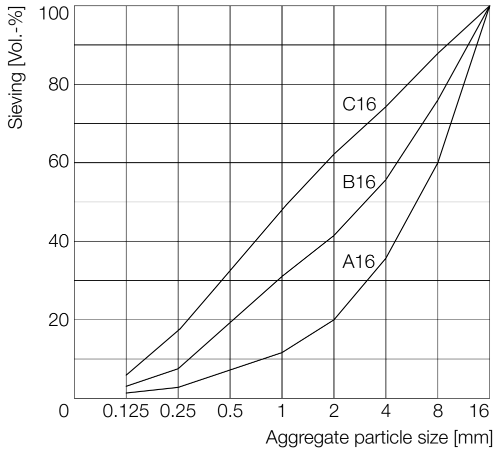
The standards set roughly the same technical requirements for all cements, regardless of their composition. This ensures that most concretes behave similarly in processing, regardless of the cement used.
A cement's material composition and some of the technical properties are indicated in its name (Fig. B 1.8, p. 27).
As well as being classified according to their material characteristics, cements are divided into strength classes (Fig. B 1.9), which are vital in planning a concrete's compressive strength. A cement's strength class can be controlled by modifying its grinding fineness. Planners normally have no influence on the cement used, unless special design requirements are made on a concrete structural component. The concrete manufacturer, usually a precasting factory or ready-mix concrete plant, often chooses the cement based solely on normative and technological criteria, which are specified by the structural component's exposure class. Even where design criteria, such as colour, play a role in selecting cement, the standard's specifications must still be complied with.

Cements – colouring and surface design
As described in detail in the chapter on "Concrete and colour" (see p. 61f.), cement influences the colour of an untreated or treated concrete surface if no other colour changes are made by adding pigments or applying a coloured glaze. A concrete's colour on a smoothly formed surface is however not the same as the colour of unset cement in its powder form, although colour nuances can also be identified in powdered cement. The following initial test can help planners choose one or more cements for further colour tests. Take about the same amount of each cement (20–50 g) heaped up a few centimetres apart on a clean glass plate and press another clean glass plate slowly onto the first. The small heaps of cement will be pressed into contiguous areas of colour that stand out sharply from each other and you will be able to easily identify the different cements' basic colours and compare them (Fig. B 1.11).
A concrete's ingredients, the influence of construction operations and maturity (age and degree of hardening) all affect the colour of concrete's subsequent surface. The concrete's fine ingredients, which emerge on the surface, are also essential. In their first years in particular, concrete surfaces lighten with increasing maturity. Cements of the same type that were made at different production locations can also have very different colours. Perception of shades of grey and other colours (blue, brown) is purely subjective. Tests on sufficiently large areas can help planners make decisions on colour.
Inherent variations in the composition of its raw materials influence cement's technical properties and can change its colour. The converse is also true. If for example, a CEM III type cement is to be used because of its lighter colour, it must be noted that its setting rate is fairly slow, which can involve longer stripping times when concreting in winter. If a cement is chosen for design reasons, the compatibility of the cement's properties with the requirements of construction operations must first be precisely checked.
White cement is technically classed as belonging to the Portland cements group (CEM I). It is made of iron oxide-free raw materials and, due to its white colour (Figs. B 1.10 and B 1.11) and ability to take on different colours, it is often used in exposed concrete surfaces, artificial stone products and for terrazzo-type floor coverings. Its higher-grade basic materials and more complex manufacturing process make it far more expensive than grey cement. Since its use is limited to special design applications for economic reasons, few companies manufacture it for sale.
Cements with lighter main ingredients include cements with a higher content of slag sand such as blast furnace cement (CEM III) and Portland blast furnace slag cement of the CEM II/B-S type. Portland white limestone cement (CEM II-LL) is also mainly light, due to its powdered limestone content. Portland composite cements (CEM II-M) usually have a lighter colour. Planners cannot simply choose the cement for a lighter coloured concrete; rather this choice must be made depending on what is available locally, because the market availability of different types of cement varies from region to region. Concrete surfaces made of cement containing more than 30 % ground slag sand sometimes emerge with a blue colour if non-absorbent formwork is used. This is usually temporary and fades a few hours after stripping.

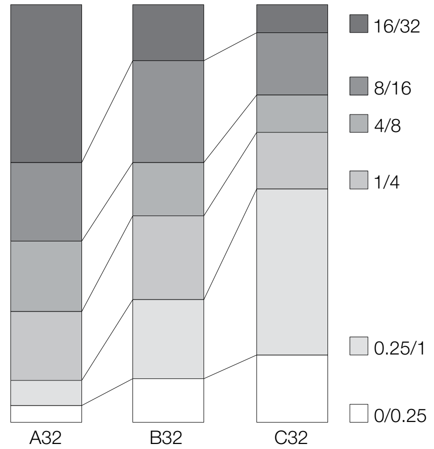
Aggregates
Aggregates were often used in earlier concrete buildings for economic reasons and to use as little as possible of what was then the very expensive material of cement in manufacturing of an ultimately hard structural component.
As concrete technology developed, it soon became clear that aggregates also significantly improve hardened concrete's technical properties. Much higher compressive and surface strengths can be achieved, there is less volume reduction while the material hardens and dries, and the concrete tends to crack less.
Apart from the aggregates used in lightweight concretes, the aggregates in concrete are generally much harder and stronger than the surrounding cement stone. Although they are not involved in the hardening reaction, they are a major element of the strengthening component in the hardened concrete.
The classification of particles into groups, the development of consistent particle composition parameters and today's grading curve system have maximised the technical effects of aggregates in concrete. The grading curve system gives a concrete technologist enough criteria to



B 1.11



B 1.12



B 1.13

analyse and design a particle composition that will enhance a concrete's workability (Figs. B 1.12 and B 1.13).
Aggregates used in concrete are defined mainly in DIN EN 12620 "Aggregates for concrete" and DIN EN 13055-1 "Lightweight aggregates for concrete, mortar and grout". Both are harmonised European standards, so they apply in all points and require no further national supplementation or specification. Each of these materials standards formulates a series of categories of aggregate's technical properties and specifies test figures and threshold values. Use of these aggregates in concrete and cements is regulated in DIN EN 206-1 and by DIN 1045-2 as a national addition. These standards differentiate aggregates as follows:

- Natural aggregates are either round-grained river or moraine gravel or crushed hard stone (basalt, granite, limestone etc.). They are extracted from natural mineral deposits and produced by solely mechanical means.
- Light aggregates are of mineral origin and have a relative density not more than 2,000 kg/m^3 (expanded clay, expanded shale etc.).
- Industrially-produced aggregates are also of mineral origin but are made in an industrial process by thermal or other modifications (e.g. expanded clay).
- Recycled aggregates consist of processed inorganic material that has been previously used as building material (e.g. concrete rubble).

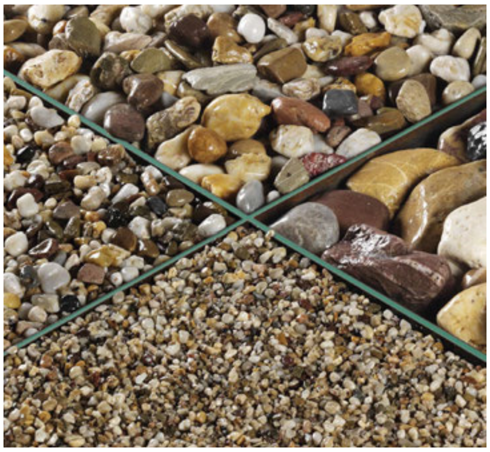
Natural aggregates
Natural aggregates are most frequently used for making concrete. These are mainly gravels and sands that have been deposited by water or the movement of ice-age glaciers of various geological origins in river valleys or moraines. They are differentiated in the market by a regional designation of origin that usually uses the name of the river in the deposit zone (e.g. Main gravel, Upper Rhine gravel, Danube gravel). Apart from the few regions in which crushed hard stone is used, most natural aggregates are extracted from natural gravel deposits by dredging or excavation and sorted in sieving plants into the same particle sizes or "screening fractions". Aggregates that may contain fine deleterious particles (loam, clay, silt etc.) generally undergo an additional wet sieving or washing process.
Screening fractions are graded according to their subsequent applications. An alternative term is the particle size group or grain size. The lower (d) and upper (D) sieve sizes are expressed as d/D. This designation includes the permitted tolerance in each particle size group, i.e. the small amounts of this fraction that fall through the lower sieve (screen undersize) or are trapped in the upper sieve (screen oversize) during a sieve test in the laboratory. Ordinary commercial forms and designations are sand, 0/4 mm, fine gravel, 4/8 mm and gravel, 8/16 mm to 16/32 mm. Depending on the region, the size range separating sand from fine gravel can be 4 mm to 2 mm.
Natural aggregates are traded and processed in particle size groups (Fig. B 1.14, p. 30). This classification means that a concrete's granulometric and overall composition can be optimally adapted to the demands of planning and construction operations and the transport and placement process. Concrete technologists can now use grading curves to design coarser or finer combinations in granulometric compositions (Fig. B 1.12).
DIN EN 12 620 specifies a series of requirement categories for natural aggregates. Chief among these the following are:

- requirements specifying the content of deleterious constituents (materials that disrupt hardening, binding components)
- requirements on the granulometric composition of individual fractions (content of screen undersize and oversize particles, finest sand content)
- requirements on aggregates' geometrical and physical properties (conformity, resistance to frost and de-icing salts, water absorption etc.)

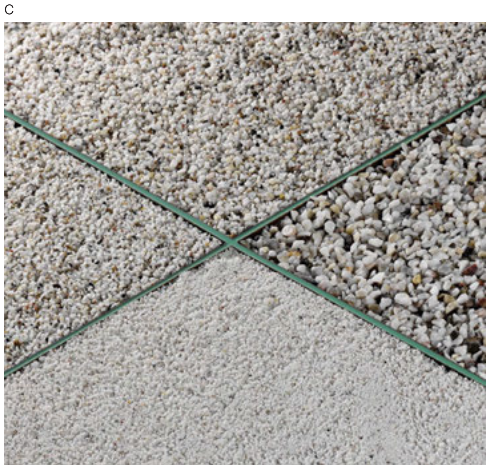
While the properties described above are the verification and test criteria prescribed in standards, planners themselves must always ascertain an aggregate's water absorption and relative density because these are indispensable in calculating granulometric and concrete composition. The relative densities of naturally rounded gravels and sands range from 2,600 to 2,750 kg/m^3. Natural aggregates used in concrete in Europe have relative densities between 2,550 and just on 3,000 kg/m^3.
As well as the requirements on the properties described above, DIN EN 12 620 prescribes a quality assurance and proof of conformity system.

Crushed aggregates are another form of natural aggregate and are produced by mechanically crushing natural hard stone. These are usually coarse aggregates with a minimum particle size of 4 to 8 mm. Adding crushed stone sand generally results in concrete that is hard to work, so it is only used in special applications. Crushed aggregates are used in regions with no or few suitable deposits of naturally rounded gravels.

Lightweight aggregates
Lightweight aggregates are used to make lightweight concretes, structurally dense concrete with a relative density ≤ 2,000 kg/m^3. Lightweight concretes have good thermal insulating properties and can reduce a structure's weight and dead load (see "Lightweight concrete (insulating concrete)", p. 36f.).
The main material standard on lightweight aggregates is DIN EN 13 055. Most commercially available products are either natural (pumice) or industrially manufactured aggregates made of expanded glass, clay or shale.
Expanded glass is a recycled product made of waste glass, which is crushed and homogenised, then a gas-forming constituent (e.g. carbon dust), which burns up in the heat of the smelting process, is added to the basic mix. The gases produced during incineration cause the molten glass to foam, creating a largely closed-cell glass foam, which granulates when it cools and is then sieved into separate particle size groups.
Expanded clay is made of clay containing very little lime and a distribution of fine organic inclusions that is ground, granulated, homogenised and fired in a rotary kiln at about


a

b

c

d B 1.14

1,200 °C. The material sinters into spherical, semi-fluid granulates and the organic constituents burn up. The gases produced make the granulates spherical and they expand to four or five times their original volume. Once cooled, the particles have a very porous core and a hard surface that is closed due to sintering. Various particle gross densities and granulometric distributions can be produced by modifying the original materials and firing process. Lightweight sands in the 0/2 mm and 0/4 mm particle size groups and coarse aggregates up to 10 mm with various gross densities are the most common commercially available types (Fig. B 1.15).
Expanded shale is made in a similar way, although its particles expand not spherically, but at a right angle to the shale's natural horizontal seams, producing elongated, flattish granules.

Recycled aggregates
Political directives aimed at creating an environmentally-friendly recycling economy that will use resources sparingly are providing new impetus to reuse material from the dismantling of concrete and reinforced concrete structures or other, similarly useable demolition materials. The basic materials are pre-sorted according to their main constituents, crushed and then classed into particle size groups in sieves (see "Sustainable construction with concrete", p. 116ff.).
The strength of these materials is usually sufficient to make aggregates for concrete out of them. Compared with natural or light aggregates, recycled concrete aggregates demonstrate far greater fluctuations in their composition and physical properties, which depend on the situation in which they were dismantled. Recycled aggregates absorb more water than natural ones, which must be taken into account in the concrete's composition. The authoritative material standard is DIN EN 12620 and use of these materials is regulated in the DAfStB guideline on "Concrete compliant with DIN EN 206-1 and DIN 1045-2 with recycled aggregates as specified in DIN EN 12620". These guidelines restrict the use of recycled aggregates to the exposure classes of moderate corrosion loads. They cannot be used in structural components in the exposure classes of combined frost and de-icing salts attack (XF2 and XF4) or in those in the higher classes of chemical attack (XA2 and XA3). The guidelines allow the use of pure concrete rubble (Type 1) and "construction aggregate" (Type 2). As well as concrete and concrete products, mixtures can contain mortar, concrete masonry, unbound and hydraulically bound aggregates, natural stone, masonry bricks, bricks and tiles, sand-lime brick, aerated non-floating concrete, bituminous materials and glass, although maximum proportions of these in the mix is limited. Mixtures should comply with composition guidelines and must meet the guideline's testing criteria.
Depending on the applicable exposure class, an aggregate mixture for concrete may only be allowed to contain precisely limited amounts of recycled aggregates. Permissible amounts vary from 25 to 45 vol. %.
Although building authorities first regulated the use of recycled aggregates in concrete in 1998, the amounts used have stayed at a very low level. The treatment process and the testing and monitoring of materials all involve high demands and make manufacturing and using it much more expensive than using nationally available natural aggregates.

Water
Water from the general water supply, i.e. drinking water, is usually used in concrete, although it is not necessary to use such high-quality water, so many concrete factories use natural water from wells, lakes, streams or rivers. Fresh water is also not essential for making concrete, because the salt and mineral content of seawater does not impede hardening. Seawater or brackish water can however generally only be used for unreinforced concrete structural components, because the maximum permitted total chloride content of 0.4 % by mass in reinforced concrete cannot normally be complied with. Industrial wastewater that has been certified as safe can also be used.
Natural water that is not from the drinking water supply must be investigated for a range of deleterious elements before it is used in concrete, because usually no analytical data is available on its quality. Regular monitoring during production is also required to check that the water does not contain constituents that could impede the concrete's hardening, such as humic acids from topsoil, or pollutants that could impair the durability of the concrete or its steel reinforcement.
The quality of water for making concrete and its testing is regulated in DIN EN 1008 "Mixing water for concrete – Specifications for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete". The regulations also cover the use of residual water, runoff from the cleaning of mixers and ready-mix concrete transport vehicles in concrete factories. This is collected in settling tanks, where the coarse constituents (gravel, sand) separate from the water, which can then be reused as aggregate in concrete production.
Residual water cannot be used in some concretes because residues of other additives, such as air-entraining agents, which are designed to increase the concrete's resistance to frost and de-icing salts, could negatively impact the concrete.

Concrete additives and admixtures
Concrete admixtures are materials that have a general or specific favourable effect on concrete's technical, and in a few cases, design properties. They are divided into "additives"

and "admixtures" according to their different characteristics and effects and include all materials not in the original ternary mix of cement, water and aggregate.

Additives

Additives are solids mixed into fresh concrete. Relatively large amounts of them are added, so their quantity and volume must be taken into account in designing a concrete composition. Classic additives are powdered inorganic materials such as hard coal fly ash, silica fume and coloured pigments. The last two are often added as a dispersion (slurry) in liquid form, with the solids first finely dispersed in water to make mixing easier and dosage more precise. Use of additives in concrete is regulated in Germany by the building regulation standards on concrete or by a building authority approval from the German Institute for Construction Technology (Deutsches Institut für Bautechnik – DIBt).

In concrete technology, additives form part of the mortar or cement matrix (cement stone with fine aggregates) in fresh concrete and hardened concrete. The following individual materials standards regulate the properties and composition of frequently used concrete additives:

- Quarry rock dust (fillers) in DIN EN 12620
- Pigments in DIN EN 12878
- Fly ash in DIN EN 450
- Silica fume in DIN EN 13263-1

Additives can be divided into two categories (Fig. B 1.16): Type I additives have no hydraulic properties, so they are not involved in the hardening reaction of the bonding agent. These materials can positively influence the properties of fresh and hardened concrete through their physical effect on the concrete's structure, because they fill the interstices between particles. Quarry rock dust and coloured pigments are additives of this type.

Type II additives are mainly hard coal fly ashes. They have a latent hydraulic effect, i.e., the hydraulic minerals in cement induce a hardening reaction and thus contribute to its strength. Hard coal fly ash is produced in coalfired power plants from the non-combustible constituents of natural coal and accrues as filter dust, so it does not have to be ground. Its mainly spherical particles can improve the workability of fresh concrete (Fig. B 1.17). Hard coal fly ash is usually added to concrete in quantities of 30 to 80 kg/m^3 and it can replace a little less than half the amount of cement. Because fly ash makes up some of concrete's potential alkalinity, only a limited maximum amount can be added.

Another Type II additive is silica fume, a by-product of silicon production. It is much finer than cement, so it can fill and compact the interstices between particles in fresh and set concrete. Adding silica fume to concrete boosts and improves the bond between the aggregate and the cement matrix and considerably increases its strength, so it is used to make high-performance concretes with compressive strengths well above 60 N/mm^2 (see "Ulta highperformance concrete", p. 40f.). Due to its greater effectiveness, much lower amounts of silica fume are usually added than is the case with hard coal fly ash.

Because Type II additives contribute to a concrete's strength, they can be offset in the water-cement ratio (w/c ratio). This is a dimensionless parameter that is easy to identify and specify as a quotient between the amounts of water and cement in a cubic metre of concrete. If additives that can be offset are present in a mix, it is said to have an equivalent w/c ratio (w/ceq). It can be calculated by multiplying the amount of additive that can be offset by the k-value and adding the result to the cement. The k-value is a dimensionless effectiveness factor that the standards correlate with each Type II additive. Hard coal fly ash has a k-value of 0.4, so it contributes about 40% to a cement's strength. Silica fume has a k-value of 1, which is equal to the cement's contribution to the concrete's strength.

The normative application regulations restrict the offsetting of Type II additives used both alone and in combination. The relevant threshold values and restrictions depend on the exposure class and type of cement involved. Because of their major contribution to strength, the DIN EN 206-1 and DIN 1045-2 application standards prescribe somewhat lower minimum cement contents for the use and offsetting of Type II additives, although additives amounting to at least the difference must then be added. The application standards also limit the maximum powder content of concrete, i.e. the sum of all constituents with a particle size ≤ 0.125 mm (Fig. B 1.19). An ultra-fine particle content that is too high can detract from some of the properties of the hardened concrete and result in an increased tendency to crack. The maximum permissible powder content depends on the largest aggregate particle size and other composition parameters. This requirement also indirectly sets the maximum possible additive content. Silica fume for example, should not be more than 11% of the cement content.

Admixtures

Admixtures are a liquid or solid chemical material added to concrete during manufacture or when it is still wet. Relatively small amounts are used and are not taken into account in calculating the concrete's composition up to a total admixture volume of 3 l/m^3. They are added mainly to improve the properties of fresh concrete and facilitate the construction process. European material standard (product standard) DIN EN 934-2 stipulates general requirements for concrete admixtures and DIN EN 206-1 and DIN 1045-2 regulate their application. Using admixtures that do not comply with the material standard requires authorisation from building regulatory authorities. To make identification

B 1.15

Concrete additives

- Coloured pigments
- Largely inert (slow-reacting) quarry rock dusts that do not contribute to strength
- Anorganic, puzzolan materials such as hard coal fly ash, silica fume in powder form or suspended in water
- Trass, which has a puzzolanic reaction

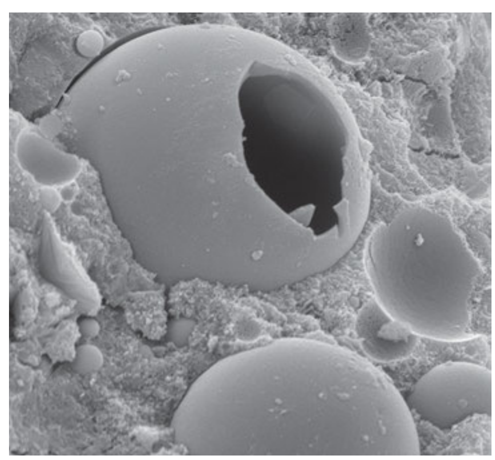
B 1.16

B 1.14 Naturally rounded aggregates in various particle size groups
a Coloured gravel
b, c Round quartz
d Quartz chip

B 1.15 Expanded glass granulate

B 1.16 Type I and II additives usually used in concrete technology

B 1.17 Bonded fly ash particle, seen through a scanning electron microscope



B 1.17

easier, every admixture is designated by an abbreviation based on the term describing its effect (Fig. B 1.20).

Admixtures are used mainly to liquefy fresh concrete. This group of active agents includes concrete flow agents and plasticisers. To ensure certain technical properties in the hardened concrete, the effective water content of fresh concrete must be limited to a maximum amount (maximum permissible w/c ratio). Concretes made in this way without liquefying admixtures would have a very stiff or earth-moist consistency and would be hard or impossible to transport or place with the usual construction methods. The properties of current admixtures make it possible to adjust the consistency of concrete, even those with a very low water content, making them easy to use or even flowing. Consistent further development has made it possible to largely "detach" a concrete's consistency from its water content (w/c ratio) so almost any consistency of concrete with any w/c ratio can now be made using current concrete technology.

Hardening retarders are mainly used in very large volume areas of concrete to ensure smooth joints between individual mounting positions. After appropriate preliminary tests, using retarders in the production of very large structural components allows the concrete's setting to be very precisely controlled. Delays of just 2 to 4 hours are usually required, although longer periods of up to 10 hours and more can also be provided. Hardening retarders can also be added to concrete in small doses as a precaution to ensure a monolithic pouring of structural components in difficult or unclear construction situations or adequate working times in exceptionally warm concreting conditions. The concrete manufacturer's technology laboratory will identify and estimate the most favourable delay times in close cooperation with technical construction site supervisors.
Stabilisers can support the properties of fresh concretes whose composition means that they can tend to segregate. Stabilisers can prevent mortar from separating from coarse aggregates in very fluid concretes.

Aerating agents improve hardened concrete's resistance to frost and de-icing salts. Their influence on the properties of fresh concrete is usually negligible. Spherical micro-pores of air form in the hardened concrete and if they are appropriately sized and distributed, they provide space for expansion if the moisture present in the pore system freezes (Fig. B 1.21). Current standards prescribe the use of aerating agents in structural components that are exposed to both high moisture levels and a significant impact from frost and de-icing salts.
One group of admixtures that is relatively new and still not widely used is shrinkage reducers. These contain organic bonding agents that can reduce shrinkage in cement-bonded construction materials by 15 to 40 %, depending on its composition. They also improve the consistency of volume and with it cracking behaviour, in large-area structural components for example. This group of active agents is currently still being developed.
Apart from plasticisers, all admixtures used in normative concrete (plasticisers, hardening retarders and aerating agents), are added

B 1.19 Highest permissible powder particle content for concrete in strength classes up to C50/60 and LC50/55
B 1.20 Concrete admixtures: groups of active agents and labels
B 1.21 Visible micro air pores designed to increase frost resistance in a sanded concrete surface
B 1.22 Formation of needle-like crystals that form in a hardening cement particle

Cement content [kg/m³]	**[kg/m³]**		
Exposure classes	XF, XM		X0, XC, XD, XS, XA
Aggregate's largest particle	8 mm	16 … 63 mm	8 … 63 mm
≤ 300	450[1)]	400[1)]	550
≥ 350	500[1)]	450[1)]	550

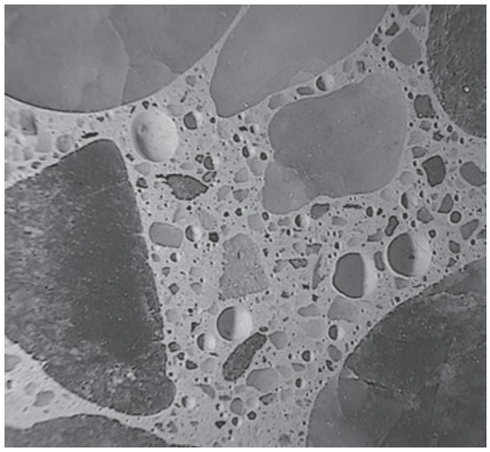
[1)] These values can be exceeded
- for cement contents over 350 kg/m³ by the larger amount
- if a Type II additive is used, by the amount of its content, but with a maximum of 50 kg/m³

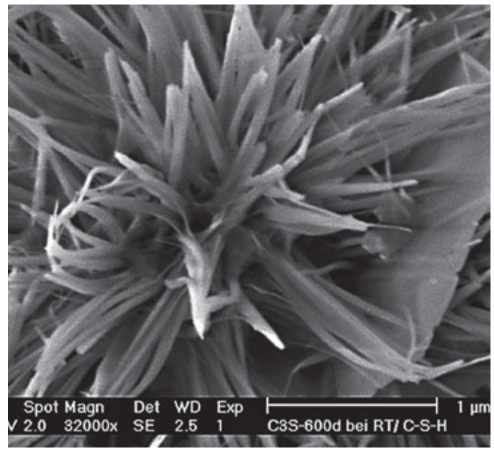
B 1.19

Active agent group[1]	**Abbreviation**	**Colour**	**CE label/Approval**
Concrete flow agents	BV	yellow	CE
Plasticiser	FM	grey	CE
Plasticiser/retarder (combination product)	FM	grey	CE
Aerating agent	LP	blue	CE
Retarder[2]	VZ	red	CE
Hardening accelerator	BE	green	CE
Hardening accelerator	BE	green	CE
Hardening accelerator for shotcrete	SBE	green	Approval
Admixtures for grout	EH	white	CE
Stabiliser	ST	violet	CE
Sedimentation reducer	SR	yellow-green	Approval
Sealant	DM	brown	CE
Chromate reducer	CR	pink	Approval
Recycling aids	RH	black	Approval
Foaming agents	SB	orange	Approval

[1] Other types without abbreviation and colour label through approval
[2] For working times extended by at least three hours consult the guideline on "Delayed-set concrete"

B 1.20


B 1.21



B 1.22

directly to the mix during concrete manufacture, which is the only way to ensure homogenous dispersion. They are added in liquid form by automatic dosing devices. Plasticisers can also be added to correct a concrete's consistency in the mixer truck on site. Relatively large amounts of plasticiser are added, so it must be precisely dosed and thoroughly mixed in a mixing truck.

Criteria for concrete compositions

It is the job of the concrete technologist to find the best possible technical and economical compromise between the various demands of construction operations in mixing concrete. Planning requirements involve only the hardened concrete and the technical properties vital to the concrete's durability and quality in the completed structure. Required compressive strengths can easily be reached. Fine-grained concretes and low-cement concretes tend to shrink less and as a consequence are less prone to cracking. Using the lowest possible w/c ratio will result in very dense and durable concretes. To summarise, the technical properties of hardened concrete can be optimised by using the lowest possible content of cement, water and sand and the highest possible proportion of coarse aggregates. Concretes designed to meet strict planning target values in the hardened concrete's properties may however be difficult or impossible to transport and place in ordinary construction operations. Concrete must have a sufficient proportion of flowing mortar for placing in construction operations, otherwise it will not be able to be pumped or transported by crane. The compacting and economically viable placing of concrete also requires light, flowing, workable and placeable concrete. This means that a larger proportion of sand and cement, additives and admixtures, and lower proportions of coarse aggregates must be used. The requirements of hardened concrete listed seem to demand high quality, including criteria such as compressive strength, resistance to corrosion, little tendency to shrink or crack and reliable durability of all the properties of the structure's components. In the practice of designing concrete, the w/c ratio alone (see also p. 32) is the main control parameter for all these properties.

Powdered cement's mineral content is homogenised into very small particle sizes. These form cement paste on contact with water, a liquid mix of materials in which cement particles are at a medium distance apart. Particle distance depends directly on the amount of water added. More water added to a fixed amount of cement increases the distance between the particles. Cement particles also absorb water from their environment and swell up into gel-like solids. This reduces the distance between individual gel particles or it shrinks away completely, so that their outer gel layers touch each other, or, if the system is moved, they fuse. In subsequent hardening, the cement's minerals recrystallise into a gel with the water in a system of needle-like crystals, which become increasingly dense and hard during hardening. Since these crystals take up less volume than the previous gel, pores are left in the system, which fill with unused water. In the concrete's final state, the needle-like crystals that developed out of the individual gel particles grow together into a monolithic solid, giving the concrete its strength. The physical property of concrete in this final state depends directly on the amount of water added at the outset. If more water is added, the crystalline connections between the gel centres are longer, thinner, less networked and therefore weaker. The overall system has less strength and low moisture-resistance and is more exposed to damaging effects because of its relatively large pores. If less water was added, the crystalline connections are shorter, thicker and more intensely networked. There are fewer pores and the system is relatively resistant to damaging influences from the environment (Fig. B 1.22).

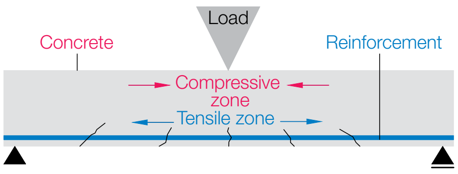
As this brief outline of the operating principle of cement and concrete hardening makes clear, the structural technological properties of concrete improve when the water-cement ratio is low and deteriorate when this ratio is increased. The limit state of this principle for pure Portland cement (CEM I) is a ratio of 0.38, which is exactly the ratio of water that cement consumes in complete hydration. The w/c ratio's central technological significance means that it is closely connected with the exposure class applying to the particular structural component. The resulting restriction is based on the current state of concrete technology. There is no technical or economic sense in falling short of these ratios in practice.

Reinforced concrete – a composite construction material

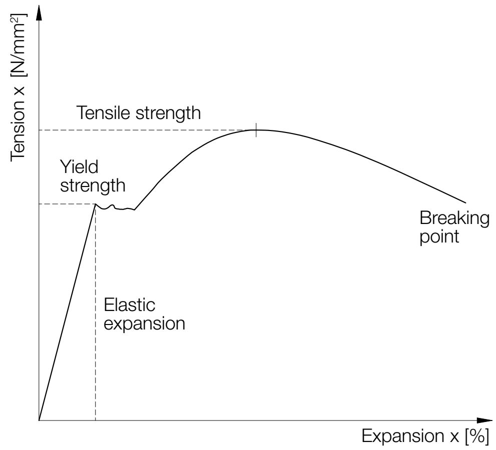
Most concrete structural components are made of reinforced concrete. Steel reinforcement is used in concrete either for structural reasons or may be a minimum reinforcement prescribed in standards. It is however also often used because it has become part of building tradition. Many reinforced structural components are moderately loaded compression members (walls, columns and supports, retaining walls etc.) that could also be built without reinforcement. In the mid-19th century, smaller structures in the area of private agriculture were built largely without reinforcement. Bending and laying steel reinforcement was a major undertaking for the smaller construction companies of the time, so the necessity of using it was very carefully considered for each structural component.

Reinforcement is indispensable in all structural components that are loaded with tensile forces. When pure shear forces are measured, it is first checked whether the concrete component can absorb the forces and stresses imposed without reinforcement, but because there are almost always bending moments, i.e. tensile forces, in shear force situations, a bending reinforcement is also usually required in the area of the shear force load.

Reinforced concrete construction works on a clear "division of labour" between steel and concrete. Concrete can absorb very high and easily calculable compressive forces. Its tensile strength is however low and hard to determine. Using standard testing methods, tensile strengths that are about 8–15 % of com-



B 1.23



B 1.24

B 1.23 Steel reinforced concrete – a composite building material. The concrete absorbs compressive forces, the steel reinforcement absorbs tensile forces. The concrete also protects the reinforcement from corrosion. The ("healthy") crack formation typical of this kind of building occurs in the area of the tensile zone.
B 1.24 Stress-expansion diagram of steel reinforcement
B 1.25 Precast lift well
B 1.26 Semi-finished slabs
B 1.27 Positioning precast walls
B 1.28 Precise integration of windows, drainpipes etc. in precast elements. Renovation of student housing in the Olympic Village, Munich (D) 2010, arge werner wirsing bogevischs buero

pressive strength are usually found in ordinary concretes. Concrete's tensile strength is a statically indeterminate property and the type of tensile failure it may be subject to is also uncertain. An unreinforced concrete structural component exposed to bending breaks spontaneously when it reaches breaking load without any visible prior indications. Damage is also done to the concrete's structure before it breaks and that further reduces the breaking load of an unreinforced concrete structural component with every stress cycle. Using concrete's tensile strength in a structure would require very high-level safety measures.
A reinforced concrete structural component's load-bearing behaviour is entirely different (Fig. B 1.23). When a beam on two supports is loaded, the strongest forces and stresses are imposed in the middle of the beam – compressive forces in the upper half of its cross section and tensile forces in the lower half. The latter can be precisely mathematically measured and are absorbed by the steel reinforcement in a reinforced concrete structural component. A support structure's design will determine the quantity, type and exact position of reinforcement in a concrete component, which is then installed in a precise position in accordance with these specifications and other structural principles. Once concrete is sufficiently hardened, the component will resist the effects of loads as planned, among them the structure's own weight.

Concrete subjected to bending loads will break in the tensile area and the tensile forces will be transferred to the steel reinforcement. Its elastic expansion also determines the width of cracks in concrete and must be limited if the concrete is to be durable. A reinforced concrete structural component without cracks is referred to in structural design as State I; a cracked state due to the activated load-bearing effect of reinforcement as State II.
There should be only low levels of elastic expansion in the steel in a completed structure's final state. This results in low utilisation of the steel's tensile strength, so the load-bearing system will exhibit very safe and reliable load-bearing behaviour.

If tensile forces impacting the steel are increased, this expansion becomes an irreversible plastic deformation. The steel rod "flows" and becomes permanently longer and thinner. Such large forces will cause enormous deformations and gaping cracks in a reinforced concrete component so their effect should be eliminated in planning. Yet even in unplanned overload situations, the reinforcement of a reinforced concrete structural component still has safety reserves. After initial plastic expansion, the steel hardens again due to typical metallurgical changes inherent in its structure and it can absorb further increases in load up to breaking point (Fig. B 1.24).
The ability of a reinforced concrete structure to visibly indicate overloading or structural weakness at an early stage while it is still in a structurally safe state with reversible deformations is a major safety factor in this type of construction.
Not all cracks in concrete develop due to the effect of external loads. Hardened concrete has a volume slightly less than that of fresh concrete, so a completed structural component shrinks slightly compared with its stripped dimensions. This deformation due to internal factors inherent in the construction material is called autogenous shrinkage and is usually about 0.1–0.2 mm/m. This, together with further thermal contraction due to the declining reaction heat of the hardening cement, results in so-called "early-age shrinkage", which is taken into account in limiting crack widths. The theoretical ultimate shrinkage of a completely dried concrete structural component is about 0.5 mm/m. Steel reinforcement usually absorbs tensile forces and can, if very large compressive stresses occur in a structural component's cross section, also function as compressive reinforcement. The same construction rules as for tensile reinforcement apply largely to the disposition of compressive reinforcement.
Concrete coverage protects the reinforcing rods from corrosion. The protective goal of the standard regulating all corrosive attacks is a minimum service life of 50 years, so the normative minimum thickness specified for concrete coverage is based on the exposure classes for steel corrosion (XC, XD, XS) (Fig. B 1.5, p. 25).

A comparison of in-situ concreting and prefabricated building methods

The number of buildings built with precast concrete components as a proportion of total construction volume is steadily increasing, so the group of planners that is convinced of the advantages of construction with prefabricated elements is also evidently growing. Decisions on whether a building should be entirely prefabricated, or just its main structures, or only some structural components, are however rarely made after consideration of the actual technical and economic advantages and disadvantages. In-situ construction seems to suggest itself to more planners than construction with prefabricated parts. In contrast, planners who have already built successfully with precast concrete components often tend to use the method in subsequent projects (Figs. B 1.25–B 1.27).

Building with prefabricated components has some decisive advantages over in-situ construction, but also some particularities affecting architectural design, structural planning and the construction operational work scheduling of the construction company performing the work and these may all be initially unfamiliar.

Using prefabricated components in building has the following advantages:
- Much better finishing quality and shorter construction times because work does not depend on the weather and seasonal influences and because of the production situation. Manufacture of structural components is largely automated. Manual processes are reduced to a few routine operations using technical equipment that site workers are thoroughly familiar with.
- Shorter construction times because assembly does not depend as much on the weather and no time is spent stripping, which has to be done with elements cast in situ.
- Spacers, reinforcement, technical installation and equipment can be precisely placed in the structural component. Extensively prefabricating technical equipment has further economic advantages if subsequent installa-


B 1.25


B 1.26


B 1.27

tion procedures are coordinated to fit in with them. Parts of the interior (floor coverings, bathroom units, doors, windows etc.) can be prefabricated or prepared in the factory.
- Far more sophisticated surface techniques can be much more exactly applied to precast elements than to components cast in situ.
- More precise planning at an earlier stage means that projects using prefabricated components are less affected by subsequent price increases due to follow-up work and re-working. Often a conventional operation seems less expensive when project costs and tender prices are estimated but there is often a different picture when the actual project costs become known after the project ends.
- Adequate standardisation can have economic advantages because re-using formwork equipment and repetitive work processes reduce manufacturing costs (Fig. B 1.28).
- One logistic advantage is the elimination of the necessity for storage area on the building site for formwork, scaffolding and reinforcement.

Among the characteristics of prefabricated building are:
- Joints between structural elements must be taken into account in construction for design reasons if they are to remain visible.
- The necessity of earlier and more comprehensive planning so that the benefits of prefabricated building are taken advantage of. In manufacturing prefabricated parts, all the details affecting the respective structural component must be conclusively decided on because such plans are difficult to change subsequently.
- Well-organised construction and assembly logistics. Preparations and subsequent work must be carried out on schedule and be clear at all interfaces and transfer points. The usual assembly can be changed or delayed. Building technology experts often no longer lay and install pipelines and equipment; rather these are assembled on the building site and put into operation.

Building with prefabricated components plays a particular role in the increasing improvement of energy efficiency of buildings, because few massive construction methods are as suitable for achieving this goal in the same way. Production on horizontal formwork tables offers excellent access to all areas of the formwork and makes it possible to build in layers and install heating and cooling elements, pipes etc. directly in structural components very easily and precisely (Fig. B 1.29). Interior gas, water and electrical installations and design and insulation elements can also be installed in a high-quality fabrication process. Much thinner structural elements can be used to create core-insulated concrete structural components compared with in-situ production. A careful review of the foreseeable demands on the energy efficiency of massive structural components makes it clear that building with prefabricated elements has particular potential in this area. Hardened concrete has a good ability to store heat and very useful thermal conductivity, so it is eminently suitable for use as a medium for storing, buffering and transporting heat. The fluid-plastic working of concrete offers a unique opportunity to position technical equipment such as ducts for exchange media safely, robustly and maintenance-free directly in the structural component. The complete coating of parts with initially fluid and then hardened concrete creates a close thermal connection

B 1.28

B 1.29

between the exchange medium and the area surrounding the structural component as well as loss-free energy transfer with maximum exchange rates, so the building's shell can be used in various ways to heat and cool the interior and generate energy. Thermal activation of the concrete core of structural elements, already frequently used in in-situ construction, is just one possible way of doing this. Solar heat energy from exterior surfaces can be used in a similar way to generate energy (in a solid absorber), either from direct irradiation or using waste heat from a photovoltaic plant (PV system).
Activating concrete structural components to produce energy does not restrict their load-bearing capacity or design applications, because the integrated system sections are usually small and do not cause any structurally relevant effects on their cross sections. In most cases no special dimensioning is necessary if load-bearing concrete structural components are used to improve energy efficiency, although adapting their geometry to optimise their energy efficiency can be beneficial in individual cases.
Modern prefabricated component production is largely computer-controlled. The preparation of formwork, calculation, preparation and positioning of reinforcement and all built-in parts is largely automated. Processes are largely standardised, since one-off manufacture of individual elements involves about the same time and effort in construction operations as the production of series of built-in part types. Professional prefabricated component manufacturers can offer architects and structural planners extensive technical support in structural planning, because companies are interested not only in the production, storage and transport of their parts but also in their successful installation. If prefabricated structural components are to be activated to produce energy, an energy planning expert should be involved in scheduling work as early as possible if the architect does not have this expertise.

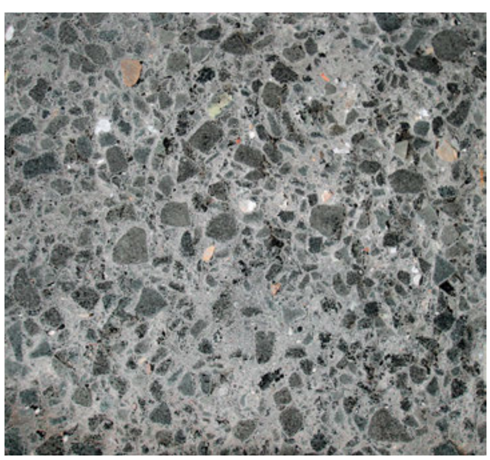
Special concretes

As well as normal concretes for general building construction and civil engineering, a range of other cement-bonded construction materials is available. Some of these, such as lightweight concrete, heavy concrete and high-performance concrete, are application-specific versions of ordinary structural concrete. Others are called "concrete", although they have little more in common with the classic building material than the hardening of cement.

Lightweight concrete (insulation concrete)

Lightweight concrete technology was developed in the 1960s with the goal of reducing concrete structural components' own weight without changing their load-bearing capacities. The aim was to make concretes with improved insulating properties, which increase with falling gross densities. Lightweight concrete technology had by then progressed enough to be able to more than halve lightweight concrete's thermal conductivity compared with normal concrete (Fig. B 1.31). Tables are drawn up for use in thermal design showing relative density classes for lightweight concretes whose values have been assigned to medium thermal conductivity. The current applicable thermal design values are specified in DIN 4108-4 on "Thermal insulation and energy economy in buildings – Part 4: Hygrothermal design values" (Fig. B 1.32).
Depending on the aggregates used, normative thermal conductivity values can be considerably reduced. If values below normative thermal conductivity are used, the concrete compositions and relevant thermal parameters must be demonstrated in testing. Approval or authorisation from the building regulation authorities in individual cases is required for the use of such concretes in Germany. Different European countries deal with the issue in various ways.
Lightweight concrete technology distinguishes between structurally dense lightweight concretes and other types such as internally porous lightweight and aerated concretes, which are used mainly for their insulating properties. The latter systems contain mainly coarse, light aggregates and only a little cement mortar, so their individual particles adhere to each other only where they touch. Aerated concretes generally consist of an expanded cement matrix, perhaps with a proportion of fine aggregates. They are usually industrially manufactured for prefabricated construction systems. Both types of concrete have very low strengths well under 10 N/mm^2. Such mixtures do not meet the requirements of building regulations standards for load-bearing concrete structural elements.
Structurally dense lightweight concretes in contrast have a composition that conforms to standards in which part of the aggregate is replaced by light aggregates in accordance with DIN EN 13055. These concretes have gross densities between 1,000 and 2,000 kg/m^3, although gross densities under 1,400 kg/m^3

B 1.30



B 1.31

B 1.29 Pipes laid for the thermal activation of a slab cast in situ, ready for concreting.
B 1.30 Exterior insulating concrete walls, Haus Meuli in Fläsch (CH) 2001, Bearth & Deplazes
B 1.31 Insulating concrete surface, cut
B 1.32 Normative ratios between relative density and thermal resistance in structurally dense lightweight concretes in accordance with DIN 4108-4
B 1.33 Compressive strength classes for lightweight concretes

involve considerable technological complications. The criterion of structural density is vital for conformity with standards, because only such structures ensure that the embedded reinforcement is protected against corrosion. There are however some special provisions in the standards that take the properties of lightweight concretes into account.
Lightweight concretes have their own system of compressive strength classes because the classifications for normal concretes do not apply due to their different fracture behaviour (Fig. B 1.33). The exposure classes for lightweight concretes also do not prescribe any minimum compressive strength classes. This specification alone normally serves to ensure the w/c ratio, although there is no linear connection between compressive strength and the w/c ratio in lightweight concretes.

Demands on the insulating properties of buildings have increased steadily over the past 30 years. Since the introduction of Germany's first Thermal Insulation Ordinance (Wärmeschutzverordnung) in 1977 and its subsequent amendments, apart from a few individual applications, the building of single-shell lightweight concrete walls has declined (Fig. B 1.30). Swiss architect Patrick Gartmann has provided impetus for a renaissance in building monolithic lightweight concrete walls with the construction of his house in 2003 (see "Concrete and heat", p. 15). Working in cooperation with the ETH Zurich, he developed a concrete with a relative density of about 1,000 kg/m³. To achieve this level of relative density and insulation, the possibilities of lightweight concrete construction were thoroughly utilised. Very light expanded glass was used as aggregate (see "Lightweight aggregates", p. 29). The thermal conductivity of this concrete was measured at about 0.36 W/mK, and thus about a quarter lower than the standard German value for this relative density. The concrete Gartmann developed has been called "insulating concrete" in publications, although this is not a defined technical term.
Some buildings with very light concrete exterior walls (approx. 1,100 kg/m³) have now been built in Germany. The current regulatory situation (e.g. since the Energy Saving Ordinance (Energieeinsparverordnung EnEV) 2014, Minergie standard) means that some very high energy efficiency standards are required for new buildings in many European countries. To meet these guidelines, including with lightweight concretes, very low relative density monolithic exterior walls with thicknesses of 60 cm and more will be required. Such low gross densities entail an almost complete replacement of natural with light aggregates, which also reduces the compressive strengths that can be achieved. Gross densities of around 1,100 kg/m³ can usually only be achieved in the compressive strength classes LC8/9 and LC12/13, which is however sufficient for building a monolithic wall. Concretes in the compressive strength classes of LC8/9 und LC12/13 can be nailed and feel warm due to their very low heat exchange rates.
Lightweight concretes demonstrate an inner load-bearing behaviour under compressive loads that is different from that of normal concretes. In lightweight concrete, the cement matrix, which is stronger than the aggregate, takes on the load transfer. Lightweight concretes therefore have an elastic modulus much lower than that of normal concretes, i.e., they deform more under compressive forces. This becomes relevant in the structural planning of a ceiling or beam.
One construction-operational effect of lightweight concrete often appears on the surfaces of structural components not cast in formwork. Coarse aggregates in particular tend to float to the surface of wet concrete. Such surfaces can therefore only be smoothed when the concrete begins to set and light aggregates remain deeper within the material's structure, although coarse aggregates may still stand out from the surface. If there are stringent requirements on a surface's look or smoothness, it can be further smoothed after the lightweight concrete sets (three to four hours after placement) by subsequent applying of mortar.

Fibre-reinforced concrete

The idea of reinforcing massive construction material with fibres is even older than concrete construction. Straw and other fibrous plants were added or laid in old mud-brick buildings to give the brittle construction material, which has a strong tendency to crack during hardening, a stronger bond. With a few exceptions, the reason for using fibres, namely to strengthen concrete or another cement-bonded system, is in principal the same and practice has shown that this initial idea has been usefully incorporated into modern construction materials technology.
Current concrete technology uses steel, plastic and glass fibres in concretes and other cement-bonded systems. It should be noted that adding fibres significantly increases the proportion of fine particles that must be moistened and encased with cement paste, so the concrete's composition must be adjusted accordingly.

Steel fibre-reinforced concrete

Classic steel fibre-reinforced concrete was developed with the idea of replacing the complex and costly bending and laying of steel reinforcement for at least some structural components and types of loads with a less expensive mixed reinforcement. Despite a similar effect, steel fibres in concrete cannot replace the load-bearing effect and safety of steel rod reinforcement (see "Reinforced concrete – a composite construction material ", p. 33). One safety disadvantage comes from the random distribution of fibres in the concrete. If the fibres are to function effectively, they must be sufficiently plentiful at the site of the required effect and be correctly oriented

	Relative density [kg/m³]	λ_R [W/mK]
Lightweight concrete and steel-reinforced lightweight concrete with a closed structure	800	0.39
	900	0.44
	1,000	0.49
	1,100	0.55
	1,200	0.62
	1,300	0.70
	1,400	0.79
	1,500	0.89
	1,600	1.00
	1,800	1.30
	2,000	1.60

B 1.32

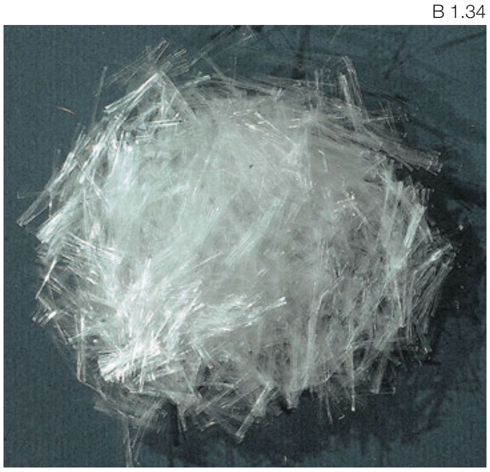
Compressive strength class	$f_{ck,\,cyl}$ [N/mm²]	$f_{ck,\,cube}$ [N/mm²]	Concrete type
LC8/9	8	9	Lightweight concrete
LC12/13	12	13	
LC16/18	16	18	
LC20/22	20	22	
LC25/28	25	28	
LC30/33	30	33	
LC35/38	35	38	
LC40/44	40	44	
LC45/50	45	50	
LC50/55	50	55	
LC55/60	55	60	High-performance lightweight concrete
LC60/66	60	66	
LC70/77 1)	70	77	
LC80/88 1)	80	88	

$f_{ck,\,cyl}$: characteristic strength of cylinders, diameter 150 mm, length 300 mm, age 28 days
$f_{ck,\,cube}$: characteristic strength of cubes, edge length 150 mm, age 28 days
1) General approval or authorisation from the building regulatory authorities in individual cases required

B 1.33

B 1.34 Steel fibres
B 1.35 Polypropylene synthetic fibres
B 1.36 Glass fibres
B 1.37 Contoured spacer fabric with various distances between textile surface areas
B 1.38 Structure made of 13 mm glass fibre-reinforced concrete slabs, Pavilion of the AA Design Research Laboratory, London (GB) 2008, Alan Dempsey, Design: Alvin Huang


B 1.34


B 1.35


B 1.36

towards the acting force. The fibres' distribution, position and orientation cannot be controlled and can only be statistically estimated, so the fibres' effects must be subjected to very high standards.
As of March 2010, the DAfStb guideline on "Steel fibre-reinforced concrete, amendments and modifications to DIN 1045, Parts 1 to 3 and DIN EN 206-1" has regulated the use of steel fibre concrete with and without additional reinforcement in load-bearing structural components.
This guideline divides steel fibre-reinforced concrete for load-bearing structural components into two performance classes:

- Performance class L1 for small deformations
- Performance class L2 for larger deformations and in combination with steel concrete reinforcement

The guideline applies to the design and construction of support structures in building construction and civil engineering built of steel fibre concrete with and without steel concrete reinforcement and with the maximum compressive strength class C50/60. It calls for the use of steel fibres with form-fitting, mechanical anchoring in accordance with DIN EN 14889-1 "Fibres for concrete – Part 1: Steel fibres – definitions, specifications and conformity", so crimped or cropped fibres or those with compressed heads (Fig. B 1.34).
In the steel fibre concrete design model, the fibres only have an effect in cracked concrete (see "Reinforced concrete – a composite construction material", p. 33), where they must span the crack and anchor it on both sides along most of its length or secure it in another way. Post-cracking tensile strength results from the sum of the effect of all the fibres on the crack. For the system to achieve a stable balance, the forces affecting the structural component after the crack may not be greater than its post-cracking tensile strength, unless other load-bearing components absorb part of this force.
Steel fibre-reinforced concrete exhibits so-called "softening behaviour", i.e.: the more a crack opens, the less tensile force the steel fibres spanning it can absorb, so crack width limitation in pure steel fibre-reinforced concrete cannot be analytically verified. The crack will remain the weakest point in the system and open further as long as the deforming forces affect the structural component. A reinforcement rod exposed to the same load will absorb the tensile force after the initial crack and prevent it from opening further.
When a cracked steel fibre-reinforced concrete system is stably balanced, the fibres absorb the acting forces or part of them. How much force they absorb depends on their type and amount. The forces must be less than the fibres' effect or the main force must be borne by other load-bearing components such as normal reinforcement or an elastic underlay under a floor slab. Technically and economically effective structures can be made using a combination reinforcement made of conventional steel rods and steel fibres, because fibre reinforcement is generally less expensive. The effect of fibres in concrete, considered from the point of view of post-cracking tensile strength in a cracked system alone, are underestimated. Extensive practical experience and the many applications of fibre-reinforced concretes – contrary to the design model – have shown that the effect of steel and other fibres with tensile strength does not only begin after cracks form. Their effect on systems in an uncracked state, which is known from practice, is to increase the construction material or structural component's ductility. This can however only be measured based on experience or in tests on the type or quantity of specific fibres, so they cannot be regarded as structurally load-bearing.

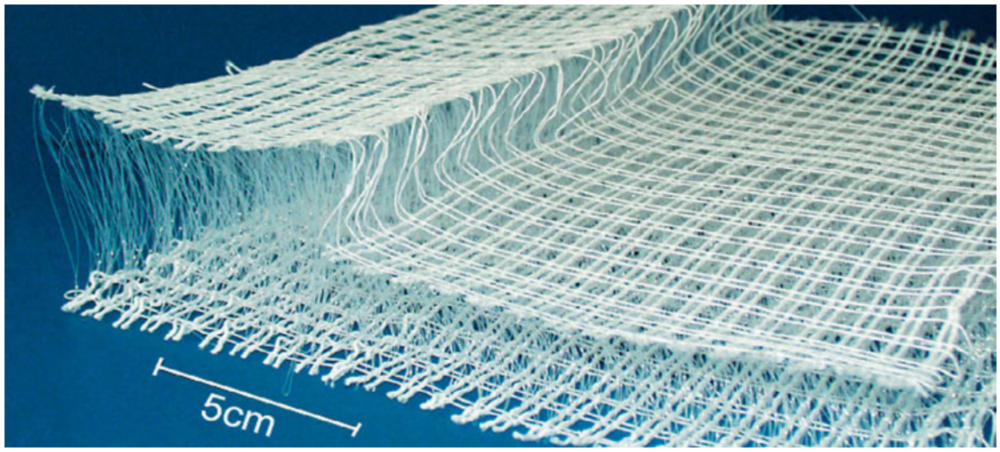
Synthetic fibre-reinforced concrete
The main reason for using synthetic fibres is to improve a concrete's cracking behaviour and resistance to blows and impact mentioned above, as well as to increase the ductile elasticity of the hardened structural component. Synthetic fibres are organic polymers (Fig. B 1.35). The range available is diverse and technically hard to categorise. Marketed under various trade names, the type and content of many synthetic fibres are not specified in ready-mix cement-bound products. To this is added the fact that not only their material composition, but also the mechanical process of manufacturing the fibres affects their properties. Synthetic fibres are rarely used in structural concrete, even though new generations of much stronger materials that are comparable with steel fibre concretes have now been available for some time. They are used mainly in normal workable and shotcrete mortar systems, floor screed and plastering.
Polypropylene fibres are often used to improve fire resistance, especially in higher-strength concretes. When concrete surface areas are heated rapidly, which typically occurs in fires, there is a danger of high water vapour pressure forming in the concrete, which can cause the concrete cover to flake off, directly exposing the steel reinforcement rods to fire. Polypropylene fibres in the concrete's structure will begin to melt at about 130°C and this fluid is forced into the pore space in the concrete. The channels that originally held the fibres can then serve to release the internal water vapour pressure.
Polypropylene fibres can also improve concrete's material properties. The effect of these fibres is however limited, because their tensile strength, at under 0.8 kN/mm^2, is comparatively low, as is their elastic modulus, with values under 10 kN/mm^2. Polyamide or polynitrile fibres have much stiffer material properties, with a tensile strength and elastic modulus double that of polypropylene fibres.
Polyacrylnitril fibres with outstanding technical properties were developed in Japan some

years ago. They can achieve a greater tensile strength than steel reinforcement at about half the elongation at breaking and are currently being intensely trialled.
Carbon fibres, whose enormous strengths are familiar from other applications, are a specialist group. They are made by stretching and carbonising polyacrylnitrile or high-strength viscose fibres and are highly resistant to alkalis. Their tensile strength exceeds that of steel reinforcement and their elastic modulus is more than double that of steel reinforcement.

Glass fibre and textile-reinforced concretes
Glass fibre concretes have been an integral part of the technology of cement-bonded construction materials for many years. Glass fibres are made of finely spun molten glass (Fig. B 1.36). Only alkali-resistant glass fibres (AR fibres) are used because only they are durable in the alkaline environment of concrete in the long term.
Glass fibres can be used as individual fibres or spun into threads. They are rarely used in structural concrete because the grinding action of coarse aggregates would damage the fibres mixed into the concrete.
The main applications for individual glass fibres in cement-bonded systems include:

- Fibreglass-reinforced shotcrete made of high-strength cement mortars for making thin-walled elements with high load-bearing capacity in three-dimensional surface geometries, e.g. for facade elements, artificial rocks, climbing walls and skate parks.
- Fibre cement slabs made of high-strength fibreglass-reinforced cement mortars, which are manufactured on production lines and cut into standard sizes after hardening. They can be used to make high-quality, mechanically tough interior or exterior surfaces and despite thicknesses of only 1 cm are very stable and can be drilled, screwed and glued. Fibre cement slabs can be made of white or grey cements and dyed with pigments in almost any colour.

Glass fibres can be spun into “rovings” (bundles of 20–40 threads), which can be used to make various three-dimensional fabric forms that are then poured with cement mortar or paste to form a structural component (Fig. B 1.38). In contrast to fibre cement, their reinforcement consists not of short fibres, but of textiles, i.e. glass or carbon fibre textiles, so this concrete is called textile-reinforced concrete because of this textile-like processing. Fibrous fabrics contain a certain number of glass or carbon fibres oriented in a specific direction whose position and distribution in the structural component are not statistically random, but are precisely positioned like steel reinforcement and so are known. The fabric’s inherent rigidity is often enough for incorporating the fibres or they are worked into the mortar like a lamination. The load-bearing capacity of textile-reinforced concretes can be precisely measured. This structural technology can be used to create low-material (and thus very light), thin-walled structural components with high load-bearing capacity. There is currently no overall safety and design concept in statutory building regulations covering fibreglass textile reinforcement.



B 1.37

High-performance concrete
High-performance concretes are used especially in structural components that have to bear heavy loads, e.g. in the lower support structures of multi-storey buildings, bridges and towers. The improved load-bearing capacity of individual structural components these concretes make possible means that the dimensions of structural components can be reduced and considerable amounts of space saved. Using high-performance concrete in the load-bearing components of a very high building’s lower storeys can be interesting because it means their overall dimensions will not have to be disproportionately increased compared with the upper storeys.
Normal concretes in the compressive strength classes C55/67 to C100/115 and lightweight concretes from LC55/60 to LC80/88 are classified as high-performance concrete. Their design, manufacture, installation and monitoring is regulated in the main statutory building standards applying to concrete construction. Manufacturing and using concretes in the two


B 1.38

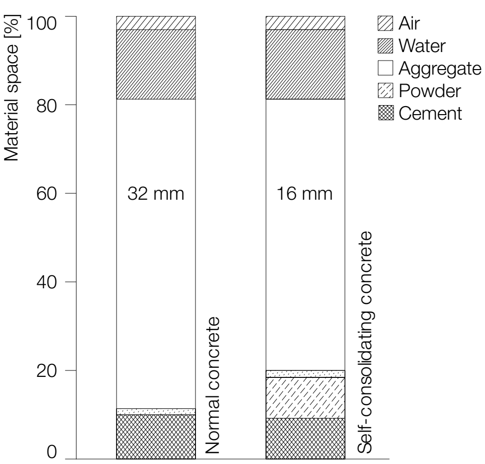
B 1.39

B 1.40

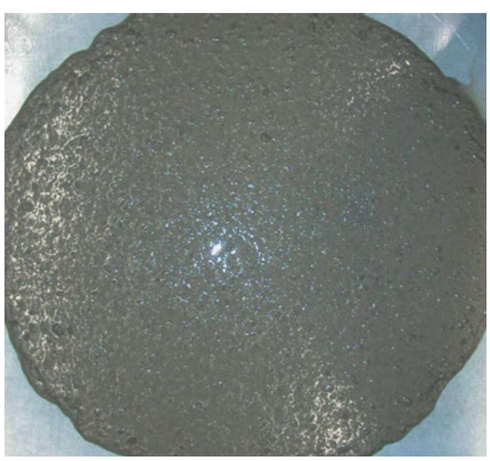
highest compressive strength classes requires special expertise and care and although standards apply to their use, an additional general construction approval or authorisation from the building regulation authorities in individual cases is required.
The guidelines in the standards based on the exposure class that apply to the particular high-performance concrete structural component must also be complied with. The type and composition of the basic materials will be determined mainly by the concrete's design feature of high strength, but a cement of the highest strength class of 52.5 is almost always used. To make the best possible use of the cement's strength potential, water content is kept as low as possible, which makes it necessary to use effective plasticisers in high-performance concretes. If its strength is to be above 70 N/mm², the addition of silica fume as a Type II additive to increase strength is also required (see "Additives", p. 31f.).
The high safety requirements made on high-performance concrete structural components mean that their use must be supervised by a certified inspection agency on the building site in compliance with the provisions of Inspection Class 3.
High-performance concretes are challenging to use in construction. Even though large quantities of plasticiser may be added to them, they are always more difficult and complex to move and work on the building site than normal concrete. Before working, a batch of the concrete should therefore always be tested under building site conditions, with all the planned methods for placing the concrete tested.
In their hardened state, very high-strength concretes are extremely brittle and the high proportion of fine particles in the concrete's composition means that they often have a relatively high tendency to crack. Their generally low water-cement ratio, which is often below the chemical-physical water requirement, means that high-performance concretes tend to self-desiccate as they mature, which can cause additional drying shrinkage. The characteristics of the material make high-performance concrete structural components especially suitable for compression members.

Ultra high performance concrete

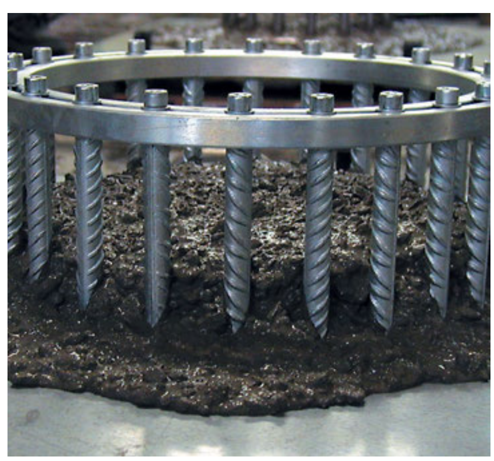
Ultra High Performance Concrete (UHPC) was developed out of high-performance concrete technology. As a cement-bonded material system, its compressive strength is however much higher and thus beyond the scope of statutory building regulations standards. UHPC can only be used with a general construction approval or authorisation from the building regulation authorities in individual cases for load-bearing structural components. Because UHPC is defined only by its lower compressive strength limit, the principle of UHPC can be explained based on a few general parameters.
The technically reliably reproducible strength of UHPC is currently about 300 N/mm², almost an order of magnitude higher than that of ordinary structural concrete. Higher strengths have already been achieved in some cases and the upper limit does not yet seem to have been reached.
These high strengths are achieved by very precisely adjusting the particle structure of the matrix. UHPCs are fine mortar systems, which contain cement as well as graded quarry rock dust, fly ash and silica fume with a structure that is as dense and low-porosity as possible. Unlike standard structural concrete, there is no excess water in UHPC, but a shortfall in the cement's hydraulic water requirement of up to 50 %, so unhydrated cement particles remain in its hardened structure.
The w/c ratio of UHPCs, depending on their desired strength, can be up to 0.20. Due to its almost completely dense structure that almost entirely resists the penetration of moisture and pollutants, UHPC potentially has a far greater durability than normal structural concrete.
The stronger a construction material is, the more brittle it will be, so UHPC structural components are often reinforced with fibres (steel, glass, plastic), which are either added during mixing or consist of carefully positioned glass or carbon fibre textiles. This can make high-strength structural components very ductile, making them suitable also for uses beyond construction, such as in mechanical engineering.



B 1.41



B 1.42



B 1.43

B 1.44

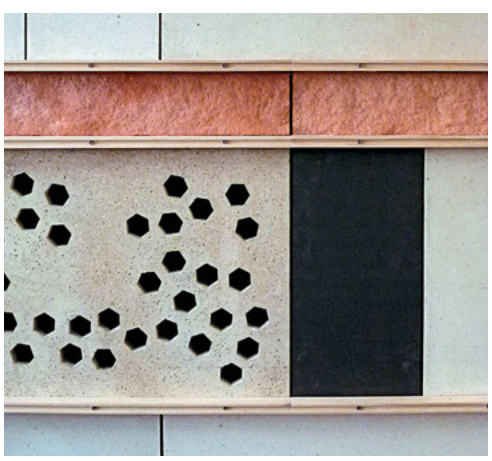
UHPC was used for the first time in Germany in 2006 in the construction of the Gärtnerplatz pedestrian and cyclists' bridge in Kassel (Fig. B 1.39). The 140 metre long bridge support structure is a composite UHPC and steel structure. Ten years earlier, a pedestrian bridge with a pre-tensioned support structure made of steel fibre-reinforced UHPC was also built in Quebec in Canada, the 60 metre-long Sherbrooke Footbridge (Fig. B 1.40).
Intense work has been continuing in recent years at institutes of higher education and research, including at publicly funded institutes, on developing UHPCs for various applications.

Self-compacting concrete

Self-consolidating or self-compacting concrete is used in especially complicated formwork geometries whose concrete cannot be compacted by internal or external vibrators. Self-consolidating concretes are also used in prefabrication to streamline work processes, because the economic advantages of easier working can be especially well exploited there. One very positive side effect is the concrete's quiet self-compaction.
The ability to self-consolidate is a characteristic which only affects construction operations and the manufacture and working of the concrete. The hardened concrete's properties are like those of structural concrete with less fluid consistencies.
Self-consolidating concrete technology is closely linked with a completely new series of plasticisers, polycarboxylates or polycarboxylate ethers, which were used in its development in the 1990s. It was developed in Japan, where self-consolidating concrete was produced and its properties demonstrated in research.
Large proportions of plasticiser are added to concretes with low water content. Their initial consistency is usually an earth-moist mixture. The working principle of self-compacting is based on the model of a very fluid mortar phase that carries the coarse aggregate (Fig. B 1.41). Plasticisers not only make the mortar phase more fluid, they also give it a pronounced viscosity with a flow rating like that of honey. This concrete fills the most complex formwork geometries autonomously, although it moves rather slowly (Figs. B 1.42 and B 1.43).
Plasticisers containing polycarboxylates can also be used to make concretes with a less fluid consistency. Amendments to concrete standards in 2000 took this technology into account with the introduction of the consistency classes F4, F5 and F6, which are referred to as highly-flowable concretes. They can be compacted by classic vibrators (internal or external vibrators). Self-consolidating concrete begins above consistency class F6.
Concretes in the highly-flowable consistency classes F4, F5 and F6 are much easier to use than self-consolidating concretes, the testing of which requires more effort and which also demands more care and attention in construction. Since few placing situations in classic in-situ concreting require the maximum fluidity of self-consolidating concrete, its use has remained at fairly low levels.

Wood fibre-reinforced concretes, lightweight wood fibre-reinforced concretes

Wood fibre-reinforced concretes or lightweight wood fibre-reinforced concretes are cement-bonded construction materials systems with a composition like that of concrete in which various raw materials from wood processing (sawdust, wood shavings) replace the usual aggregates. The addition of much lighter wood means that structurally dense wood fibre-reinforced concretes have lower gross densities than normal concrete, ranging from 500 up to 1,500 kg/m^3, depending on the type of wood and wood content used. They are also called lightweight wood fibre-reinforced concretes.
Wood fibre-reinforced concretes do not fall within the scope of statutory building regulation standards applying to concrete and cannot be used for load-bearing concrete structural components. There are also lightweight wood fibre-reinforced concretes with a low binding cement paste or mortar content and porous structures.
Wood fibre-reinforced concretes are not yet established on the wider market. Although new approaches to researching and developing wood fibre-reinforced concretes and lightweight wood fibre-reinforced concretes are

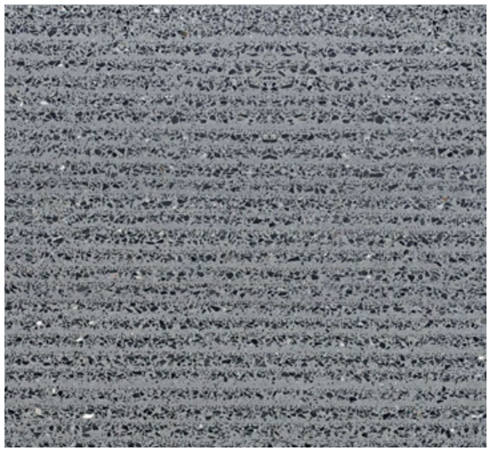


B 1.45

B 1.46

B 1.39 Gärtnerplatz pedestrian and cyclists' bridge, Kassel (D) 2006, Universität Kassel, Michael Schmidt, Ekkehard Fehling
B 1.40 Sherbrooke Footbridge, Quebec (CDN) 1997
B 1.41 Comparison of the composition of normal concrete and a self-consolidating concrete
B 1.42 Testing the rheological parameters of self-consolidating concrete
B 1.43 Testing procedure with a lock ring
B 1.44 Self-consolidating concrete deck, coastal resort in Kaltern, Caldaro (I) 2006, the next ENTERprise – architects
B 1.45 Test components made of wood fibre-reinforced concrete
B 1.46 Test piece surface, wood fibre-reinforced concrete

B 1.47



B 1.48

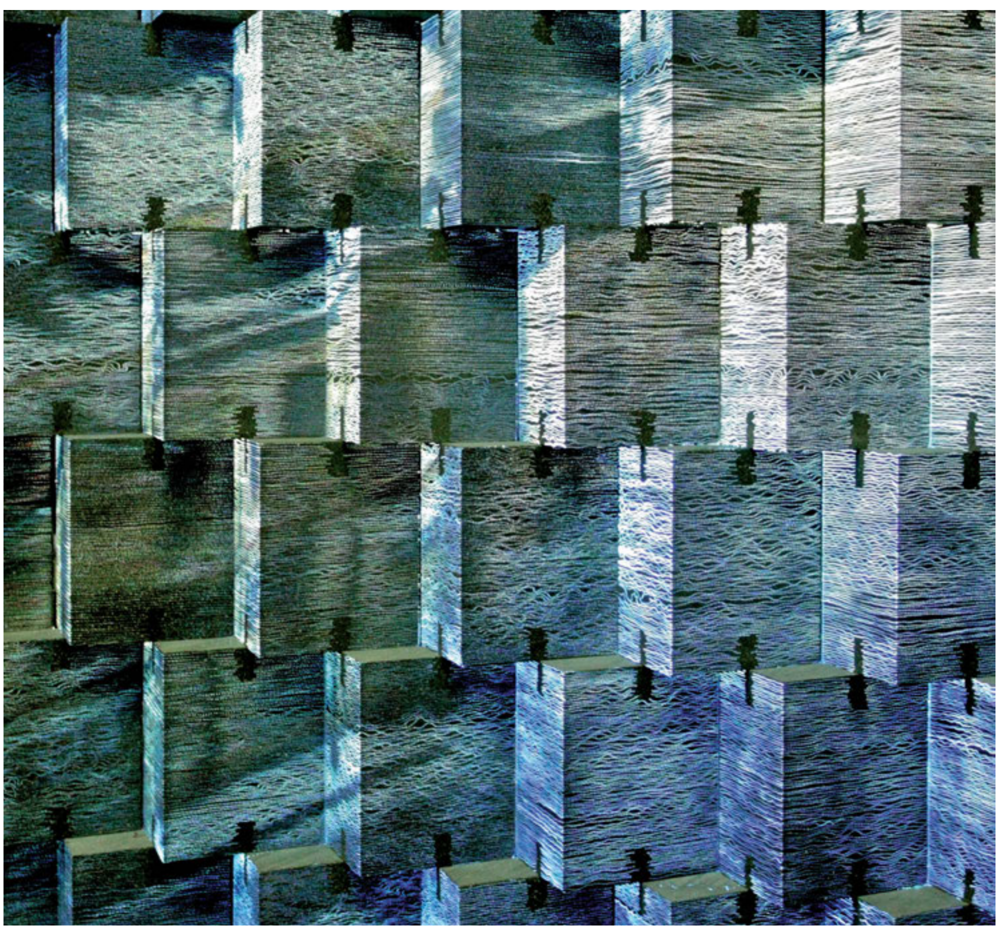
currently emerging. Bonding very coarse shavings with cement paste at various points creates a porous wood fibre-reinforced concrete with a sound-absorbing surface. Profiling can further enhance this effect. Structural components made of this material are used to provide acoustic insulation in large interiors and in noise barriers.
Wood shavings are prepared for use in a cement bonded construction material by mineralisation, a process in which the surface of the wood shavings is covered with a mineral layer that makes them less absorbent, neutralises pollutants that could impede the concrete's hardening, makes the shavings harder, and supports bonding between the wood shavings' surface and the cement matrix. Since wood fibre-reinforced concretes are used mainly in structural elements of low thickness and bulk, they are especially suitable for factory production. Although there are already wood fibre-reinforced concrete elements that are largely durable against frost and moisture, they are used mainly in the interiors of houses and non-residential buildings.
Using timber by-products in a cement-bonded system involves some specific technological features that have to be taken into account in designing mixtures, in manufacture and in use.

- Unlike cement and its hardening products, wood is an organic material that is subject to natural decay and related changes to its properties, which can limit the durability of structural components made with it.
- Wood shavings contain water-soluble constituents, which can interfere with the hydraulic hardening of cement and water to varying degrees. Mineralising the timber by-products can largely neutralise this negative effect.
- The relative density of cement paste is about 1.5 to 2.5-times that of ordinary industrially produced types of wood. Wood shavings tend to segregate in fluid cement-bonded systems.
- Wood absorbs water to varying degrees in fluid cement paste, which can cause significant changes in fresh wood fibre-reinforced concrete, even after mixing. Mineralising the wood shavings can reduce and stabilise their absorbency.

Depending on the proportion of wood and cement mortar in wood fibre-reinforced concretes, the material's wooden or mineral properties can predominate as required. These composition parameters can to a certain extent also influence the way the material and structural elements made with it behave in fire. If a relatively high proportion of cement paste is used, other fibres can be added. Wood fibre-reinforced concrete surfaces feel pleasantly warm and can balance out humidity. They contain very few harmful substances and are highly resistant to mechanical impact. The material can be dyed and its typical textural effects can be used to create appealing architectural surfaces. Wood fibre-reinforced concrete elements' light weight means that they can also be handled without heavy lifting equipment (Figs. B 1.45 and B 1.46, p. 41).

Translucent concrete

Translucent or light-transmitting concretes are cement-bonded structural element products with similar properties that have been sold on national and international markets since the late 1990s.
Translucent concrete is made of thin optical



B 1.49

glass fibres laid in the same direction and embedded in regularly arranged layers of glass fibre matting in high-strength fine-grained concrete. Orthogonal blocks with edge lengths between 80 and 200 cm are produced, from which slabs are cut at right angles to the direction of the fibres. At their cut surfaces, the slabs show a more or less regular pattern of glass fibre points that transport light striking them from the light to the dark side without reducing the light or changing its colour (Figs. B 1.47 and B 1.48). The fibres can be seen as bright points of light on the dark side and due to their density, they can produce a wide range of light and other visual effects. The optical effects created depend on the fibres' density and distribution and the difference in brightness between the lighter and darker sides. Depending on local conditions, light, changing light, silhouettes and movement can be seen on the dark side. Projecting light with projectors or similar devices onto such concrete surfaces can make images visible in full colour and text can also be read through their elements. Fine-grained concrete has a very high compressive strength ranging from 80 to 100 N/mm^2, which means that the slabs' surfaces can be polished and used to create very high-quality surfaces.
Fine-grained concretes can also be coloured in a range of various standard colours. The material is not sensitive to the impact of the weather and it can be used on exterior facades and in interiors. The glass fibres have a round cross section and a diameter of up to 2 mm, although fibres with a diameter of less than 0.2 mm are usually used. Various manufacturers offer translucent concrete elements in various standardised sizes of slabs ranging from 1.5 to 4 cm thick. A combination of standard elements can be used to create larger areas, for which the manufacturers of such elements offer suitable joining and fastening systems (Fig. B 1.49).

Special construction methods

Some structural engineering structures involve special aspects of concrete technology and require in-depth specialist knowledge. Among these are water-impermeable concrete structural components and buildings in particularly aggressive corrosion situations, such as multistorey car parks and underground garages.

Water-impermeable concrete structures

Water-impermeable concrete structures are built mainly below ground level as so-called "white tanks". They combine static load-bearing capacity with waterproofing but without additional coatings or construction materials. The DAfStb guideline on "Water-impermeable structures made of concrete" is the national regulation for this type of structure and is also supplemented by more precise explanations and technical planning and installation specifications (e.g. DAfStb Heft 555). The guideline has not been adopted as part of statutory building regulations however, so its application in planning and installation must be contractually defined and agreed on.
The guideline defines water impermeability as the prevention of the passage of liquid water through concrete, through installed parts (permeation) and cracks, through joints, construction joints and cross sections with controlled cracks. Water-impermeable structural components are not physically waterproof, because the unilateral impact of water usually soaks the surface of the structural component facing the water due to the capillary absorption of the concrete.
The most important input variable in planning a water-impermeable structure is the design-basis water level, which is the highest expected level of groundwater, aquifer water or floodwater and requires that long-term measurements and expected future conditions over the planned period of use be taken into account. The guideline defines two stress load classes (1 and 2), which are based on the design-basis water level and ground conditions. The stress load class is identified during planning and defines the stress loads on water-impermeable structures ranging from moist soil through water not under pressure and up to water under pressure.
The guideline also formulates two performance classes. Here too, planners must decide which class applies in consultation with developers and taking the building's planned use and function into account. The performance class is a direct quality and usage characteristic of the building that the developer must specify for planning and installation. Performance class A applies to higher-order types of uses such as housing, offices or storerooms for goods sensitive to moisture. No damp spots can be allowed to form on the insides of structural components in structures in performance class A.
Performance class B permits "limited ingress of water" and applies to spaces whose use is not incompatible with higher ambient humidity levels, such as utility rooms, installation and supply shafts or channels, single and underground garages and storerooms with lower requirements. In structures in this class, smaller damp spots can be allowed to form on the inner surfaces of water-impermeable structural components in the area of separation cracks, cross sections with controlled cracks, joints and construction joints, although no measureable or discernible amounts of liquid water are permitted.
The water-impermeable concrete structures guideline specifies three possible planning principles for a water-impermeable structure:

- Avoiding separation cracks (no uncontrolled separation crack formation). Construction and concrete technology measures such as unrestrained laying of the floor slab, short spacing between crack control joints in walls, a concrete mix designed to prevent cracking and limiting thermal gradients during the early stages of the hardening phase will largely prevent restraining stresses in the structure.
- Construction designed to limit crack formation. The limiting of crack widths will depend on the type and pressure effect of the water.
- A building method with permissible separation cracks and subsequent planned sealing measures. Cracks channelling water are grouted under pressure as planned. Choosing this construction method requires that the loading case occurs as planned during or shortly after construction or the inner sides of structural components remain permanently accessible for crack sealing measures.

The construction method with limited crack formation is based on the assumption and on experience that has shown that the penetration of water from surrounding soil into small cracks initiates a "self-healing" process that quickly closes a crack for the long term. This self-healing occurs due to the re-hardening of unhydrated cement particles in the concrete and the depositing of limestone and suspended solids in the water in the crack. This construction method cannot usually be used for structures in performance class A because of the temporary permeation with water required for "healing". A construction method with reduced restraint without separation crack formation should always be the first choice here.
The following planning steps must be taken in planning a water-impermeable structure:

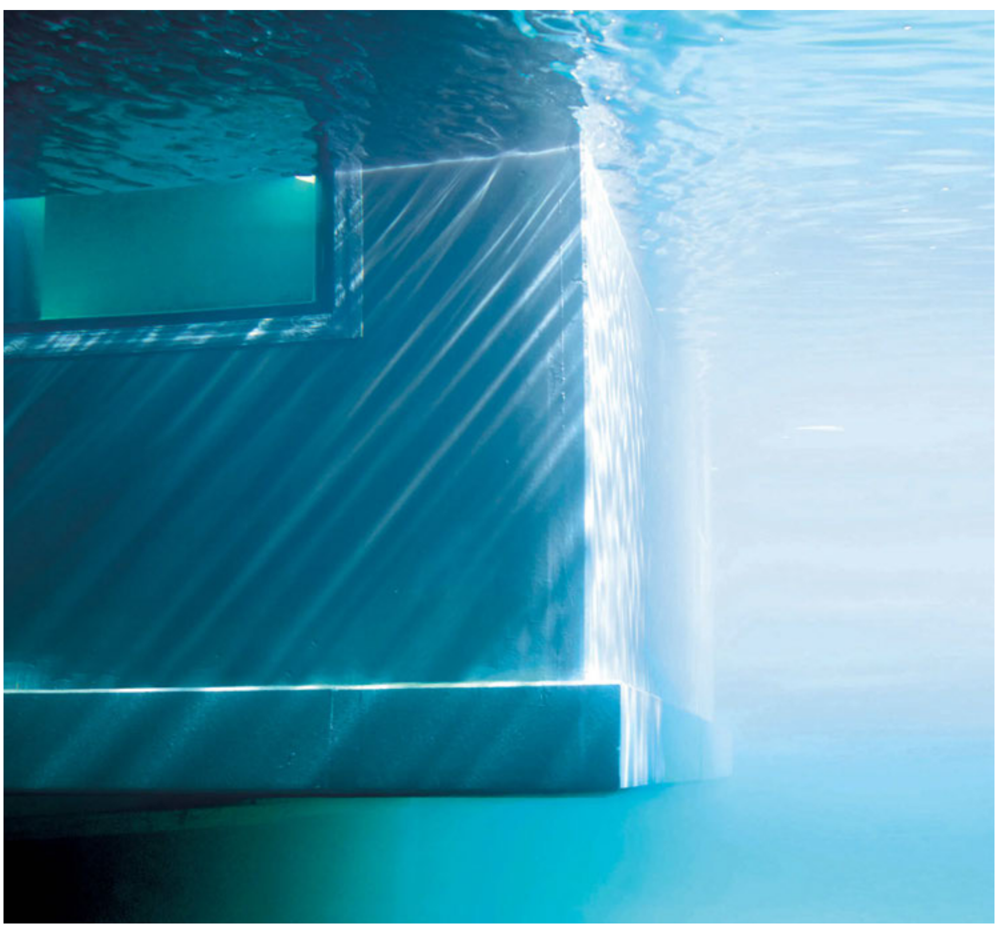
- Ascertaining the design-basis water level and ground conditions
- Determining the stress load class
- Determining the performance class
- Defining planning principles
- Identifying any physical requirements on the structure arising from its use
- Specifying minimum thicknesses and establishing the thicknesses of structural components
- Defining pressure differences i and calculated crack width wk as required
- Optimising the structure in terms of constraining forces
- Determining the distribution of joints and the sealing system (including parts to be installed, permeation)

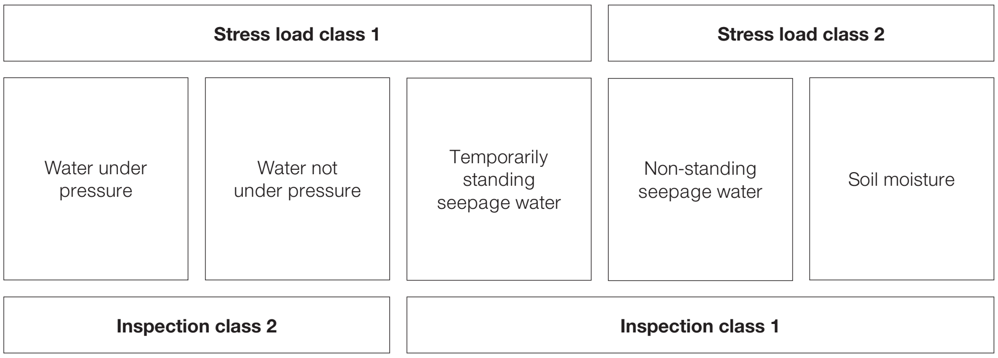
Condensation must not be allowed to form on the inner surfaces of exterior walls in spaces with higher-order uses. The question of whether exterior insulation is planned and whether its insulation effect will be enough to prevent condensation must first be answered. Depending on the insulation's efficiency and the protec-

B 1.47 translucent concrete, back-lit
B 1.48 translucent concrete, not back-lit
B 1.49 Pavilion made of 440 translucent fine-grained blocks. Installation in the Design Museum, Triennale di Milano, Milan (I) 2009, Kengo Kuma

tion required, additional ventilation, heating or overall air conditioning measures may be necessary or advisable.
A planner working with performance class A must inform the developer separately about the possible need to plan and check the building's physical spatial conditions if this is not otherwise within the scope of his mandate. The provisions of the Energy Saving Ordinance on indoor climates also usually have to be taken into account.
Condensation moisture often forms in the lower corners of affected spaces and usually leads to assumptions of leaks or the transport of moisture through diffusion. Any possible vapour diffusion through a water-impermeable structure would however be extremely small and, as various tests have proven, such vapour cannot transport any amounts of water that could produce visible damp in an interior [1]. What has a greater impact on an interior's humidity balance is the drying of building moisture on the external surfaces of concrete inside buildings. Because the interiors of water-impermeable storeys are not generally very well-ventilated, evaporation can cause condensation if their insulation is inadequate. If interior wall and floor surfaces are sealed by means of floor installations, watertight floor coverings or the like, building moisture cannot dry out, so interior sealing under these surfaces will be required.
Planners must investigate and ascertain the sealing of building or construction joints between the structure's sections, including all openings and ducts through water-impermeable concrete structural components. Various manufacturers offer a range of suitable products for pipe ducts, connections to window and cellar openings and formwork anchors. Joint seals should be systematically planned and put together because there are always connections (T-joints, cross-joints or transitions from construction to expansion joints) that only fit each other within one manufacturer's system. These may include seam sheet metal plates, elastic joint tape and control crack joint elements. Different joint sealing types and systems are not usually compatible. The guideline recommends minimum thicknesses for floor slabs and walls for the prefabricated element, semi-precast element and in-situ construction methods.
Concreting on structural components in stress load class 2 and "periodic standing seepage water" in the load case should be carried out and monitored in compliance with inspection class 1, if no higher inspection class applies for other reasons. The provisions of inspection class 2 also apply to structural components in stress load class 1 (Fig. B 1.51).
If semi-finished parts (double-wall elements) are used, the joints connecting the floor to the wall must be free of dirt and the formwork used to prefabricate parts must not be cracked. Wall elements must be at least 30 mm tilt-mounted so that the concrete can run down them. The inner surfaces of semi-finished parts should be as rough as possible and must be wetted before concreting to improve bonding.

Multi-storey car parks and underground garages
Multi-storey car parks and underground garages are reinforced concrete buildings that have to be planned, built and maintained with particular care. Their usage means that they are in a particularly aggressive corrosion situation, requiring a specific, specially tailored set of building regulations. The corrosion situation in car park buildings is mainly due to chloride-induced steel corrosion. This especially aggressive corrosion affects all concrete building components that come into contact with de-icing salts and moisture and especially attacks the steel reinforcement in concrete. Every winter, vehicles entering car parks bring de-icing salts in with them in rain or condensation runoff and distribute them throughout the building. Chloride in the de-icing salts can, when dissolved in water, reach the steel reinforcement in concrete relatively quickly and directly through faults (cracks, joints) in the structure.
Iron (steel) and chloride are highly chemically reactive, so chloride corrosion can also damage steel reinforcement that is passivated by the alkalinity of the surrounding concrete and protected against atmospheric corrosion. Chloride-induced corrosion requires moisture and oxygen, which are almost always available. The affected steel reinforcement is attacked not across its surface, but at various points, and damage is intense (pitting corrosion). The corrosion products are small in volume, so the corrosion process may not initially be discernible, through a flaking concrete cover for example, even though damage to the steel may be very advanced. Floor slabs, park decks and areas around the joints of adjoining walls and supports at or near floor level are typically at risk. Technical durability planning for reinforced concrete structural components exposed to chlorides generally begins with a classification of the component in the relevant exposure class (XD1, XD2 or XD3).
The risk of chloride-induced corrosion especially affects the circulation areas of car park buildings and their overall structural situation is decisive in evaluating the attack situation. Floor slabs in car park buildings require special attention. Unlike the floor slabs of multi-storey car parks or underground garages, they are always relevant to the structure's safety and load-bearing capacity. When park decks are also floor slabs, they function as continuous beams in the structure. In this type of structure, bending cracks can open up on the deck's topside due to the support moment and extend to just below the top reinforcement layer. Chloride-induced corrosion in these cracks risks damaging or dissolving the steel reinforcement that bears significant static loads in the support structure.


B 1.50



B 1.51

This means that cracks in park decks must be reliably closed with tested materials and/or coated to bridge any cracks. All the circulation areas in a multi-storey car park are usually coated using one of two main alternatives:
The reinforced concrete structural element can be planned and installed according to the criteria of exposure class XD3, with three subsidiary alternatives offering additional protection [2].

- If cracks can be reliably avoided (prestressing), a nominal concrete coverage of 55 mm will be sufficient as corrosion protection.
- If all the cracks on the deck's topside are safely closed (e.g. with crack-bridging bandages) the concrete cover will also be adequate for the crack-free part of the circulation area.
- Complete coating of the deck's surface, at least in the area of the cracks, with a crack-bridging system (OS11) or bandages.

A second alternative is an extensive dense, bituminous sealing of the concrete surface in accordance with DIN 18195-5 or DIN 18195-2 (OS10) and the direct application of a protective layer of mastic asphalt that vehicles can drive on. The protective effect of this type of construction means that the possibility of corrosive attack from de-icing salts will be negligible for the purposes of durability planning, because if it is properly laid, this coating will protect the structure against the infiltration of water containing chloride for a very long time without further maintenance. Only exposure class XC3 and (perhaps) XF1 need be applied here.

Deck surfaces, at least in the area of the cracks, are usually completely coated with a crack-bridging system (OS11) or bandages are applied. Bitumen sealing is the second most frequently-used alternative.
The floor slabs of underground garages in contrast, are only reinforced concrete structural elements with a structurally load-bearing effect if they either serve as a spread foundation for the entire building or are also water-impermeable structural components. Reinforced construction is necessary in these cases. No support or bending moments occur in bedded slabs as a result of their support function, although larger floor slabs in particular are not usually free of cracks, into which water containing chloride must not be allowed to penetrate. The protective measures outlined above could therefore also be used for reinforced concrete floor slabs in underground garages. The slab's statically motionless position means that the coating does not generally need any crack-bridging properties.

As well as horizontal structural elements, areas around the joints of supports and walls in multi-storey car parks require particular attention. The construction joints here are not as waterproof as an intact concrete cover is, so water containing chloride can permeate to the reinforcement through cracks. If the first corrosion protection measure is chosen, this area must be protected with a coating. To make the coating durable, a channel is first made with a suitable mineral mortar at the foot of the rising structural component. This channel provides an additional seal for the construction joint, spreads the right angle out to two intersections of about 45° and provides a sufficiently smooth, clean, load-bearing and geometrically defined base for the coating. It should terminate in a permanently dry area of the wall, about 30 to 50 cm above the channel, to prevent water from seeping under the coating and to give the coating sufficient protective reserves.
To avoid the risk of corrosion from chloride in de-icing salts, planners can check whether an underground garage's floor slab could perhaps be built without reinforcement and thus without the risk of chloride-induced corrosion. An underground garage floor could for example be made of (permeable) paving. Steel-reinforced concrete foundation components under the floor slab will however then lie in the drainage area of water containing salts (wall panels, supports, foundations), so they must be designed and protected accordingly.
As well as the chloride attack already mentioned, the question of whether frost or freeze-thaw attack must be taken into account in multi-storey car parks often arises. Exposure class XF4 for horizontal surfaces applies here. In deciding whether there is a risk of frost or freeze-thaw exposure as well as chloride attack, the possibility of a structural component being soaked with water is decisive, because freezing causes little or no corrosive damage to dry or only slightly damp structural components. Only exterior structural components in the entries and exits of a multi-storey car park or underground garage are usually exposed to such frosts. A frost or freeze-thaw attack need only be considered a possibility in parts of multi-storey car parks that are open to the elements. Because circulation areas in a multi-storey car park are usually covered with a waterproof coating and freedom from ice is a basic prerequisite for operations, frost or freeze-thaw attack conditions do not usually occur in them, not even in temperatures well below zero, because their coated concrete surfaces do not get soaking wet. Underground garages are generally assumed to not be subject to frost or freeze-thaw exposure unless the structure is an open type and it seems likely. The exterior circulation areas of multi-storey car parks must be evaluated separately.
Vertical structural components are usually classified in exposure class XF1, because it is possible for these structural components to freeze, but the water content in the concrete's structure is low. Attacks from water containing de-icing salts splashed or sprayed (XF2) onto vertical surfaces must not generally be assumed to occur in multi-storey car parks and underground garages due to the low speeds of the vehicles in them.

B 1.50 "Floating" water-impermeable cellar made to demonstrate permanent waterproofing
B 1.51 Water-impermeable structures: allocation of load stress classes to inspection classes

Concrete construction operations

Martin Peck

B 2.1

B 2.1 Formwork supports for beam or slab formwork
B 2.2 Formwork systems for columns, vertical panel formwork for walls
B 2.3 Slab formwork for an upper storey, temporary supports in the lower storeys, initial column formwork for the next storey
B 2.4 Large-scale custom formwork for non-standard building geometry

Concrete construction operations have developed directly out of the properties of concrete, whose invention in the 19th century made it necessary to find new ways of making buildings and structural elements. Building with large volumes of a heavy, first fluid then plastic material was new to the construction technology of the time. The approach of making almost every structural component by first planning and creating a form, a stable, load-bearing structure that would then be dismantled, was familiar mainly from the building of masonry domes and vaults, although only in concrete construction did the design and construction of moulds and formwork become a separate area of the building trade.

Concrete cast in situ

Casting structural components in situ is the classic method of concrete construction. Components are produced where they will be used in their final structural position. Although the structural components that were the subjects of Joseph Monier's first reinforced concrete patent in 1879 were essentially precast concrete elements, in-situ concrete construction was always regarded as the main construction method in the application and development of modern concrete construction.
The first stage of in-situ concrete construction is to erect formwork (a mould) to shape the subsequent structural component's geometrical form. If reinforced concrete is used, the next step is to make and lay reinforcement. These operations are often carried out step by step, because formwork can only be completed after reinforcement is completely laid.
Concrete cast in situ forms the basis for a monolithic concrete structure from start of construction to the completion of the building's shell. The friction-locked connection to the next structural component forms an adequate connecting reinforcement. Apart from a few exceptional cases, formwork is removed after the concrete sets.

Formwork and formwork skin
Wood is still mainly used to make in-situ concrete formwork. In the early days of concrete construction, formwork was laboriously made by hand from rough, single-layer, untreated pine planking. Carpenters usually made small, manageable formwork units because of a widespread lack of powerful lifting equipment (cranes and the like). Only in the second half of the last century did construction with reusable, high quality formwork skins made of plywood with lined surfaces in partly standardised formwork systems develop. Formwork skins made wholly or partly of plastics are now also in use.
It is essential that concrete formwork is leakproof, load-bearing and geometrically stable under the pressure of the heavy concrete and the dynamic effect of filling the formwork. Ensuring formwork's load-bearing ability in every state of building, reinforcement and concreting is the responsibility of the constructing company and their on-site construction supervisors. Depending on the type and position of the structural component, formwork pressure and the loads imposed by formwork and concrete can affect a structure together or separately.
Foundations or structural slabs bear the weight of the formwork and the concrete in vertical structural components such as walls. The formwork pressure must be monitored here, i.e. the hydrostatic pressure of the concrete on the sides of the formwork, which can reach different maximum figures depending on the concrete's consistency, the formwork's current filling level and the pour rate. Maximum formwork pressure can be estimated using diagrams such as those in DIN 18218 "Pressure of fresh concrete on vertical formwork". The concrete's consistency class is a fixed input from which ensues either the maximum rise rate of concrete in the formwork (pour rate) with a limited formwork pressure, or maximum formwork pressure with a specific pour rate.
In estimating formwork pressure, it must be ensured on site that the concrete being poured does not have a more fluid consistency than has been assumed in planning. The information in the diagrams includes only limited safety specifications, so construction site supervisors

must carefully check whether the diagrams are suitable and applicable for the job at hand. If no specific information is available on the formwork's load-bearing ability, the total hydrostatic fluid pressure of the fresh concrete's relative density must be assumed.
In producing horizontal structural components that are not extensively supported by an existing structure, such as floor and ceiling slabs, falsework bears the entire weight of the formwork, reinforcement and fresh concrete. The constructing company must provide proof of its load-bearing ability, for which either the manufacturer's authorisation from the building regulation authorities or the specifications of DIN EN 12812 can be used. Because falsework is relevant to a structure's overall safety, verification of its load-bearing ability is required in building regulation law and must always be carried out, regardless of any contractual construction agreements. In designing scaffolding for a rising building, it must be ensured that the structural elements the scaffolding rests on can also bear the working loads imposed on it safely and without being damaged by overloading.
Manufacturers offer various formwork systems for structural components, which can be categorised according to their form, handling and construction type.

Frame formwork
Frame formwork is the system most commonly used in structural engineering for components of all types and sizes (Fig. B 2.2). It consists of a bracing metal frame with a formwork skin mounted on one side that can be renewed or changed as required. The metal frame determines the formwork element's size, so it cannot be increased or reduced. Variable element sizes within a system are available however, and can be combined to make structural components of almost any size. Individual elements can be joined, with clamps for example, to form larger groups of elements, which can be moved as required and do not have to be reassembled or dismantled every time they are used. Complicated formwork geometries may have to be supplemented with adapters in some cases.
In most systems, the edge of the frame on the concrete side forms part of the poured surface, i.e. the frame's imprint remains visible in the concrete's surface. This must be taken into account in planning exposed concrete elements. There are also types of formwork frames for exposed concrete that leave hardly any imprint of the formwork on the completed surface.
Frame formwork is very easy to handle and efficient, so medium-sized segments can be transported and installed without lifting equipment. The frame's stiffness is usually enough to absorb bending stresses under the pressure of fresh concrete in normal storey heights, so it needs fewer walers or braces. Formwork anchors fitted closely to the formwork's frame absorb the pressure of fresh concrete in ordinary double-sided formwork. The anchor's position is largely set and cannot be arbitrarily changed. There are also versions with anchor points in the centre of the element for exposed concrete systems.

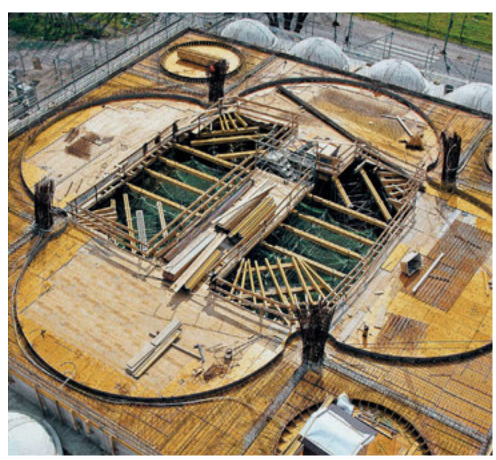
Girder formwork
Girder formwork's skin is attached as a sheet to service girders and tensioned with braces. Several formwork skin elements are usually pre-assembled, then installed in one piece. The formwork skin transfers the pressure of the concrete to usually vertical girders. They transfer loads to braces passing at right angles behind them, which transfer the pressure either to formwork anchors or external supports. Girder formwork requires a more stable formwork skin than frame formwork because the free surface elements are usually bigger, so the formwork skin has a greater structural effect in the overall system. If very high-quality formwork skins are used for high-quality surfaces, so-called "open formwork" can first be made of less expensive material, on which a higher-quality formwork skin is then mounted. If open formwork is used, the higher-quality formwork skin can be thinner, so less expensive, and surface elements do not have to be completely dismantled when the formwork skin is changed. Girder formwork's stiffness is determined by the formwork skin's thickness (possibly including open formwork), the type and number of girders and their distance from each other, and the type, number and position of braces, formwork anchors and external supports. The more support and anchor points a formwork segment has, the less it deforms under the pressure of concrete. Girder formwork is used mainly for covering large areas or in high quality exposed concrete formwork and typically produces a smooth exposed concrete surface with formwork skin joints and anchor holes at planned intervals.

Formwork tables
As well as these two main groups, which are mainly used for vertical surfaces, there is a series of systems for making laminar structural components such as floor and ceiling slabs. These can be made using frame or girder formwork, but formwork tables are usually used. These are square or rectangular formwork elements with at least four supports at the corners and a reinforcing support structure under the formwork skin. Either the formwork skin forms the table's surface or open formwork of sufficient stiffness is installed and functions as a support for a formwork skin that is laid or screwed onto it. Formwork tables are generally set up on existing ceiling or floor slabs and form part of the scaffolding, so they must be included in the analysis of a structure's load-bearing capacity. Here it is particularly important that the structural elements they stand on can safely bear the weight of falsework, formwork, reinforcement and the poured concrete until stripping without being damaged. After they are set up, the table surfaces are adjusted to the required height with adjusting screws and the individual elements are braced together. Stopends are either integrated into the system or built on by carpenters. Formwork skin joints are pressed together by bracing the table and it is sealed with compressible sealing tape. It's a very efficient way of making large horizontal surfaces.

Climbing formwork
Another system used to efficiently produce storeys with similar floor plans in building shells is so-called "climbing formwork". Climbing formwork is classified not by the type of formwork skin used or its frame and stabilising, but

B 2.2

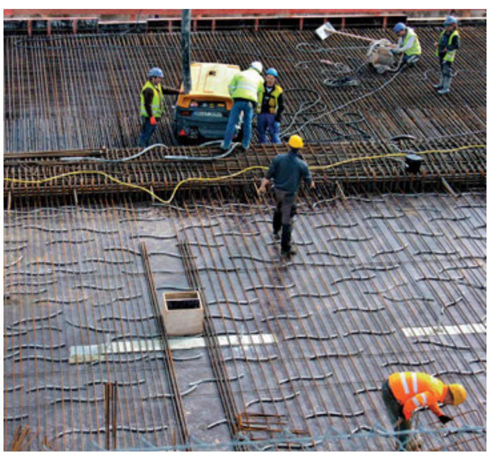
B 2.3



B 2.4

B 2.5

B 2.5 Self-climbing formwork system for serial storey construction, Burj Dubai, Dubai (VAE) 2009, Skidmore, Owings & Merrill
B 2.6 Preparations for concreting a slab, continuous connecting reinforcement in the foreground
B 2.7 Laying and tying reinforcement in a slab
B 2.8 Pumping concrete, beginning concreting
B 2.9 Pouring concrete into the lower layers of a downstand beam, compacting work with internal vibrators



B 2.6

B 2.7

by the way it works. It can be used to carry out extremely efficient climbing sequences of "stripping – moving – reinforcing – concreting". Climbing formwork stays on a structure from the beginning of the first stage of construction through to installation of the final structural component and moves along the work cycle from one position to the next. Work to open, move, then close the formwork is limited to a few quick manual manoeuvres and partly automated processes. Climbing formwork is usually used to build very high buildings (Fig. B 2.5). There are climbing and self-climbing systems – the former have to be partly supported by a crane, while the latter have lifting mechanisms and can move up buildings largely independently.

Reinforcement

The reinforcement in reinforced concrete components is arranged based on the structure's design and shown in execution plans (reinforcement plans or drawings). The most important information in a reinforcement plan is

- details on the type of steel used (normative reference),
- the number of reinforcing bars and their diameter (or a reinforcing mesh laying plan),
- the precise position of each reinforcement element in the structural component and exact details on the concrete cover and distances between bars.

Position of reinforcement

In practice, it is by no means certain that the reinforcement shown in a reinforcement plan can be laid or properly concreted over after it is laid, because reinforcing bars, regardless of their actual thickness, are shown only as lines. Reinforcement laid too closely together is a frequent problem that cannot always be solved by an intense adaptation of the properties of the fresh concrete. For this reason, a structural engineer should closely monitor reinforcing work, at least in situations in which laying reinforcement is clearly difficult, so that they can provide expert advice quickly if it becomes necessary to adjust the reinforcement layout.

Concrete cover

The most important criterion for the durability of reinforcement and thus of the overall structural component is the concrete cover, which must be produced and maintained during reinforcing work. It is specified in standards as a nominal value (c_{nom}) and a minimum value (c_{min}). Concrete cover depends on the applicable exposure classes on the side of the component in question and on the diameter of reinforcement bars close to the concrete surface. Since tolerances are unavoidable in bending and laying reinforcement, an allowance ($\triangle c$) is added to a normative nominal value. This allowance must not be deliberately utilised, but serves to ensure a minimum concrete cover ($c_{nom} = c_{min} + \triangle c$). Structural planners set the position of each reinforcement bar in the reinforcement plan as a layout measurement (c_V). This is based on structural and practical construction criteria and must not be less than the nominal value of the minimum concrete cover ($c_V \geq c_{nom}$). Once reinforcing work is completed and the structural component is concreted, the concrete cover must in practice have at least the minimum normative measurement (c_{min}) over every reinforcement bar. There are measurement methods for checking the concrete cover of a completed structural component and the German "Additional technical terms of contract and guidelines for civil engineering works" (Zusätzliche Technische Vertragsbedingungen and Richtlinien für Ingenieurbauten – ZTV-Ing) prescribe such concluding quality testing. Testing is however complicated and not always feasible in structural engineering. The best way to ensure an adequate concrete cover in a reinforced concrete structural component is to have an experienced builder check it by looking into the formwork after reinforcing work is completed.

A contractual agreement on construction based on the "Quality of reinforcement – supplementary stipulations regarding the subsequent treatment of reinforcing steel and installation of reinforcement" guideline from the German Committee for Reinforced Concrete (Deutscher Ausschuss für Stahlbeton – DAfStb) will significantly improve the quality of organisational and practical reinforcement production processes. The guideline supplements the specifications of reinforcing work standards and makes specific demands on all parties involved, prescribing a continuous quality chain from the planner through the manufacturer of the steel reinforcement and the contractor bending and laying the reinforcement to the workers building the building's shell.

Reinforcing work

Reinforcing work is typically done by subcontractors. Employees of specialist construction companies will be familiar with the practical aspects of working on a construction site building a building's shell, but cannot be expected to be experts on the wider context of construction operation processes and their results. It is therefore advisable to entrust reinforcing work to selected supervisors from the company building the building's shell to ensure sufficiently high quality performance of the work, taking all the demands of preparations and subsequent work into consideration. Reinforcing work is done at or on already erected or laid formwork or formwork skin, so it must be ensured that existing work is not impaired. There is a danger of:

- excessive staining and/or damage (scratches) from floor or ceiling formwork,
- shifting of or damage to existing installed parts, openings or building technology installations,
- damage to or overloading of the formwork skin caused by the depositing and shifting of reinforcement, tools or auxiliary materials.

Concreting
Every concrete pour requires comprehensive preparations, including the organisation of procedures for ordering, accepting, conveying and compacting the concrete during the pour and measures to protect the concreting from disruptions due to possible damage to machinery and equipment.

Concrete delivery
Concrete is usually ordered the day before concreting, or with very large volume concreting, a few days in advance, and delivery requested by phone on the day of concreting. Concreting should be able to begin as soon as the first delivery truck arrives and be carried out without disruption. Supervisors should again precisely check the construction operations work sequence immediately before requesting delivery of the concrete. Formwork and reinforcement must be ready for concreting, conveying equipment (pumps and cranes) ready to start and the smaller tools and equipment (compactors, spreading and smoothing tools and equipment) the concreting workers will need must all be ready on site. If concreting begins in darkness or ends after sunset, adequate lighting for all work must be ensured. A reserve supply of all machinery and equipment that can be picked up quickly at short notice must also be organised.
Other preparations for concreting include the establishing of access to the positions of and unloading points for concrete pumps or mobile cranes and concrete trucks, including any space required for turning and manoeuvring. If two trucks can stop at an unloading point at the same time, it will be possible to switch smoothly from unloading one truck to the next without disruption and no time will be lost moving trucks. The following data should be provided when ordering concrete from a ready-mixed concrete plant:

- the concrete's class number and total batch amounts of individual types. Usually just one type of concrete is used in one structural component. Another type of concrete, a concrete with an aggregate with smaller particles for connecting mixes or a more fluid consistency for example, may be required in some cases in areas where reinforcement leaves very little space or in certain segments of a structural component,
- the time the concreting is scheduled to begin, the position and types of pumps and location data on installation and unloading locations and route directions,
- planned hourly output and a delivery schedule if necessary.

Concreting work
The planned hourly output should first be precisely coordinated with the ready-mixed concrete plant and pump rental company. Estimating a pouring rate (m³/h) for a particular structural component under specific building site conditions demands experience in construction operations. Depending on the number and size of their mixers, modern ready-mix concrete plants can produce and load 40–120 m^3/h. On-site concrete pumps, depending on their type, have outputs realistically ranging from 50 up to 150 m^3/h, and outputs of up to 25 m^3/h are possible with concrete delivered by crane with buckets of the appropriate size.
For very high-volume concreting it is advisable to draw up a delivery schedule and a concreting plan to plan the work in detail. Normal concrete begins to harden at average temperatures about 120–150 minutes after mixing. The loading time entered on the ready-mix concrete delivery docket is taken as the time at which mixing begins. Setting times can vary significantly depending on the cement's hardening characteristics and temperature conditions.
Every fresh joint plane of concrete already poured must be poured again with fresh concrete before the surface hardens and seamlessly joined with it in a compactable and at least plastic state. When very large structural components are poured, intermediate states can arise in which very large fresh joint planes are created due to the usually very flat angle of repose formed by the concrete already poured, so the joint planes can no longer be concreted over in the time scheduled for the following delivery. It is important to recognise such situations in good time and deliberately prolong the concrete's workability period by adding setting retardant admixtures. The overall concreting plan should therefore also include a retardant plan, which must be developed and precisely defined in close cooperation with the concrete plant's concrete technology department. This plan will specify which concretes, with their setting and retardant times, are to be placed in each phase of concreting and it must be precisely adhered to during concreting.


B 2.8


B 2.9

Concrete consistency
Selection of the right concrete composition for concreting is generally based on the fresh concrete's properties, with the structural planner deciding which properties of the hardened concrete are required. It must also be specified when concrete is ordered and is derived from technical structural planning documents (drawings, scheduled performance specification texts) when the concrete is ordered. A complete and correct concrete order contains the following minimum details:

- exposure class and humidity class (established during planning in technical structural planning documents)
- the concrete's compressive strength class (established during planning in technical structural planning documents)
- the concrete's consistency (determined by construction supervisors depending on concreting conditions on site)
- the aggregate's maximum particle size (determined by construction supervisors depending on the density of the reinforcement and its concrete cover)
- setting speed (determined by construction supervisors depending on the scheduled stripping time).

The building contractor's decision on the concrete's consistency will partly depend on the method of conveying the fresh concrete. If the concrete is to be pumped, suitable concrete mixtures and consistencies must be chosen. If large quantities are required, it makes sense to take advantage of the maximum output rates of the concrete pumps and adjust the concrete's consistency accordingly. When placing concrete its consistency must be adapted to the compacting process. Complicated structural component and formwork geometries and high reinforcement densities require more fluid consistencies than large-volume or laminar structural components, where the poured concrete can be easily accessed at any point for compacting. Concrete poured from a crane must have a minimum fluidity because it has to flow out of the buckets under the pressure of its own weight. Stiffer consistencies can be placed using a conveyor belt or, if trucks can get close enough to the placement point, moved direct from the trucks into the structural component. The regulations on manufacturing and processing concrete specify various consistency classes, according to which concrete is ordered, manufactured and delivered. The consistency of delivered concrete can be tested using the so-called “flow table test” a simple test that can

B 2.10

Consistency	Class	Flow table measurement [cm]
Stiff	F1 [1)]	≤ 34
Plastic	F2	35 … 41
Soft	F3	42 … 48
Very soft	F4	49 … 55
Flowable	F5	56 … 62
Very flowable	F6 [1)]	≥ 63

[1)] Outside the recommended scope of testing

B 2.11

be performed on site and offers a rough, but usually adequate precision. Concrete consistency is measured in some countries by a so-called "slump test", which originated in British building standards. This is similar to a flow table test, but uses a cone with a different geometry and after the cone is lifted, the surface the test is carried out on is not shaken.
The concrete's consistency is then expressed as the difference measured between the height of the cone and the height of the unmoulded concrete after the cone is lifted off it. The mean value of two practical measurements is the value measured in testing. Because concrete's consistency is subject to permissible fluctuations, the consistency classes define a range of flow table measurements for the plastic to fluid concretes usually used in structural engineering. The value measured must lie within the range specified in the desired (ordered) consistency class. Testing can reveal discrepancies that are due to handling and processing, so the result is more of a qualified estimate than an exact measurement. Concretes that slightly exceed the maximum permissible consistency value in a flow table measurement test should be mixed again in the truck for several minutes and another sample taken before a delivery is rejected. The relatively low mixing rate in the truck and vibrations caused in transport mean that there is often more fluid fresh concrete in the upper layer of the batch of fresh concrete that is first unloaded than in the core volume of the batch delivered.
Standard consistency classes have flow table measurements ranging from 34 up to 70 cm (Fig. B 2.11). They begin with class F1 (very stiff) and end with class F6 (very fluid). The extremely stiff consistencies in class F1 with a flow table measurement of 34 cm or less can only be measured very imprecisely. The permissible flow table measurement in the following classes (F2–F5) increases by 6 cm per class. Concretes in consistency classes F3 and F4 are now mainly used in ordinary concrete construction. Concretes in the consistency classes ranging from F4 to F6 require the use of liquefying admixtures (plasticisers) to improve the concrete's workability. Fresh concrete in the consistency classes F1 and F2 cannot be pumped or can only be pumped with difficulty and over short distances. It is difficult for workers to place and compact, so it also takes longer to place. These concretes are only used where absolutely necessary, for concreting in angled and sloping formwork to make structural components with large surface areas, for example (in concrete stairs cast in situ, ramps, solid concrete ceilings etc.).
If the consistency class chosen turns out not to be suitable for a particular structural function (e.g. exposed concrete), it is also possible to specify to the ready-mixed concrete plant a fixed target value for an individual class with a tolerance of ± 3 cm. If it is necessary for technical reasons, the class's range can be further restricted. Classes with ranges less than 4 cm (± 2 cm) cannot however be reliably produced and measured.
Current concrete technology means that a concrete's water content and its consistency are no longer necessarily interdependent due to the use of highly developed plasticisers. Since concrete of almost any consistency can be made with very low water contents, the consistency for construction operations can be chosen largely independently of the concrete's compressive strength requirements. Using highly flowable concretes in the consistency classes F5 and F6 allows the constructing company to take advantage of the maximum output rates of concrete pumps and reduce the effort involved in compacting. If highly flowable concretes are used, compacting can largely be dispensed with in large-volume structural components with low levels of reinforcement or in those with large surface areas, such as foundations and floor and ceiling slabs.

When fresh concrete is accepted at a building site, only the concrete's consistency and largest aggregate particle size can be estimated (or tested) and compared with the order data by means of a quick visual inspection, even by an experienced builder. The air void content of fresh concrete with micro-pores of air, which increases freeze-thaw resistance and/or resistance to de-icing salts, must also be checked. A buyer cannot check all the other properties of the wet or set concrete ordered when a delivery is accepted, which is why the standards prescribe compulsory monitoring of the placing of concrete on building sites, at least for concretes in inspection classes 2 and 3 (see "Regulations on and requirements of construction operations", p. 24ff.). A delivery contract between a ready-mix concrete's manufacturer and a buyer of concrete is only regarded as having been fulfilled if the concrete demonstrates the properties specified in the contract and they are verified in the prescribed tests when the concrete is delivered to the site.
The concrete delivery docket must be checked by appropriately skilled employees on the building site and this is far more than a mere delivery formality. It is often criminally neglected or left to unauthorised persons, such as concrete pump operators, who are not on the staff of the company constructing the building's shell and are not legally authorised to accept the concrete. The placing of the "wrong" concrete in a load-bearing structural component is therefore still a typical construction logistics error that often has serious financial consequences. For this reason, boards should be put up at all unloading points on which the main delivery dates for each upcoming concreting for each day are very visibly displayed in weatherproof writing. Information should include:

- the concreting date, structural component being cast and concrete class number
- the total quantity of concrete of this type ordered
- the concrete consistency ordered
- other properties to be tested as required (e.g. maximum aggregate particle, air void content).

Defective deliveries can only be adjusted on site to provide the properties ordered in a few individual cases. If for example, the air void content is too low in initial testing, a second test should be carried out on another sample after the concrete has been mixed for several minutes in the truck. If the consistency is too stiff, plasticiser can be mixed in in carefully dosed quantities in the mixer vehicle on site. Adjusting a concrete's consistency by adding water on the building site is not permitted because this significantly alters the concrete's technical properties. Concretes altered in this way should always be rejected.

Safeguarding concreting work

In practice, the safeguarding of concreting work is often neglected. The worst possible scenario is an unplanned disruption to the concreting process allowing poured concrete to partly or completely harden before a structural component is completed. In such cases a so-

B 2.10 Concreting with a crane and bucket, concreting double wall elements with core insulation
B 2.11 Consistency classes of fresh concrete
B 2.12 Unloading concrete into a concrete pump

called "cold joint" is created, in which the concrete is no longer joined "wet on wet" and there is no consistent monolithic bond between the hardened and fresh concrete as there is in continuously poured concrete. Depending on the structural component and its loading, a structural planner and perhaps an expert must decide or establish whether and by which measures it is possible and permissible to continue concreting that has been disrupted. In many cases, it will be necessary to remove the concrete already poured and begin the formwork, reinforcement and concreting work again from scratch. Such disruptions will have a relatively slight effect on smaller structural components such as supports or walls, because the resulting damage will at most involve removing and re-building the defective structural component and perhaps a slight delay in the contractually agreed construction period. Too long a disruption or the discontinuing of concreting once begun on larger structural components on which high static and structural demands are made, such as large foundations, structural slabs in buildings or bridge superstructures, can have catastrophic technical and financial dimensions. It is essential to ensure concreting work in such cases and it must be thoroughly planned and organised. Among the necessary measures are in particular:

- ensuring an electricity supply for the necessary machinery and equipment, lighting gear, and the presence of an electrician during concreting,
- organisation of backup tools and machinery for conveying the concrete. If the concrete is to be pumped, at least two cranes with sufficiently large buckets (and a lifting capacity over the required operating radius) should be available if needed. At least one backup pump must be available to start operating within 45 minutes. Areas where backup tools and machinery are stored must be accessible for vehicles and free.
- a reserve concrete manufacturer on standby. A reserve concrete manufacturer should always be on standby during concreting, ready to supply the site with the concrete required at short notice if necessary. In pouring exposed concrete, it is essential that a reserve concrete manufacturer be able to supply concrete of the same composition. The reserve concrete manufacturer must have the same basic materials on hand and the right mixture in their plant control system. For other types of concreting, a backup supply of concrete with the same properties when wet and when set will suffice.
- a back-up supply of ready-mix concrete trucks and drivers. This is not only relevant if a truck drops out, but it makes it possible to quickly increase the delivery capacity and avoid long delays in delivery if concrete has to be delivered from another ready-mix concrete plant.
- preparation of replacement machinery and tools for compacting the concrete.

Building with precast components

Industrial construction with precast components began in the mid-20th century and its share of the total volume of concrete construction is still constantly growing. The drive to increase efficiency in particular has advanced the development of construction with prefabricated components but has also given it a reputation for being serial rather than bespoke, which has caused architects in particular to view construction with precast components from a certain critical distance. In fact, it was precisely the large numbers of repetitions that made early techniques for producing steel reinforced concrete precast components for individual structural components especially efficient. Today's precast component plants can produce a one-off structural component as efficiently as they can produce many identical units because mould construction, production, the installation of reinforcement and other built-in elements, concreting and even finishing, stripping and storage logistics, are all electronically controlled and largely automated.

Joining techniques

In contrast to a quasi-monolithic concrete structure cast in situ whose foundation forms a direct monolithic bond with almost every load-bearing structural component, parts of a structure built with prefabricated components will consist of steel-reinforced concrete structural components precast in factories that are usually only connected to adjoining structural components at various points and by planned joining techniques where these are structurally necessary. This building method makes it possible to save construction time, improve the quality of structural components and the overall structure, maintain high-quality architectural surfaces of various kinds, and install smaller prepared groups of building technology structural components (see "A comparison of in-situ concreting and prefabricated building methods", p. 34ff.).

Design of precast components

Precast components are made of steel reinforced concrete because they are designed for at least two different load situations:

- A structural component's own weight is distributed throughout the component by a reinforcement specially designed for this loading condition, which is crucial when the component is lifted by indoor crane and moved to a hanging point just a few hours after it has been poured. Reinforcement also keeps a component that has been damaged or broken by impact or overloading together, making the safe removal and replacement of a precast component possible.
- As well as this "self-supporting" function, precast structural components also often have a primary structural function in a building's support structure and are designed accordingly.

B 2.12

Precast structural components are usually stripped after just 14–18 hours, because efficient production requires that formwork be refilled daily. The concrete must have hardened sufficiently in this time to take the initial load, resulting from lifting of the structural component out of its form and transport to a storage area, without being damaged. The compressive strength of concrete in precast structural components is therefore designed with stripping and lifting times in mind, so this concrete is often one or two classes stronger than the support structure's design otherwise specifies. Heat-treating concrete with very short hardening times can ensure that the concrete has the compressive strength it needs when it is lifted. Together with good compacting of the concrete, increased compressive strength also significantly improves the concrete cover's imperviousness and with it the structural component's durability. Standards take this into account with a "double" bonus: the concrete covers of precast structural components can generally be reduced. Further reduction in the cover is allowed if the component's concrete can be demonstrated to be at least two strength classes stronger than the compressive strength the structure requires, which is often the case with precast structural components.

Compressive strengths of the concrete in precast components

Very high compressive strengths in structural components cast in situ mean that they have an increased tendency to crack and as a result usually have high, structurally necessary, levels of reinforcement, which increases the component's material costs, prolongs reinforcement times and can make concreting more difficult. Sometimes concrete cannot adequately spread because reinforcement has been laid leaving very few gaps, so the reinforcement layout must be subsequently changed. These problems often only become apparent on the building site because reinforcement bars, regardless of their actual thickness, are usually only shown in plans as lines. High compressive strengths in the concrete of precast components do not have the same effect, because

B 2.13

B 2.13 Precast component production, double wall element production, concreting the second outer shell
B 2.14 Erecting and preparing semi-finished components (double wall elements) with core insulation
B 2.15 300 mm concrete hollow slab made of 50 mm concrete, hollow concrete blocks (700/25/25 mm) and semi-finished concrete beams between them, council housing in Badajoz (E) 2011, Gálvez & Algeciras architects
B 2.16 Thermo-active semi-finished elements for production of core-activated slabs
B 2.17 Laid slab elements with integrated thermal and footfall sound insulation, connecting reinforcement

they are not usually in their final position during the decisive "early-age shrinkage" stage so there are no restrictions caused by tension on deformation. Some techniques used to join precast components and the main structure also allow precast components to deform slightly (due to thermal or hygric effects), ensuring stress-free mounting, even once the component is in its final position, and preventing subsequent cracking in the component and connected structural components.

Structural elements
Building with prefabricated components is an essential part of civil and underground engineering and building construction, although it is hard to clearly categorise branches of the prefabricated component manufacturing industry. Structural elements supplied as precast concrete components can be roughly categorised as follows:
- prefabricated elements for load-bearing structural components (bridges, industrial buildings, ceilings and walls in structural and industrial engineering etc.)
- precast exposed concrete components with or without load-bearing function (facades, interior walls, structural components in public spaces etc.)
- functional components for buildings (stairs, light wells, parapets, balconies etc.)
- precast components for underground engineering (wastewater pipes, shafts, tanks, drainage channels, gutters etc.)
- precast components for traffic route engineering (protective concrete walls, noise protection elements etc.)
- precast components for tunnel construction (elements for pipe jacking, tubbing segments etc.)
- semi-finished parts for adding to concrete cast in situ in buildings (element slabs, double wall elements etc.)

Semi-finished parts
Semi-finished parts play a special role in construction. These precast components function as formwork during construction and join with a segment cast in situ to form a complete monolithic structural element. They are available as elements of floor and ceiling slabs (element slabs, filigree slabs) and as double wall elements of concrete walls ("Triple walls", Fig. B 2.13). Both types of semi-finished parts make it possible to work very efficiently with high-quality structural component surfaces prefabricated in a factory.

Element slabs are laid on the supporting walls and supports like a formwork slab made of concrete cast in situ. The slabs already contain the lower layer of reinforcement that the structure requires. Because semi-finished parts are only about 5–7 cm thick, integrated lattice girders are concreted in with the reinforcement and protrude about 20–35 cm out of the side without the formwork, depending on structural requirements. The lattice girders are laid in a specific direction at fixed distances in parallel to each other and have several functions:
- They give structural components the necessary bending stiffness during laying, so that slabs do not break under their own weight before supports are installed.
- They support the upper layer of the reinforcement and can be integrated into that reinforcement. Here their height must be taken into account in planning.
- They secure and improve the friction-locked, monolithic connection between the semi-finished part and the segment cast in situ.

Because lattice girders have a statical function in the structure, their orientation and the orientation of the slab elements in which they are laid in are matched and set out in a layout plan, which also specifies the position and direction of the lower level of the slab's reinforcement that has already been concreted. After slab elements are laid, they are supported like in-situ concrete slab formwork to bear the concrete's weight. Once the upper reinforcement is laid and stopends are set, the structural component can be concreted. To improve the bond between the set concrete of the semi-finished part and the fresh concrete of the segment cast in situ, the semi-finished part's surface should be as rough as possible (vibrated but not smoothed) and wetted shortly before concreting. After the side rails and supporting scaffolding is removed, the slab's underside shows the smooth, even surface of the prefabricated semi-finished part and is complete, apart from possible further treatment of joints between elements.

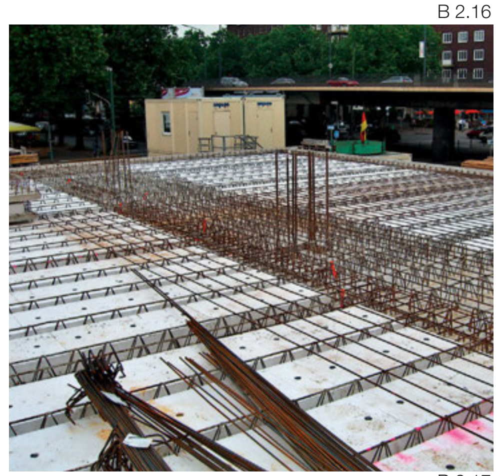
The same construction principle is used to produce double-element wall units. These consist of two thin, semi-finished sheets, each like an element slab. Lattice girders connect the two wall slabs, spanning the space to be concreted and cast-in-situ concrete addition like formwork elements. The two wall slabs also contain the wall segment's structural reinforcement. Their rigid connection fixes the inner and outer geometry of the semi-finished part and absorbs the formwork pressure during installation of the segment cast in situ. They are designed to absorb formwork pressure, so a maximum pour rate is usually specified for them.
Double wall elements can be used for interior and exterior walls as well as below ground level. Special building regulations and the specifications of the DAfStb "Water-impermeable structures made of concrete" guideline apply to the use of semi-finished parts in water-impervious concrete structures. These specify in particular the minimum thickness of walls and roughness of their inner sides to improve the bond between a precast component and a section cast in situ.

Double wall elements, especially those designated for a water-impervious walls, should also be installed with a gap of at least 3 cm at the base, so that concrete can be seen to flow under both sides of the prefabricated element slabs. This allows a visual inspection to be made to check that the element is completely filled and produces a thicker layer of concrete in the area of the lower construction joint, which is usually sealed with metal seam sheets. The prefabricated elements' rough inner surface must be thoroughly wetted before concrete is placed (see "Water-impermeable concrete structures", p. 43f.). Double wall elements and elements slabs are also available as thermo-active concrete structural components. Another option is to use double wall elements with pre-installed core insulation, whose thermal

B 2.14

B 2.15

B 2.16



B 2.17

resistance planners can specify (Figs. B 2.10, p. 50 and B 2.14). This provides optimum, permanent protection for the insulation against fire and mechanical damage. Double wall elements with architecturally sophisticated surface qualities and joints designed for insulated walls that meet the high demands of exposed concrete on both sides are available. A core-insulated reinforced concrete wall made of pre-insulated, semi-finished parts is generally much thinner than a wall with the same function made of concrete cast in situ.

Thermo-active structural components
Thermally activated slab elements for producing floor and ceiling slabs that can be heated or cooled are a relatively new development (Figs. B 2.16 and B 2.17). They make it possible to manage buildings in an especially energy-saving way, using the concrete structure's ability to store heat. Activating large areas of space at very low flow temperatures quickly establishes constant interior temperatures, making it easier to make use of alternative and low-energy heat generation technologies. Thermally activated slabs could previously only be made using classic in situ concrete construction, but prefabricated slabs can now also be used and the construction process is no different from installing classic slabs.

Tolerances
Buildings made mainly of prefabricated elements will also usually contain a number of concrete components cast in situ. Because the production tolerances common in construction with concrete cast in situ are usually much greater, depending on the joining and fastening techniques chosen and planned, the transition points between a concrete structure cast in situ (often a main load-bearing element) and an installed prefabricated component require particular attention. Planners must transfer the structural and technical requirements of construction using prefabricated components to construction with concrete cast in situ and ensure compliance with requirements during construction.

Surface qualities
The surface of precast concrete components with high-quality surface must be protected and secured during all the logistical processes of storing, transport and moving the component up to installation in its final position in the building. The transport of a precast concrete component from the manufacturer to the building site through to installation in its final position in the building occurs along a chain of obligatory construction operations that can involve potential damage or staining of the component, so in handling surfaces with special quality requirements, individual stages in the process must be closely checked and observed. Details on the subsequent treatment of structural components and their storage until delivery should be checked with the manufacturer. The protection of elements and high-quality surfaces during loading, transport, unloading and storage on the building site and installation in their final position must be checked and organised in advance. To ensure a part's quality, the aspects of its handling during construction operations mentioned above should be agreed in a joint logistics plan with all those involved.

Acceptance
In working with precast concrete components, the legal boundary between laws governing ordinary contracts for services and those covering contracts of sale is often fluid, which can affect aspects covering the acceptance and warranty of concrete. These details should be known to everyone involved. In contrast to structural components cast in situ, to which laws on the provision of work and services apply, a warranty on a prefabricated component ends after it is accepted at delivery. Buyers often find it difficult to have defects that are identified later remedied, even if the defects are obviously the manufacturer's fault. It is therefore extremely important that prefabricated components are checked before they are unloaded.

Materiality and surface

Martin Peck

B 3.1

In the early days of concrete construction, there was a focus on using the material with new structural technology options and methods that were revolutionary at the time. Eventually though, builders also turned their attention to the finished concrete surface. An exposed concrete structure is characterised by the shape and texture of the form that holds the wet concrete, the formwork.

As concrete construction methods developed further, new ways of designing surfaces also evolved. While exposed concrete construction initially concentrated on the material itself, there was an increasing focus on the surfaces that could be created. The appearance of an exposed concrete surface can vary depending on the kind of formwork skin and manual finishing methods used. In time, the influence of various skilled manual building and treatment methods also became formative in creating exposed concrete surfaces. Such methods expanded the range of possible architectural variations, but also demand appropriate expertise, control and construction experience.

In Central Europe at least, exposed concrete is characterised by a smooth, flawless surface that has become a key trend in recent decades. Although this trend seems to be continuing unabated, there is now also a strong inclination to explore other options. Heavy restrictions and the narrow range imposed on the material's expressivity is increasingly giving way to a willingness to experiment and a desire for diversity and material authenticity in the appearance of surfaces.

After a long phase as the dominant surface design, it will be some time however, before other forms are established as equally valuable alternatives.

Surface design techniques

The techniques currently available for architects to create, control and vary the appearance of a concrete surface allow design options as diverse as they are bewilderingly complex for architects. Older or what could be regarded as "yesterday's" design techniques, such as the use of timber formwork or washed concrete techniques have faded from view and no longer seem to be present on the market. But after a phase of intensive development of concreting techniques and technologies, it would make sense to reconsider some older surface design techniques in the light of changed technical and technological conditions and perhaps achieve entirely new results.

Using the formwork skin in design

Now as then, the formwork skin usually determines concrete's visible surface. Fresh fluid concrete hardens in the formwork and the surface of the structural element created reproduces the inner surface of the formwork.

Historic and current philosophies of surfaces

Concrete surfaces were deliberately left visible for design reasons for the first time around 1900. The formwork and concreting techniques of the time produced components with a very rough, uneven finish and relatively strongly displaced surfaces bearing the imprint of the coarse texture of the small timber parts which made up the formwork, usually rough-sawn or planed planking.

After about 1920, developments in concrete technology led to more reliable construction methods whose technical properties could be more easily controlled. This could not fail to have an impact on surface design. While the focus in the early years of exposed concrete was on the material itself, the appearance of concreted surfaces could be increasingly varied due to the different properties of formwork skins and the influence of construction operations. The use of coated plywood panels to manage large areas of formwork economically in the years after 1960 resulted in the creation of a new quality of very smooth concrete surfaces. A smooth exposed concrete surface with formwork joints and anchor holes is still the standard surface structure of this type.

As smooth concrete became part of architectural language, architects increasing wanted (and contractors had to produce) flawless surfaces.

B 3.1 Interior surface created using planed timber formwork with planks of various widths and visible nailing
B 3.2 Interior surface created using planed timber formwork with visible light and dark effects due to the timber's various absorption rates
B 3.3 Church of St. Nicolas, Val d'Hérémence (CH) 1970, Walter Maria Förderer

B 3.2

Timber formwork
Timber formwork is the oldest kind of mould making in modern concreting. It uses the natural wooden surfaces of traditional construction timber. Untreated softwood planks can be used for formwork twice and up to a maximum of four times. A distinction is made here between tongue and groove (matchboards) formwork and butt-jointed timber formwork without tongue-and-groove joints, which can be made with regular or irregular board widths. Timber formwork surface textures vary from rough-sawn to planed. Higher quality woods are also sometimes used in concrete formwork to produce a particular grained texture or joint pattern.
Formwork made from butted-jointed softwood planking is hard to seal against fluid leaks. Leakage at joints between planks almost always results in an undesirable dark discolouration on the finished concrete surface. This effect did not appear in traditional construction with earth-moist tamped concretes because the concrete did not contain a fluid matrix. Butt-jointed timber formwork without tongue-and-groove joints was used until around 1950. Increasingly fluid concretes have been used since the 1960s however, and these have to be poured in a properly sealed formwork of precise dimensions. Very absorbent raw timber formwork skins imprint the concrete surface with their own rough texture while reliably preventing visible air pores from forming because the wood absorbs air and water bubbles close to the surface. This rough formwork does not generally produce structural components with precise edges but also rarely requires triangular fillets or similar measures to form edges.

The growing technical mechanisation of timber processing in the 1950s meant that tongue-and-groove planks were increasingly used in formwork. This type of formwork, when used with timber with medium moisture content and carefully sealed joints, prevents significant cement paste leakage. Applying formwork oil as a preservative and mould-release agent makes plank surfaces smoother so they can be reused several times in formwork. Equipment for lifting and moving larger formwork elements was being developed during this period, making it more economical to join softwood planks to make large formwork elements and move them with cranes several times without first disassembling them. Industrial timber processing was also developing at this time, so smoother, planed planks could be produced at lower cost. The rough-sawn butt-jointed timber formwork that had been standard began giving way to very high quality tongue-and-groove planed timber formwork, which is still used in some areas of architecture and construction (e.g. bridge construction).

The following construction operations issues must be taken into account when using timber formwork:

- Before being used for the first time, new formwork skin must be “aged” with cement slurry, concrete or by being sprayed twice with a 3–5 % caustic soda (sodium hydroxide) solution because untreated wood can contain substances that can impede the fresh concrete’s hardening and result in washed-out concrete surfaces and defects.
- When wood first comes into contact with fresh concrete, not only water, but also the cement matrix (water, cement and the finest aggregate) is absorbed by the void system

B 3.3

of the wood near the surface. The cement matrix hardens and stays there. This changes the absorbency of the void system and the look of the concrete surface when the timber is used again in formwork.

- Varying moisture levels in natural wood can cause swelling and shrinkage and thus significant deformations. Joints between formwork planks that are too damp can open up when they dry and then leak. Formwork that is assembled too dry can warp on contact with the fresh concrete due to swelling, which can lead to bulges or distortions in the concrete surface.

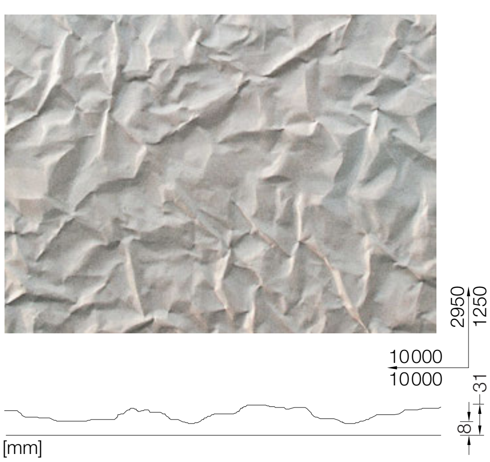
For these reasons, untreated wood formwork skins only produce a fairly consistent surface on their second or third use. The intensity of the surface colour can vary initially because the absorbency of the formwork skin changes although this stabilises in subsequent use (Fig. B 3.2, p. 55). Using timber formwork to produce high-quality exposed concrete surfaces – rather than the more usual plywood boards – requires that those performing the work have a certain degree of experience and skill in working with the formwork materials and a knowledge of its interaction with fresh concrete. The specific skills required for building and using timber formwork are however now rare and are largely no longer taught to construction industry trainees, so producing exposed concrete surfaces with timber formwork is an especially difficult construction task. The company doing the work should be able to demonstrate the relevant construction operations experience.
It is advisable to first trial and develop potential surface finishes on test areas and that this process should be allowed for in planning and commissioning high-quality exposed concrete surfaces.

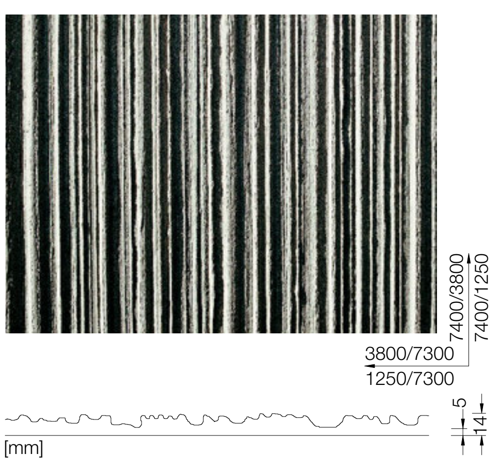
Smooth formwork skins and colours.
A smooth formwork skin is currently synonymous with a textureless type of formwork skin with a hardened surface that absorbs practically no water or cement paste and is used for largely consistent, smooth surfaces. Any texture on these very smooth surfaces is usually reduced to the unavoidable visible marks of formwork, to joints in the formwork skin and to the anchor holes, which are caused by the necessary bracing of the long sides of the formwork.
The possible variations in smooth exposed concrete surfaces are of course slight and are generally limited to anchor hole and joint patterns, colours and lighter and darker tones. These latter properties are largely determined by the cement used; aggregates influence a concrete surface's colour only very slightly. The colours of cements and the concretes made from them can vary greatly depending on the type and origin of their basic materials. Usually the architect chooses a concrete of a suitable colour from a series proposed by the constructing company. To assist in this choice it can be helpful to look at current projects during the construction phase to make a realistic assessment of the concretes that may be used.
If no ready-mixed concrete of a suitable colour is available in the usual delivery area, a concrete's colour can be modified to some extent by adding pigments. Here it must be determined whether the desired surface colour will be within the range of a normal concrete's colour or whether the aim is a colour that is not inherent in the building material itself (red, yellow, ochre etc.) (see "Concrete and colour", p. 61f.). A grey colour, which cannot be produced with the available cements alone, can be lightened (with titanium dioxide) or darkened (with iron oxide black) depending on the target colour, by adding small amounts of various pigments. The materials used, increased expense and effort involved in production, and greater care required in construction operations all mean that this does however involve more cost and effort.

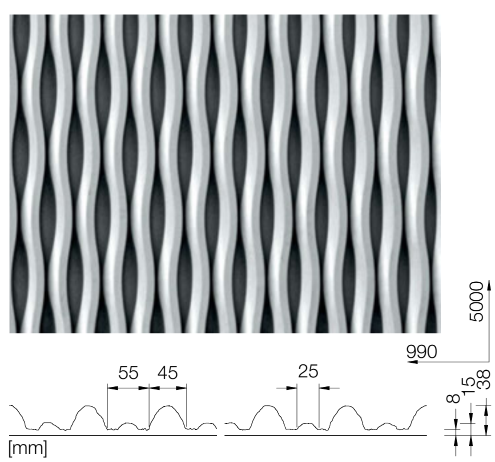
The attributes "smooth" and "non-absorbent" suggest that any number of identical surfaces showing few material or artisanal variations can be reproduced by using such a formwork skin. For this reason, these types of formwork skins are used mainly when a flawless surface is expected. The natural variations in construction materials and technique are not concealed by the smooth, textureless concrete surfaces. On the contrary, various "signs of life" of the material or construction techniques become more apparent in the surface and may easily be regarded as undesirable flaws. Designs where a high degree of consistency is expected require adequate preparations and testing before construction.

Matrices/matrix formwork
A matrix is an elastic formliner or synthetic formwork that textures a surface in a way that is very true to the original (Fig. B 3.4). Their surface is the negative of the surface desired for the concrete structural component. Depths of textures usually range from completely smooth matrices through to depths of 80 mm, in some cases. Deeper structures can also be achieved if the technical possibilities of production are fully exploited.
As well as creating catalogued standard textures, the matrix technique can be used to create special textures and individual artistic pieces. An original sculpture or relief made of plaster or a similar material is first created and the original is then negative-moulded with an initially fluid and then rubbery-elastic, hardening synthetic material. A mould is a form (formwork skin or form) used to produce the desired concrete surface or structural component. Such synthetic matrices and forms have very long service lives and can produce a consistent surface more than 100 times if they are looked after appropriately. A distinction is made here between matrices and "matrix formwork" in formwork technology. Both systems provide a formwork skin surface that prevents any water or cement paste leaking out and they are easy to shape, so they can also be used to create undercut textures.

Matrices are made of a rubbery-elastic mat with a back approx. 8 to 10 mm thick, to which is added the depth of the structure. They are made of a single material, in this case of the same synthetic material. The casting process described above is usually used to form the surface texture, or alternatively a heat-curing synthetic material is used, in which the texture is produced by vulcanising moulding. Synthetic matrices are not rigid, so they are stuck to a stiff underlying formwork. If they are reused







B 3.4

only a few times, matrices can also be simply laid in horizontal formwork (e.g. for prefabricated parts).
Matrix formwork is usually made of two materials. The texturing layer is made of rubbery-elastic synthetic like the one used in matrices and it has a back made of reinforcing foam. This kind of formwork is suitable for producing surfaces with textures with depths of more than 20 mm. The back gives individual elements a certain stiffness and reduces their weight, making them easier to handle, so matrix formwork does not always have to be stuck to underlying formwork.
Matrices and matrix formwork can only produce elements of a certain size. All geometric structural forms can be produced according to planned specifications, but if the planned exposed concrete surface is bigger than the maximum element size, the texture will be repeated. The surface will also show joints, which can however be rendered almost invisible if appropriate care is taken. Textured surfaces must also still have the prescribed concrete cover.

From 1965 until 1980, exposed concrete surfaces were often planned and built using synthetic matrices. The intention was to create high quality concrete surfaces with often complicated and seemingly natural textures in a technically simple and reliable way. Architectural tastes then changed and technical perfection was no longer recognised as a desirable quality; rather it was regarded as alien to the building material and artificial and the patterns were seen as incongruous. Matrices disappeared almost completely from the market with the advent of the next trend for smooth exposed concrete.
In the current search for alternative ways of designing surfaces, it may be well worth re-examining the suitability of this technique for use in individual cases and more widely in future, not simply so as to “quote” past trends, but also in the light of current concrete technology and design culture conditions.

Experiments

Architects’ increasing willingness to experiment means that materials that previously were not regarded as suitable for exposed concrete formwork are now being trialed. These trials often remain just that – trials – if the first surfaces produced are not useful. Longer development processes may not be embarked on because of their uncertain outcomes, yet sometimes chance can produce cogent results.
Inexpensive oriented strand board (OSB) has been used to make high-quality exposed concrete surfaces in recent years. The boards are made of compressed wood chips and glue and could be regarded as an inferior-quality material. In the manufacturing process, very coarse elongated wood chips are aligned in the longitudinal direction of the board, giving it better bending stiffness in the direction of the strands than ordinary finer particleboards. The boards’ manufacturers state that they can be used for concrete formwork, although they are very rarely used for this purpose. OSB is more usually used to make strong large packaging and temporary or concealed wooden structures. These boards are almost always used in formwork skins as double-layered formwork for a large area or framed formwork. Element joints must be integrated into the design or – like the anchor holes in wall elements – tolerated. OSB has a very absorbent surface and swells strongly, which has a clearly visible effect on the concrete surfaces it is used to form.

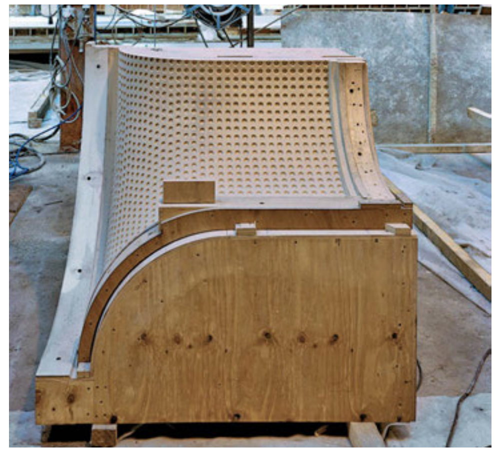
- The strand structure of OSB is transferred to a concrete surface as intensive, dominant markings overlaying almost all other visible surface effects (fill layers, cloudy discolourations etc.) (Fig. B 3.6).
- The boards’ powerful absorbent effect produces almost entirely pore-free surfaces.
- The glue in the boards and distribution of the woodchips greatly reduces and equalises the slight disruption to hardening that fresh natural wood can cause on a concrete surface, producing a slightly rough, darker surface.
- Because the raw timber of formwork elements swells strongly on contact with wet concrete, the junctions in the faces and at the corners of the formwork close up. This prevents cement paste leakage, the resulting discolouration and it slightly textures the concrete surface, which can be seen clearly especially at sharp, unbroken edges.

Before concreting, a controlled wetting of OSB formwork should be tested to see whether the use of mould-release agents could be dispensed with. Wetting causes the formwork to swell, making it watertight. This makes it easy to control the look and quality of concrete surfaces made with OSB formwork, which can produce exposed concrete surfaces far more reliably than smooth formwork can. The boards’ dominant pattern means however that construction operations will have scant influence on the look of the surface and even light-coloured concretes will tend to have a darker hue.

The use of inexpensive plywood panels in formwork has been trialed several times with very varying results. Individual formwork panels often produce surfaces with very different colours and textures. The untreated wood has an uneven retardant influence that varies greatly from panel to panel. An overall deformation of individual formwork panels due to swelling and associated sealing of formwork skin joints was not observed.

Tamped concrete

Before the Second World War, concrete was usually placed earth-moist and compacted by tamping due to a lack of other concreting technology options and the low level of the mechanisation of transporting and placing concrete. This historic construction method is recognisable in the surfaces of structural ele-



a

b B 3.5

B 3.4 Matrix formwork, technical representation of the usual sizes, structures and depths of some standard textures
B 3.5 Administration building and bus center in Thiais (F) 2007, Emmanuel Combard Dominique Marrec (ECDM)
a Rubber matrix, 7 mm studs with a diameter of 24 mm set at evenly spaced intervals of 14 mm
b Precast concrete components, just 30 mm thick, made of fibre-reinforced concrete with high bending strength.
B 3.6 Surface with OSB formwork

B 3.6

B 3.7

ments, depending on the concrete’s composition, the type of tamper used, the thickness of the tamped layers, the force used and commitment of the constructing company. As well as the usual marks of formwork, tamped layers, unevenly compacted large areas or surfaces, and porous defects in the aggregate are also often visible.
Tamped concrete construction is currently attracting attention again as a building and design method, with the planning and construction of buildings such as the Bruder-Klaus Chapel by Peter Zumthor in Wachendorf in Germany’s northwestern Eifel region (Fig. A 15, p. 19). It can only be used in unreinforced structural components because this kind of compacting does not adequately protect reinforcement from corrosion. Producing load-bearing structural components can also cause difficulties with building authority regulations. The compressive strength of such components cannot be verified because tamped concrete has a texture with many pores occurring at varying levels throughout the concrete. There is no continuous, reliable, acceptable minimum compressive strength because it changes every few centimetres, depending on the number of pores in a given area. The usual cube tests cannot represent the strength of the concrete because tamping works much better in a small test area than in large volumes in formwork, so conformity with applicable standards cannot be clearly demonstrated. Planning architects need to agree on regulations in individual cases with the developer or with building inspection authorities in such cases.
The term "tamped concrete" in fact currently describes two very different technologies and design aims:

- The classic historic tamped concrete technique with earth-moist concretes that contain enough sand, cement and other fine particles to create a closed texture. The potential defects visible in the formwork and everywhere on the inside of the structural component, such as joins between layers, are the result of the compacting process. The tamper’s impact on the concrete surface compacts the concrete directly under the tamper very well, but its impact weakens further below the surface, so compaction within a tamped layer weakens from the top down.
- Current developments, which now focus less on construction techniques than on creating surfaces with a tamped concrete look, including complete internal porosity of aggregate particles in the texture. To promote and secure this effect, concretes with a low mortar content are used so the grain structure can no longer completely close. The concrete in such structures is still usually placed by tamping, but this process is not entirely necessary. A visibly open-pored texture can also be created by placing concrete in layers using external vibrators. The Waldfriedhof (forest cemetery) at Landsberg am Lech by Kehrbaum Architekten (Fig. B 3.7) and the Giardin residential complex in Switzerland by Mierta & Kurt Lazzarini (Fig. B 3.8) are two examples of the use of this technique. Albert Dischinger used a combination of both techniques for the Waldfriedhof (forest cemetery) in Eichstätt-Rebdorf.

Producing tamped concrete structural components requires close cooperation and coordination between a building’s developer, architect and the building company, regardless of which technical process is used. The stiff consistency of this type of concrete must be taken into account, it cannot be pumped and placed with the usual construction methods and it can usually only be moved with difficulty and after preliminary testing with the usual types of crane buckets. These concretes also behave unusually in formwork, so handling them requires a certain level of manual skill, and they must be developed and trialed. Every project of this type includes an experimental aspect until it is completed, which also makes it much harder to estimate costs in advance. Tamped concrete walls of the second technological type are also regarded as not completely weatherproof. If they are used to build interiors, sealed areas must be planned separately or the structure’s use must be adapted to accommodate this factor, so this construction method is more suitable for components in garden and landscaping structures.

a

b

B 3.8

B 3.7 Tamped concrete, Waldfriedhof, Landsberg am Lech (D) 2011, Kehrbaum Architekten
B 3.8 Giardin residential complex, Samedan (CH) 2007, Mierta & Kurt Lazzarini
a Visible layers of tamped concrete with varying colours
b Porous concrete texture resulting from a low proportion of mortar
B 3.9 Photo concrete
a Backing foil
b Precast component before installation
c Detail of various washout depths

Subsequent treatments of concrete surfaces

The subsequent treatments of a concrete surface for design reasons covers all the processes used to modify a concrete surface after the concrete hardens. Such modification, the creation of a washed concrete surface for example, can be carried out on the structural component at a very young age. Other processes require a hardened concrete surface and can be carried out on concrete surfaces of any age.

Washing and acid etching

"Washing" or "acid etching" both remove cement mortar from a concrete surface. Both methods produce a surface with an open texture and a more or less visible aggregate. These methods are now used mainly only on pre-cast components because it is generally only possible to treat resulting runoffs (acid solutions, contaminated wash water) as prescribed by regulations in a factory setting. Using these techniques on structural concrete components cast in situ involves an extremely extensive construction logistics effort and their use on vertical concrete surfaces usually produces unsatisfactory results due to the uneven distribution of particles in the concrete's texture on and near the surface.
Due to the even textures the formwork produces, it is usually the bottom surface of a pre-cast reinforced concrete component facing the formwork that is treated by washing or acid etching during production. Using certain aggregates can also give a concrete surface the desired look. Because concretes for these aesthetically sophisticated surfaces are usually expensive due to the effort involved in designing and producing them, they often form only a thin surface layer on a normal concrete core.

Washed concrete surfaces

Washed concrete surfaces are exposed concrete surfaces in which the hardening of cement mortar on the surface is delayed by about one day. After the core concrete hardens, the mortar is removed by washing and the aggregate structure becomes visible. Building and designing with washed concrete surfaces was a real trend from 1965 until 1980, one that faded fast in subsequent years. The technique has survived largely only in the production of cast stone (for landings, stairs and the like). Yet washed concrete's design potential extends well beyond traditional applications, so it may be a construction method worth re-examining. These types of surfaces are currently again being increasingly planned and built. Compared with the deeply washed out, coarse-grained textures of traditional washed concrete, the focus is now more on surfaces with low washing depths that do not reveal coarse aggregates but attempt to reproduce colours and textures like those of natural stone.

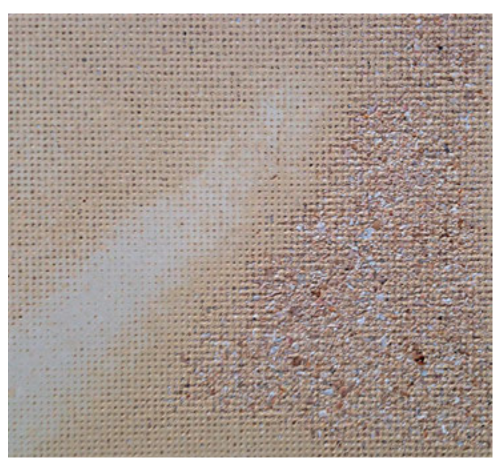
Producing a structural component with a washed concrete surface differs in only a few points from the processes used to produce a normal concrete structural component. A setting retardant agent – usually a paste – is first applied to the formwork skin and dries to form a white coating. Alternatively, foil or paper soaked with setting retardant can be laid in the formwork. Mould-release agent is not necessary because unhardened mortar will not stick to the formwork skin. Fresh concrete is then poured. Washing depths can be very precisely varied through the choice of retardant and are usually in a range up to about 3 mm, although greater depths are also possible. The depth of washing should be determined in preliminary testing.

Photo concrete

One special form of washed concrete is photo concrete. This is a technique in which a photo is digitally recorded, translated into grey tones and then transposed into rugosities (washing depths) that reproduce the grey tones on an originally smooth concrete surface. A depth profile is created and a computer is used to very precisely dose the surface retardant on the backing foil. The various thicknesses applied and resulting different washing depths reproduce the original image on the concrete surface (Fig. B 3.9 c). The primed backing foil is laid in the formwork, concreted over, and the surface washed after the structural compo-


a


b


c

B 3.9

B 3.10 Various treated concrete surfaces
a sandblasting
b drove work
c bush hammering
B 3.11 Sandblasted cast-in-situ concrete surface, Museum of the Celts and Romans, Manching (D) 2006, Fischer Architekten
B 3.12 Waldorfschule (school), Augsburg (D) 2007, Ott Architekten
a Untreated shaped concrete surface in an interior
b Red coloured faced formwork shell
B 3.13 Double-shelled, insulated, pigmented concrete exterior wall, bush-hammered by hand, family home, Munich (D) 2012, lynx architecture

B 3.11

a

b

c

nent hardens (Fig. B 3.9a). The deeper a surface area, the darker it looks. The washing depths are extremely low and vary only slightly between different surface areas. Images reproduced in this way can look very realistic (Fig. B 3.9b).

Acid-etched surfaces
A similar surface effect to that of washed concrete is produced by treating a concrete surface with a dissolving acid. Here the surface stripping is controlled not by the penetration and effect of retardant, but by the intensity, frequency and duration of the acid solution. Usually organic acids (e.g. citric acid) are used to dissolve the calcium compounds in the cement stone and the dissolved cement mortar can be washed out and removed with mechanical aids (brushes, high-pressure water jets). Acid-etched applications are especially suitable for producing textures with relatively low depths, because the texture's degree and depth can be easily controlled. As with washed concrete, the coarsest visible aggregates in the surface largely determine its colour. Compared with washed concrete surfaces, acid-etched surfaces usually have more brilliant colours and look crystalline, which is why this technique is especially used for lighter surfaces.

Blasting with solid blasting media
Blasting techniques use air pressure and natural sand or industrial blasting grit to modify concrete surfaces (Fig. B 3.10a). Surfaces can be blasted wet or dry depending on local conditions. Wet blasting has the advantage that it produces almost no dust.
Here it is important whether the concrete surface to be treated was the bottom of a pre-cast surface or is the side of a concrete structural component cast in situ. The bottom surface of a pre-cast component has an even texture because the aggregate in concrete has a higher density than the surrounding cement mortar so it usually sinks to a lower contact area before the concrete hardens. This produces a homogenous mixture of coarse and finer aggregates with a very thin, almost pore-free layer of mortar over the aggregate. The concrete's mechanical strength also develops very evenly on such surfaces. Blasting creates a pore-free, very homogenous surface texture. The side of a concrete wall cast in situ in contrast, has a very heterogeneous texture. Because concrete is placed in several layers, amounts of aggregate, mortar, and air and water voids alternate several times along the sides over the height of a pour and within the layers. These relatively large variations in composition also change the strength of the cement mortar on the structural component's surface. Smooth surfaces are practically impossible to achieve under these conditions. Compared with a sandblasted precast component, the surface produced by sandblasting concrete structural components cast in situ is largely unforeseeable and often accompanied by unexpected (and undesired) side effects, such as significantly increased porosity and damage to the edges of structural components. Sandblasted concrete surfaces cast in situ are however sometimes built, such as the one at the Museum of the Celts and Romans in Manching (Fig. B 3.11). The great variation in surface characteristics was part of that building's design concept.
The surface pattern is created mainly by the depth of sandblasting, which is dependent on the strength (maturity) of the concrete, which is usually still "young" when it is treated, and the intensity of the sandblasting. If a structural component has already achieved high strength, results can be well controlled, although the process will take longer and involve additional expense. If a structural component is still too soft, it is hard to produce consistent results across a series of surfaces, so this technique requires intensive preliminary testing. Pre-cast surfaces are usually sandblasted after about two or three days. When treating concrete surfaces cast in situ, the minimum age of the surface can usually be identified based on the sequence of construction operations.

Treatment with stonemasonry techniques
Bush hammering (Fig. B 3.10c), drove work (Fig. B 3.10b), grinding and polishing are usually carried out by specialised masons, who use hand-held tools to remove part of the


a


b B 3.12


B 3.13

concrete's outer surface. In planning, it is important to ensure that the concrete cover is maintained to protect the reinforcement from corrosion. Bush hammering and drove work removes about 5–10 mm of material. If the surface has points, up to 30 mm of material must be expected to be removed and aggregates must be calculated accordingly. To ensure that the concrete cover is not too large, the precise amount of material to be removed should be precisely estimated in testing.
Treating an originally smooth concrete surface usually produces very even, clearly predictable results. The generally high qualifications of construction company employees give planning architects sufficient opportunity for consultation, testing and variation and ensure that results will largely conform to the architects's expectations.
Bush hammering or drove work requires an untreated structural component with certain basic features. The evenness of the untreated surface and watertightness of formwork are essential prerequisites for creating a smooth surface. Gaps between two formwork elements resulting in leaking water or mortar can produce areas of dark discolouration extending several centimetres into the concrete that will still be visible and objectionable, even after reworking with a medium-coarse bush hammer. Bush hammering and pointing must stop a few centimetres before the edge of a structural component to avoid damage to edges and these areas must be treated separately. This involves a much smaller area but is far more complicated than treating a smooth surface. The edges of bush-hammered surfaces are bush hammered to a width of 4–5 cm on both sides. The edges of pointed surfaces are manually treated with demolition chisels. If they are very deeply pointed, the edge to be treated can be wider than 5 cm. The process used means that mechanical hammers cannot be used for working with demolition chisels.
It is not difficult to treat sharp, unbroken edges on structural components with stonemasonry techniques.
The following terms are used to describe various ways of treating an exposed concrete surface using stonemasonry techniques:

- drove work
- fine bush hammering (with drove work on of corners and edges)
- bush hammering with a medium-coarse bush hammer (with drove work on corners and edges)
- coarse bush hammering (with drove work on corners and edges)
- pointing (with chamfered corners and edges)

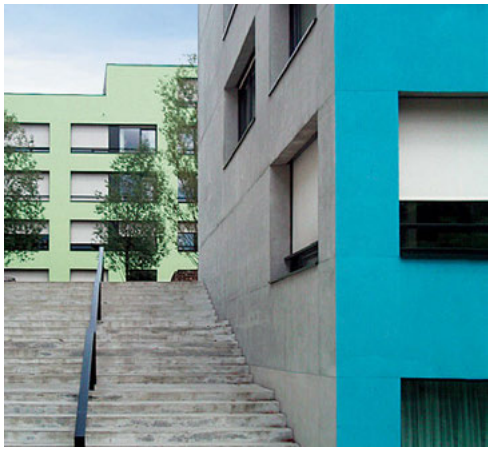
Concrete with an aggregate that has a low level of mineral hardness should be used to make large droved exposed concrete structural components. If very hard mineral gravels are used, no visible drove work texture usually results on the surface.

Concrete and colour

There are two main ways to colour concrete surfaces: by dyeing the concrete itself or by subsequently colouring a completed surface. Penetration dyeing of concrete structural components cast in situ with colour pigments completely dyes all of the structural component's material. The use of dyed concrete in precast elements can however also be limited to a thin surface layer to save costs. Dyeing the concrete in a precast structural component is often combined with forms of surface design mentioned above (acid-etching, washing, treatment using stonemasonry techniques).
Pigmented exposed concrete surfaces on exterior structural components whose target colour does not fit in with concrete's usual grey scale, but are designed to be lighter, darker or a different colour, require a protective glaze to prevent lime film from forming due to rainwater. This must be applied as early as possible, preferably immediately after stripping, unless the structural component is protected from direct contact with water in another way until it is treated. If a glaze coating is necessary anyway – especially for concrete structural components cast in situ – it should be considered whether the structural component could not perhaps be directly coloured using a coloured glaze instead of with pigments, because the colour effect is largely the same, but a coloured glaze is more likely to be successful.

Colouring concrete with pigments
A concrete's cement and water-cement ratio are largely responsible for its inherent colour. If locally available cements produce concrete surfaces that are too dark, adding 0.5 up to 2 % white pigment (titanium dioxide – TiO_2) can effectively lighten their colour. Up to a dosage of about 1.5 % titanium dioxide, this process is uncomplicated, because this concrete can be made and treated without comprehensive measures (cleaning of mixing vehicles and equipment, longer mixing times).
It is often not enough to just add coloured pigments to produce very light or white concrete surfaces; white cement must be used from the outset. The use of white cement alone is also often not enough to produce a white concrete, so it can be necessary to add much lighter and neutrally coloured aggregates as well as white pigments.
Coloured pigments can be added to concrete to produce surfaces with other colours than the material's inherent greys. There are a number of pigment manufacturers in the market, some of whom offer sound technical advice on this topic. Light colours (yellow, red, green, blue etc.) are usually used in white concrete with white cement, with the desired colour achieved by adding pigments (Fig. B 3.12 b). Dark colours (ochre, brown, black etc.) can be produced by combining very light grey cements with colour pigments.
Depending on the desired colour, 2 to 6 % of coloured pigment is added to the concrete's cement content during production, sometimes also as a composition of several individual colours. Pigments are always added by weight, usually by hand, to the mix in the concrete mixer. Almost all colours require more care and attention in weighing the concrete's basic materials, longer mixing and intensive cleaning of mixing equipment and transport vehicles. The additional time and effort involved significantly increases the material and production costs of these concretes compared with normal concretes.

Coloured glazes
It is not only recently completed surfaces of new buildings that can be coloured; existing surfaces can be coloured too. This only



B 3.14

B 3.15

B 3.14 Exposed concrete with a coloured glaze, residential complex and conversion, Pflegi-Areal, Zurich (CH) 2002, Gigon Guyer Architekten
B 3.15 Dark grey glazed exposed concrete, library and auditorium building, Weimar (D) 2005, Andreas Meck (meck architekten) and Stephan Köppel

involves the surface of a structural component, so the colour can also be contrasted or varied. A range of coloured glazes that retain surfaces typical of this kind of construction are available for the subsequent colouring of smooth concrete. The material presence of glazes on a concrete surface is very slight, although it varies from product to product. Glazes do not form a film as paint does, but they contain a hardening bonding agent that makes it possible to permanently incorporate colour pigments. Depending on the colour desired very light or white concrete surfaces may be more suitable for this purpose than darker ones. Glazes are applied by specialist companies and should be tested before a decision is made on colour. A colour's intensity can be controlled by the amount of pigment added, the application method, and possibly also by several applications. As long as appropriate tests are carried out, the resulting colour effects can be well controlled and reproduced without making surfaces too uniform. Features of the construction materials used, such as formwork joins, colour shading, porosity, nail and screw heads etc. also remain visible after the application of glazes. If a surface does not achieve the desired look, it can be cosmetically treated before or during the application of glaze. Because the pores in the concrete surface absorbs most of the glaze, which then hardens, the concrete's ability to absorb moisture through its surface is reduced to a minimum. As with pigmenting, the look of the concrete that is typical of this kind of construction is essentially retained, the concrete becomes harder and less sensitive to moisture, frost and biological colonization (algae, lichen, moss). The surface no longer chalks and is far less easily soiled. A glaze (coloured or colourless) can preserve the quality of a very smooth, delicate exposed concrete surface for many years. Current experience with relatively young concrete glazes indicates a possible durability of 20 years and more. Glazes can be renewed and touched up at any time. Glazes are mainly suitable for concrete surfaces that are textured by the formwork skin alone. Coloured glazes on subsequently treated concrete surfaces do not generally produce a surface typical of this kind of construction. Colourless glazes can also effectively protect surfaces against the formation of lime film (efflorescence).

Planning exposed concrete surfaces

Planning exposed concrete structural components demands experience and caution. The purely technical description of a concrete structural component in a tender or construction contract covers three main elements: the component's geometry (formwork plan), the type, quantity and position of reinforcement (reinforcement plan) and the definition of the hardened concrete's properties. It is usually left to a structural engineer to provide a very clear, simple description of these. Characterising the desired appearance of surfaces is the architect's task. The resources and means of communication available for performing it are however extremely limited. Even planning with the help of guides such as the "Exposed concrete" data sheet (Merkblatt) [1] from the Association of German Cement Manufacturers (Bundesverband der Deutschen Zementindustrie – BDZ) and the German Society for Concrete Construction and Technology (Deutscher Beton- und Bautechnik-Verein – DBV) is in some cases not enough to comprehensibly describe and explain the planning architect's ideas to everyone in a way that will avoid subsequent disputes. Exposed concrete, with the various characteristics of its appearance and the special processing steps required to produce it, is almost impossible to standardise and is therefore largely unregulated. There is also no generally accepted specialist terminology, which makes the communication essential in bids and tenders and construction contracts more difficult and always involves a risk of misunderstandings. Some fundamental, frequently asked questions and possible solution drawn from practical experience are presented and discussed below.

Regulatory background

Various technical and legal building regulations and concrete construction standards apply to the planning of exposed concrete structural components. A completed surface's appearance is not subject to any set standards, so this issue must be entirely contractually regulated. One publication that can serve as a guide for planning and building exposed concrete structural components is the current BDV/BDZ "Exposed concrete" data sheet, which summarises current experience with exposed concrete construction in a series of guiding principles and is designed to aid planning and construction. The data sheet's guidelines will however only be valid for any specific building project to the extent that they are agreed on in a construction contract and may not be useful in all cases, given the emerging diversity of exposed concrete applications.

Demarcating responsibility in planning and construction

In planning concrete buildings, it is in practice often difficult to demarcate the architects' tasks and duties from those of the constructing company.
It is the planning architect's responsibility to specify and precisely and completely describe an exposed concrete surface.
As already mentioned, this can be difficult in some cases given the absence of generally accepted specialist terminology, so there is a tendency to describe the features of a required surface not directly, but by means of the usual (or assumed) production process. When drafting construction contract documents, planners and architects should allow the constructing company as much scope as possible to choose their building methods and materials and not unnecessarily restrict their ability to innovate.
The demarcation of responsibility between planning and construction is a "goal and path" system. The architect formulates the goals in the construction contract using generally accepted specialist terminology, preferably the terminology of the relevant technical regulations. The constructing company for its part chooses an economically and technically appropriate way of achieving the planned goals under the prevailing conditions and brings their specialist technical qualifications and experience to bear. The company has the

duty and freedom to choose the necessary materials and construction methods, depending on the requirements. This freedom of choice and combination of means offers a constructing company the possibility of turning technical and innovative potential to their economic advantage by achieving the goals set and building with less cost and effort, faster and/or with a higher quality. The construction company's freedom to choose can motivate it to be innovative in building and should therefore not be restricted unnecessarily.
Construction operations are not the concern of the planning architect. Interventions in this area of responsibility in the form of restrictions and specifications on the concrete's composition (cement content, type of cement, water/cement ratio, water content, use of concrete admixtures and additives, granulometric composition of aggregates etc.), transport requirements, processes and subsequent treatment (not post-processing) of the concrete and other stipulations and restrictions on construction operations are however often made in construction contracts regulating the production of exposed concrete structural components. This is usually motivated by an essentially well-meaning intention on the part of planning architects to contractually stipulate what they believe is the right way to achieve the goals set and ensure the quality of surfaces by imposing requirements on construction. Such contractual requirements are often stipulated based on earlier construction contracts however, so they usually turn out to be entirely inappropriate for the construction at hand and in the worst case may be impossible to comply with.
If architects intervene in construction operations in this way, the responsibility if the contractually prescribed process does not subsequently lead to the desired result (which frequently happens), will also be theirs.
The planning of construction operations (construction material, formwork and formwork skin, technical processes) defines its fitness for purpose solely by the resulting completed surface. If the surface complies with contractual specifications, then the construction operations process was right. If a surface fails to meet the requirements, the constructing company must optimise the materials (formwork, formwork skin, concrete) and/or technical process until the required quality is provided. The success or failure of construction operations is the sole responsibility of the construction company.
This division of responsibilities becomes unclear when an architect or structural engineer intervenes in construction operations planning, because if such intervention fails it is often no longer clear whether the contractual specifications or the practical execution of the constructing company caused it to fail, so it is unclear who bears exactly what responsibility for the failure and any resulting damage caused.
DIN 18 331 "German Construction Contract Procedures (VOB Vergabe- und Vertragsordnung für Bauleistungen) Part C: General technical specifications in construction contracts – concrete work" describes the technical scope for action and responsibilities of the constructing company:

- Point 3.2 on "Concrete production" states that, "The way in which the concrete is produced to achieve the required properties and is mixed, processed and subsequently treated is left to the contractor."
- Point 3.3 on "Formwork and concrete surfaces" states that, "The choice of the type of formwork and its implementation is left to the contractor."

These regulations also apply to the building of exposed concrete structural components and stipulate the separate areas of responsibility of architects and builders that must be maintained in construction contracts.

Planning aids

Since an exposed concrete surface is not a construction task that can be clearly described in technical terms, there are also no general criteria for describing it. The specification "exposed concrete" indicates only that the architect and/or developer have more or less set notions on the look of the completed concrete surface, a description of which is usually improvised in pre-contractual and contractual documents, in the absence of a generally recognised specialist terminology. To remedy this situation, planning and building regulations on exposed concrete design features and construction operations have been published in Germany, Austria and Switzerland. The "Data sheet for exposed concrete structures (Merkblatt für Sichtbetonbauten)" from the Swiss industry association Betonsuisse, the "Exposed concrete – formed concrete surfaces (Sichtbeton – geschalte Betonflächen)" guidelines of the Austrian Society for Construction Technology (Österreichische Vereinigung für Beton- und Bautechnik ÖVBB) and the DBV/BDZ "Exposed concrete" data sheet have become an established part of planning and construction in these countries because they define basics for technical communication and can help to ensure good planning and building. The structure of their contents and systematic values of each of these sets of regulations is very similar because they have largely inspired each other.

Each of these sets of regulations defines a class system for smooth exposed concrete surfaces. The exposed concrete classes are assigned to requirement criteria, construction specifications and recommendations. A suitably experienced architect could produce a design that meets the requirements on an exposed concrete surface like those in these classifications in an individual construction contract without direct reference to these sets of regulations, but it is always worth consulting existing data sheets. The regulatory principles and some of the contents of the German BDV/BDZ "Exposed concrete" data sheet will be explained below.
The data sheet (with data sheets from the prefabricated components industry) is essentially the only national building regulation on planning and building exposed concrete surfaces, although there are some aspects that limit its application.
The exposed concrete classes SB1–SB4 outlined below form a quality hierarchy analogous to the assumed construction costs. These classes, with their subordinate individual criteria, are essentially technical degrees of flawlessness that alone often do not fit in with the architect's ideas. Architects must check

against the individual criteria of an exposed concrete class whether their design intentions can be adequately described within the parameters of the exposed concrete class or whether they want to describe other features in the tender and construction contract.
Architects currently tend to make use of other, new or re-discovered techniques as well as the classic smooth, grey, flawless surfaces, so the planning, production and contractual evaluation of surfaces by a developer or constructing company can vary greatly and will require prior agreement. The further a surface diverges from the classic technique of smooth concrete cast in situ, the harder it is to find suitable aids to work with. This applies in particular to the individual criteria of the exposed concrete classes. Demands for a very even colour and low porosity may not be reasonable for a surface that will subsequently undergo stonemasonry treatment or sandblasting, but a demand for a high level of smoothness and watertight formwork skin joints may, in contrast, be entirely justified.

Terminology
There is no useful definition of the term "exposed concrete" in current national regulations. DIN 18 217 "Concrete surfaces and formlining" defines exposed concrete surfaces as "Concrete with a specified surface finish" a definition too imprecise for use in performance specifications. The "Exposed concrete" data sheet classifies exposed concrete surfaces according to technical criteria and has developed useful definitions of the respective classes.

- Exposed concrete with few requirements describes concrete surfaces corresponding with the planning and performance conditions of the evaluation criteria of exposed concrete class SB1.
- Exposed concrete with normal or special requirements are concrete surfaces corresponding with the planning and performance conditions of the evaluation criteria of exposed concrete classes SB2, SB3 and SB4.

The legally very imprecise terms "sample" and "sample area" have also been redefined. A distinction will be made in future between trial surfaces and reference surfaces:

- Trial surfaces are all surfaces on which trials are made. The reasons for such trials may vary and are not definitive, although the cost burden of trials depends on the intention behind the trial. If a developer or architect requires a trial on a structural component (which is always advised), this testing should be remunerated. Trials carried out to train a constructing company's own workers will also have to be paid for by that company.
- Reference surfaces are those on which the required appearance is usually achieved in a trial. They are agreed on as a binding contractual reference and serve to provide a comparative evaluation for the final acceptance of exposed concrete surfaces agreed on in a contract.

In applying these regulations, the client should be aware that surfaces of existing buildings cannot be used as contractually agreed reference areas, because this makes an inadmissible selection from the overall quality of the existing building. The construction materials and methods that produced the surface are not generally known and the effects of ageing cannot be reproduced. These surfaces can also not be used in an acceptance comparison due to the spatial distance involved.

Exposed concrete classes and examples of structural components
The selection and fixing of an exposed concrete class in accordance with individual criteria formulates defined specifications on construction conditions and a surface's quality. This suggests that an exposed concrete surface can only be accepted by examining individual criteria. Because an architect first plans an idea, that is, an "imagined" surface, it cannot be authenticated using individual criteria. What is decisive is the overall impression of the completed surface, which the architect compares with his idea. It is therefore useful to commit the overall impression to the fulfilment of individual criteria. If the architect is satisfied with the overall impression of a surface, the individual criteria will not have to be further examined, so in a positive case, the individual criteria have no function. If however the result diverges from the architect's idea, there will probably also be anomalies in one or more individual criteria that can be identified. The result of this test is useful in a negative case in two ways. On the one hand, it provides immediate clear information for the construction company on how such anomalies can be prevented in future construction operations. On the other hand, the anomalies, if no remedial work is carried out, can be transparently and comprehensibly assessed for all contracting parties and translated into a contractually defined reduction in value or in payment.

The data sheet assigns individual criteria, specific execution information and examples of structural components already mentioned to the four exposed concrete classes SB1–SB4. The individual criteria are formulated using abbreviations that will be explained below. Examples of structural components represent the principal character and design value of structures in the respective classes.
Exposed concrete class SB1 is the one with the fewest requirements on the production technique and appearance of a surface. According to the definition it is "Concrete surfaces with low design requirements" and the examples of structural components given are "Cellar walls or areas mainly for commercial or industrial use". This usage requires only surfaces that are planned with the lowest minimum standard and without further design intentions.
Exposed concrete class SB2 defines "Concrete surfaces with normal design requirements" and the examples of structural components given are "Stairways and retaining walls". In contrast to the previous class, these are areas in which the public moves and remains. Class SB2 therefore demands a more even and unobtrusive surface, but also formulates a minimum quality without special design intentions.
Exposed concrete class SB3 describes the first qualitatively-relevant exposed concrete class."Concrete surfaces with stringent design requirements, e.g. facades of buildings" are specified as examples. These are surfaces planned with much higher requirements on their appearance in situations where the developer expects the surface to fully comply with design specifications. Most exposed concrete surfaces in buildings will fall into this exposed concrete class.
The highest exposed concrete class, SB4, defines "Concrete surfaces of particularly high design significance" and the examples of structural components given are "prestigious structural components in buildings". Its demarcation from exposed concrete class SB3 is not very clear, and in fact class SB4 builds on the requirements of class SB3, intensifying them in just a few criteria. Class SB4 is usually required for exposed concrete surfaces in culturally significant buildings such as museums, theatres or concert houses, and particularly prestigious government and commercial buildings, such as those housing banks or insurance companies, so on or in buildings for which the look of the surface is particularly important, buildings that have high public profiles and where the idea behind the design must be very precisely complied with.

Individual criteria
Numbers are added to the abbreviations to express a grading of the requirements and restrictions of individual criteria. A distinction is made according to individual criteria:

- Texture and formation of element joints (T1–T3): This criterion evaluates a concrete surface's compactness and visible defects caused by cement paste leaks through formwork skin joints. These defects occur along formwork skin joints that have leaked and stand out as dark and sharp, although their visible width is limited.
- Porosity (P1–P4) is limited to a permissible maximum value of the entire areas of pores over a test surface measuring 500 × 500 mm (0.25 m^2) and measures pores with a diameter of 2 to 15 mm. Because absorbent formwork skins will create less porous surfaces than those created using non-absorbent skins, even though they are produced with the same care and attention, different requirements are assigned to the exposed concrete classes SB2, SB3 and SB4 depending on the formwork skin type (s = absorbent, ns = not absorbent). Porosity criteria are very hard to assess and can only be tested using a protracted and fairly imprecise measuring technique.

- Evenness of colour (FT1–FT3): Discolourations of any kind arising from any cause are assessed. Because specifications and restrictions on the evenness of a concrete surface's colour cannot be physically or arithmetically classified, they cannot be formulated with exact parameters, so the specifications are only described in texts. These are therefore relatively "soft" specifications, which in practice allow for and require fair interpretation by all parties involved. Because absorbent formwork skin systems often produce more even colouring, the FT2 requirement is specified for exposed concrete class SB4 for a surface made with non-absorbent formwork skin, and the FT3 requirement is specified for a surface made with an absorbent formwork skin.
- Evenness (E1–E3): Requirements on evenness are shown in Table 3 in the DIN 18202 "Tolerances in building construction" standard.
- Construction joints and formwork skin joints (AF1–AF4):

These criteria limit displacements between two formwork skins or elements, which frequently occur in practice. Displacements may be caused by construction operations (unexpected higher formwork pressure or formwork that is not stiff enough) or a lack of care in setting up formwork. Displacements between surfaces are measured in millimetres with defined maximum values and in practice are very easy to precisely determine.

Formwork skin classes

The data sheet also specifies formliner or formwork skin classes. There are three grades of these (SHK1–SHK3) and the criteria of the classes mark a significant qualitative grading of the permissible condition of the formwork skin. Each exposed concrete class is clearly assigned to a formwork skin class, which largely relieves the planning architect from having to describe and determine the quality of formwork skin with criteria he develops himself. It is entirely up to the constructing company to satisfy the demands formulated by the relevant formwork skin class. The formwork skin class must be complied with in producing every contractually stipulated exposed concrete surface, so the formwork skin must be inspected and tested before each use.
In deciding on an exposed concrete class, the planning architect must check the conditions prescribed for the relevant formwork skin class to ensure that they fulfil his concept of the completed surface's look. A different formwork skin class than the one assigned to the exposed concrete class can be contractually stipulated or individual condition criteria can be specified, excluded or further restricted if necessary. This must be made particularly clear in drafting bid and tender documents and in construction contracts.
Formwork skin class SHK3 is assigned only to exposed concrete class SB4. Despite the generally high level of requirements of this exposed concrete class, the condition criteria of formwork skin class SHK3 are deliberately flexible and designed to be selected and determined by the architect. This is based on the assumption that an architect will usually have very precise ideas of how a surface should look, as individual planning decisions on the criteria of the formwork skin would suggest.

Tendering and construction contracts

In building high quality exposed concrete surfaces, the construction process is vital to the surface's quality and look, yet inadequate tender documents (and construction contracts) often make it difficult for everyone involved to achieve the quality desired in construction. "Exposed concrete", in German construction contracts at least, is one of the worst described areas of building work. Incomplete and unclear contractual specifications around exposed concrete were and are the direct results of a lack of appropriate technical specifications and information. Chapter 5 "Planning and tendering" of the "Exposed concrete" data sheet provides a useful overview of the formwork and formwork skin systems usually available on the market and the resulting surfaces. Chapter 5.2.2 of the data sheet on "Design features" includes a list of the minimum descriptions that should be included in performance specifications. The following checklist can be used to check the coherence and completeness of planning documents:

1. specification of the exposed concrete class
2. description of the formwork system where applicable
3. details on the formwork skin and texture of the completed surface
4. information on formwork joints
5. description of the position, formation and closure of anchor holes (formwork plan)
6. description of the surface structure, details on the dimensions of formwork elements and on the course of visible formwork skin and formwork element joints (formwork plan)
7. specification of the position, width, formation and course of joints (if not included in descriptions under point 6 – formwork plan)
8. description of the colour (cement chosen, aggregate chosen, colouring with pigments, application of glazes or coatings), where applicable
9. information on the surface's condition and the treatment of structural component surfaces not created using formwork, where applicable

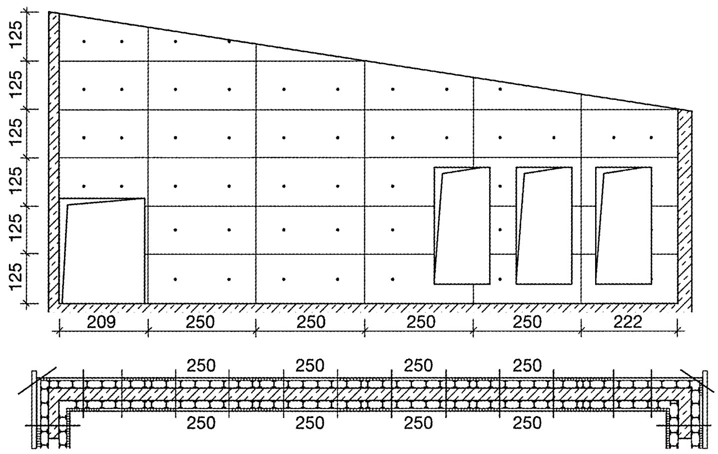
Formulating "exposed concrete" as an extra item in the creation of a reinforced concrete structural component usually brings considerable disadvantages in subsequent construction. It means that the architect leaves allocation of the value of the technical reinforced concrete structural component and the design of its surface, so a financial assessment of "exposed concrete" as an element in construction, to the building contractor. If items are divided in this way in a performance contract, it must be ensured when pricing is checked that individual prices entered under "exposed concrete" are appropriate and not set too low.
The form of contracting must also be decided on when contracts are drafted. The production of complex exposed concrete surfaces should be awarded to companies whose expertise the architect and/or developer have confidence in, so it is advisable to limit the bidders tendering for exposed concrete work to a select few.

A "Bill of Quantities", a list of individual tasks required to create a building, is usually understood as being synonymous with the term "performance specification". A "Bill of Quantities" is however only part of a performance specification. It is almost always useful to describe a surface's desired appearance more precisely in a separate description because it helps ensure that bidders provide a realistic estimate in their costings. Elements of contracts outlined in the "General technical specifications in construction contracts" (cf. Section 1 of the VOB B) can be used to draft a separate description of a surface's quality.
The desired quality can first be developed on a trial structural component in a comparatively simple and fair process. Reference areas can then be chosen from among these to test the practical feasibility of the architect's ideas. This allows the architect's ideas to come to maturity and helps avoid surprises and disappointment. Creating trial areas may seem a costly and time-consuming way of determining a surface's quality. Experience has shown however, that more than one trial structural component is rarely necessary for reaching agreement among all the parties involved and its planning and the coordination of the technical procedure ensures that all parties involved are similarly motivated, which results in swift success.

Formwork plans

A formwork plan usually contains the main planning details on structuring exposed concrete surfaces by arranging the formwork skin and formwork elements and anchor holes. Drawing up this plan is a part of the architect's responsibility.

To ensure economically and technically efficient formwork planning and guarantee the punctual provision of formwork plan during construction operations, it can be advisable to outsource the drafting of formwork plans to the construction company as part of contract. If the construction company is to accurately calculate the cost and effort of their work in the bid they submit, they must accurately describe what this work includes in their bid. It can be advantageous to add the formwork plans of some representative structural components in which the fundamentals of the design, desired surface structure and other main details can be seen. Architects should explain that the surface structure they are presenting is just an example



B 3.16

and encourage the bidder or constructing company to make alternative proposals. They will almost always make a counter-proposal that combines what they regard as the best economical and technical mix of the formwork skin, formwork system and production process, which fulfils the architect's design intentions. This procedure can give the architect and developer some specific advantages:

- The constructing company will always offer a low-cost, readily available formwork and use formwork skin grids with simple layouts. This saves construction costs without resorting to the use of inferior materials or problematic technical processes. Companies can often take advantage of long-term supply relationships with certain manufacturers to include additional advantages in their costs estimates.
- Responsibility for punctually completing formwork plans and formwork lies with the constructing company, so the possibility of planning delays is formally excluded.

In practice, a construction company is contractually obliged to submit a formwork plan showing the formwork skin joints and positioning of anchor holes to the architect for approval at an early stage for each exposed concrete structural component (Fig. B 3.16). It has been shown that after a short while, all the parties in a project usually work together informally on formwork plans using rough sketches and verbal agreements, which normally produces good cooperation and a satisfactory result for everyone involved.

Setting the construction period

A building's construction period is usually estimated and set during planning, so without the involvement of the company that will in fact subsequently build it. The criteria used to estimate the required construction period are still fairly uncertain at this early stage of planning. How realistic the estimate is depends largely on the practical experience of the planning architect and structural engineer, if one is involved, but mainly on the estimate of construction operations, their combinations and duration. The developer includes this estimate in his personal utilisation planning, so it becomes a fixed input – including an economic one. In the planning dialogue between the architect and developer, developers always tend to aim for the shortest possible construction periods and earliest possible use, which the architect seeks to secure as far as possible.

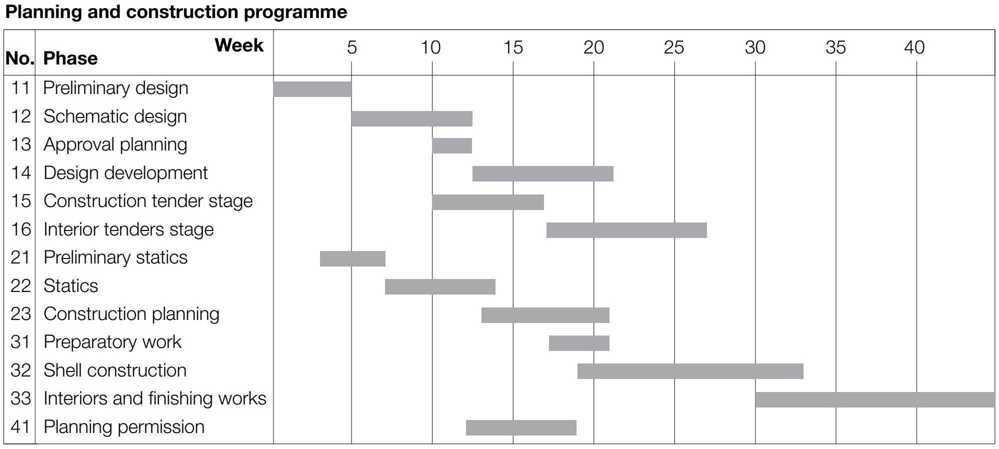
Although a building's construction period is often shortened almost to the technical boundaries of the feasible, construction can usually be adapted to such conditions in a purely material creation of a building shell by deploying workers and equipment efficiently and through sound organisational planning. Practical experience has shown however, that drastically shortened construction periods are almost always achieved at the cost of construction quality and are hard to reconcile with special quality specifications, such as high quality exposed concrete. Most avoidable difficulties and consequent quality problems in projects with exposed concrete arise out of too short a construction period.

Practice has shown that exposed concrete work carried out under high time pressure usually results in lower construction quality and a stressful atmosphere for all involved.

It is therefore advisable in building shell projects with a large number of exposed concrete structural components to subject the estimated construction period to a separate internal review and coordinate final scheduling with everyone involved in planning and the subsequent construction management before making any statements to the developer. The following construction factors should in particular be taken into account:

- Construction times for work whose implementation as part of construction operations is not yet settled in all points should be estimated only after appropriate expert consultation.
- Construction carried out in winter months or extending over an entire cold season should be granted an additional time allowance of 15 to 30 %. Shorter additional times can be stipulated for compact or more massive structural components or building sites in warmer climates. Structural components with

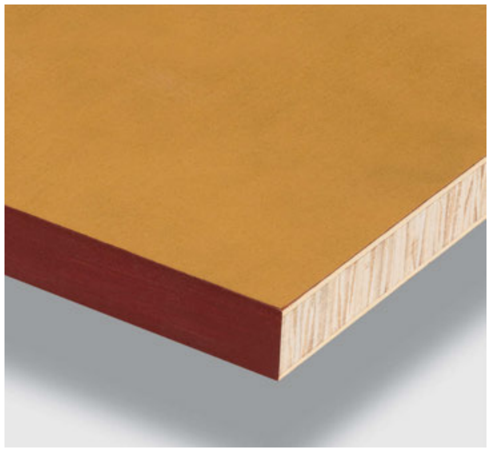
Planning and construction programme



B 3.17

B 3.16 Formwork plan
B 3.17 Gantt chart used to schedule the development of a high-rise building
B 3.18 Various formwork patterns
a Plywood with a film coating, slightly absorbent
b Wood-plastic composite board made of laminated core strips with a fleece-reinforced film coating
c High-density fibreboard, sanded, slightly absorbent


a


b


c

B 3.18

fragmented and filigree geometry and small minimum dimensions (walls, supports, structural slabs, corbels) and building sites in colder areas will require higher additional time allowances.

- Concrete structural components with surfaces in exposed concrete class SB3 should be granted an additional time allowance of at least 20 % over the deadline for purely technical work. Much longer construction periods, up to double the estimated time required for a comparable structural component, should be specified for exposed concrete structural components in class SB4 or for surfaces with special features. Longer additional time allowances can also be imposed based on the experience that it is better not to cast exposed concrete in classes SB3 and SB4 outside in temperatures under 10 °C because the quality of surfaces made under these conditions will be significantly impaired.

Construction tips

Building a high quality exposed concrete surface is a task for a building contractor but it can also be useful for planners to acquire some knowledge of aspects of the relevant construction operations.

Formwork skins

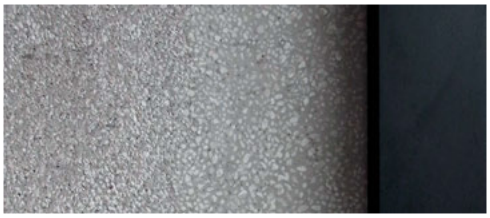
Since the formwork skins used to produce smooth exposed concrete surfaces are in principal no different from those used in ordinary concrete construction with no particular requirements, many constructing companies tend to also make high-quality surfaces using existing materials or ordinary formwork skin qualities. Decisions on formwork skin and mould-release agent for high-quality exposed concrete surfaces should however only be made after positive test results are achieved. Experience from research and development as well as practical experience also shows that the single use of a formwork skin often stipulated in contracts for the purposes of quality assurance is a complicated yet completely unnecessary undertaking in terms of the resulting surface. Many of the formwork skin materials currently available on the market only produce a robust and high quality surface on the second and third use and if treated carefully they can be used, depending on the quality of their coating, at least 10 and up to 50 times and always produce completely consistent results.

Mould-release agents

Mould-release agent has a decisive if not primary influence on a surface's quality, especially on smooth exposed concrete surfaces. This has been shown in the practical experience of polishers, construction managers and other experts, who have been intensely engaged in producing smooth exposed concrete surfaces over a long period of time. Findings from a current collaborative German research project on interactions between formwork skins and concrete surfaces confirm their practical observations [2].
Mould-release agents are designed to prevent a mechanical or chemical bond between the concrete surface and the formwork skin surface and ensure easy and damage-free stripping (de-moulding) of the concrete component. The initially fresh, then setting and hardening concrete is in contact with the mould-release agent film in its first hours and only indirectly in contact with the formwork skin surface. This also explains why it is not possible to classify formwork skins according to their effect on quality: the influence of mould-release agent is at least equivalent, if not dominant.
Depending on the basic conditions of their use, mould-release agents can produce unexpected effects for reasons that may be hard or impossible to identify, even though they may have worked perfectly last time they were used. Some mould-release agents for example, reliably prevent air voids from forming in the formwork, i.e. on or near the concrete's surface, resulting in surfaces with very few pores. Other products facilitate intensive pore formation by bringing rising air to the formwork skin surface and binding and concentrating it there. Mould-release agents can be chemically entirely inert, not reacting chemically with any surrounding substances, or completely disperse on contact with fresh concrete. The releasing effect of some mould-release agents is based on such chemical reactions.
Mould-release agents are essential in the production of high-quality exposed concrete, but their effect usually means that they are unfortunately unpredictable secondary materials whose suitability under specific local construction material and operational conditions must first be tested and verified. Tests must be carried out on an appropriate trial area to determine whether a product is suitable for a specific project. For this reason, no further contractual demands should be made on mould-release agents, for environmental protection reasons for example, at least for exposed concrete structural components. Given the powerful influence of mould-release agents on the appearance and quality of exposed concrete surfaces if flaws occur, the suitability of the mould-release agent used should first be investigated. All mould-release agents, regardless of their material or physical characteristics and effects, produce the best results on a surface when they are applied as the thinnest and most even film possible.

Concrete

It is sometimes claimed that high quality exposed concrete surfaces can simply be achieved with the right concrete composition, but this contradicts current knowledge and experience. As explained above, many other factors can decisively influence a surface and, taken together, may even predominate.
Given developments in concreting techniques and technology in recent years, it no longer makes sense to prescribe standards and parameters on concrete composition for making high quality exposed concrete surfaces, because the highest requirements on these surfaces can be met with the most diverse concrete compositions and fresh concrete properties.
In practice, it is always helpful to ask the concrete technologists of prospective ready-mix concrete suppliers to propose suitable concrete compositions because manufacturers usually have many years of experience concerning the suitability of their concretes for producing exposed concrete.


a

b B 3.19


a

b B 3.20

B 3.19 Subsequent cosmetic concrete profiling
a Initial condition
b The result
B 3.20 Cosmetic concrete treatment of blotches
a Initial condition
b The result
B 3.21 Glaze with a lightening effect, Sparkasse (bank) Ulm (D) 2006, Stephan Braunfels Architekten

Remedial work

If the quality of an exposed concrete surface is flawed, it is important to first quickly analyse the reason for the flaws, then remedy them if possible. Such repairs should be carried out as late as possible after curing and any "self-healing" processes and with the necessary expert care. The term "remedial work" suggests supplementary work to provide a relatively slight improvement expected to involve little time and effort compared with the fundamental work. The practice of qualified concrete cosmetic work by a specialist company shows that this is not usually the case. Creating a surface in exposed concrete class SB3 on a very flawed pre-existing surface for example, can involve a great deal of time and effort and be accordingly expensive.
Remedial work must be strictly contractually linked with formal authorisation by the developer or architect. The construction company has the right and the duty to rectify any identified damage or defect. All parties involved should agree on the type and intensity of the remedial work before it is carried out.
Most flaws on exposed concrete surfaces (e.g. clouding, displaced surfaces, discolorations caused by leaky formwork skin joints, light and dark blotches etc.) can only be rectified by appropriately trained persons or specialist concrete cosmetics companies. Discolouration has a particularly good chance of spontaneously resolving and often fades away or disappears on its own after a few months, although sometimes this can also take years.
The repair of mechanical damage, such as broken edges, should first be trialed on a minor structural component by deliberately recreating the damage and using various repair processes and materials. A decision must also be taken on whether to work with commercially available mortars or whether the repair mortar could be made on site from the components of the concrete itself.

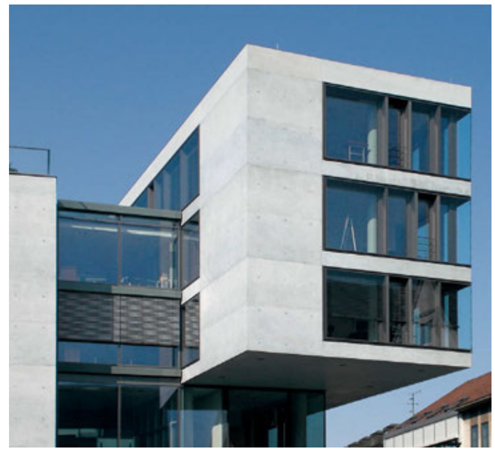
Cleaning by polishing

Rust or other coloured stains on lower areas or the usual basic soiling of exposed concrete surfaces after the completion of interior construction can usually be removed by polishing. Concrete surfaces are cleaned with a synthetic abrasive fleece, manually or by machine. These are available in various degrees of hardness, to achieve good results it is extremely important to identify the hardness best suited to prevailing conditions in tests. This will depend on the type of treatment, main soiling and the concrete surface's strength. If the fleece is too soft it soon loses its abrasive effect and won't remove or reduce all the dirt. If it is too hard, it can cause ugly scratches and erosion and ruin an exposed concrete surface.
This process is also suitable for the partial cleaning of surfaces. The greater the cleaning effect however, the more necessary it will be to clean entire connected areas of buildings (rooms, stairways, corridors) or categories of structural elements (walls, ceilings).
The process is not difficult and can be quickly and easily carried out, especially if machinery is used. Drywall sanders are available for this purpose. The combination of a rotating disc sander and an industrial vacuum cleaner ensure almost completely dust-free operations. Machines are also available to hire, although they were not originally designed for cleaning exposed concrete surfaces. When they are used for the first time, it sometimes therefore requires some investigation of the market to find the right synthetic sanding pads for the disc radius. Hand-held pads bought from building materials or car accessories retailers can be used to manually polish smaller areas or corners where mechanised cleaning is not possible.

Qualified concrete cosmetic work

All flaws that cannot be rectified by abrasive polishing require treatment by a qualified specialist company. This is especially the case if defects in the surface's quality are obvious, e.g. discolourations, formwork skin joints that have leaked, peeling or flaking, and displaced surfaces of any kind. Concrete cosmetic work mainly remedies the following optical properties:
- surface texture
- colour
- other optical effects (sheen, appearance when the surface's moisture content changes)
- variation in surface texture and colour

An area very close to the flawed area that complies with the client's wishes is first identified and designated. This serves as the "target" look and identifies the flawed look of the area to be rectified. Repairs therefore strictly speaking create a replica; not an exact copy of the approved area, but one designed to blend in with it unobtrusively. It takes an artistically trained and experienced hand, a very good feel for colour and texture, and precise knowledge of the application, suitability and durability of the materials used to create this kind of surface.
Work begins with cleaning of the affected area, often by abrasive polishing. If extensive areas of discolouration that cannot be improved by polishing (e.g. dark staining due to damp cold weather) there is no need to remove material and rebuild the surface. In this case, the surface is slightly roughened and a coloured glaze applied (Fig. B 3.20). To blend this area's colour and variation with that of the adjoining target area, several coats of glaze with slightly varying colours are always applied next to each other and over each other. They are applied by dabbing (with brushes, sponges or cloths), or by spraying, spattering, rolling or painting.
Excessively large and conspicuous pores in areas of varying porosity are closed until an unobtrusive surface is created. A glaze provides the subsequent coloured finish.
It may also be necessary in some cases to conceal an excessive lack of porosity by painting on pores.
Treated areas or defects to which material must be added are first given one or more layers of filler, as in the case of mechanical damage to surfaces or edges, pockets of loose gravel, water discharge and similar flaws. Reconstruction will also be necessary if projecting areas of concrete must be removed due to displacement between two sections of formwork.
Layers close to the surface of this reprofiling are covered with a fine filler as close as possi-



B 3.21

ble to the target colour. Once it has hardened, a fine polish levels and smoothes the surface. The concrete surface's colour is then adjusted by retouching with a tinted glaze. The application of glaze is obligatory for almost all cosmetic work as a surface finish. Because glazed exterior surfaces differ greatly from unglazed areas in changing moisture conditions, glaze is applied to the structural component's entire surface as a finishing measure. This improves the optical conformity of the cosmetically treated area with the adjoining untreated area, regardless of moisture levels in the air or in the surface.
It is more complicated to correct flaws on strongly textured, deeply structured surfaces (e. g. those cast using timber formwork, OSB board, formwork matrices) or treated surfaces (e.g. washed concrete, sandblasted or acid-etched surfaces or those treated using stonemasonry techniques) so these must be treated as special cases. Reproducing the texture is usually the hardest part of this kind of treatment and requires stucco-type work or the moulding of formwork textures.

Protecting and conserving surfaces

Interior exposed concrete surfaces are not generally exposed to any corrosive effects. Outside however, they are exposed to considerable corrosive factors, especially due to weather. Changing humidity conditions, large temperature fluctuations, frost, atmospheric carbon dioxide and biological colonisation can considerably change and detract from a surface's look.
The greater the influences of weather and environment and the smoother the concrete surface, often made with non-absorbent formwork skins, the faster and more marked will be the change in appearance.

If the architect and developer have very precise ideas about the quality of a surface, changes will not be seen as an age-appropriate patina, but as an unwelcome sign of deterioration. Since there are now many suitable products for protecting exposed concrete surfaces on the market, it is advisable during planning to think about the possibilities of almost invisible protection and a farsighted and careful conservation of exposed concrete surfaces.
Current protective and conservation processes are based on the constituents of the glaze used in subsequent colouring and certain repair techniques. The protective effect of such systems was discovered through coincidental observations of the side effect of repairs and touch-ups. Because surfaces partially treated with glaze differed noticeably from untreated areas, especially in changing moisture conditions, the surface's entire section was often covered with a colourless glaze. As they aged, the glazed surfaces showed an evident protective effect. Compared with the adjoining untreated surfaces, these surfaces retained their colour and texture for many years, stayed cleaner and showed hardly any degradation (roughening) due to weather. Rainwater ran off almost without leaving a trace and there was less algae and moss colonisation.

Glazes

Glazes applied in dry conditions are absorbed into the void system of the concrete close to its surface. They do not form a measurable film, like painting or coating does, but are not completely invisible. Some products give a smooth concrete surface an optical depth or a slight sheen although the construction material's own appearance is retained. Glaze hardens a surface, binds dust particles and seals the concrete's surface pores or reduces their size and permeability. All the transport processes that normally occur through capillary absorption or diffusion are then significantly reduced or entirely prevented. This improves the technical properties of the concrete cover and concrete surface. These effects make glazes especially suitable for protecting smooth exterior surfaces and they should always be used here. Since a glaze always offers an opportunity of slightly modifying the colours of certain areas or the entire surface, they can also be used to conceal slightly anomalous areas of a surface (Fig. B 3.21). Acid-etched, washed and other types of exposed concrete surfaces textured using formwork skins are rarely glazed. The outer surfaces of concretes that have been dyed with pigments and textured by the formwork skin or subsequent treatment at a young age should at least be given a colourless glaze as early as possible. Depending on the environmental conditions, current products will work for around 10–20 years and can be reapplied as required.

Hydrophobing agents

Hydrophobing agents are often offered or considered as an alternative to glazes. Their material characteristics are different from those of glaze because they don't usually contain any hardening substances. Hydrophobing agents are also absorbed by the void system near the concrete's surface and have a water-repellent (hydrophobic) effect that reduces or prevents moisture and pollutants being transported to areas near that surface. The hydrophobic effect on the concrete surface dissipates slowly over time. Durable for about ten years, the zone near the surface begins to absorb water again after half this time, so soiling and slight erosion caused by rain, frost and biogenic colonisation can occur, even though the deeper structure of the concrete still reacts hydrophobically.

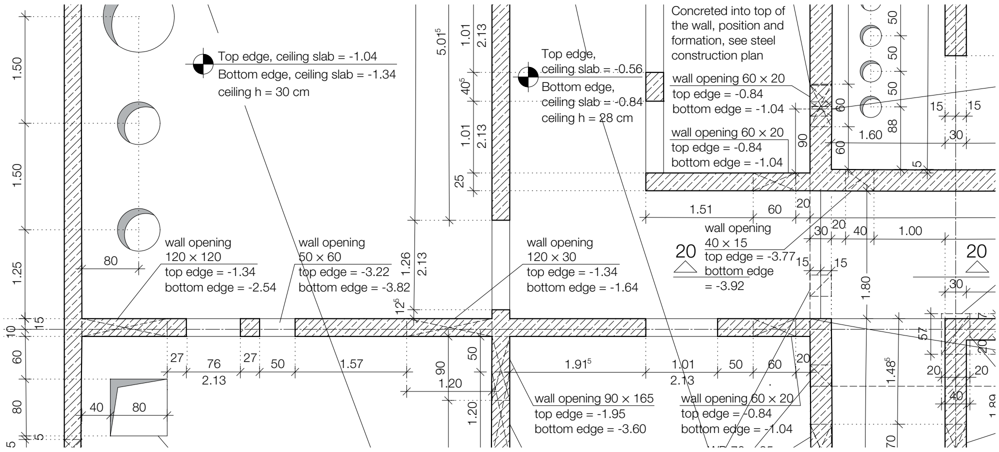
Glazes and hydrophobing agents are not products with standardised ingredients and effects, although their growing acceptance and widespread use means that they are currently still being developed. Preliminary tests should be made on reference areas in each case to determine which product best fulfils the desired technical and design goals.

Notes:

[1] Association of German Cement Manufacturers (Bundesverband der Deutschen Zementindustrie – BDZ); German Society for Concrete Construction and Technology (Deutscher Beton- und Bautechnik-Verein – DBV): Exposed concrete data sheet (Merkblatt Sichtbeton). Berlin 2008
[2] IGF-Vorhaben Nr. 15873: Neue Sichtbetontechnik – Integration der Erkenntnisse zu Wechselwirkungen zwischen Schalhaut, Trennmittel und Betonoberfläche in die Prozesskette beim Sichtbeton

Designing structures with structural concrete

Stephan Engelsmann, Stefan Peters,
Valerie Spalding, Franz Forstlechner



B 4.1

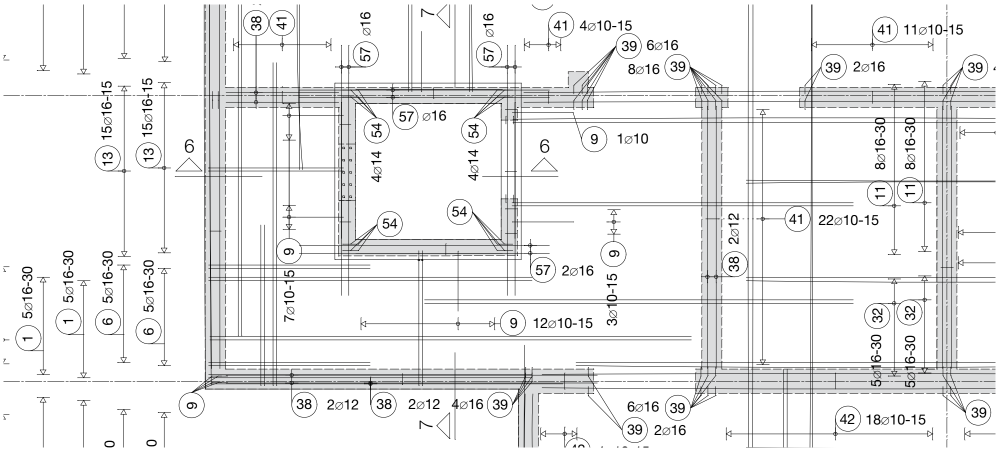
This chapter deals with the design of concrete structures with a focus on structural and technological aspects. Large-scale civil engineering structures, especially bridge construction, will be deliberately left out so as not to exceed the scope of this work. The chapter is addressed mainly to planners of multi-storey buildings and other building structures, as well as to architecture and civil engineering students. It also gives interested readers insights into and an overview of typical concrete structures, without claiming to be exhaustive. Practical guidance for the design of individual structural components as well as building structures up to halls and plane load-bearing structures is provided. One without the other, i.e. design without construction, is not possible. Nor will we go into detail on dimensioning concrete components and reinforcement layout, instead referring you to the large body of specialist literature for structural engineers for more information on this topic. Special sections focus on particular aspects such as designing with strut-and-tie models, monolithic construction and the design of joints, which play a major role in practice. Recent research results and new developments are included where these would seem helpful. This chapter takes new European regulations and standards into account but does not explore them in detail. It is underpinned first and foremost by the authors' theoretical and practical building experience. In conclusion, the authors note explicitly that it is not possible to provide a complete overview of all the scientific fundamentals and possible applications of concrete construction within the scope of this chapter.

Planning processes

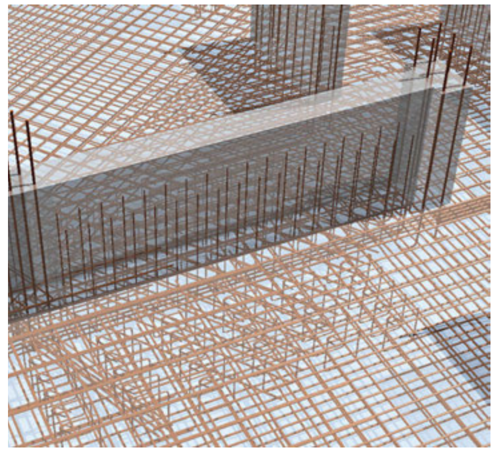
Like all other construction methods, the design of concrete structures is based on the (project) design phases described in the German scale of fees for architects and engineers (Honorarordnung für Architekten und Ingenieure – HOAI): Grundlagenermittlung (predesign) (LPH 1), Vorplanung (preliminary planning) (LPH 2), Entwurfsplanung (design planning) (LPH 3), Genehmigungsplanung (design development) (LPH 4), Ausführungsplanung (construction documents) (LPH 5), Vorbereitung der Vergabe (preparing tender documents) (LPH 6), Mitwirkung bei der Vergabe (bidding) (LPH 7), Objektüberwachung (site supervision) (LPH 8), Objektbetreuung und Dokumentation (site management and documentation) (LPH 9).

The process of designing concrete structures does, however, involve some specific features that are fundamentally important in successful planning and construction. It requires a comprehensive and sufficiently precise coordination of the geometry of structural components in the early phases of planning because, unlike steel construction, it is almost impossible to make subsequent corrections. This requires close coordination between the architect, structural engineer and m&e engineer (mechanical & electrical) in preliminary and subsequent design phases. The dimensions of structural components and reinforcement ratio in the preliminary design form an important basis for estimating the costs of concrete structures. The structural engineer draws up the verifiable structural analysis of the building component at the design development stage.
For the dimensioning of structural components in LPH 4, the geometry of the routing of pipes and cables for technical building services must already be firmly established. Thermal activation of structural components usually only slightly influences components' dimensions, while the planning of holes and recesses has a major influence on their size since openings, holes and recesses in structural components can be relevant to the design, especially of structural components such as beams subject to bending stress. The dimensions of structural components in concrete structures must also comply with sound insulation and fire protection requirements. If, for example, the dimensions of columns, which arise out of a verification of the fire resistance rating with the help of tabulated data, fall below the prescribed minimum, a mathematical verification of the structure's fire resistance rating must be com-

B 4.1 Formwork plan
B 4.2 Reinforcement plan
B 4.3 Three-dimensional planning and representation of reinforcement



B 4.2


B 4.3

missioned during structural planning because, in this case, an analysis of the structure's load-bearing behaviour in the event of fire will be required.
The architect prepares the construction documents based on the results of the structural planner's dimensioning. A structural engineer then draws up formwork plans that define the geometry of the building's shell and form the basis of the execution of construction work (Fig. B 4.1). These must be checked and approved by the architect. Creating reinforcement plans (Fig. B 4.2) and formwork plans is a basic part of structural planning and is done only after the architect approves the formwork plans. Reinforcement plans are extremely complex and precise. Reinforcement is now often shown in three dimensions to prevent construction errors (Fig. B 4.3). The necessary planning periods involved are relevant for scheduling because the formwork plans and reinforcement plans of structural planning form the basis for subsequent construction. Structural components with very complex geometries, such as doubly curved surfaces, are a particular challenge for concrete construction planners and builders because there are almost no tools available for representing and producing reinforcement curved in three dimensions. The preparation of plans of the building's shell that do not have to be supplemented by the plans of the architect on the building site, and of element plans in prefabricated construction, form additional services of structural design.
A failure to take this sequence into account in scheduling and insufficient coordination of different planning professions can significantly disrupt planning and construction operations, especially in concrete construction, unfortunately a frequent occurrence in practice. It usually takes a considerable effort to subsequently incorporate even slight changes to the geometry of a structural component once reinforcement planning has begun. This often leads to unnecessary discussions and can justify additional planning fees. The architect is responsible for effective scheduling and timely coordination.

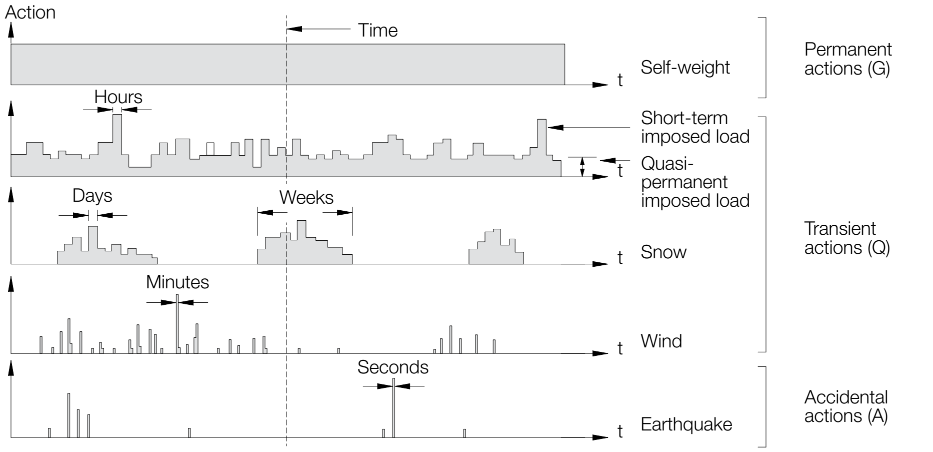
Due to the widespread notion that technical implementation of any design is now completely unrestricted, architects usually prioritise the layout of floor plans and align the vertical support structure to the shape of the floor plans. Fundamental structural planning requirements, especially the continuity of vertical load transfer, effective horizontal bracing of the building and the special requirements of monolithic construction particularly in large buildings, are not always sufficiently taken into account in the early phases of the building design. It is not only the "logic" of the support structure and flow of forces that suffer from such inadequate planning, which is usually the result of insufficient experience and expertise. Inadequate calculations can restrict a structure's serviceability if there are excessive deflections of the structure, for example. An increased material consumption also impairs the structure's appearance and economy in many cases. It is generally better to avoid an indirect load transfer and superfluous load diversion unless there are particular reasons to do so. Earthquake-proof construction requires especially close coordination between architect and structural engineers because regular load transfer is extremely important here. Intelligent structural engineering results in effective structures and an economic use of materials and complies with the fundamental principles of sustainable planning.
For these reasons, it is essential to regard planning processes as the joint achievement of various planning disciplines. Only a holistic planning process, in which all the technical disciplines work together towards a common goal from the outset, will produce a successful result.
It should perhaps be noted here that inspecting and approving reinforcement is not a standard service of the structural engineer's scope of work. Given the vital importance of reinforcement for the load-bearing ability and serviceability of concrete structural components, it is advisable to commission a technical engineering inspection of the construction of the support structure for compliance with the verified structural documentation as an additional service.

Design fundamentals

European standards, which developed out of efforts to standardise normative building regulations within the European Union, currently encompass ten standards that deal mainly with designing load-bearing structures. Eurocodes have now been incorporated into building codes in most European countries, so the application of Eurocodes has become binding, while earlier national documents are no longer valid.

Standards and design fundamentals

Eurocodes consist of two parts: the general document, which is the same in all European countries, and a national appendix, in which countries supplement the main document by setting national parameters and rules. In Germany, the Eurocodes are published under the title "DIN EN". It is mainly Eurocodes 0 (DIN EN 1990), 1 (DIN EN 1991), 2 (DIN EN 1992), 4 (DIN EN 1994) and 8 (DIN EN 1998) that are of importance in the dimensioning of structural concrete components. Eurocode 0 prescribes general requirements as to the safety of load-bearing structures, serviceability and durability of structures as well as the required verification procedure. Eurocode 1 defines possible actions on structures and prescribes their size, distribution and duration of effect. Eurocode 2 contains the material-specific stipulations for designing, calculating and dimensioning reinforced concrete structures. Eurocode 4 regulates the design, calculation and dimensioning of composite steel and concrete structures. Eurocode 8 deals with structures subjected to seismic action.
As well as European standards, the highly-recommended publications of the German Committee for Reinforced Concrete (Deutscher Ausschuss für Stahlbeton, DAfStb), which contain reports on research that deals equally with scientific fundamentals and practical issues, are available in German-speaking countries. Relevant research results are included in the DAfStb guidelines, which in many cases are also incorporated into building inspection regulations. These are established codes of engineering practice.



B 4.4

B 4.4 Actions and their changes over time
B 4.5 Categories in accordance with DIN EN 1991-1-1
B 4.6 Imposed loads according to the usage categories specified in DIN EN 1991-1-1

The safety concept

One significant change from the previous generation of standards is the introduction of a safety concept, with partial safety factors for loads as well as for structural resistance. The load-bearing ability of structural components is no longer verified by means of a global load safety factor set after the calculations as an increase factor on the action side or as a reduction coefficient on the structural resistance side. The Eurocodes' semi-probabilistic safety concept means that the calculations are much more detailed, with uncertainties in the respective steps in the calculations directly and far more precisely taken into consideration with the help of separate partial load safety factors γ for both action and structural resistance. Increasing or reducing the nominal values with the respective partial load safety factors gives you the essential design values. Once loads are identified, taking the partial load safety factors on the action side into account, it must be verified that the design values of the loads are less than that of the structural component's resistance.

European standards clearly differentiate between the ultimate limit state and the limit state of serviceability in the dimensioning of structural components. The ultimate limit state describes the load-bearing behaviour immediately before a structural component fails and is connected with large deformations and in concrete structures with large cracks, which clearly indicate imminent failure at an early stage. Load safety factors are used to ensure a sufficiently large margin against failure during design.
The limit states of serviceability describe load-bearing behaviour under actual expected imposed loads. Loads as well as stress levels on structures are generally much lower and deformations usually unobtrusive. In the verification process, the partial load safety factors γ are usually assumed to be 1.0. These verifications in concrete construction ensure that deflections and especially cracks do not impair a structure's use and durability.

Actions and combinations of actions

DIN EN 1991 classifies actions on structures according to their probability of occurring into permanent, variable and exceptional (Fig. B 4.4). Permanent actions "G" change only slightly during a structure's service life. In multi-storey buildings, these actions include the structure's self-weight and imposed loads and in buildings with basements, the permanent earth pressure. The partial load safety factor γ_G is set at 1.35 because the magnitude and distribution of permanent actions can be very accurately predicted. One particular form of permanent action in concrete construction is prestressing P. Because prestressing is very precisely monitored, the partial load safety factor γ_P can usually be assumed to be 1.0. Transient actions Q, such as imposed loads, snow and wind loads and thermal actions, change frequently and/or significantly during a structure's service life. The partial load safety factor γ_Q is set at 1.5 because of the greater unpredictability of these factors compared with permanent actions. If several variable loads are imposed simultaneously, the standards allow for a reduction of partial load safety factors. A distinction is made between the main actions, which are crucial in planning and design, and secondary actions. Only the full extent of main actions need be taken into account in designing structural components. Variable secondary actions can be reduced, depending on the verification, with so-called combination coefficients ψ.
Accidental actions A are events such as pressure from an explosion, impact of a colliding vehicle, fire or an earthquake. These can be very severe but are very unlikely to occur. Most partial load safety factors γ on the action and on the resistance side can be assumed to be 1.0. The essential actions to be considered in designing normal multi-storey buildings are listed in DIN EN 1991-1-1 (self-weight and imposed loads), DIN EN 1991-1-3 (snow loads) and DIN EN 1991-1-4 (wind loads). Imposed loads depend on usage categories in accordance with DIN EN 1991-1-1. The categories of use for roofs are A (residential), B (office areas), C (areas where people may congregate), D (shopping areas), E (storage areas) and F and G (traffic and parking areas). A distinction is made in category of use A between roofs, stairs and balconies. For roofs, the categories of use are H (roofs that are not accessible, apart from normal maintenance and repair activities), I (accessible roofs used according to categories of use A to G) and K (accessible roofs with special uses, such as helicopter landing pads) (Figs. B 4.5 and B 4.6). Snow loads depend on the snow load zone, altitude of the site and pitch of the roof. Wind loads are applied perpendicular to building and roof surfaces, and the position of the building, its form and height, and wind speeds and direction also play a role.
The verification of ultimate limit states takes into account basic load combinations for permanent and non-permanent actions, which are based on partial safety factors and combination coefficients, as well as exceptional design situations. In practice, this means that many different combinations of actions must be investigated because it is impossible to predict which action will be the most adverse main action without conducting calculations.
In verifying limit states of serviceability, a distinction is made between quasi-permanent load combinations, frequent load combinations and rare load combinations (for which the partial load safety factors γ_F can be generally assumed to be 1.0, but the combination coefficients vary).

Designing concrete structures

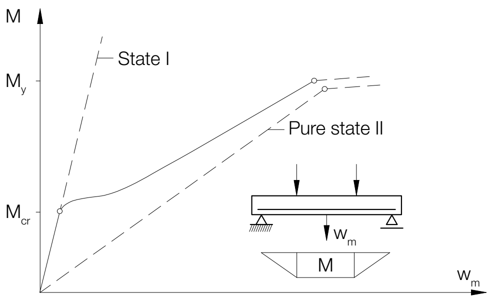
Concrete structures are usually made of reinforced concrete, with plain concrete now only used in secondary structural components. The concrete in reinforced concrete structures exposed to tensile loads will crack under relatively low loads due to concrete's low compressive strength. This process is described as a transition from an uncracked state (I) to a cracked state (II). The reinforcement laid to absorb tensile loads enables a structural component to still absorb loads, even after cracking, although cracking greatly reduces a component's stiffness (Fig. B 4.7). Prestressed concrete structures behave simi-

Usage category	Cate-gory	Specific use	Example
	A	Areas for domestic and residential activities	Rooms in residential buildings and houses; bedrooms and wards in hospitals; bedrooms in hotels and hostels, kitchens and toilets.
	B	Office areas	
	C	Areas where people may congregate (with the exception of areas defined under category A, B, and D1)	C1: Areas with tables, etc., e.g. areas in schools, cafés, restaurants, dining halls, reading rooms, receptions. C2: Areas with fixed seats, e.g. areas in churches, theatres or cinemas, conference rooms, lecture halls, assembly halls, waiting rooms, railway waiting rooms. C3: Areas without obstacles for moving people, e.g. areas in museums, exhibition rooms, etc. and access areas in public and administration buildings, hotels, hospitals, railway station forecourts. C4: Areas with possible physical activities, e.g. dance halls, gymnastic rooms, stages. C5: Areas susceptible to large crowds, e.g. in buildings for public events like concert halls, sports halls including stands, terraces and access areas and railway platforms.
	D	Shopping areas	D1: Areas in general retail shops D2: Areas in department stores
Areas for storage and industrial activities	E1	Areas susceptible to accumulation of goods, including access areas	Areas for storage use including storage of books and other documents.
	E2	Industrial use	
Garages and vehicle traffic areas (excluding bridges)	F	Traffic and parking areas for light vehicles (≤ 30 kN gross vehicle weight and ≤ 8 seats not including driver)	Garages; parking areas, parking halls
	G	Traffic and parking areas for medium vehicles (> 30 kN, ≤ 160 kN gross vehicle weight, on 2 axles)	Access routes; delivery zones; zones accessible to fire engines (≤ 160 kN gross vehicle weight)
Categorization of roofs	H	Roofs not accessible except for normal maintenance and repair.	
	I	Roofs accessible with occupancy according to categories A to D	
	K	Roofs accessible for special services, such as helicopter landing areas	

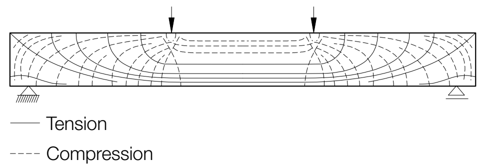
B 4.5

Usage category	Category		q_k [kN/m²]	Q_k [kN]
	A	Roofs Stairs Balconies	1.5–2.0 2.0–4.0 2.5–4.0	2.0–3.0 2.0–4.0 2.0–3.0
	B		2.0–3.0	1.5–4.5
	C	C1 C2 C3 C4 C5	2.0–3.0 3.0–4.0 3.0–5.0 4.5–5.0 5.0–7.5	3.0–4.0 2.5–7.0 (4.0) 4.0–7.0 3.5–7.0 3.5–4.5
	D	D1 D2	4.0–5.0 4.0–5.0	3.5–7.0 (4.0) 3.5–7.0
Imposed loads on floors due to storage	E1		7.5	7.0
Imposed loads in garages and vehicle traffic areas	F[1, 3]	Gross vehicle weight: ≤ 30 kN	q_k	Q_k
	G[2, 3]	30 kN < Gross vehicle weight ≤ 160 kN	5.0	Q_k
		[1] For usage category F, a figure of between 1.5 und 2.5 kN/m² can be chosen. The figure of Q_k can be chosen in the 10–20 kN range. [2] For usage category G, a figure for q_k of between 40 and 90 kN/m² can be chosen. [3] For the areas specified in notes 1 and 2, the figure can be set in the National Appendix, so the underlined figures are recommended.		
Imposed loads on roofs of category H	H[1, 2, 3, 4]		q_k [kN/m²]	Q_k [kN]
		[1] For usage category H, a figure for q_k of between 0 and 1 kN/m² can be chosen. The figure of Q_k can be chosen in the 0.9–1.5 kN range. The national appendix can set figures if areas are specified for the figures. The following figures are recommended: q_k = 0.4 kN/m²; Q_k = 1.0 kN. [2] The figure of q_k can be made conditional on the pitch of the roof in the national appendix. [3] q_k can be applied to a surface A, which can be specified in a national appendix. A size of 10 m² is recommended for this surface. [4] Service loads on roofs (especially those in category H) do not have to be applied in combination with snow and/or wind loads.		
Imposed loads on roofs of category K for helicopters	**Class of helicopter**	**Take-off load Q of helicopter**	**Take-off load Q_k**	**Dimension of the loaded area (m x m)**
	HC 1 HC 2	Q ≤ 20 kN 20 kN < Q ≤ 60 kN	Q_k = 20 kN Q_k = 60 kN	0.2 × 0.2 0.3 × 0.3

B 4.6



B 4.7



B 4.8

B 4.7 Moment deflection line of a steel reinforced concrete beam
B 4.8 Drawing of the main stress trajectories in a beam in an uncracked state (I)
B 4.9 Designing for bending: elongation, stresses and the position of the resulting forces
B 4.10 Reinforcement of a reinforced concrete beam
B 4.11 Strut-and-tie model
a Designing for shear forces
b Designing for torsion

larly, although pre-stressing means that the cracked state (II) occurs under much higher loads (see “Prestressed concrete”, p. 80ff).

Verification of the ultimate limit state

Designing structural components is an iterative process, the first step of which is to define the actions impacting components. The dimensions of components' cross sections are then assumed and internal forces and moments calculated. Internal forces and moments are almost always calculated in concrete construction based on elasticity theory and the stiffness of structural components in their uncracked state I (first order effects). The calculation of internal forces and moments on the deformed system, taking second order effects into account, are unusual for concrete structural components because this calculation is only useful if the deformations can also be very precisely identified at the same time. Precisely estimating or predicting deformations is, however, very complex due to the material's non-linear behaviour, and only done in rare cases. The internal forces and moments calculated in this way form the basis for the component's design.
Only the model of the cracked state (II) is used in the verification of the ultimate limit state, which describes a structural component's behaviour just before failure. The concrete's tensile strength is not directly taken into account here because it is subject to great variation, and its contribution to the structure's load-bearing capacity is slight. In areas where structural components are subject to tensile stress, the reinforcement required to absorb tensile forces results from the calculations. Reinforcement must be positioned in the selected cross section, taking construction regulations into account. The minimum thickness of concrete cover must also be taken into consideration in determining reinforcement. Adequate concrete cover is required to ensure the durability and fire resistance of structural components, and it secures the bond between the reinforcement and the concrete. During design and planning, a structural component's chosen dimensions are also checked against the stresses and loads that will be imposed on it. In areas where structural components are not subject to tensile stress, especially the edges, secondary reinforcement is usually laid.

Designing for normal force

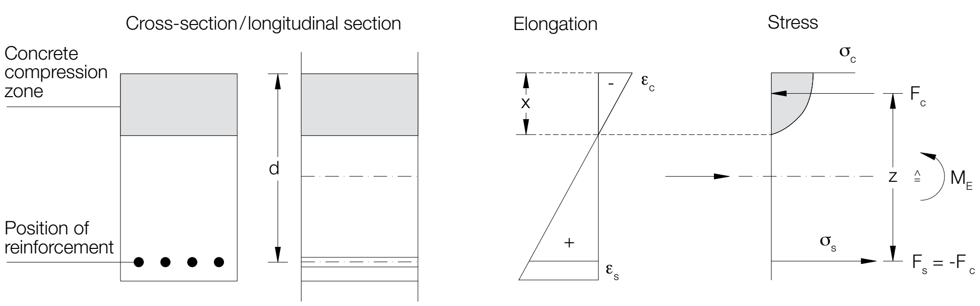
Concrete exposed to normal tensile forces will bear loads until its compressive strength is exceeded and it cracks. In this cracked state, the reinforcement absorbs tensile loads, and only a tensile failure of the reinforcement will cause the structural component to fail. The load-bearing capacity of reinforced concrete structures under normal tensile force is therefore solely determined by the cross-sectional area of the reinforcement.
Under normal compressive force, only normal compressive stresses occur in the concrete and reinforcement. In column-type structural components, whose slenderness can endanger their stability, imprecision in geometry resulting from the manufacturing process combined with second order effects can cause significant additional bending stress, which can greatly reduce their load-bearing capacity. A verification of stability, which takes these additional stress loads into account, is therefore vital for slender columns. The load-bearing ability of columns depends on buckling length, cross-sectional area, degree of reinforcement and the quality of the concrete, with a higher compressive strength of the concrete resulting in considerably reduced column cross-sections. Aids, such as design programmes and design charts, are available for verifying the stability of compression members. Reinforced concrete columns are reinforced with longitudinal and shear or stirrup reinforcement.

Designing for bending and bending

The principal stress trajectories of a steel-reinforced concrete structural component under bending stress describe its load-bearing behaviour (Fig. B 4.8). Load-bearing capacity in structures subject to bending depends mainly on the structural component's geometry and level of reinforcement. A distinction is made between the following two forms of failure at the ultimate limit state:

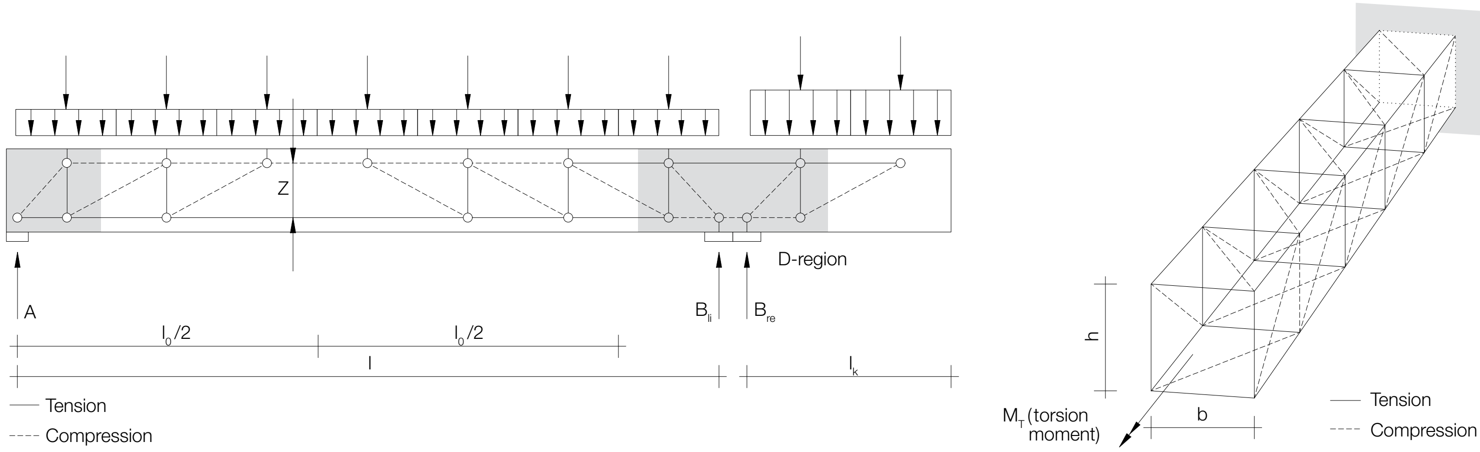
• Steel reinforcement in lightly reinforced structural components can fail before the con-

d statically effective height
x height of the compression zone
z internal moment arm
ε_c concrete elongation
ε_s steel elongation
σ_c concrete stress
σ_s steel stress
F_c resulting concrete compressive force
F_s steel tensile force



B 4.9

B 4.10



a

b

B 4.11

crete's compressive strength in the compression zone is exceeded. Steel failure is preceded by large plastic elongation, creating large deformations and crack widths. If a structural component is so lightly reinforced that its reinforcements' tensile strength is already exceeded during the transition from an uncracked to a cracked state, the component will fail without notice when the first crack forms. This form of failure is prevented in planning and design practice by stipulating minimum reinforcement, which ensures that there will be cracking before failure ("crack before failure" concept).

- Even if the reinforcement is sufficient to absorb tensile forces, concrete in the compression zone can fail if the structure is too lightly reinforced. This can be prevented by verification of the bending compression zone.

In designing a structure to accommodate bending or – in the case of additional normal force loads – bending with axial loading, the bending moment is divided into an inner force couple made up of compressive and tensile force. The compressive force is assigned to the concrete and correlates with the integral of stresses in the concrete compression zone (Fig. B 4.9). The reinforcement must be able to absorb tensile forces. The inner moment arm is calculated from the spacing of the compression stress resultant and the reinforcement and must be iteratively calculated to fulfil the conditions of equilibrium and compatibility. Countless practical planning and design aids are available for this purpose; especially design programmes and charts for manual calculations. Longitudinal reinforcement on the side of the structural component subject to tensile forces will always be required (Fig. B 4.10).

Designing for shear force

Shear force loads often occur in combination with bending stresses. In designing concrete structural components to accommodate shear force, a distinction is made between structural components with and without shear reinforcement. Structural components without shear reinforcement are, for example, roofs subject to only low shear force loads. Strut and tie models, in which tensile forces are met by reinforcement and stress fields are allocated to the concrete, are now used to design structures to accommodate shear force or represent shear force bearing behaviour (Fig. B 4.11 a). It must be verified that the diagonal compression struts do not exceed the concrete's compressive strength and that shear reinforcement bars can absorb vertical tensile forces.

Designing for torsion

As with designing for shear force, only a verification of load-bearing capacity has to be provided in designing for torsion. Construction regulations ensure the serviceability of structures. Torsion analysis is only usually required in concrete construction if torsion loads are necessary for equilibrium (equilibrium torsion). A spatial strut and tie model is used in this design context to help determine the ultimate limit state (Fig. B 4.11 b). The model will indicate the longitudinal reinforcement and shear or stirrup reinforcement required for a beam subject to torsion loads. Torsion loads that arise in statically indeterminate systems from the monolithic connection of structural components and are not essential to stability (compatibility torsion) are not generally taken into account in the verification of load-bearing capacity in concrete construction because torsional stiffness is normally very slight after the transition to a cracked state (II).

In design and planning, separate verifications are conducted for combined loads consisting of bending moments and normal forces, shear force and torsion in concrete construction, although the mutual influence of separate loads and stresses is taken into account through additional design rules to simplify the calculations.

Verification of limit states serviceability

Verifications of serviceability limit states in concrete construction include the limiting of deformation and a verification of the limiting of cracking widths. These ensure the intended functioning of a structure under imposed loads. These play an extremely important role in design and in many cases are essential in establishing the dimensions of structural components and their degree of reinforcement.

Limitation of deformation

Deformation of load-bearing structures and structural components must be limited to acceptable levels for various reasons. A structure's appearance needs to be maintained, and its users must feel safe. Deformations also cannot be allowed to impair adjoining structural components, such as non load-bearing partitions or facade elements. Excessive deformations can also negatively impact a structure's functionality, e.g. systematic drainage.

If they are not regulated in standards, permissible deformations must be agreed on at the outset of planning. In principle, deformations in reinforced concrete structures can be compensated for by cambering, but cambered concrete structural components are very complex to cast and mould, so this is only rarely resorted to for ordinary multi-storey buildings and simple camber geometries.

Concrete structures are subject to shrinkage and creep. Shrinkage is the contraction or reduction in concrete's volume due to the release of moisture as it hardens. Creep is the increased expansion of concrete under constant stress over time. Both processes abate as time goes on and can significantly influence the deformation behaviour of concrete structural elements. A realistic estimate of deformations in concrete construction must take non-linear material behaviour, shrinkage and creep into account. Deformation calculations for concrete construction are very complicated because in contrast to the ultimate limit state, they take the contributory effect of the concrete between cracks into account, so they are always somewhat imprecise. To simplify this process, the standards allow verifications of serviceability to be provided through compliance with construction regulations, by limiting span/depth ratio, for example, (Fig. B 4.12) or the distance between bars or bar diameters in many cases.

Verification of crack width limitation

Cracks are unavoidable in concrete structural components subject to bending and tensile forces and do not as such represent damage or a defect. Crack widths must, however, be restricted to an acceptable level because

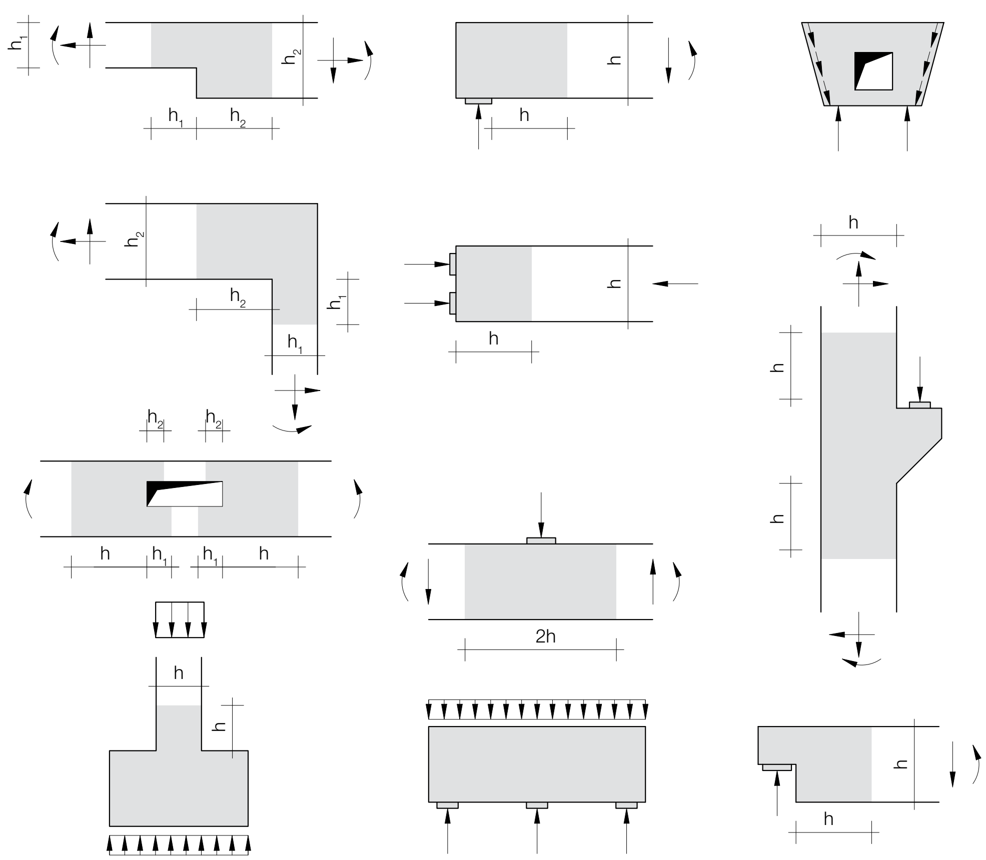
Structural system	K	Concrete highly stressed (ρ = 1.5 %)	Concrete lightly stressed (ρ = 0.5 %)
Simply supported beam, one- or two-way spanning simply supported slab	1.0	14	20
End span of continuous beam or one-way continuous slab or two-way spanning slab continuous over one long side	1.3	18	26
Interior span of beam or one-way or two-way spanning slab	1.5	20	30
Slab supported on columns without beams (flat slab) (based on longer span)	1.2	17	24
Cantilever	0.4	6	8

K: Coefficient for taking various static systems into account. Values of K for use in a country may be found in its National Appendix. Recommended values of K in Germany are given in Fig. B 4.12.
ρ: Tensile reinforcement required in the centre span to absorb the design moment (on a single-span cross section for cantilever beams)

Note 1: The values given have been chosen to be generally conservative and calculation may frequently show that thinner members are possible.
Note 2: For two-way spanning slabs, the check should be carried out on the basis of the shorter span. For flat slabs the longer span should be taken.
Note 3: The limits given for flat slabs correspond to a less severe limitation than a mid-span deflection of span/250 relative to the columns. Experience has shown this to be satisfactory.

B 4.12

B 4.12 Span/depth ratio in accordance with DIN EN 1992-1-1 for steel reinforced concrete structural components without axial compression
B 4.13 Division of structures into B and D-regions (grey); D-regions with non-linear strain distribution due to
a Geometrical discontinuities
b Static discontinuities
c Static and geometrical discontinuities



a b c B 4.13

cracks that are too wide not only impair a structure's appearance; they also compromise the durability of reinforced concrete structures. For this reason, verification of crack width limitation is an elementary part of designing concrete structural components. In practice, it is not usually done by precisely calculating crack widths, but through the level of reinforcement and construction regulations. Higher requirements on the restriction of crack widths, for water-tight concrete structural components, for example, can result in considerable additional work and expense to produce the necessary reinforcement.

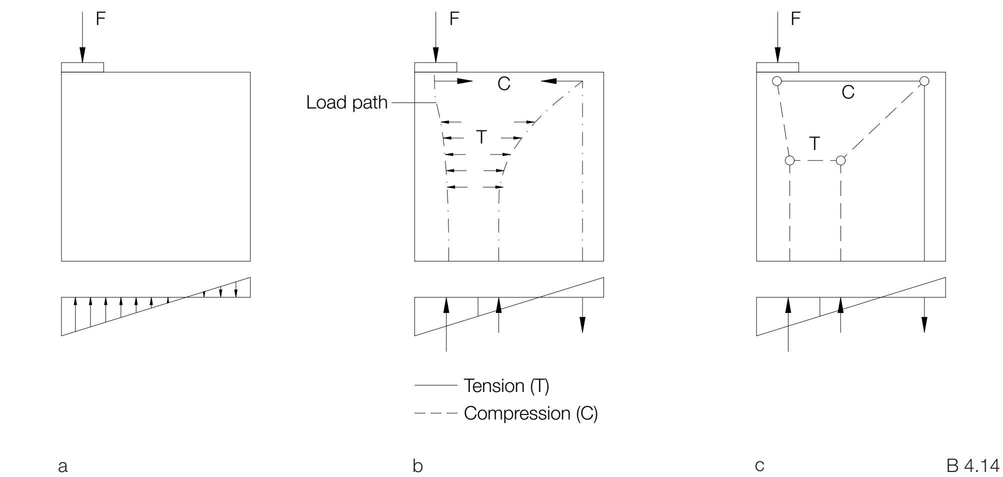
Planning, designing and building with strut and tie models

As well as familiar numerical methods, designing with strut-and-tie models is a method that has now been incorporated into the current generation of standards.
It is especially common in practice because it can provide a calculated verification of the properties of structural components, especially in designing detailed areas in which conventional design methods fail and the planner would otherwise be reliant on experience and intuition.
The strut and tie model method is used mainly in so-called "Discontinuity regions" (D-regions), in which in contrast to "Beam" or "Bernoulli" regions (B regions) the standard design process cannot be used because Bernoulli's hypothesis on plane cross sections of beams remaining plane after deformation no longer applies (Fig. B 4.13).
D-regions are areas of changes of cross section (geometric discontinuities) or concentrated loads (structural discontinuities). Examples of geometric discontinuities are changes in cross sections, frame corners and openings and recesses. Examples of structural discontinuities are load transfer areas, load-bearing areas and tension cable anchorage points. Planes subject to a non-linear elongation are also included in Discontinuity regions. In concrete construction practice these areas must be particularly carefully planned to avoid structural damage.
After differentiating D-regions from B-regions in a concrete structure, the boundary conditions, i.e. acting forces, supporting forces and internal forces and moments, must first be identified. It is not necessary to determine the internal force if a structure consists only of D-regions, such as a plate: the D-regions can then be separately dealt with. The load path in a structural component can be modelled using the load path method (Fig. B 4.14). The load paths connect the resulting force of the acting forces and supporting forces, or in the case of cut-out areas of a structure, the internal forces on one side with the internal forces on the other side. After the load paths are modelled, they can be represented as polygons. Deflection forces created by the curvature of load paths must be taken into account. In this process it is advisable to orient models towards the elastic-

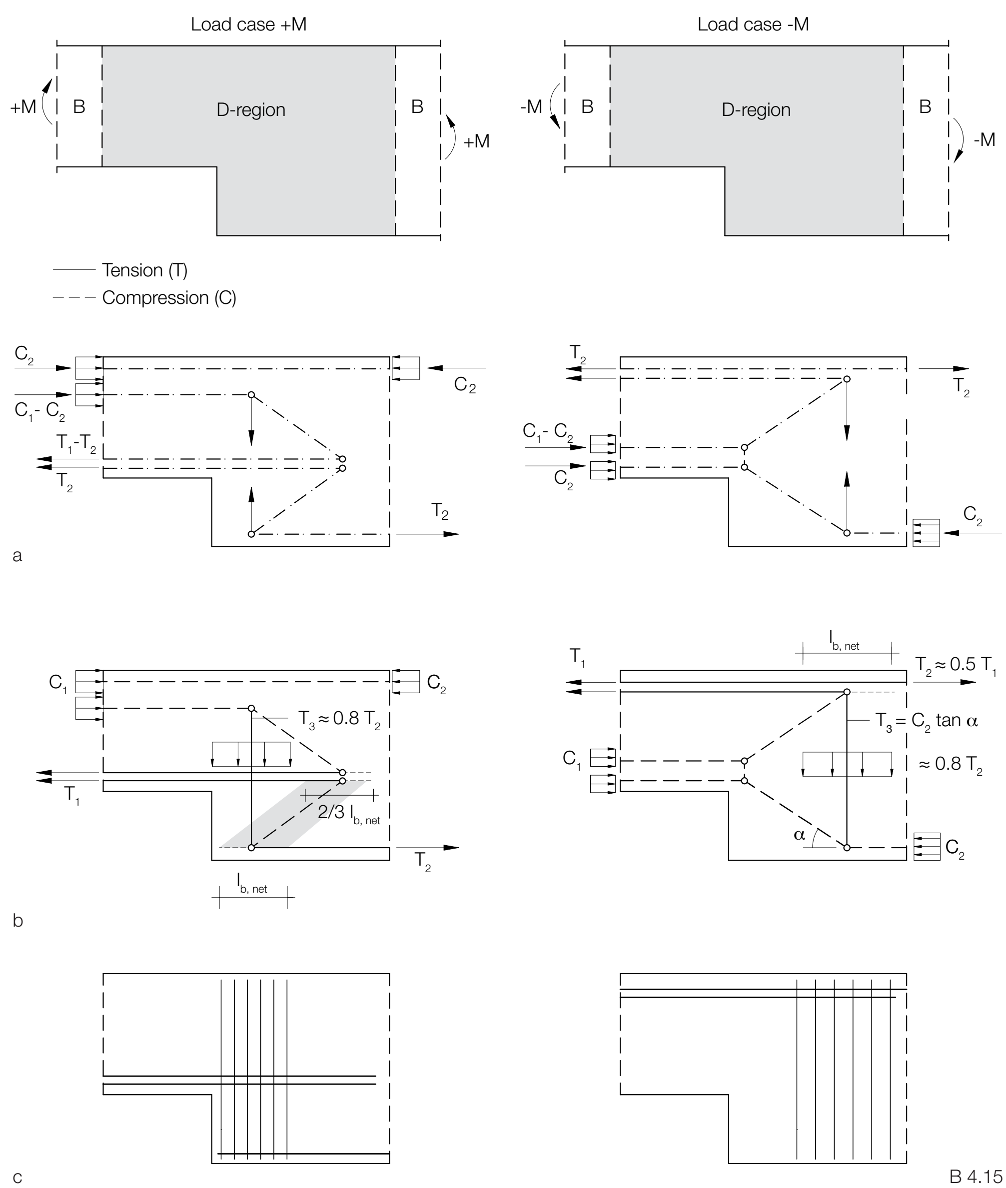
ity theory. The course of load paths can be deducted from the directions of the principal stresses, so the strut-and-tie model method can be combined very well with the Finite Element Method (FEM).
The result of these processes is a strut-and-tie model whose individual members represent the forces resulting from the stress fields, thus clearly showing the load path (Fig. B 4.15). Planar strut and tie models are usually used for this purpose, although spatial strut-and-tie models may also be useful in special cases. The individual members in a strut-and-tie model can represent compression and tension members. During modelling, it must be ensured that the angle at which the compression and tension members meet at the junction points is not too tight. Tension members should also run parallel or vertical to the edges of the structural component as far as possible for practical construction reasons. The external acting forces and forces in the members of the frame must be in equilibrium at every junction point, so identifying the forces in the members is similar to calculating a truss. The compressive stress fields in the concrete compression members must be verified and reinforcement sufficient to cover the tension members must be calculated. In a further step, the frame's junction points, where the forces intersect and which are often crucial to the design, must be established.
It should be pointed out at this point that designing with strut-and-tie models will not necessarily yield definite solutions. This is due to the special nature of the material, whose load-bearing behaviour depends largely on their reinforcement.
Using the strut-and-tie model method to design structural components requires comprehensive experience and knowledge of load-bearing behaviour. In contrast to many other schematic design processes, strut-and-tie models make it possible to extremely clearly and comprehensibly describe the load path in a reinforced concrete structural component. This makes them very useful in designing structural concrete components, and they can help establish a structure's reinforcement down to the last detail (and this is a major part of building with concrete). They also make it possible to train a planner's understanding of load transfer and load paths in a special way. A comprehensive description of designing and building with strut-and-tie models with many examples can be found in the German annual concrete construction almanac, the "Beton-Kalender" [1].

Verification of fire resistance rating

For multi-storey buildings there are fire protection requirements concerning the flammability of materials and verification of the fire resistance rating. Concrete and concrete steel reinforcement are classified as non-flammable materials. The fire resistance rating of concrete structural components depends, however, on how they are designed.



B 4.14 Application of the load path method in designing with a strut-and-tie model
a Geometry and loads
b Load path and deflection forces
c Strut-and-tie model



B 4.15 Strut-and-tie model for a beam with a jump in the cross section with positive and negative moment (C = tension, T = compression)
a Load path
b Model
c Reinforcement

Building regulations requirements	Load-bearing structural components not enclosing space	Load-bearing structural components enclosing space	Non load-bearing interior walls
Fire resistant	R 30 F 30	REI 30 F 30	EI 30 F 30
Highly fire resistant	R 60 F 60	REI 60 F 60	EI 60 F 60
Fire-proof	R 90 F 90	REI 90 F 90	EI 90 F 90
Fire wall	–	REI-M 90	EI-M 90

Key:
R = load-bearing capacity, E = spatial enclosure, I = heat deflection under exposure to fire, M = mechanical action (impact stress)

B 4.16

B 4.16 Standard fire resistance and building regulatory authority requirements for various structural components
B 4.17 Tables showing fire resistance in accordance with DIN EN 1992-1-2: Minimum requirements for the dimensions of the cross sections of beams, slabs and columns, concrete cover and the dimensions between axes of reinforcement for concrete in strength classes ≤ C 50/60

In Germany, the fire resistance rating of structural components is classified in DIN 4102-2 “Fire behaviour of building materials and building components” using five standards of fire resistance F 30, F 60, F 90, F 120 and F 180. The numbers indicate that structural components must resist a standard fire test for a period of more than 30, 60, 90, 120 and 180 minutes. The European design concept in DIN EN 13 501-1 “Fire classification of construction products and building elements” classifies fire resistance in the separate standards of R (load-bearing capacity), E (spatial enclosure), I (heat shielding in case of fire) and M (mechanical acting force), which can be used to distinguish between load-bearing and non load-bearing structural components and between structural components for and not for room partitioning (Fig. B 4.16). It has already been incorporated into German building law. Building regulations in the German States (Länder) regulate fire resistance rating requirements for structural components in Germany, depending on building type.
Fire safety design for reinforced concrete structural components is prescribed in DIN EN 1992-1-2 “Structural fire design”, which sets out three distinct verification methods. For verification with the help of tabulated data, the minimum requirements on cross section dimensions, concrete cover and the centre distances of reinforcement for concrete ≤ C 50/60 for ordinary fire resistance ratings are listed in tables (Fig. B 4.17), in accordance with the structural component involved. For columns in particular, this will mean that much larger minimum dimensions will be specified compared with those resulting from earlier regulations.
If the cross-section dimensions or spacing of reinforcement bars fall short of the minimum figures shown in the tables, calculation methods are used in planning and design to analyse the structure’s load bearing behaviour in the event of fire. In accordance with DIN EN 1992-1-2, simplified calculation methods that allow for a calculation based on comparatively simple methods, are distinguished from general design and planning processes, which require fairly complex numerical simulations.

Concrete cast in situ, precast concrete and construction using semi-finished components

Concrete structural components can be cast in situ or precast or made using a combination of these two methods. A decision to use one construction method will affect planning, the construction of structural components, load-bearing behaviour, the sequence of construction operations, building site logistics and construction costs as well as influence the appearance of structural components. The decision to use a particular construction method should be made as early as possible and include everyone involved in planning. The advantages and disadvantages of construction methods must be carefully weighed up (see ”A comparison of in-situ concreting and prefabricated buiding methods”, p. 34ff.).

Construction using concrete cast in situ

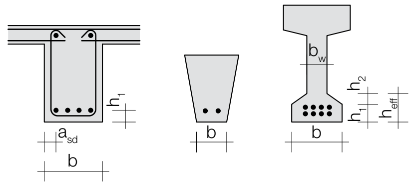
One advantage of casting concrete in situ is that a structural component’s geometry can be adapted to fit local conditions (see “Concrete cast in situ”, p. 46ff.). The monolithic character of concrete – one of its outstanding properties – is retained because casting concrete in situ of necessity produces structures with monolithic transitions between structural components. The resulting, usually statically indeterminate load-bearing systems have good load-bearing capacity and high levels of system redundancy. With appropriate reinforcement, a biaxial load transfer and continuous effect can be achieved without extra time and effort, resulting in economical dimensioning of the structural component. Structural systems, such as point-supported flat slabs, are in practice almost always cast in situ because monolithic transitions between structural components that are subject to high loading are easier to form in this way. The statically and structurally advantageous connection of a ceiling joist and structural slab to form a T-beam with a broader load-bearing area is inherent in concrete cast in situ. Flush ceilings can also be comparatively easily built in this way. Foundations and floor slabs are almost always cast in situ, as are the lower areas of concrete structures impervious to water, also called “white tank” foundations.

Construction using precast components

In construction using precast components, the structural elements made from structural concrete are almost always produced in stationary precasting plants using standardised formwork, and then transported to the building site. Their use is especially appropriate in a modular building structure in which the same types of structural components recur. Individual companies often make specific prefabricated elements and issue them in ranges of types designed to serialise manufacture and standardise their products. The range of types defined by the German precast concrete industry association, the “Fachvereinigung Deutscher Betonfertigteilbau e. V.”, offers a guide to designing and building with precast concrete components. Their range of types includes examples of structural components, such as precast columns, beams and slabs, which can be produced in various size increments for concrete frame construction depending on the structural requirements and geometric boundary conditions. Precast components can be made with more slender cross sections than those cast in situ due to the monitoring of the concrete’s quality and execution of work in the factory, among other factors. Cross sections, such as T and I profiles, which are rarely cast in situ, are also typical of concrete construction with precast components. In practice, constructing companies often make special proposals in line with their firm’s own production, although precast structural components can also be individually designed.

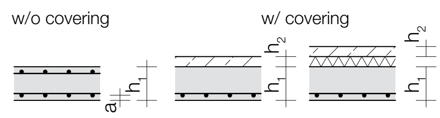
Precast structural components are usually made as large as possible to minimise the number of joints between components and the effort involved in installing them on the building site, but the maximum structural component sizes imposed by their production notwithstanding, there are various restrictions on their transport and installation. The maximum size and weight of precast structural components have to fit in with the load capacities and

dimensions of transport trucks and the load capacities and clearances of road routes. In Germany, the permissible maximum size of components for road transport without a special permit is 2.55 m wide, 4 m high, 15.50 m long and a total weight including the truck of 40 t. Structural components up to 24 m long, 3 m wide, 4 m high and with a total weight of 48 t can be transported with a permanent permit. Transporting larger or heavier components requires a special permit. In exceptional cases where precast structural components are definitely too big for road transport, concrete plants are set up on site. The jib working radius and maximum payload of lifting equipment are also crucial for installation.
Controlled production conditions make it possible to fabricate precast concrete components with high quality in terms of the accuracy of their dimensions, surface and edge geometries. Cast-in mounting parts can also be very precisely integrated into a precast concrete component. As well as mounting parts, openings and installation pipes and cables must be taken into account in planning. The components' high surface quality, especially of those with exposed concrete surfaces, is one argument often made in favour of building with prefabricated components. Precast structural components can be cast vertically or horizontally. It should be noted, however, that vertical formwork creates two different surfaces. The lower side facing the formwork skin is a precise impression of the skin, while the open upper side is usually smoothed subsequently. High quality and smooth surfaces on both sides can be produced by using battery formwork and are often used in the production of wall elements.
Transporting and installing such components requires careful planning and must be taken into account in their design because they may be crucial factors. The verification required for such planning will also involve additional time and effort. Transport anchors are integrated into structural components to make it possible to lift and position individual elements.
One typical structural engineering application for construction with prefabricated components is frame construction, structures built in a modular fashion. Industrialised concrete



	Standard fire resistance R 30	R 60	R 90	R 120
Min. width b – reinforced and prestressed concrete beams	80	120	150	200
Minimum web width b_w for beams with an I cross section	80	100	100	120
Minimum spacing a and a_{sd} of reinforcement for a prescribed beam width b	b = 80 a = 25[1)]	b = 120 a = 40[1)]	b = 150 a = 55[1)]	b = 200 a = 65[1)]
	b = 160 a = 15[1)]	b = 200 a = 30[1]	b = 300 a = 40[1]	b = 300 a = 55[1)]
Minimum spacing a and a_{sd} of prestressed steel reinforcement[2)] for a prescribed beam width b	b = 80 a = 40[1)]	b = 120 a = 55[1)]	b = 150 a = 70[1,3)]	b = 200 a = 80[1,3)]
	b = 160 a = 30[1)]	b = 200 a = 45[1)]	b = 300 a = 55[1)]	b = 300 a = 70[1,3)]

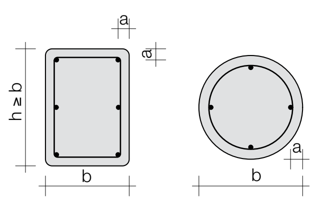
[1)] a_{sd} = a + 10 mm for single-layer reinforcement, for multi-layer reinforcement the 10 mm increase can be dispensed with.
[2)] Increase by Δa = 15 mm for strands and wires with θ_{cr} = 350 °C is taken into account in accordance with DIN EN 1992-1-2, 5.2 (5).
[3)] For reinforcement spacing a ≥ 70 mm, surface reinforcement should be built in accordance with DIN EN 1992-1-2, 4.5.2.



$h_s = h_1 + h_2$

	Fire resistance class REI 30	REI 60	REI 90	REI 120
Minimum thickness h_s of reinforced and prestressed concrete slabs for statically determined and indeterminate support systems	60	80	100	120
Minimum spacing a for uniaxially spanning steel reinforced concrete slab[1)]	10	20	30	40
Minimum spacing a for a biaxially spanning steel reinforced concrete slab[1)]				
with $l_y/l_x \leq 1.5$[2)]	10[3)]	10[3)]	15[3)]	20[3)]
with $1.5 < l_y/l_x \leq 2.0$	10[3)]	15[3)]	20[3)]	25[3)]

[1)] For prestressed concrete slabs (strands and wires with θ_{cr} = 350 °C), the value must be increased by Δa = 15 mm.
[2)] l_y and l_x are the spans of a biaxially spanning slab, with l_y the greater span.
[3)] The values apply to a biaxially spanning slab supported along all four edges. If this is not the case, slabs must be treated like uniaxially spanning slabs.

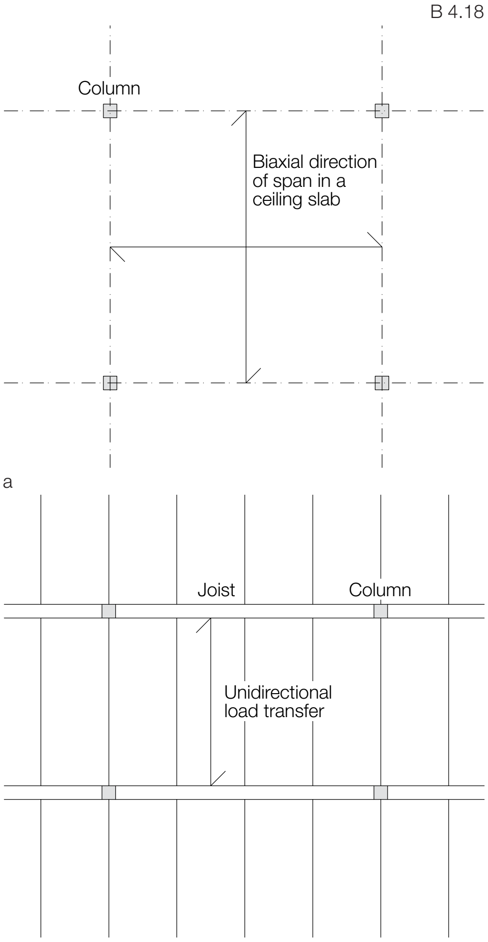


	Standard fire resistance R 30	R 60	R 90	R 120
Minimum width b and minimum spacing a with **multi-sided** fire exposure, depending on the load factor in case of fire μ_{fi}				
μ_{fi} = 0.2	b = 200 a = 25	b = 200 a = 25	b = 200 a = 31	b = 250 a = 40
			b = 300 a = 25	b = 350 a = 35
μ_{fi} = 0.5	b = 200 a = 25	b = 200 a = 36	b = 300 a = 45	b = 350 a = 45[1)]
		b = 300 a = 31	b = 400 a = 38	b = 450 a = 40[1]
μ_{fi} = 0.7	b = 200 a = 32	b = 250 a = 46	b = 350 a = 53	b = 350 a = 57[1)]
	b = 300 a = 27	b = 350 a = 40	b = 450 a = 40[1)]	b = 450 a = 51[1)]
Minimum width b and minimum spacing a with **single-sided** fire exposure, depending on the load factor in case of fire μ_{fi} = 0.7	b = 155 a = 25	b = 155 a = 25	b = 155 a = 25	b = 175 a = 35

[1)] at least eight rods

B 4.17

B 4.18



B 4.19

B 4.20

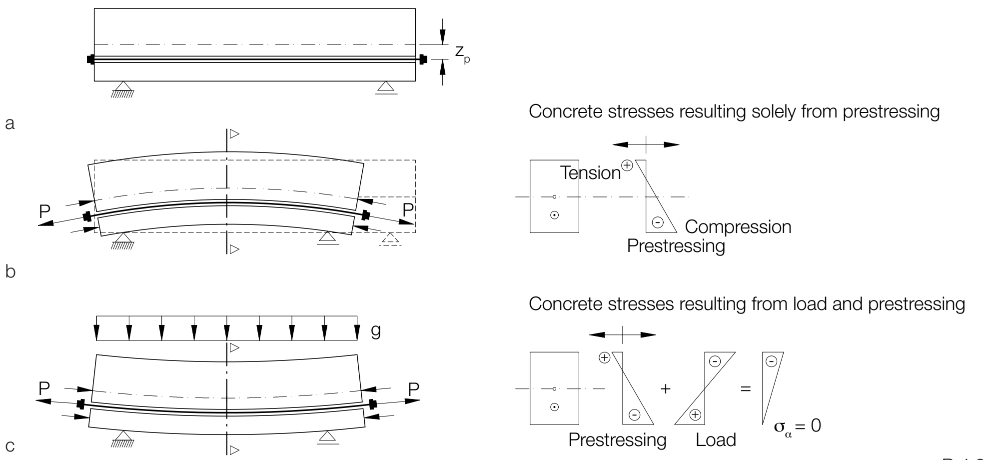
slab construction (in prefabricated high-rise concrete slab buildings or "Plattenbau") has not become established as a way of building multi-storey buildings in Central Europe. Prefabricated elements are used in systems like concrete frame construction, used mainly in industrial and hall construction, as well as for individual structural components such as stairs and facade elements. Since precast components are not regulated construction products, they require either a national technical approval from the German Institute for Construction Technology (Deutsches Institut für Bautechnik – DIBt) in Berlin, a national test certificate from the DIBt or an approval from the highest building inspection authority in individual cases.

Construction using semi-finished components

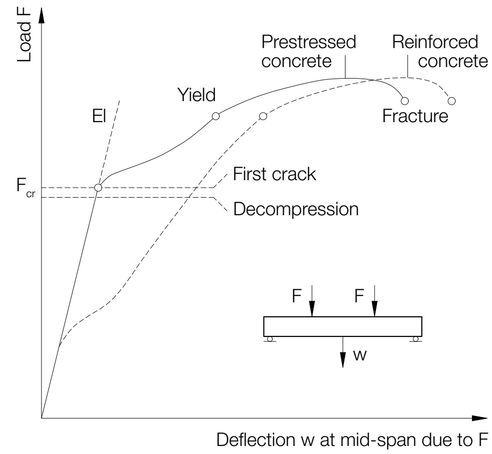
Construction using semi-finished components or modular construction combines the advantages of casting concrete in situ with those of construction using prefabricated parts. Thin-walled precast components serve as permanent formwork, with concrete poured onto them in situ after they are erected. This can make formwork and scaffolding much easier. Modular slabs are given an extra upper layer of reinforcement on the building site. Structures built with semi-finished components can be classified as partly monolithic. A continuous effect can be achieved with modular slabs because the upper layer of reinforcement, over which concrete cast in situ is added, can be continuous. There is, however, no biaxial load transfer beyond the modular slab joints. Construction with semi-finished components can be an alternative to casting concrete in situ, and they are now widely used to make slabs and walls. In practice, structural planning is carried out mainly for concrete cast in situ, with this planning then forming the basis of the tender. Construction with semi-finished components is usually based on a special proposal made by the constructing company, which re-works the concreting in situ to fit in with the use of semi-finished components. Planning and production are standardised but can also be adapted to individual floor plans.

Prestressed concrete

Concrete's low tensile strength means that cracks can form even under slight loads, considerably reducing a structure's stiffness. In prestressed concrete, prestressing tendons are prestressed against the concrete. The concrete can be pressed in areas subject to tensile loads and achieves a fictive tensile strength through prestressing (Fig. B 4.21). The tensioning of the tendon transfers an eccentric prestressing force P into the concrete, which, depending on the position of the tendon, can produce a constant bending moment $M_p = P \cdot z_p$ as well as a normal force $N_p = -P$ in the structural component, with z_p the distance of the prestressing cable from the cross section's centroid. Prestressing results in compressive stresses on the lower edge of the cross section and light tension stresses on the upper edge, not taking the structure's self-weight into account. If external loads are imposed in addition to prestressing, the loads from the two loading cases are superimposed and the resulting tensile stresses on the underside are less than those in a non-prestressed structure.
Decompression of the cross section begins when stresses from prestressing and external loads cancel each other out at the tensioned edge of a structural component. Only if loads increase further is the concrete's tensile strength exceeded and, like a non-prestressed reinforced concrete beam, it cracks (Fig. B 4.22). The ultimate breaking load of a prestressed concrete beam is not very different from that of a reinforced concrete beam. Prestressing a structural component does not increase its load-bearing ability, prestressing instead produces a state of internal stress.
Prestressed concrete structural components undergo much less deformation than non-prestressed components of the same dimensions and can be made much more slender in cases in which deformations are the determining factor for dimensioning. Prestressing considerably reduces cracking. Cross sections in which cracks can occur under infrequent loads, for example, will be over-compressed



B 4.21



B 4.22

under quasi-permanent loads. Less cracking means more durable structures. Another advantage of prestressed structural components is that there is less fluctuation in the tension caused by loads on the reinforcement. Prestressed concrete construction is a very appropriate method of building with concrete and has many advantages.
While the aim is to have as few cracks as possible in ordinary conditions of use, imminent component failure in the ultimate limit state, as well as in prestressed concrete elements, should be signalled by clearly visible cracks and deformations. Prestressing force is usually calculated in accordance with serviceability, so it should not be too high. The amount of reinforcement required to ensure load-bearing can be economically supplemented with reinforcing steel.
Prestressing tendons have a higher strength than ordinary reinforcing steel. Their steel can achieve high steel strains, and the decline in prestressing force caused by concrete creep can be compensated for. They are available as round or oval, smooth or profiled wires with diameters of up to 10 mm, as strands of three or seven interwoven wires, and as bars with thread ribs and diameters of up to 50 mm. Prestressing tendons are classified according to their characteristic yield or tensile strength, which is specified in DIN EN 10138. A typical specification for prestressing steel is "St 1570/1770", for example.

Prestressing methods and techniques
Prestressing methods are systems from certain manufacturers that include tendons as well as anchorage systems, couplers and sliding sheaths and are usually approved by national building inspection authorities. In planning the geometric dimensions of prestressed structural components, the space required for anchorage systems must be taken into account because they can be crucial, especially in slender components. Prestressing techniques differ from each other in terms of the tendons' positioning, the type of composite action, the timing and application of prestressing force and composite action. Some of these distinct methods are described below.

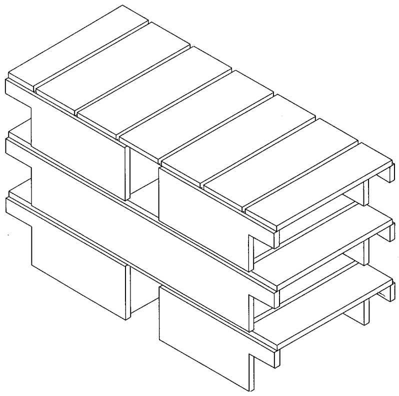
Pre-tensioning
For pre-tensioning, profiled prestressing tendons are tensioned in a prestressing bed between two anchor blocks and concrete is poured in over them. After the concrete hardens, the anchoring of the strands is released and the prestressing force is transferred to the structural component through the composite action. Prestressing components in a prestressing bed requires stationary production facilities and can really only be carried out in a plant. Prestressed, precast concrete components are usually made using this method. Straight prestressing tendons cannot be deflected, so prestressed, precast concrete components made using this technique are not suitable for beams, such as continuous beams, whose internal moment is subject to a change of sign.

Bonded post-tensioning
Post-tensioning involves concreting sheaths into a structural component. If the tendons are not in sheaths during concreting, they are threaded in or injected and tensioned against the concrete after it hardens. After post-tensioning, the sheaths are injected with cement mortar and the stressing jacks released. Injecting mortar creates a bond between the tendon and the concrete and protects the prestressing steel tendons from corrosion. These components are produced on site on a scaffold. In contrast to prestressing in a prestressing bed, the geometry of their tendons can be freely chosen as long as the minimum curvature radius is taken into account, so post-tensioning can be adapted to the component's internal moment. Post-tensioning of this kind creates deflection forces. The injection process must be carried out with great care and in a controlled manner to avoid damage.

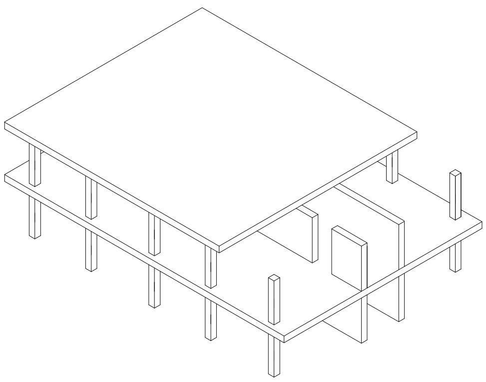
Unbonded post-tensioning
Unbonded post-tensioning uses strands coated with grease by the manufacturer to protect them from corrosion and a plastic casing – usually a PE casing – which are laid in the formwork, fixed with spacers at the desired height and concreted in. No bonding occurs. After the concrete hardens, the

B 4.18 Load-bearing concrete structure cast in situ, University library, Tokyo (J) 2007, Toyo Ito & Associates Architects, Structural engineers: Sasaki Structural Consultants
B 4.19 A comparison of slab systems
a Concrete slab cast in situ
b Slab made of precast elements
B 4.20 Load-bearing structure made with precast components
B 4.21 Principle of prestressing and stress states, using the example of a single-span girder
a Self-weight not effective, no prestressing
b Self-weight not effective, prestressing effective
c Self-weight and prestressing effective, decompression
B 4.22 Load-deflection diagram comparing a non-prestressed and a prestressed reinforced concrete beam
B 4.23 Prestressing a flat slab with a prestressing jack

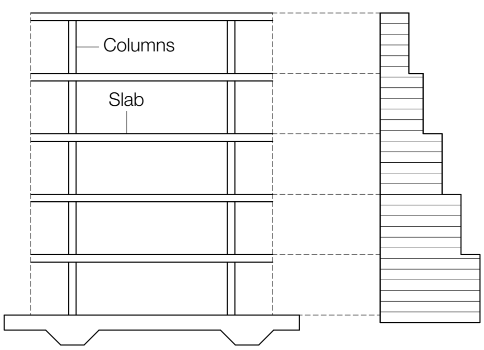

B 4.23



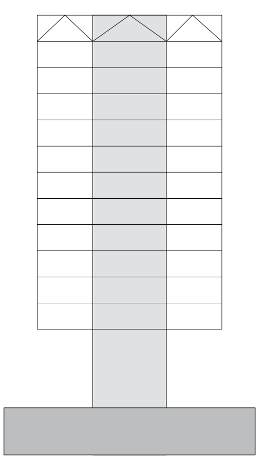
B 4.24



B 4.25



B 4.26



B 4.27

strands are prestressed (Fig. B 4.23, p. 81). The tendons of externally prestressed components run outside the concrete cross section and are deflected over saddles or transverse bulkheads. The advantage of external prestressing is that the tendons can be controlled and exchanged. Additional corrosion protection is required.

Prestressed concrete structural components are very complex to plan, design and produce, especially for statically indeterminate, prestressed structures. In practice, prestressed concrete structural components are used mainly for precast components in engineering works. One suitable area of use in multi-storey buildings is prestressed flat slabs. The architectural and structural potential of this construction method, in particular the possibility of making elements with more slender cross sections, has not yet been fully exploited in ordinary building construction.

Multi-storey buildings

Multi-storey buildings consist of floor plans that can vary depending on different usage of individual levels. Requirements in terms of spatial planning, but also in terms of access, fire protection and the building's technical equipment can also vary depending on their use. For structural reasons, it is advisable to draft a consistent structural plan and make load-transferring structural components continuous, unless specific requirements in the design should prohibit this.

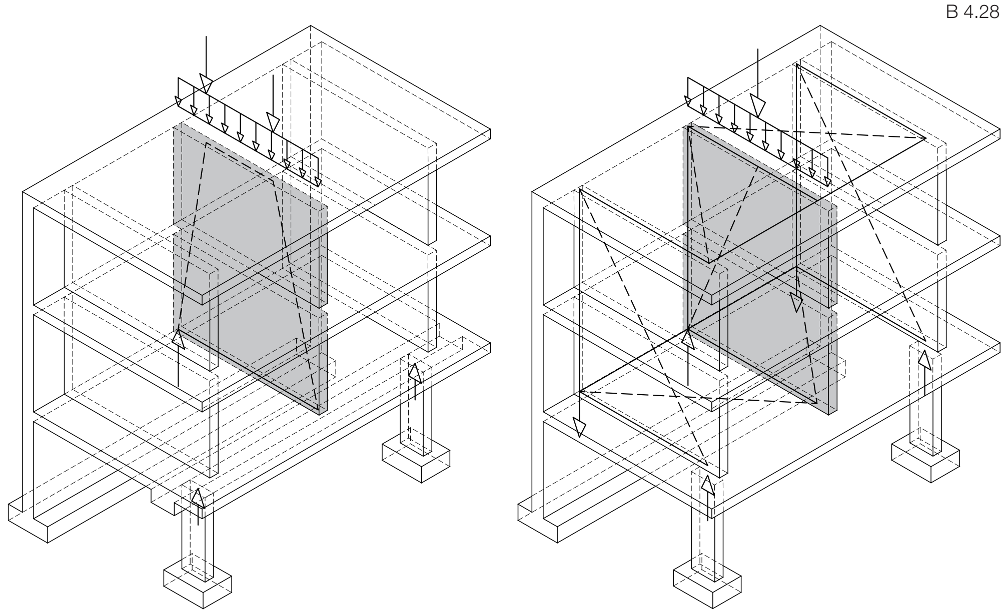
The principles of vertical load transfer

Vertical forces acting on multi-storey concrete buildings are transferred through linear structural components (concrete framework construction), through panel-type structural components (wall construction method) or through a combination of linear and panel-type components.
The use of columns allows for comparatively high levels of interior flexibility. Non load-bearing elements can be used to separate interior spaces and enclose space against the outside. Columns are not generally used for lateral bracing.
Concrete walls can have both a load-bearing and an enclosing function, although this will make the design of the floor plan and facade less flexible. Openings created subsequently will be subject to various restrictions and a thorough static and structural analysis will be required in every case. Standard construction methods are used for varying usages and floor plans, such as cross-wall and longitudinal wall types for office buildings, (Fig. B 4.24 and B 4.25).

The loading of individual structural components depends on the forces acting on them and the support structure's geometry. Load-bearing elements on the lower floors of multi-storey buildings are subject to greater loads than elements on upper floors (Fig. B 4.26). In very high buildings with many storeys, this can result in columns increasing in size from the top down. It is usually advisable not to set columns bearing point-supported flat slabs right on the edge of a slab, but to slightly indent them to reduce punching shear stresses on the slab. Leaving a slab's edge free can also be advantageous when it comes to mounting the facade.

Columns and walls should ideally stand one above the other. Disruption to direct load transfer, such as load-bearing structural components not standing one above the other, should be avoided as far as possible, especially in lower storeys, because of the high loads on columns and walls lower down. In practice, load transfer can be disrupted by different usages in individual storeys, such as a transition between a basement storey with an underground garage and upper storeys or between a ground floor with shops and upper storeys used as offices. If the load paths of structural components must be disrupted for functional reasons, appropriate measures should be very carefully planned since such disruptions are associated with major deformations. Vertical restraints for columns and walls subject to high loads will always require very stiff structural components such as ceiling joists, frame struc-

B 4.28



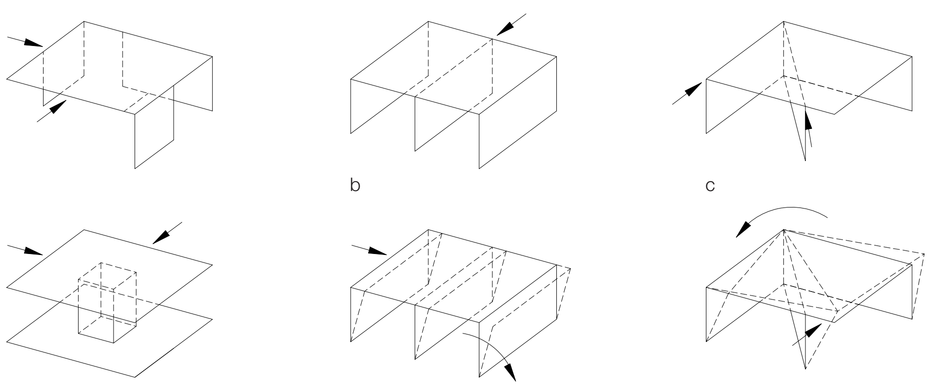
a b B 4.29

tures, large frame structures or floor-to-wall panels (Fig. B 4.29). These can be theoretically resolved into frameworks, and openings can be incorporated into them based on a load path analysis with the help of strut-and-tie models. Because of their low overall height, slabs with a solid cross section are not suitable for carrying large vertical loads. To reduce deformations, it can be advisable to use prestressed structural components in certain areas.

Cantilevering elements also make major demands on the stiffness of structural components. It is usually advisable to support a cantilevering slab with a wall panel rather than make the slab uneconomically thick. The supporting forces of projecting wall panels can be centred by the ceiling slabs, although the resulting additional loads should be taken into account in their design (Fig. B 4.28).
Suspension systems, in which vertical loads are not directly transferred downwards, but are first hung up by load-bearing tension members, usually within the plane of the facade, are a special type of load transfer. Their forces are transferred into a core through sufficiently rigid and in many cases floor-to-ceiling cross-beam structures. The loads can be transferred via the cores into the foundations through mainly compression forces. Unevenly distributed service loads, however, can cause considerable additional bending loads in the core, which must be taken into account in design. Suspension systems make it possible to build large areas unobstructed by vertical supports on the ground floor (Fig. B 4.27).

The principles of horizontal load transfer
Horizontal loads consist mainly of wind loads, earthquake loads and stabilising forces. Walls are usually used to brace concrete multi-storey buildings. A building is securely braced when it has at least three wall panels, whose lines of action do not intersect at one point, and a ceiling slab (Fig. B 4.30). Interaction between horizontal and vertical structural components is usually required to brace a building. If precast ceiling slabs are used, individual structural components must be joined so as to be shear resistant by means of suitable structural

B 4.24 Cross-type wall made of precast parts
B 4.25 Longitudinal-type wall made of precast parts with two centre walls
B 4.26 Increase of compressive normal forces in columns from the top to the bottom of a structure
B 4.27 Drawing of the principle of a suspended structure
B 4.28 Load-bearing and architecturally successful indirect transfer of vertical loads using inclined columns, Double Gymnasium of the Kantonal School (kantonale Berufs- und Handelsschule), Chiasso (I) 2010, Architects: Baserga Mozzetti Architetti, Structural engineers: Ingegneri Pedrazzini Guidotti
B 4.29 Indirect transfer of vertical loads in a cross-type wall
a By joist
b Through shear wall action
B 4.30 Horizontal bracing of a building using wall panels and ceiling slabs
a Stable bracing using three vertical bracing elements
b Parallel panels can only transfer loads parallel to the panels' orientation
c Intersecting panels can only transfer loads that are applied in a single panel plane
d Stable bracing using a core
e Unstable behaviour of parallel panels under horizontal loads
f Unstable behaviour of intersecting panels under horizontal loads



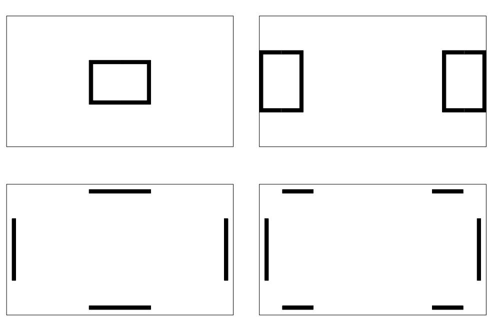
a b c d e f B 4.30

measures to ensure the slab's structure effect. In practice, access and service cores are used to horizontally brace multi-storey buildings whose vertical loads are transferred by columns. In buildings with extensive longitudinal expansion in particular, these must be positioned in such a way as to avoid constraining stresses. Sufficient building bracing must be mathematically verified for larger multi-storey buildings with a low number of bracing walls.
Building frames consisting of columns and ceiling joists can be another way of transferring horizontal loads. In buildings that are not particularly high, cantilevering columns can be used for bracing, although this structural system is not very economical because it transfers horizontal forces via bending.
Very close cooperation at an early stage between the architect and structural planner in developing an architectural and structural planning concept is especially crucial for multi-storey buildings with indirect load transfer. Laying out the floor plans of individual storeys, without taking the overall structural context into account, usually results in uneconomical buildings. Complex structures with indirect and disrupted load transfers require planners to have a very good understanding of spatial and static-structural issues. Creating a spatial representation of the load-bearing structure, such as an isometric drawing, is a good way of developing a functional and effective structural design concept in the early phases of planning.

Monolithic construction and integral concrete structures

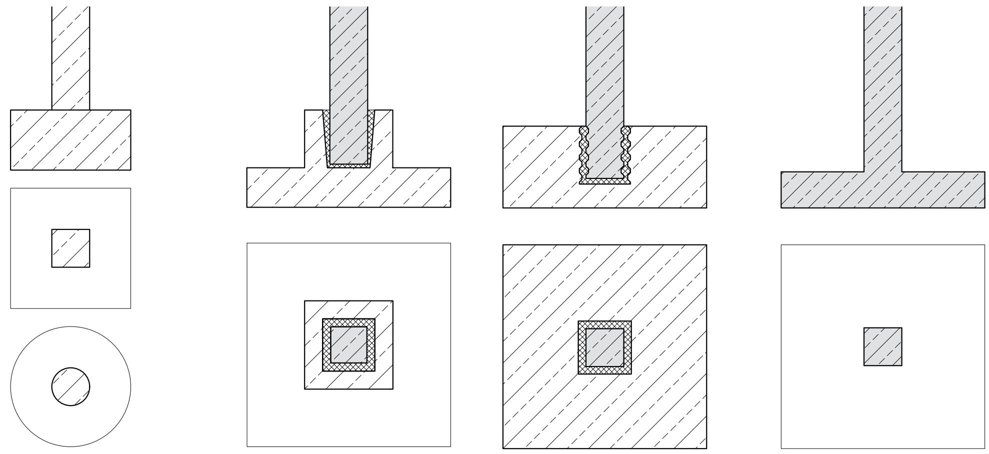
Very large concrete structures are, in many cases, built with expansion joints to avoid excessive cracking due to constraint. Expansion joints are designed to enable largely unrestrained deformations in the structure resulting from changes in temperature and moisture levels. As well as mainly horizontal deformations due to temperature and shrinkage, differences due to deformations in a vertical direction may also have to be taken into account. This can be done by using settlement joints, which are installed where there are varying sections of foundations or changes to ground conditions to avoid unplanned loads on a support structure.
Joints involve a planned dissection of a structure into individual sections. They affect not only the structure, but also its facade and finish. In facades and at ground level, for example, sealing strips are required to prevent moisture from penetrating. Joints detract from the homogeneity of structural components, and if detail planning is superficial, they can produce unfavourable design results. They are used out of physical necessity, but they are inconsistent with the monolithic character of concrete as a material.

Monolithic construction arises out of a desire for robust, durable, low-maintenance structures and a simple, clear architectural language. Monolithic or integral structures more or less prevent deformations. Temperature fluctuations with constant temperature gradients cause elongation throughout the height of a structural component. Preventing this deformation results in centrical stress. An increase in temperature produces compressive stress, while a drop in temperature results in tensile stress. Differences in temperature with linear or non-linear temperature gradients throughout the height of a structural component, transitions between structural components and sudden variations in stiffness result in bending stress. Unlike bridges and roofed structures without walls, heat-insulated buildings are usually only exposed to slight temperature fluctuations. Constraint loads resulting from concrete shrinkage, which, like a decrease in temperature, can cause tensile stress and cracking and can be calculated, are an essential factor in multi-storey buildings. Shrinkage can be realistically represented in a calculation model by converting shrinkage strain into a temperature load. The fact that cracked structural components are less rigid can be appropriately accounted for with a reduction factor.
Internal forces resulting from constraint essentially depend on stiffness; for example, the constraint of a column or slab under centrical stress and complete prevention of deformation results at $N = \varepsilon EA$. Structural components with low stiffness are not as exposed to constraint, but deformation is rarely completely prevented and might only be observed in very stiff deformation-preventing structural components. A sufficiently precise estimate of deformation prevention and the resilience of adjoining structural components are therefore essential to a realistic estimate of constraint.
Monolithic structures are very demanding for engineers to design and must be especially carefully planned. It is, for example, advisable in case of tensile forces caused by constraint, to calculate internal forces resulting from constraint, taking the material's physical non-linear behaviour into account since cracking decreases the tensile stress in the concrete. If this fact is not taken into account, internal forces resulting from constraint may be greatly overestimated. Crack widths due to load and constraint must be limited to



a b B 4.31

B 4.31 Positioning of access cores and wall panels
a Not exposed to restraining loads
b Exposed to restraining loads
B 4.32 Shallow foundations: pad foundations
B 4.33 Shallow foundations: strip foundations
a Sections
b Floor plan
B 4.34 "White tank" (GL – ground level, DFL – design flood level)



B 4.32

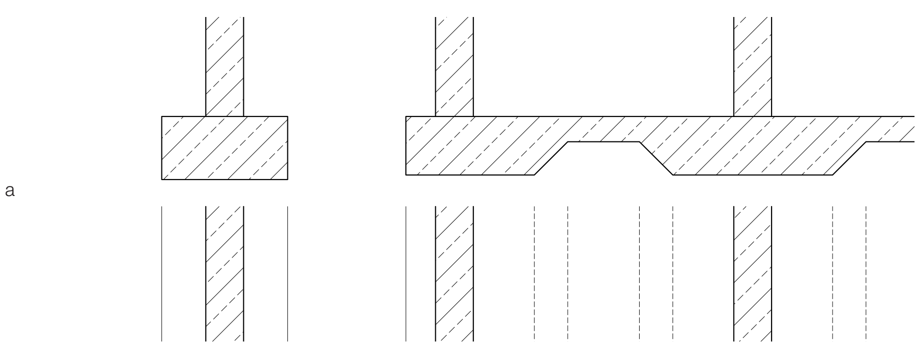
acceptable levels by appropriate reinforcement to ensure fitness for serviceability. There are higher requirements for crack width limitation for areas of structures required to be waterproof, such as for structural components standing in groundwater. Information on crack width limitation can be found in Eurocode 2 and in specialist literature (see Appendix, p. 260ff.). Monolithic structures therefore require increased reinforcement to limit crack widths. Cost savings derived from dispensing with the creation of joints in construction and lower maintenance – assuming that there is sufficient ductility – are complemented by a beneficial load-bearing behaviour with a high level of system redundancy. Monolithic buildings, in contrast to those with expansion joints, do not require each individual section of the building to be braced to resist horizontal forces. Finally, monolithic construction makes it possible to build monolithic transitions between structural components in high quality design that follow the load path and do justice to the plastic character of concrete as a material.
Monolithic structures systematically use the ability of structural components, columns and walls to deform. Structures should therefore be built so that adjoining structural components prevent deformation as little as possible and constraint in floor slabs remain low. Access and service cores prevent deformation because of their high stiffness. They are, thus, usually positioned in areas with only slight deformation-preventing action, such as near the building's anchor point (Fig. B 4.31).
Walls should be positioned so that they can warp around their weak axis. This will be the case if a wall is positioned lateral and not parallel to the direction of the prevention of deformation. The deformability of affected structural components must be verified by calculation and is one of the main limitations of monolithic construction. The deformability of columns and walls also depends on normal force loading. The deformability of columns decreases together with the column's increased utilisation of normal forces. It is usually easier to build monolithic buildings with just a few storeys than those with many storeys. The deformability of foundations can also play a role here. Pile foundations, if built correctly, can increase the rotation capacity and thus deformability of columns. Concrete technology measures, such as a suitable concrete mixture or the construction of contraction joints, can also contribute to an overall structural plan for a monolithic building. Monolithic construction can also have architectural consequences in many cases, e.g. on the positioning of stairwell cores and on the choice of dimensions for structural components, especially columns and walls. It is both advisable and necessary to take relevant interactions into account in preliminary design planning before the floor plan is completed. Monolithic construction is demanding, but can produce structures with outstanding technical and design qualities. Material-specific design in concrete construction means, first and foremost, expressing the monolithic character of structural concrete, with all the consequences that it can have for structures and their details.

Foundations

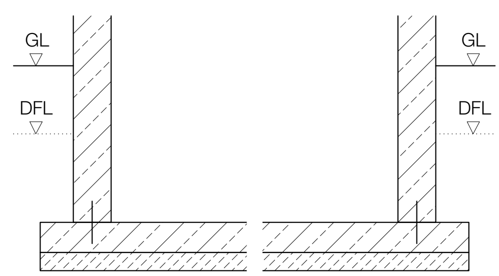
Buildings need foundations. Foundations must distribute the loads imposed by rising structures over a larger area. When properly planned and of the right size, they limit subsidence to an acceptable level, and if they are built in a structurally appropriate way, they prevent different parts of a building from subsiding unevenly. If foundation bases are built at frost-free depths, they also help to prevent frost damage in climate zones subject to frost. Foundations are now usually made of structural concrete cast in situ, although plain concrete can also be used where loads are very small. In terms of foundation types, a distinction is made between shallow and deep foundations. ,
A building and the ground it stands on interact in various ways: buildings impose loads on the ground, the ground deforms and the building's loads change until a state of equilibrium is achieved.

Shallow foundations

Shallow foundations transfer loads directly into the ground under the bottom of a building's foundation. The prerequisite for shallow foundations is ground that is sufficiently load-bearing. The base of a foundation must be deep enough (in Central Europe about 80 cm below ground level) to ensure that it does not become unstable due to the freezing and thawing of the layers of soil below it. Frost damage occurs more frequently with cohesive soils. Non-cohesive soils tend not to be sensitive to frost. Foundations under walls are usually laid in the



B 4.33



B 4.34

Performance class 1		Performance class 2	
Pressing water	Groundwater, artesian water, flood water or other water exercising hydrostatic pressure (even temporarily)	Non-accumulating seepage water	Water that can seep without accumulating through very porous soil ($k_f \geq 10^{-4}$ m/s)
			Water drained from not very porous soil by permanently functioning drainage in accordance with DIN 4095
Non-pressing water	Water in fluid droplet form exercising no or little hydrostatic pressure (water column ≤ 100 mm)	Soil moisture	Water capillary bound into the soil
Temporarily accumulating seepage water	Water that can accumulate on not very permeable layers of soil without drainage (building's footing at least 30 cm above the design water level)		

B 4.35

Usage class		Requirements
A	• Standard for residential construction • Storage space for high-quality usages	• Permeation of water in liquid form not permitted, also not temporarily through cracks • No damp areas on the surface (dark discolouration, water droplets)
		Additional requirements (as agreed): • No accretion of condensation • Dry climate Possible additional measures: • Ventilation, heating • Dissipation of building moisture • Insulation to prevent surface condensation
B	• Single and underground garages • Installation and supply shafts and ducts • Storage spaces with low-level requirements	• Damp spots permissible near penetrating cracks, rated crack cross sections, joints and construction joints • Dark discolouration, possibly water droplets • No water permeation due to water collected on the surface of the structural component • Condensation formation may be permissible (subject to possible specific agreement in construction contract)

B 4.36

Performance class

- Building site soil properties
- Design water level

Usage class

- Structure's function
- Structure's usage

- Definition of the extent and exclusion of moisture transport through the water-impervious structural component
- Demands on the interior climate and moisture levels
- Analysis of requirements resulting from a suitable method and execution of construction.

Water-impervious structural components

- Structural component's thickness
- Crack width limitation
- Any additional sealing measures
- Composition of the concrete
- Technical measures taken during construction
- Structural measures, e.g. prevention of restraint forces

B 4.37

Structural component	Performance class	Type of construction		
		Concrete cast in-situ	Element walls	Prefabricated parts
Walls	1	240	240	200
	2	200	240[1)]	100
Floor slab	1	250	–	200
	2	150	–	100

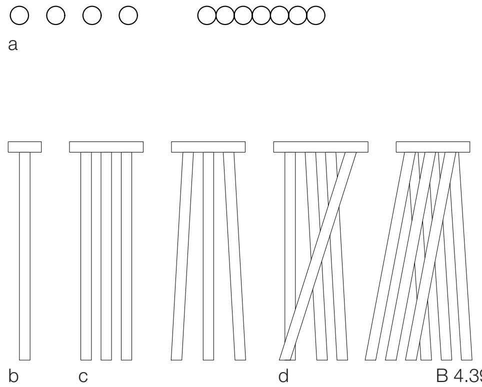
[1)] If special technical concreting and construction measures have been carried out, this can be reduced to 200 mm.

B 4.38

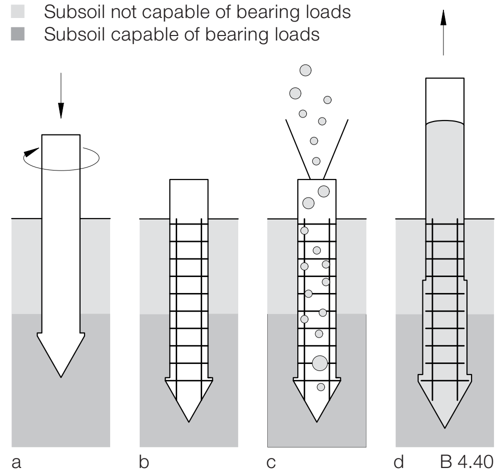
form of strip foundations. If they run straight down a slope, they are usually built in steps. Columns are founded on pad foundations, so circular foundations are an optimum planning solution for centrally-loaded, round columns. Sleeve foundations can be used with prefabricated columns. Pad and strip foundations can be used to strengthen a floor slab as well as being integrated into the base plate (Figs. B 4.32 and B 4.33).
Foundations are always larger than rising structural components, because the ground is much weaker than the concrete in rising structural components. Their acting forces must be transferred into the soil by increasing the size of the area under compression. A designing planner first calculates the pressure on the soil, the mathematical expression of loading on the ground. The size of foundations depends on the loading and load-bearing capacity of the ground and is normally specified in the form of permissible soil pressure. In principle, soil can absorb practically no tensile loads. Foundations can be loaded centrally or off-centre. If they are loaded off-centre, it must be noted that joints may only gap to the centre of gravity of the foundations. There must be no gaps under permanent loads.
A lean concrete sub-base of about 5 cm thickness is usually poured under foundations to ensure that the fitness for purpose and load-bearing capacity of the lower concreted areas are not impaired by soiling. Foundations usually contain foundation earth electrodes connected to a building's conductive metallic systems to protect people from dangerous currents if they touch such objects.

If a site's soil is bad and large loads are to be imposed on it, a raft foundation can distribute loads more evenly and prevent uneven subsidence. Raft foundations are especially beneficial and economical if columns are close together and horizontal loads are large. For the structural planner, this will involve an analysis of an elastically bedded slab.
Tank foundations are built mainly when the groundwater level is above the basement floor slab. They are usually made of waterproof concrete and also referred to as "white tanks".

B 4.35 Performance classes for water-impervious concrete structures
B 4.36 Usage classes for water-impervious concrete structures
B 4.37 Planning for water-impervious concrete structural components
B 4.38 Recommended minimum thicknesses of structural components for water-impervious concrete structures
B 4.39 Positioning of micro piles
a Wall of micro piles
b Single micro pile
c Group of micro piles
d Micro piles arranged to form a net-like structure
B 4.40 Production of full displacement piles
a Introduction of casing tube
b Installation of reinforcing cage
c Pouring of concrete
d Withdrawal of casing tube
B 4.41 Casting concrete ram piles in situ



B 4.39

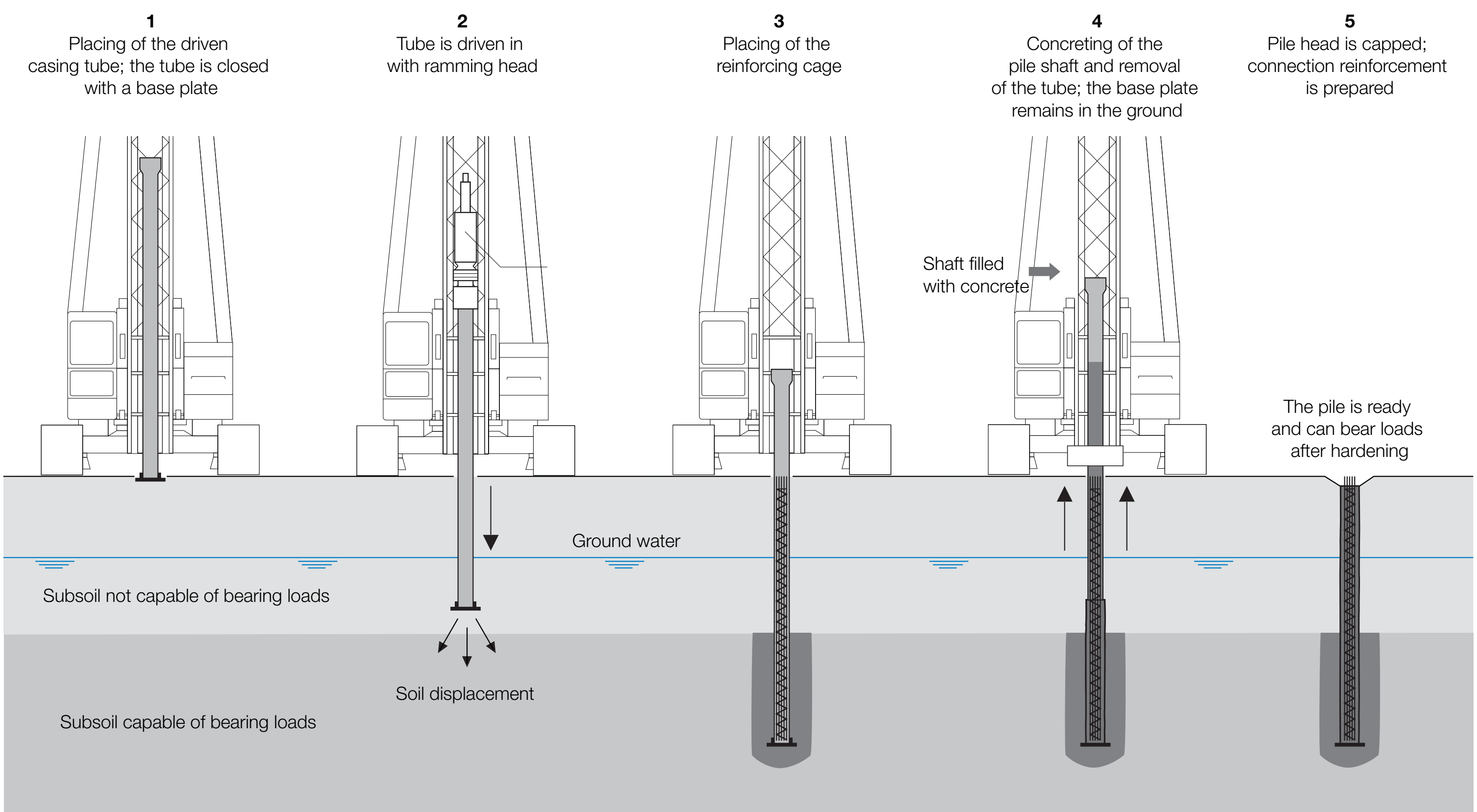


B 4.40

Minimum thicknesses of structural components and crack widths for white tanks can be set depending on the performance class and utilisation class (Figs. B 4.35 to B 4.38). Permissible crack widths for white tanks range between 0.1 and 0.2 mm depending on the difference in pressure between the structural component and the surrounding water. White tanks have comparatively high levels of reinforcement to limit crack widths to an acceptable level. It must be ensured that construction joints are waterproof (Fig. B 9.34, p. 85).

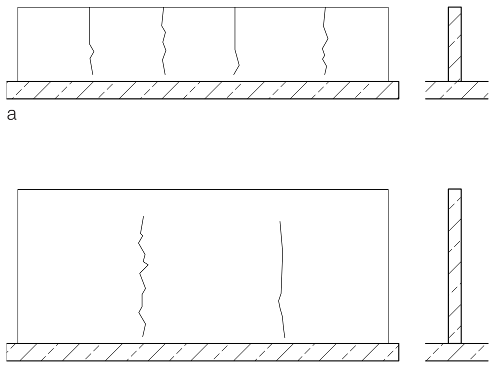
Deep foundations

Deep foundations are necessary if load-bearing layers of earth are not near the base of the foundations, but lie deeper. The usual form of deep foundation is pile foundations, nowadays usually made of structural concrete. Piles range in size from so-called “micro piles” less than 30 cm in diameter (Fig. B 4.39) and up to large-diameter bored piles with diameters of 2.50 m. Piles can transfer acting forces through friction and/or pile tip pressure into the ground. Calculations of permitted loads are often checked by means of test loading. Piles of an appropriate size can also be stressed to accommodate bending. A pile cap usually connects individual piles to form the building's foundation.
Depending on the way they are executed, a distinction is made between driven, bored or drilled and injection piles. Driven piles have a pile tip to make them easier to drive in (Fig. B 4.41). The disadvantages of driven piles are the high levels of noise and vibration caused by ramming them into the ground. To avoid this, prefabricated piles can also be drilled or driven in. Bored pile foundations are made by drilling out the required cavity and securing it with a casing pipe. The reinforcing cage can then be installed and the cavity filled with concrete (Figs. B 4.40 and B 4.42, p. 88). Bored piles can be drilled into the ground straight or at an angle. One special form of pile foundation uses injection piles (Fig. B 4.43, p. 88). These have very small diameters and steel cores in the form of threaded rods that act as load-bearing cores. They transfer acting forces into the ground through skin friction and are used mainly to transfer tensile loads into the soil.
As well as classic pile foundations, there are

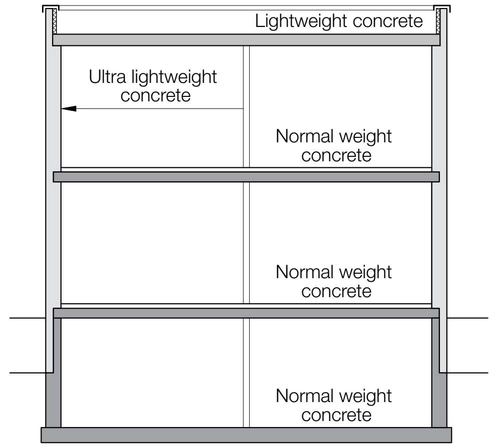


B 4.41

B 4.42

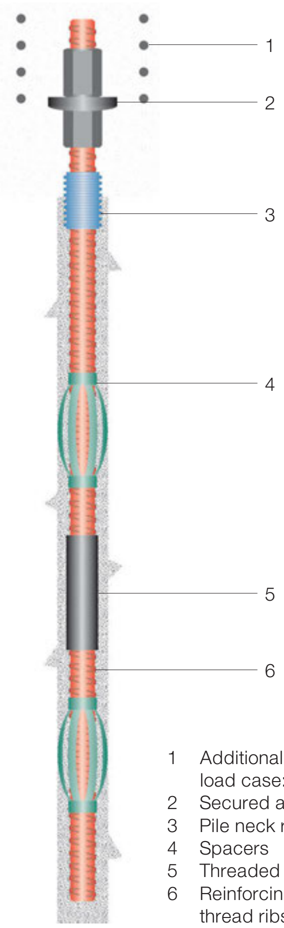


B 4.44



B 4.45

B 4.42 Installing a reinforcing cage for a bored pile
B 4.43 Injection pile
B 4.44 Crack formation in a concrete wall due to the cooling of hydration heat and shrinkage
a Low walls: cracks begin just above the base plate and extend up to the upper edge of the wall.
b High walls: cracks also begin just above the base plate, but often end below the upper edge of the wall. Distances between the cracks are greater here than they are in low walls.
B 4.45 Cross-section of a building with ultra lightweight concrete exterior walls and floor and ceiling slabs made of normal and light-weight concrete
B 4.46 Filled concrete masonry blocks
B 4.47 Drawing of the loaded area of a column
B 4.48 Cross sections of composite columns
B 4.49 Profiled UHPC concrete transverse section



1 Additional reinforcement load case: compression
2 Secured anchor piece
3 Pile neck reinforcement
4 Spacers
5 Threaded sleeve
6 Reinforcing steel bars with thread ribs

B 4.43

special forms of deep foundations such as open caisson foundations (the same as caisson foundations) and slurry wall foundations. Gravity caissons are circular wall elements, usually made of structural concrete or steel. They are set on the ground and the soil inside them is dug out. The elements' own weight overcomes the friction on the containing wall and the piles sink in. Caissons are then usually filled with concrete. Slurry wall foundations, foundations with machine-cut trenches that are filled with concrete, are often used in buildings with several basement floors. As well as functioning as foundations, slurry walls also usually serve to shore up the excavation pit.
A floating foundation consists of a hollow box, the size of which can be calculated from the specification that the original imposed load on the soil must be equal to the loading of the finished building. These foundations are used if the layer of load-bearing soil cannot be economically reached in any other way. Mixed forms of shallow and deep foundations, such as combined pile and raft foundations (see above), are also suitable for high-rise buildings (see also "High rise buildings", p. 96ff.). As well as the foundations described, there are other special forms that may be useful in certain cases depending on soil conditions and the structure's function, but these will not be dealt with in this chapter.

Walls

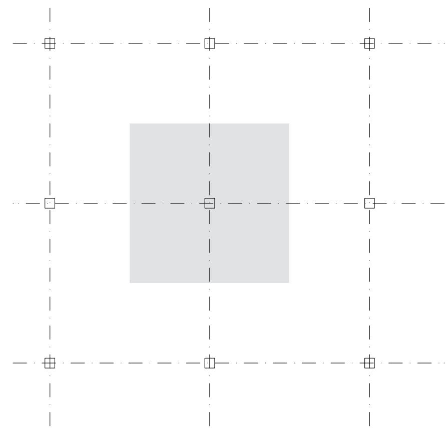
Walls are structural elements, usually made of concrete or masonry, which enclose spaces within buildings. A fundamental distinction is made between load-bearing and non load-bearing walls. Non load-bearing walls are not usually made of concrete and have no structural function. Load-bearing walls do have a structural static function, acting as both plate and slab. The plate load bearing effect is activated by loads acting in the direction parallel to the wall, especially by forces acting vertically. Plate load bearing is indispensable in stabilising buildings against horizontal forces because these forces are often transferred through stiff wall panels into the ground. Mainly normal stresses are imposed along the plane of the walls. The structural stiffness can be assumed to be very high in plane direction compared with the slab load bearing effect. Slab load bearing is activated by acting forces normal to the wall plane. In multi-storey buildings, it locally transfers loads caused by horizontal actions such as wind and earth pressure and causes bending stress in walls. Roof slabs function as horizontal supports, adjoining walls as vertical supports for wall elements and define spans and the load path in the walls. Concrete walls are often cast in situ, especially if high demands are made on their imperviousness and load-bearing ability. Their minimum thickness, specified in DIN EN 1992 on the "Design of concrete structures", is 12 cm. In practice, structural concrete walls, for reasons to do with their manufacture, are almost always thicker since it must be possible to compact the concrete between two layers of reinforcement. Concrete should be poured into the formwork in horizontal layers of a maximum of 50 cm. A maximum drop height of 1 m must also be observed to prevent the concrete from segregating. When pouring very high walls, it must be ensured that the formwork is sufficiently stable as the pressure of fresh concrete increases with the height of the wall.
Reinforcement to limit crack widths is required to control cracking caused by shrinkage and the discharge of heat hydratation in concrete walls sections more than 4 to 6 metres long. Tensile stresses that cause cracks can occur, especially when a new section is concreted onto a structural component that has already hardened, a wall onto a foundation or floor slab, for example. Fresh concrete develops heat during setting, while the concrete in the first section has already cooled and hardened. As it cools, the subsequently concreted section tries to contract, but is prevented from doing so by the bond with the earlier section (Fig. B 4.44).
Exterior concrete walls must be insulated to fulfil current heat insulation requirements. New materials, such as ultra lightweight concrete, make it possible to build single-shell wall structures that fulfil insulation requirements without additional insulation, so it is possible with a single-shell wall structure to achieve decorative

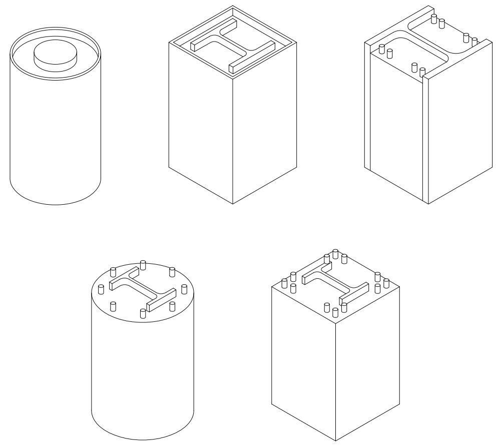
concrete quality both inside and outside in concrete components cast in situ (Fig. B 4.44). Such walls will, however, be thicker than a normal wall without insulation. Transitions between sections of buildings, such as from normal concrete slabs to ultra lightweight concrete walls, require careful planning if this construction method is used.
Concrete walls can also be built using semi-finished components in the form of cavity walls (Fig. B 1.27, p. 35). Cavity walls are double-shell elements made of reinforced concrete slabs with a thickness of about 6 cm connected by slender steel trusses and filled with concrete on site. The semi-finished components and infilled concrete form a frictional bond, so these elements can be treated like monolithic reinforced concrete walls because additional reinforcement is installed near the joints. Cavity walls are generally 18 to 30 cm thick, and core insulation can be integrated into them.
One special form and mixed construction method uses concrete masonry blocks, mainly on small building sites and for structural components exposed to light loads (Fig. B 4.46). With this construction method, wood-fibre reinforced concrete or expanded clay concrete masonry blocks, which can also have integrated insulation, are filled with concrete. There is no need for formwork. Concrete masonry walls are usually 15 to 40 cm thick.
Wall elements can also be precast, although industrialised modular slab construction (Plattenbau) no longer plays a major role in multi-storey construction. The reasons for this are mainly the architectural and design limitations of standardised construction systems as well as inconclusively resolved issues around joining technology and physical properties.

Columns

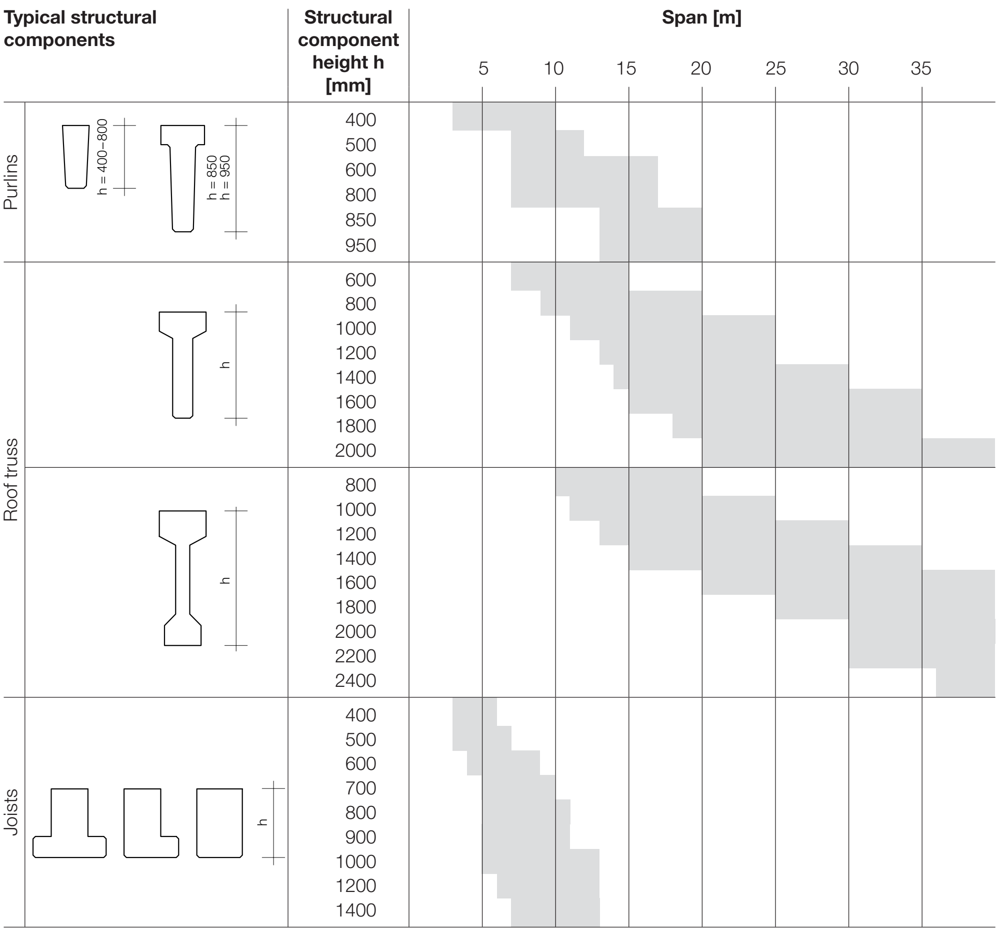
Columns in multi-storey buildings transfer slab loads downwards. It is usually better to transfer horizontal forces through wall panels instead of columns. Columns are structural components subject mainly to compressive loads. The amount of normal force in a column is very easy to calculate roughly by multiplying the loaded area by the number of storeys (Fig. B 4.47). The live loads for several storeys of slabs built one on top of the other can be reduced because maximum live loading is unlikely to be imposed on all the storeys at the same time.
In contrast to walls, linear structural components are defined as columns if the longer side of the base does not exceed the shorter side by a factor of four. Square and round columns are mainly used in reinforced concrete buildings to withstand pure compressive stress and for reasons to do with the structure and formwork technology. DIN EN 1992-1-1/NA "Design of concrete structures, Part 1: General rules and rules for buildings (National Appendix)" specifies that the smallest cross section dimension of a column that is concreted upright on site may not be less than 20 cm. DIN EN 1992-1-2 (Part 2: General rules – Structural fire design) specifies much greater minimum sizes compared with previous regulations depending on the fire resistance class and static-structural utilisation if no analysis of the structure's load bearing behaviour in the event of fire is carried out. The minimum cross section size for horizontally precast concrete columns is 12 cm. Minimum dimensions for elements subject to very high loads can also result from the degree of reinforcement, which must not exceed 9 %.
In design and planning practice, columns cast in situ are usually assumed to be simply supported for simplicity's sake. If required, an end restraint can be formed with connecting reinforcement of appropriate dimensions between columns and adjoining sections of the building. Precast columns and those cast in situ are designed in the same way. Precast columns are usually set in sleeve foundations and concrete is poured over them. They can then absorb normal forces, shear forces and bending moments and be used to brace a building. Transitions between beams and columns made in prefabricated construction are not monolithic. Column-beam connection details, such as forked supports or supports on brackets, are typical of this type of construction. Eccentric connections impose additional bending and torsion loads on a column. Square, precast columns can be concreted vertically or


B 4.46


B 4.47


B 4.48


B 4.49



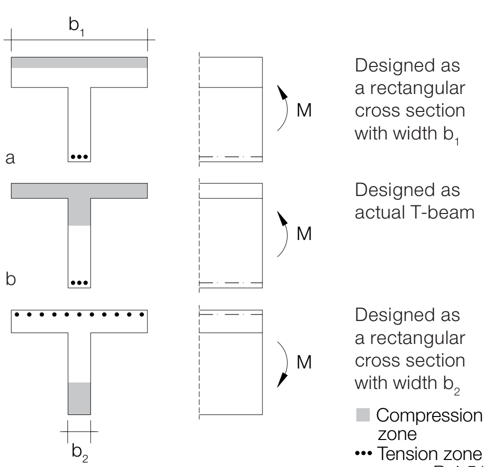
B 4.50

horizontally. Round columns can be made using spun or centrifugally cast concrete in a process that involves pivoting the formwork on castors and rotating it with electric motors. The resulting centrifugal forces press the concrete outwards and a space is created in the middle. Spun concrete columns feature high quality concrete and concrete surfaces.

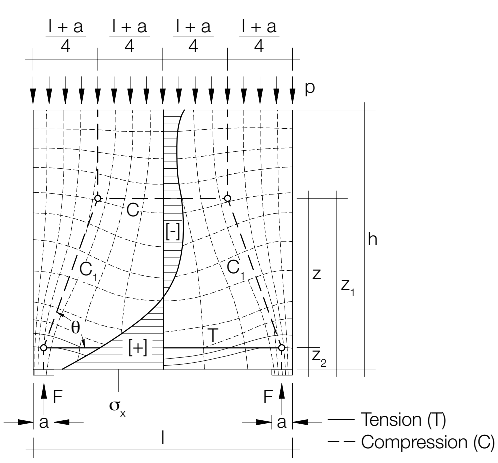
Composite columns are structural components that combine concrete and steel profiles (Fig. B 4.48). They consist of hollow steel profiles filled with concrete. The steel remains visible on the outside. They do not need on-site formwork and can be filled from above or by pumping from below. An internal load-bearing steel core is often added. Solid core profiles, I profiles or bundles of sheet metal are used for these internal profiles. Installing them in graduated sizes makes it possible to keep the exterior diameters of columns constant over the entire height of a high-rise building. Composite columns can also be made of open steel profiles, which are filled with cavity concrete or completely encased in concrete. Composite columns completely filled with concrete require formwork. Cavity concrete columns are produced in plants and used mainly in buildings with extensive services installations because they make it possible to simply weld on brackets for installations. Composite columns can be built as fire-resistant structural components whose behaviour in fire is ascertained in tests. They are high-performance structural components and are an interesting alternative to concrete columns for designers since in many cases they can be made much more slender than conventional concrete columns.

Beams, T-beams and diaphragm beams

Beams, T-beams and diaphragm beams are standard structural components in concrete construction. They are both precast and cast in situ, usually with solid cross sections. Beams with rectangular cross sections are mainly used because their formwork and reinforcement can be easily built. Profiled cross sections with lighter web sections and possibly tensile zones, such as T and I profiles, are mainly used in construction with prefabricated components. Tables are available to help with the preliminary design of standard beam forms (Fig. B 4.50, p. 90). High-performance materials, such as ultra high performance concrete (UHPC), now make it possible to produce high-performance, profiled cross sections with very slender webs and flanges – a very promising construction method for future applications (Fig. B 4.49, p. 89). Hollow box cross sections made from reinforced concrete require more complex formwork, but they can be used to considerably reduce a structure's own weight compared with solid cross sections. They also demonstrate advantageous load-bearing behaviour under torsion loading. Hollow box cross sections are very suitable for large spans as long as they are prestressed, and are used primarily in bridge construction and more rarely in building construction.
It is also possible to make a steel reinforced concrete beam with a cross section that changes along the beam's length – e.g. with sloping undersides and/or upsides. In this form, they can be better adapted to moment loading. In halls with sloping roofs, the sloping of the upside makes it possible to adapt the beam to the form of the roof. Deflection forces arising in buckled areas must be taken into account in planning and design.



B 4.51



B 4.52

B 4.50 Tables showing the load-bearing capacities of pre-cast concrete components with solid cross sections
B 4.51 Load-bearing behaviour of a T-beam
a Compression zone lies completely in the slab
b Parts of the compression zone lie in the web
c T-beam under negative bending stress, the compressive zone is entirely in the web
B 4.52 Load-bearing behaviour of a wall panel, stress distribution in a critical section, stress trajectories and strut-and-tie model
B 4.53 Reinforced concrete slab
a With linear supports on the ceiling slab
b Joist ceiling
c Slab with upstand beam
B 4.54 Thermally separated connection between a floor slab and a balcony slab.
a Three-dimensional representation
b Section

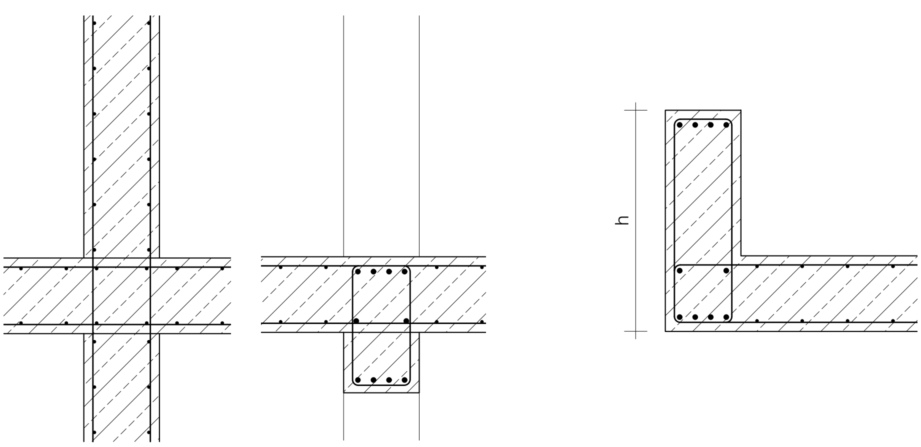
Steel reinforced concrete beams can also be made with changing cross sections, often with recesses for supports in prefabricated beams to reduce a structure's overall height. Openings in steel reinforced concrete beams should be made in areas with low shear force loads. The size of openings and their distance from each other must be chosen so that the concrete compressive zone, the installation of bending tension reinforcement and the transfer of shear forces through compression and tension rods are not impaired. Changes in cross sections and openings are D-regions. The load path and installation of reinforcement in these areas can be planned very well using strut-and-tie models.
Ceiling joists cast in situ in multi-storey concrete buildings are usually joined monolithically with slabs because they are created in one operation, resulting in the T-beams typical of concrete construction. The structurally effective depth of a T-beam is equal to the sum of the thickness of the slab and ceiling joist. Areas of a slab connected to a ceiling joist can be regarded as having a structural effect in the area around the web, forming a very wide concrete compression zone for positive moment loads, if reinforcement is appropriate. In designing T-beams, a distinction must be made between positive moment loads, which mainly produce compressive forces in the adjoining slab, and negative moment loads, which result in tensile forces in that area. The width of the load-bearing slab in the case of a positive moment depends on the static system, the span, the type of loading and the T-beam geometry. T-beams whose neutral axis lies within the adjoining slab can be designed like a rectangular cross section, whose width corresponds with the load-bearing adjoining slab width. If a T-beam has its neutral axis in the web, the resulting compressive force is harder to calculate: these are dimensioned with the help of special design tables. If there is negative moment, they are designed like a rectangular cross section whose width is equal to that of the web (Fig. B 4.51).
For these reasons, T-beams are much more efficient than structures of the same height in which beams and slabs are not frictionally joined. Upstand beams joined to a ceiling slab are equivalent to an inverted T-beam, although if there is positive moment, in this case the compression zone cannot be increased because the flange is in the tensile zone. A second operation is usually required to make the upstand beams. The slab and the upstand beam are concreted in two steps since formwork for the upstand beam is erected on the ceiling slab.
Floor-to-ceiling walls are also often used to transfer loads in multi-storey buildings. They are usually very rigid structural components, but their load-bearing behaviour is very different from that of beams (Fig. B 4.52). Stresses and elongation are no longer linear in high diaphragm beams, so they do not conform to Bernoulli's Principle. Loads are calculated by means of finite element calculations or with the help of strut and tie models.

Slab structures

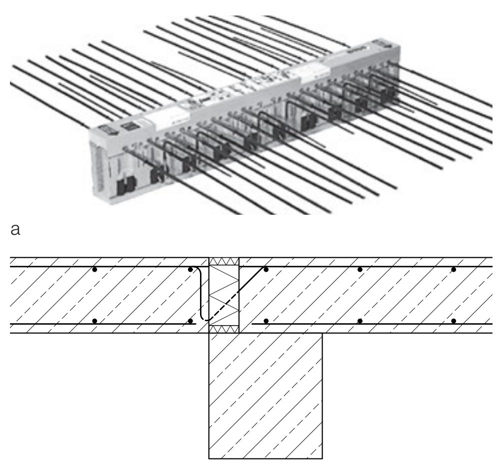
Slabs are an essential element of multi-storey buildings, being both load-bearing and enclosing structural components. They transfer vertical actions from the slab's dead weight and live loads into columns, beams and walls. Additional structural loads, such as plaster and suspended ceilings, etc. on the underside and screed and flooring, etc. on the upper side, must be taken into account in calculating the load imposed by the structure's dead weight, as must the additional weight of partition walls, which covers non load-bearing interior walls. Slabs also often play a part in the horizontal bracing of buildings in concrete construction, even if this loading is not verified by calculation in many cases.
Load-bearing ability and fitness for purpose are essential factors in the construction of slab structures. A verification of serviceability includes in particular the verification of deflection limitation to prevent large cracks forming in slabs or in the walls standing on them as well as to prevent unplanned loads on non load-bearing walls under the slab. Since deformation calculations for concrete construction can be very complex and are always somewhat imprecise, the standards offer, for simplicity's sake, the possibility of limiting the slab's span/depth ratio l_{eff}/d. For an initial estimate of a slab's thickness, span/depth ratios determined in this way are a good approximation.
As well as structural-static issues, there are also fire protection and noise insulation requirements for normal multi-storey buildings. Slabs fulfil noise insulation functions because their mass prevents the transmission of airborne sound. A large mass tends to have a positive effect on sound insulation. This must especially be taken into consideration for slabs with hollow cavities. Footfall sound insulation is usually added to ceiling slabs to dampen noise from footfall.

Thermal and physical issues can be crucial to the dimensioning of slabs with short spans. Fire protection requirements impose minimum thicknesses on concrete slabs, which are specified in the current DIN 4102-4 standard, "Fire behaviour of building materials and elements – Overview and design of classified building materials, elements and components". These focus on the support and mounting of slabs, the concrete cover thickness, floor construction and on the required fire resistance class. Additional regulations on designing fire-resistant concrete, reinforced concrete and prestressed structures are stipulated in DIN EN 1992-1-2 and for steel and concrete composite structures in DIN EN 1994-1-2 "Design of composite steel and concrete structures, Part 1-2: General Rules – Structural fire design".

Ceiling slabs can be cast in situ, made of semi-finished components with an extra layer of concrete cast in situ, or entirely prefabricated; there are also composite ceiling systems. The decision to build a particular ceiling system influences not only the ceiling's construction and installation, but also its structural design and load-bearing capacity. Concrete slabs can be easier to cast in situ over irregular floor plans because it makes adapting the slab to the prescribed form simpler than it would be if precast components were used. Semi-finished slab systems can now be built with great

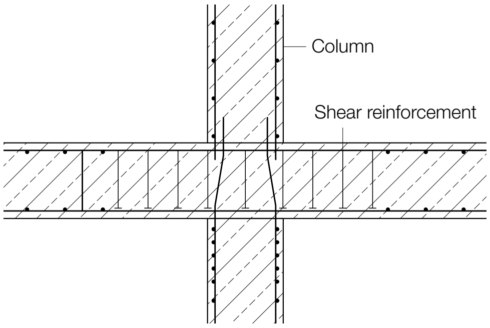


a b c B 4.53

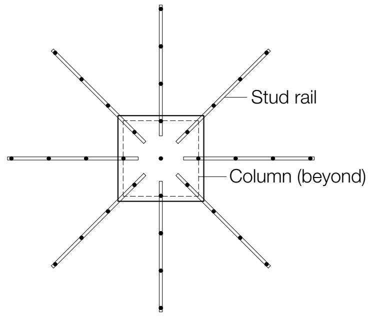


a

b B 4.54



a



b

c

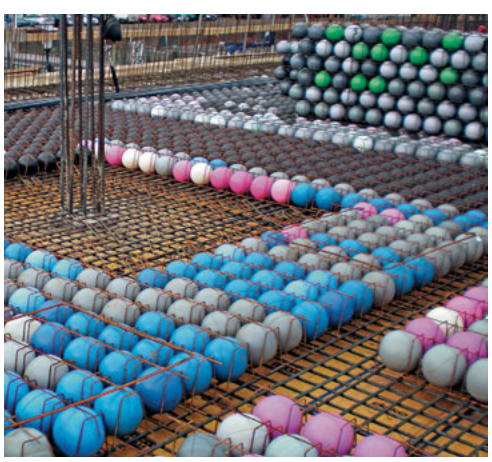
B 4.55

geometric flexibility and adapted to irregular floor plans. Concrete slabs cast in situ and precast slabs, with or without prestressed reinforcement.
Openings and recesses also have to be taken into account in producing slabs. The positioning of slab openings and penetrations for access, services and installations depends on the structure's support system and the direction of span of the slab. Large slab openings should be positioned parallel to the slab's main direction.
Concrete slabs can transfer acting forces uniaxially or biaxially, with a distinction made between linearly-supported and point-supported ceiling slabs. It is also possible to combine linear and point support in a slab. The position of load-bearing walls and columns depends on the utilisation concept, but should be chosen so as to avoid an ineffective and uneconomical ceiling span.

Casting ceilings in situ
Ceiling slabs cast in situ can be linearly mounted on load-bearing structural concrete or masonry walls to be freely-rotatable. Partial restraint can be implemented with load-bearing structural concrete walls. If the floor plan needs to be as open as possible, ceiling slabs can be supported on ceiling joists instead of on walls. In this case, the ceiling joists provide linear support and are bonded with the ceiling in one concreting operation (Fig. B 4.53 b). A partly load-bearing width of concrete slab may be added in the design of these downstand beams. Slabs are suitable for large spans and loads when a flat slab is no longer advisable. They are used mainly in buildings where height is not a vital aspect, and they can be easily installed, such as in halls or multi-storey car parks. Slabs with upstand beams (Fig. B 4.53 c, p. 91) are built on the same principle as those with downstand beams but with beams above the ceiling slab. Structural elements, such as parapets and roof upstands, are often used as ceiling joists.

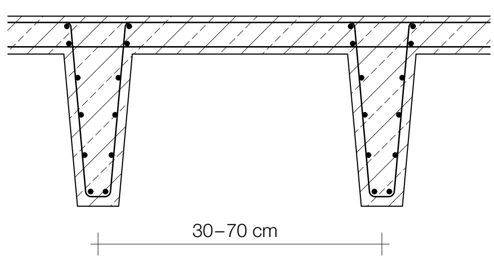
In terms of their static and structural function, balcony slabs are usually regarded as part of the slab structure, but for insulation reasons, they must be thermally separated from interior slabs if the balcony slab is not insulated on its upper and lower sides. They can be connected using standardised products approved for use by building regulatory authorities (Fig. B 4.54, p. 91).

Flat slabs are point-supported slabs without joists, supported solely by columns. This is a preferred construction method for office and administrative buildings because it enables spaces to be used flexibly. Light dividing walls can be added as required and pipes and cables can be run under the slab without having to take ceiling joists into consideration. Loads are normally transferred biaxially. Flat concrete slabs are almost invariably cast in situ. Resistance to punching shear must be verified for areas around columns, which often makes it necessary to provide additional punching shear reinforcement in the form of studrails (Fig. B 4.55). Point-supported flat ceilings are generally thicker than linearly-supported ceiling slabs supported by joists, so they have a higher material consumption. On the other hand, their even formwork and simple reinforcement arrangements mean they can be made very efficiently. A flat slab system is most efficient and economical with spans of 7 to 8 metres and slabs less than 30 cm thick. Larger spans can be built, but these require thicker slabs and are usually no longer economical. It can be advisable to prestress flat slabs to reduce deflection, which makes it possible to either build larger spans with the same thickness or the same spans with more slender proportions. Slabs can also be prestressed to reduce cracking, usually in the form of post-tensioning, with so-called "mono-strands" laid in the formwork in a plastic sheath and tensioned after the concrete has hardened. Concrete ceilings supported by mushroom columns with a special head reinforcement are a special form of point-supported flat slab. Making the column heads larger increases their punching shear resistance, but also increases the time and cost required to create the formwork. Column head reinforcement and transi-



B 4.56

B 4.57



B 4.58

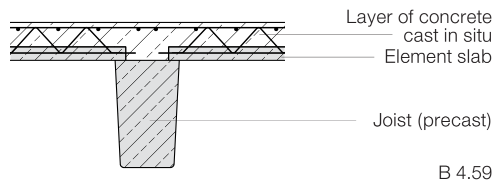
tions between structural components with a geometry that follows load paths will produce optimum structural and design results.
One special form of flat slabs is hollow core slab containing hollow plastic elements between the upper and lower layers of reinforcement. The slabs are usually 20 to 60 cm thick (Fig. B 4.56). These slab systems offer considerable savings on materials and weight compared with solid slabs. The hollow core elements must be left out around the area of columns bearing heavy loads.

Ribbed slabs are a special form of joist slabs built with a thin slab. This is an economical, low-weight support system because it reduces the amount of concrete in the tensile zone to a necessary minimum. The ribs running in the main span direction are more delicate than joists and closer together, usually about 30 to 70 cm apart. Ribbed slabs make it possible to build larger and lighter spans than normal slabs. A continuous system, they are usually built with horizontally tapering reinforcing ribs in the support areas or as a solid cross section throughout. They are usually cast in situ, and their formwork is relatively complicated, but they can also be made in combination with or entirely of prefabricated elements. This construction method is economical for spans of up to 10 metres (Fig. B 4.58).

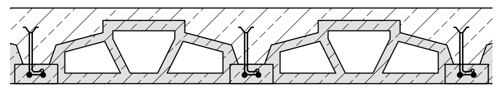
Coffered slabs consist of intersecting ribs friction-bonded with a slab. Like ribbed slabs, they are usually cast in situ using special plastic formwork (Fig. B 4.57). Their biaxial direction of span ensures sound load-bearing behaviour. Among their disadvantages are their comparatively complex production and the fact that the building services installation is complicated to build from a technical and design point of view. Ribs usually intersect orthogonally for reasons to do with their production, although they could also be oriented towards the main stresses. There are also special forms of these slabs that have intersecting concrete ribs forming a load-bearing grid but no ceiling slab. Such a grid of beams can enclose the tops of structures while also letting in natural light from above.

Slab systems built with semi-finished components
Element slabs (lattice girder slabs) are semi-finished components that function as lost formwork to which a layer of concrete cast in situ is added (Fig. B 4.59). These semi-finished components, roughly 5 cm thick, are adapted to the floor plan geometry, which can form the underside of the slab and contain a lower layer of reinforcement and steel lattice girders projecting upwards, ensuring an adequate bond between the semi-finished component and the concrete cast in situ. They also serve as spacers for the upper layer of reinforcement and form the shear reinforcement. Element slab ceilings usually span uniaxially. A limited biaxial load transfer can be achieved with additional reinforcement. In special cases, element slab ceilings can be point-supported, so they can be used to make flat slabs, although they will require special filigree punching shear reinforcement [3]. Element slab ceilings have to be supported during construction in some cases, but are still comparatively easy to install. They combine prefabricated components with concrete cast in situ in an economically expedient way and are used mainly in housing construction.

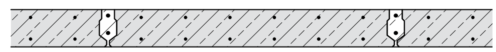
Beam and block slabs as described in DIN EN 15 037 “Precast concrete products – Beam and block floor systems” consist of slender concrete beams, usually laid 62.5 or 75 cm apart, with blocks hung between the beams, which are poured with concrete after laying (Fig. B 4.60). Bricks or precast lightweight concrete blocks are used as blocks. DIN 4160 regulates the use of brick. They are not regarded as a load-bearing part of the structure and serve only as lost formwork. The concrete blocks described in DIN EN 15 037 can be partly or wholly load-bearing parts of the structure or not a load-bearing part of the structure, depending on the formation of the concrete added in situ. A hollow block ceiling’s support system is uniaxially stressed. Beam and block spans are usually less than 5 m. Hollow block slabs can be built without heavy lifting equipment because of their comparatively low weight. They are used mainly when no lifting equipment is available on a building site for logistical



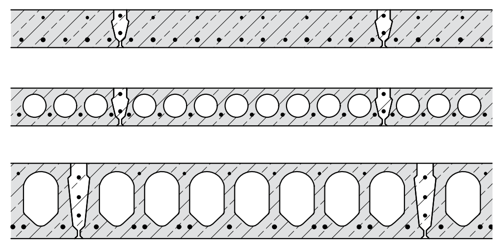
B 4.59



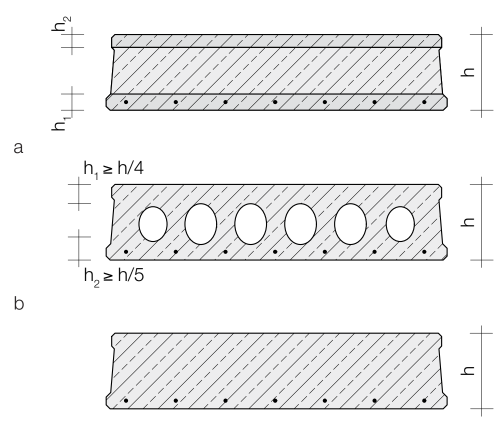
B 4.60



B 4.61

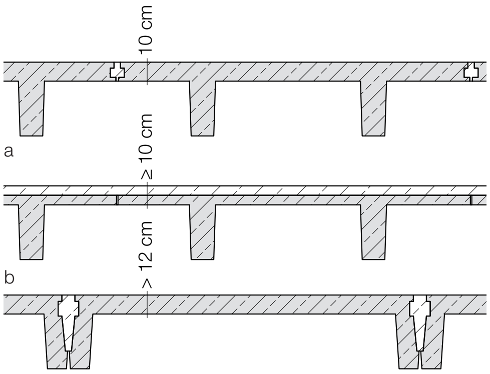


B 4.62



B 4.63

B 4.55 Flat slab with shear reinforcement near the column heads
a Section
b Floor plan
c Studrail
B 4.56 Flat slab with hollow bodies. The hollow bodies are left out around the columns.
B 4.57 Plastic formwork for a coffered slab
B 4.58 Ribbed slab made of concrete cast in situ
B 4.59 Element slab on a precast joist
B 4.60 Beam slab with block spacers
B 4.61 Non prestressed, precast slab consisting of a solid slab with an upper and lower layer of reinforcement
B 4.62 Prestressed, precast concrete slab with poured joints. The prestressing tendons are in the lower layer of the reinforcement.
B 4.63 Lightweight concrete slab elements
a Multi-layer slab
b Hollow slab
c Solid slab

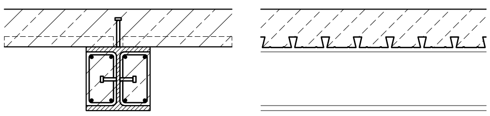


a

b

c

B 4.64

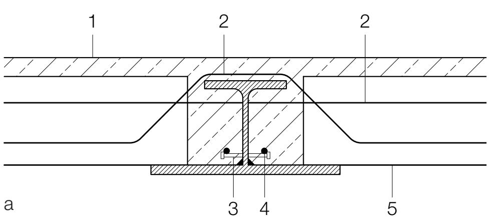


B 4.65

B 4.64 Double Tee slabs
a Double Tee slab with poured joints
b Double Tee slab with concrete topping
c Trough slab with poured joints

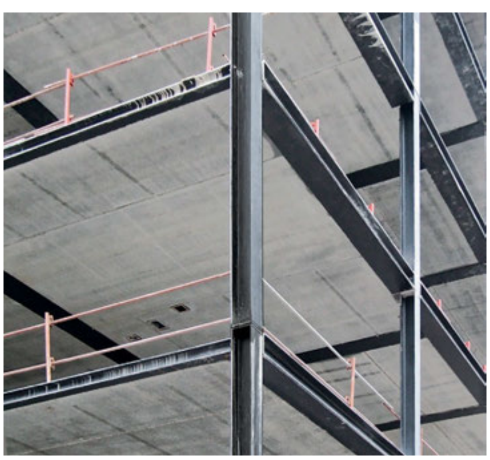
B 4.65 Composite ceiling slab supported by a concreted steel beam (longitudinal and cross section)

B 4.66 Flat slab system made of precast slab elements on steel beams
a Cross section of the bearing
b Underside



a

1 Concrete topping
2 Connecting reinforcement
3 Studs
4 Longitudinal reinforcement
5 Precast slab element



b

B 4.66

or economic reasons. They provide relatively good insulation, but their load-bearing behaviour is less than optimal because there is no plate or T-beam load-bearing effect.

Slab systems built with prefabricated components

Slabs made of prefabricated components, such as solid slabs, are used mainly for short spans of up to 6 metres. They are delivered in panel strips up to 3 metres wide and assembled without formwork (Fig. B 4.61). They are joined with a longitudinal groove and concrete is poured onto them after laying. Low-shrinkage concretes or cement mortars are suitable for this purpose. The panels' edges are usually indented to provide a slab load-bearing effect shear wall action.
Precast, prestressed concrete slabs are uniaxially spanning slabs that can be precast in a plant. They are produced as solid or hollow slabs of various thicknesses with spans up to 18 m (Fig. B 4.62). Prestressed hollow concrete slabs have a continuous cavity in the slab's span direction. They are much lighter than solid slabs, even if the slabs are thicker; they save a considerable amount of material and are an economical ceiling construction system. They can be installed using suitable lifting equipment and do not usually have to be supported during construction.

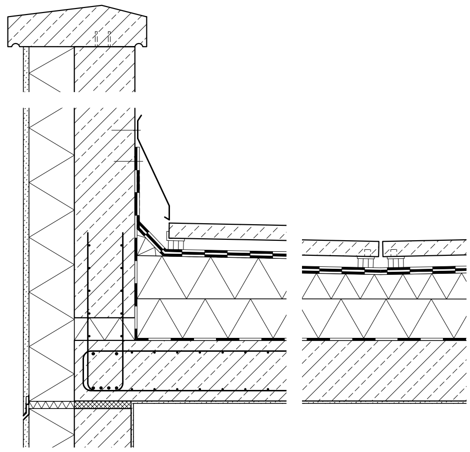
Lightweight concrete slabs are usually produced as precast slabs, and DIN EN 1520 stipulates the relevant regulations on them. Lightweight concrete slab elements have either a solid cross section or are hollow slabs with longitudinal hollow spaces or sandwich slabs. They are made in widths of up to 3 metres and lengths of up to 6 metres (Fig. B 4.63) [4]. Hollow core, steel-reinforced concrete planks are small, hollow, steel-reinforced concrete slabs that can be laid by hand. They are produced with a set width of 33 cm in standardised lengths ranging from 80 cm up to 3 metres. They are not prestressed and have only longitudinal reinforcement. Most of these products are only in fire resistance class F30.
Double Tee slabs, usually with slightly conical webs to make it easier to lift them out of the formwork (Fig. B 4.64), are very widely used. They consist of two webs and laterally projecting slab strips between concrete ribs. A bond is created by adding concrete in situ or by sealing the joints. Slabs with U-shaped cross sections with two external webs, which are laid directly next to each other and bonded with a pour to seal joints, are also used. Single Tee slabs are used in buildings with large spans and live loads, such as multi-storey car parks and industrial structures. For spans up to 20 metres, the elements, which are 1.50 to 3 m wide, can be laid without additional support because the ribs function as beams. These ceiling slabs are 6 to 25 cm thick, and a layer of in-situ concrete is often added to improve the distribution of shear forces and to activate load-bearing in the plane of the slab. Depending on the span and loading, the total height of an element can be up to 90 cm. Tee slabs can be made with and without prestressing.

Composite slab systems

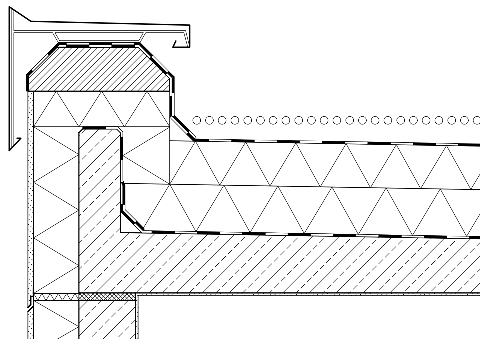
Composite slabs consist of concrete cast in situ on profiled steel formwork. The profiled metal sheets serve as integrated formwork during concreting and are uniaxially spanned between beams or walls (Fig. B 4.65). After the concrete has hardened, they have a reinforcing function due to their shear-resistant bond with the concrete. Suspending brackets for services installations can be attached in their corrugations. Steel beams, the sides of which are filled with concrete to ensure fire protection, support the slabs. The advantage of this system is the steel beams' lower depth compared with a concrete joist and the effective load-bearing behaviour of composite cross sections. If there is positive moment, the concrete slab absorbs planned compressive forces, while the steel lies in the tensile zone. The steel beam has shear stud connectors on the top side of the flange to produce a shear-resistant bond with the ceiling slab, which is cast in situ. The ceiling slab can be made of semi-finished components, to which concrete cast in situ is added or of prefabricated parts. Prefabricated parts are joined with bonded dowel or screw connectors.
One special form of composite slabs are flat slabs in which steel beams are fully or partly integrated into a slab cross section made of precast concrete components (Fig. B 4.66). This system allows for even thinner structural components. The lower flanges of the beams are wider and support the ceiling slab, for which precast, prestressed concrete slabs are suitable. The joints are poured with concrete and concrete cast in situ is poured over the entire slab. When joints are poured to seal them, the steel beam is encased down to the underside of the flange, which may require additional protection depending on the required fire resistance class. The beams can be economically used for spans from 8 to 12 m. At 25 to 40 cm thick, these slabs are comparatively thin. DIN EN 1994-1-1 describes the designing and planning of composite steel and concrete structures.

Roof structures

Roof structures differ from slabs mainly in that they are exterior structural components that drain off precipitation. If the space directly under a roof is used, they must also satisfy heat and noise insulation requirements, and a roof may also slope, depending on its geometry. Roofs are subject to loads different from those acting on ceiling slabs.
A concrete roof is a rational continuation of the structural concept of a multi-storey concrete building. The change to timber construction for roofs, which developed out of masonry building



B 4.67



B 4.68

B 4.67 Flat roof that can be walked on, with a thermally separated attic as a parapet, scale 1:20
B 4.68 Flat roof that cannot be walked on, with concrete cover and parapet, scale 1:20
B 4.69 First detail of a concrete roof built with semi-finished components, scale 1:20
B 4.70 Concrete sandwich slab roof with internal insulation, scale 1:20
B 4.71 Concrete roof made with precast, exposed concrete slabs on the outside, office building, Stuttgart (D) 2011, Blocher + Blocher, Structural engineers: Bornscheuer Drexler Eisele

traditions, seems, on closer examination, only partly logical for concrete construction because it involves an unnecessary change of material and load-bearing behaviour and additional section of shell construction on the building site, complicating technical construction operations. Concrete roofs can be built as flat or pitched roofs and provide very good fire protection and soundproofing compared with wooden roofs. Concrete's mass, which can be used to store heat, also has a beneficial heat insulation effect in summer, preventing rooms under the roof from overheating.

Concrete roofs usually consist of a load-bearing concrete component, moisture barrier, insulation, sealing and a protective coating and are therefore – apart from their support structure – no different from roofs made of other materials. A roof can be either a "warm roof" without ventilation between the sealing and insulation, or a ventilated "cold roof". Providing ventilation between insulation and sealing also enables accumulated moisture to evaporate, but it is not necessary if the moisture barrier functions properly. Thus it is only rarely used in concrete construction due to the extra effort involved.

Flat roofs

Flat roofs are suitable for irregular building floor plans and can be built like ceiling slabs. They usually have an attic, which can take on the static function of a upstand beam in the structure (Fig. B 4.68). Otherwise, the attic structure can also be added with thermal separation by connecting the facade insulation with the roof's insulation through the attic. This can be advisable if there are high upstands (Fig. B 4.67).

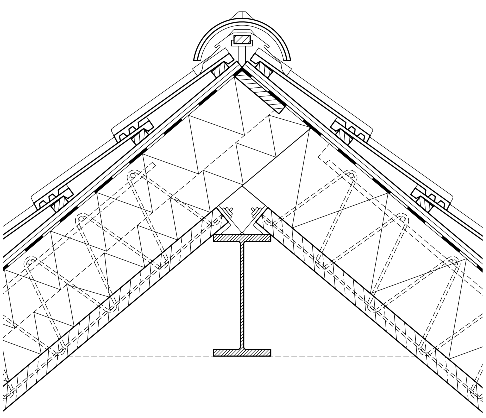
Flat roofs require a slope to drain precipitation, and roofs usually drain inwards. Drainage openings must be taken into account in planning. Gradients are not built in structural concrete for reasons to do with their production, instead an additional layer of concrete, or nowadays usually insulation, is sloped. When calculating the necessary gradient, especially for large spans and flexible support structures, attention must be paid to the deflection of roofs to prevent the accumulation of standing water and ensure drainage over the planned gradient.

Roofs with a very low pitch make higher demands on sealing systems, which usually use synthetic or bitumen sheeting. Another now very widespread option is a fluid coating of polyurethane sealant. The concrete surface must have sufficiently hardened and its surface must be dry before this sealing is applied. "Greening" roofs for ecological reasons, especially intensive greening with relatively thick layers of substrata, considerably increases loads on a roof.

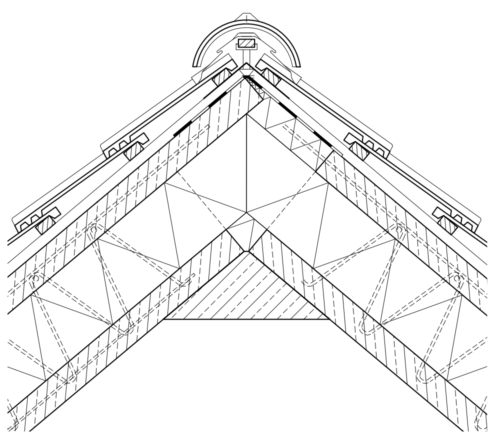
Pitched roofs

Pitched roofs are usually somewhat difficult to build over irregular floor plans because complex floor plan geometry requires lots of valleys and ridges for a sloping roof. For this reason, they are especially suitable for buildings with geometrically simple outlines. Pitched roofs are built in concrete when attics are partly or entirely used as living space and a change in the construction of the building envelope needs to be avoided.

Sloping concrete roofs cast in situ normally require opposing formwork. The concrete's consistency and fluidity must be adapted to the slope. For housing, prefabricated and semi-finished components in the form of planar structural components are used, forming a closed surface on the inside. In the ridge area, the slabs usually rest on walls or steel beams installed in the same direction as the ridge (Fig. B 4.69). Small openings are made in solid slabs by steel angles attached on both sides and the slabs are then fixed to the two adjoining slabs to support the roof slab. For larger openings, steel profiles have to be integrated into the joint, to which profiles spanning in transverse direction can be attached. If a conventional roofing is planned, rafters can be attached on the outside to bear the substructure supporting the roofing. Prefabricated components with rafters attached during production and semi-finished elements with lattice beams are also available, on whose external ends support battens for roof coverings can be mounted. The gaps between the beams are filled with insulation. There are also sandwich structures with interior insulation (Fig. B 4.70).



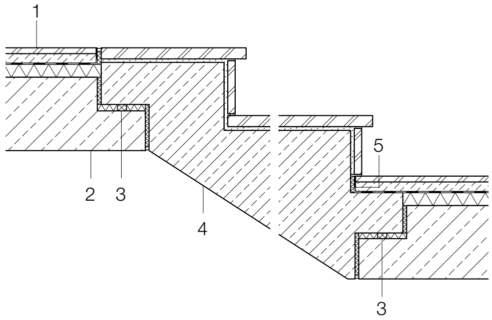
B 4.69



B 4.70

B 4.71

a



1 Flooring, floating screed, separating layer of footfall sound insulation
2 Precast landing
3 Elastomeric bearing
4 Precast stairs
5 Edge insulation strip

b B 4.72

B 4.72 Precast stairs
a Delivery to the building site
b Joint between a landing and precast stairs, scale 1:20

B 4.73 Measures for de-coupling concrete stairs for sound insulation purposes
a Staircase showing the position of noise insulating elements
b Connection between the concrete landing cast in situ and the wall showing the support element, scale 1:20
c Sound-insulated support element with starter bars for connecting the concrete landing cast in situ

B 4.74 Support structure designs for high-rise buildings
a Storey frames
b Using the building's core to brace it
c Outrigger system

Access

Stairs can be cast in concrete in situ in any geometrical shape. In contrast to precast elements, they are not subject to size limitations, although building steps, even in simple, straight flights of stairs, is relatively complicated. Casting curving concrete stairs in situ, which are geometrically very complex, especially on the underside, is work for a highly skilled tradesperson. The protracted on-site formwork and reinforcement processes and the fact that concrete stairs cannot be used until the concrete hardens can impose logistical limitations on construction site operations. Concrete stairs cast in situ cannot achieve exposed concrete-type surface qualities because the steps are only smoothed after pouring.

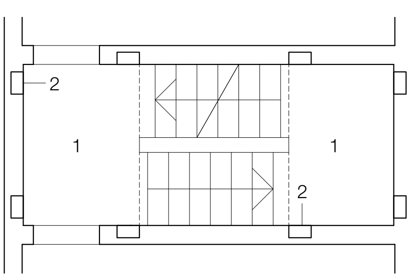
Prefabricated stairs, also called stair elements, are now mainly used (Fig. B 4.72). DIN EN 14 843 sets out the standards and regulations for prefabricated stairs. A straight staircase with a flat underside is the most common form. Another option is to build folded stairs, whose steps are formed on the underside. Solid stairs with a central stringer that acts as a beam supporting cantilevering steps from below, are relatively rare. Straight staircases can be up to 2.50 metres wide while curved stairways are often less than a metre wide. DIN EN 14 843 stipulates that the concrete used must be at least of concrete strength class C 30/37. Stairs are planned to fit in with individual requirements and geometric boundary conditions. A staircase is usually cast on its side as a complete structural component so that the underside and upper side are smooth and of exposed concrete quality. Protective edge profiles made of plastic, aluminium or stainless steel can be integrated into the stairs as desired. Structural tolerances and the installation process also play a role in planning structures with prefabricated components. Threaded fittings are concreted in, into which eyelets or cable hangers can be screwed for lifting and installation. Precast stairs can be used as soon as they are installed.

Staircases are usually supported by landings. Staircases and landings must be separated from staircase walls for technical reasons to do with sound insulation. Joints may not be larger than 60 mm and they can be filled with special insulating panels.
Concrete landings can be cast in situ or built using semi-finished or prefabricated components. If precast stairs are combined with landings built with semi-finished components, the precast stairs are built with starter bars so that when concrete is poured over them, a frictional bond is created between the two structural components. If there are increased sound insulation requirements, special connecting elements can be integrated into the precast component, which provide optimum insulation against footfall noise and are connected with landings by means of starter bars (Fig. B 4.73 e).
For stairs built with prefabricated components, small brackets with a minimum support thickness of 10 cm are usually attached to the bottom and top steps. The load-bearing surfaces of the stairs and the entire landing are insulated against footfall noise. The height of the brackets is designed so that upon completion, the steps are flush with the landings. It is also possible to produce staircases and their landings in one piece. The lowest step is attached to the floor slab by pins set in the floor slab, which are inserted through cylindrical slots in the step, over which concrete is then poured.

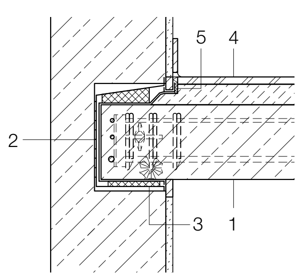
High rise buildings

German building law defines a building as a high-rise when the floor of its highest room is more than 22 metres above ground level. The structural system, access and technical building equipment influence the floor plans of high-rise buildings far more than they do other multi-storey buildings. Access and the support structure usually take up a comparatively high proportion of floor space in high-rise buildings. In functional terms, the floor plan is particularly influenced by the demand for natural lighting. High-rise buildings often have compact floor plans with a central core or longitudinal floor plans with a central access core and floor space arranged on each side of it. Apart from the ground floor, the storeys in high-rise office buildings are usually about 3.30–3.80 metres high. As well as the required ceiling height, a building's technical equipment and ceiling structure can have a major influence on storey height.

Materials and construction technology also play a major role in high-rise buildings, with concrete now widely used. High-strength con-

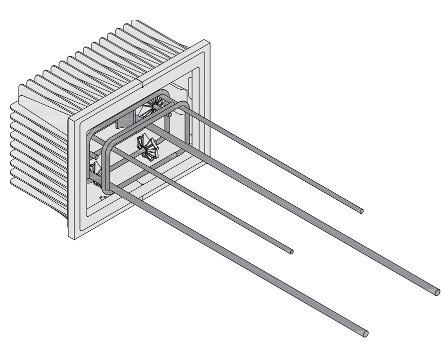


a

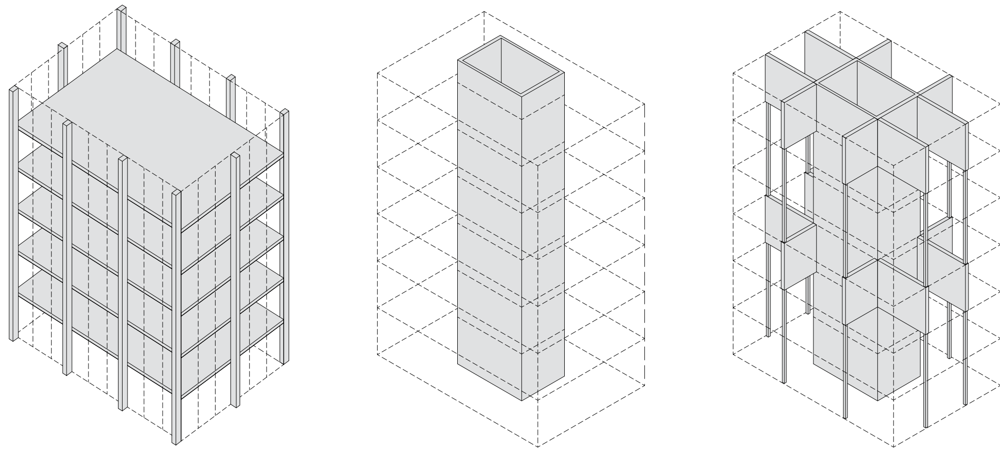


1 Landing cast in situ
2 Sound-insulated bearing element with connection reinforcement
3 Elastomeric bearing
4 Flooring on a floating screed
5 Edge insulation strip

b



c B 4.73



a b c B 4.74

cretes make it possible to build heavily loaded columns with appropriate dimensions that are also acceptable in terms of the economy of the building's floor plan. Slender composite structures with high load-bearing capacity that meet fire protection requirements are now becoming widespread. According to the guidelines on high-rise buildings, load-bearing and bracing structural components must comply with fire resistance class F 90, or for buildings over 60 metres high, with F 120. Essential preconditions for the use of concrete in very high buildings are effective formwork and conveying techniques that will make it possible to concrete at great heights. High-rise building cores are often built using sliding or climbing formwork (see "Climbing formwork", p. 47f.).

Planning an effective support structure is extremely important in high-rise buildings, not only in the structural and static sense, but also for economical reasons. With certain restrictions, high-rise buildings can be regarded in structural terms as vertical cantilevers. As well as vertical acting forces from the structure's own weight and live loads, horizontal loads imposed by wind and earthquakes and from downforces due to geometric imperfections are all relevant to the building's design. Wind tunnel tests are usually used to estimate wind loads. A building's form, wind loads and the structure's reaction in a transverse direction, which is often vital in very high buildings, can also exercise a considerable influence. Buildings with rounded floor plans for example, show better flow characteristics when exposed to wind loads than rectangular buildings and are exposed to lower wind loads. Moment loads due to horizontal loads increase in a cantilever's static system towards its base. A building's height exercises a disproportional influence because wind speeds increase with the height of the building. The costs of columns, walls and horizontal bracing also increase in proportion with the height of the building. Verification of stability and serviceability are of utmost importance in high-rise building construction. Other essential design criteria usually include the restriction of horizontal deformations and limitation of acceleration (sway behaviour and comfort criteria). Maximum lateral deflection should not exceed 1/500 to 1/1000, although these requirements vary from country to country. One vital criterion for an efficient load-bearing structure in terms of horizontal load transfer is slenderness, the proportion of height to the smallest dimension of the floor plan. Normative requirements result in a maximum building slenderness of about 8–9:1.

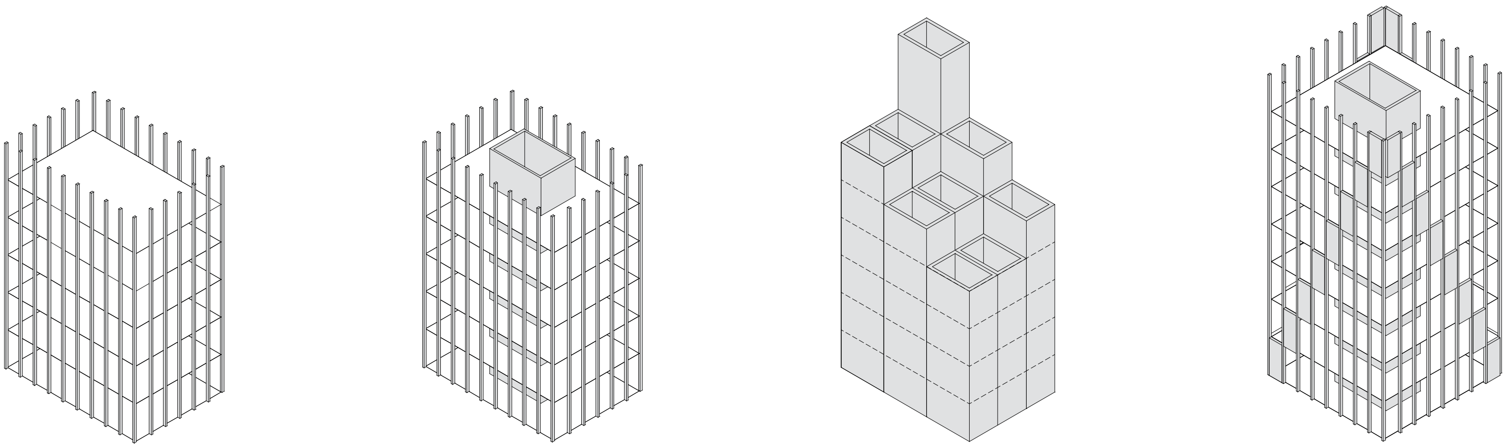
Vertical loads are usually transferred through wall panels in core areas and columns in the facade areas, allowing for a transparent facade construction. Normal force loads increase from top to bottom in almost linear fashion. The contraction of structural components due to shrinkage and creep must be calculated in, both mathematically and structurally, while taking given deformation into account. Support structures for an indirect vertical load transfer in lower storeys require a great deal of time and effort in construction due to the high loads on the supports and should be avoided if possible. Regarding the slenderness of walls, it must be taken into account that ground floors usually have extremely high ceilings for functional reasons.
High-rise buildings of medium height (up to 20 storeys) can be braced with storey frames consisting of concrete columns and supporting beams (Fig. B 4.74 a). Interior columns can also be used for this purpose. A large part of horizontal deformations in load-bearing multi-storey frames result from the bending deformation of columns and beams. The effectiveness of this principle can be improved with crossed bracing if necessary (braced frames).

Core systems have a central core set in the basement or foundations that usually contains access and services areas and exists anyway for purely functional reasons (Fig. B 4.74 b). The core is usually centrally positioned to keep torsion loading to a minimum. Positioning the core off-centre allows for more flexible utilisation because large contiguous spaces can be created, but it is structurally more difficult due to the resulting torsion loads. A large load-bearing area can be advantageous to provide the highest possible compressive forces on the core which counteract any flexural tension, although the comparatively low stiffness in bearing horizontal loads due to the short inner moment arm can be a disadvantage. Depending on the core's diameter, core systems of up to 40 storeys can be built economically.

Core-brace structures combine a core with additional colums through hinge-connected ceiling slabs (up to approx. 40 storeys). Cores can also be combined with frames (up to approx. 50 storeys) or "outriggers" (up to approx. 65 storeys). In a core-outrigger support structure, horizontal props (outriggers) connect the core to mega-columns at the edges at certain storeys (Fig. B 4.74 c). "Outriggers" can be built in the form of upright slabs or trusses. Core-outrigger systems use the maximum moment arm while allowing for relatively flexible facade design.

"Tubes" are load-bearing structures designed as hollow structural sections in the plane of the facade to make maximum use of the moment arm in the structure. "Framed tubes" are hollow structural sections that incorporate reinforced concrete storey slabs as bracing elements. They usually consist of columns and beams joined to form a frame. The particular advantage of this construction method is that interior spaces remain free of bracing elements. "Diagonal truss tubes" are horizontally braced trussed tubes used mainly in steel construction. "Tube-in-tube" systems are support systems built with external hollow sections and a central inner hollow section, e.g. a unicellular "framed tube" and a central access tube that are connected through the slab support system. Planners should note that load-bearing and bracing structural components extend over the facade's entire height, so there can be no projections or recesses in the structure. "Bundled tube" structures are made of "bundled" multi-cellular hollow sections divided by vertical diaphragms, which are usually frame-like structures. (Fig. B 4.75)

Mega-structures are frame or truss systems whose individual parts no longer extend over individual storeys, but extend over



a b c d B 4.75

10–15 storeys. Composite construction methods are often used to build their heavily loaded individual elements. Mega-structures built as truss structures are especially efficient (Fig. B 4.76). Special forms in the support structure typology of high-rise building are structural systems that bundle vertical loads in the lower storeys in a reduced number of vertical supports or buildings with suspension systems. These systems, however, are only used in buildings of lower heights.

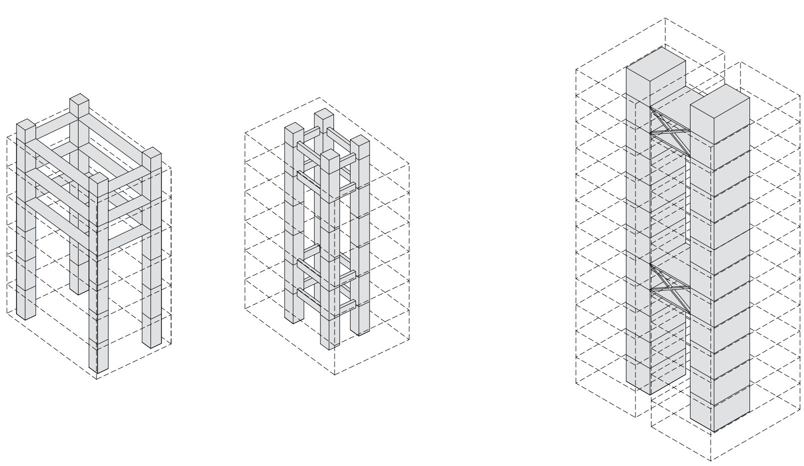
The large vertical loads that must be transferred into the ground and in particular large horizontal actions, which can cause eccentric loading in the foundations, often make it necessary to build foundations with an area larger than the area of the floor plan. The condition of the building site soil and the minimisation of subsidence are vital criteria for the design of the foundations of these structures. If there are several basement storeys, it is advisable to build their wall and floor slabs as a stiff basement coffers, which can be used to hold a building's bracing core. As well as the shallow and deep foundations described above (see "Foundations", p. 85ff.), combined pile and raft foundations are also used in high-rise buildings, in a method using a very thick foundation slab and piles to jointly transfer the structure's loads into the ground.

Halls and other roofed structures

Halls are single-storey buildings with large interiors, often free of support columns and regular floor plans. Halls are often used in industry, as well as for sports, trade fairs, shopping and events. Halls for industrial uses are usually planned and built subject to very tight schedules and budgets.

Concrete framework construction

Concrete framework construction is relatively efficient and very suitable for industrial uses. Concrete framework structures are almost always built with prefabricated components (Fig. B 4.77). Its advantages include a high flexibility of use, the ease with which usage can be changed and the fact that it is an economical construction method. The building's use and structural grid must be adapted to each other. Structural components, such as columns, beams, wall and slab elements, are standardised and can be adapted to design and structural requirements and to loads.
For technical reasons to do with their manufacture, columns are usually built with square cross sections. Multi-storey columns are used in halls with several levels, with brackets supporting the beams, which are usually linked through a hinged connection. The central distance of the columns is the same as that of the roof beams and the same size as the facade elements. If the distance between the centres exceeds the maximum size of the facade elements, an additional facade sub-structure will be necessary. As well as the usual acting forces, crane loads imposed on columns or beams can play a vital role in designing the structural components of halls. If forklifts are driven inside the hall, impact loads must also be taken into account in designing and planning supports.



B 4.76

Roof beams are produced as parallel beams or double pitched beams with haunched upper edges to ensure drainage, usually with T or I-shaped cross sections. They are not usually prestressed for spans less than 24 metres, although prestressing them will enable them to cover spans of up to 40 metres. The junction points between column heads and beams are usually forked, with the beam, notched on the outside, laid in a forked support (Fig. B 4.79). Concrete is then poured over the joints. This kind of forked mounting stabilises tall and slender structural elements during installation, preventing them from tipping over.

The distance between the beams is determined by the roof panels' load-bearing capacity. Spans up to 8 metres can be spanned with trapezoidal metal sheeting. If the trapezoidal metal sheets span directly from beam to beam and do not run in the same direction as drainage, it is usually necessary to add a layer of sealant (usually insulation plus sealing) over the trapezoidal metal sheets to ensure that the roof is adequately drained. For larger distances between the centres, steel reinforced concrete purlins are longitudinally spanned over the beams to reduce the span required for the roof cladding. The purlins usually have a trapezoidal cross section with chamfers and are notched in the area of the supports (Fig. B 4.78). Spans of up to 15 metres are common, although with prestressing it is possible to increase the distance between beams to about 20 metres. Precast concrete elements are sometimes used in roofing. They offer a high level of noise insulation, can store heat in summer and meet

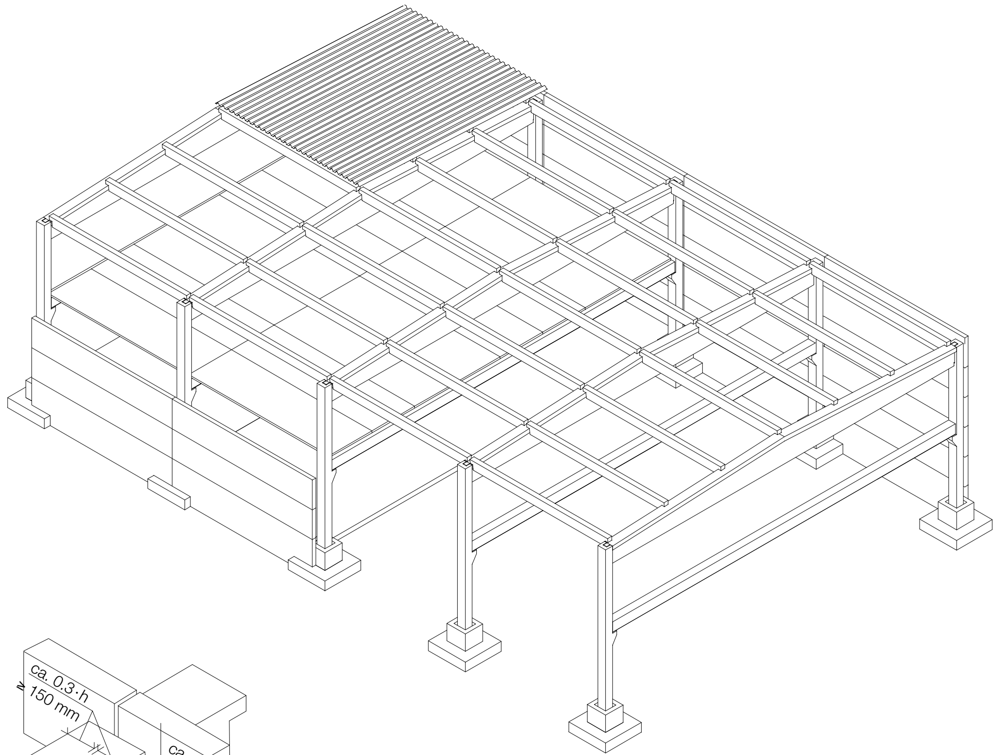
B 4.75 Tube systems
a Framed tube
b Tube in tube
c Bundled tubes
d Braced tubes
B 4.76 Mega structures
B 4.77 Hall structure made of prefabricated components
B 4.78 Purlin supports on roof beams
B 4.79 Supports for precast beams at roof level, column heads with unilateral and bilateral connections with roof beams
a T-beam
b I-beam

high fire protection requirements. Aerated concrete slabs are used for short spans, for example, and not prestressed steel reinforced slabs. Hollow, prestressed concrete slabs or Double Tee slabs are used for larger spans (Fig. B 4.81, p. 100).

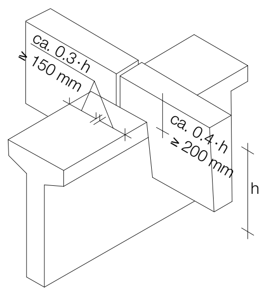
The wall elements of halls can be built of lightweight trapezoidal metal sheet structures with insulation, sandwich elements or concrete panels. Aerated concrete slabs can be made in lengths of up to 6 metres and installed upright or lying. Depending on the insulation requirements, precast normal concrete components may require additional insulation. This is installed in multi-layered wall panels between a load-bearing inner shell and an external concrete facing shell. Facing anchors connect the external shell with the inner concrete layer. Special edges for butt joints and corners make it possible to seamlessly join elements (Fig. B 4.82, p. 100). The maximum dimensions, at about 3.60 metres, are, however, much smaller than those of solid slabs. If wall elements are used as panels to transfer horizontal forces, there must be a shear-resistant bond between them and the columns. Special gable panels are used for gable walls.

Underground frost footings in the plane of the wall elements prevent water from seeping under the base plate. They are single span girders spanning the space between the pad foundations and should be embedded at least 80 cm into frost-free ground. They are usually cut back supporting areas so as to reach this depth. Insulation can be added to the exterior or integrated into the cross section.

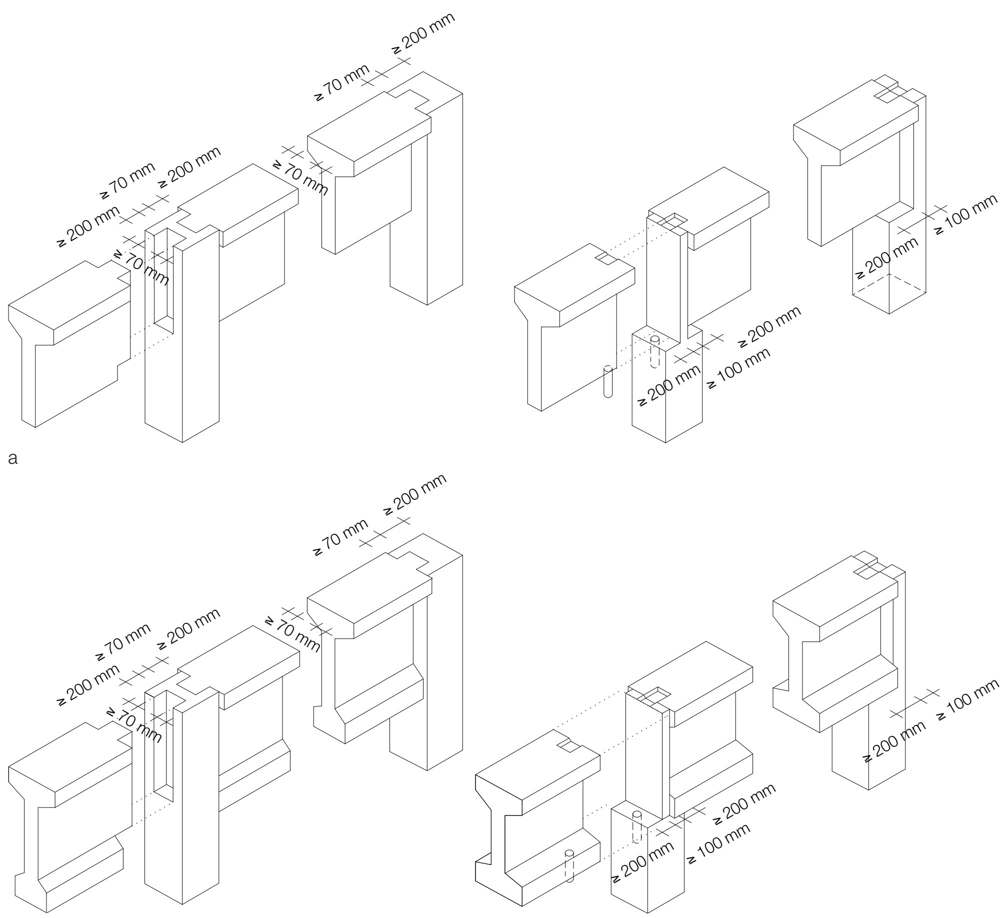
The bracing systems usually used in framework structures are suitable for horizontal load transfer. Halls up to 10 metres high can be braced by constructing the columns as vertical cantilevers. Another option is to achieve in-plane action by designing parts of the building envelope as panels or shear areas. Halls can also be stiffened with braces, but this is rare in concrete framework construction due to the additional time and effort involved in connecting diagonals.



B 4.77



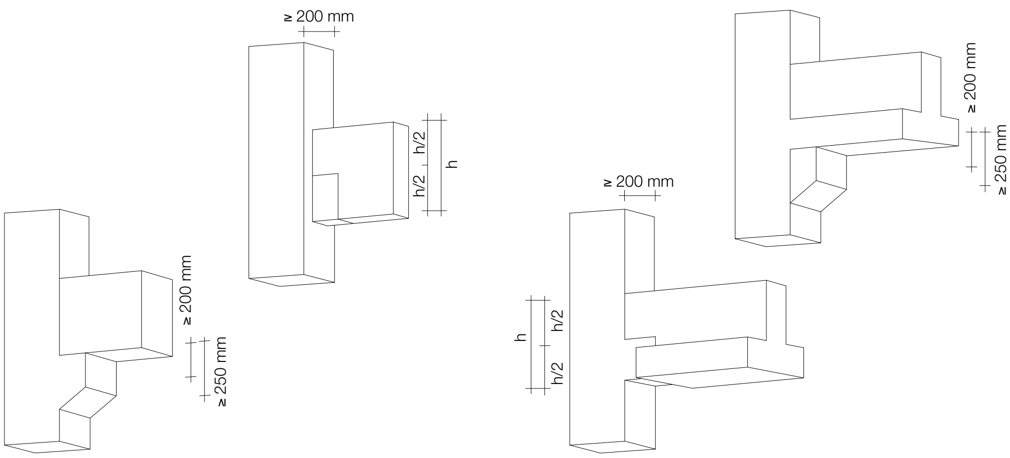
B 4.78



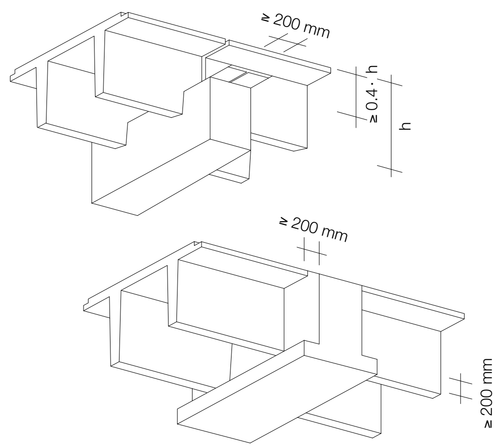
a

b

B 4.79



B 4.80



B 4.81

Concrete halls, like steel halls, can also be built as frame-like structures braced in one or in both directions by the frame effect. The columns in framework structures with base points linked through a hinged connection do not need to be designed as vertical cantilevers, so the column base points and foundations are easier to build. The maximum bending loads occur in the framework's corners. Forming a rigid connection between columns and beams is, however, relatively complex in concrete framework construction, so frame construction is not a standard concrete framework construction method (Fig. B 4.83).

Framework structures subject mainly to compression, such as arches, are very suitable for concrete construction from a static and structural point of view. If they are properly statically designed, arched support structures will follow a catenary curve or parabolic function. For construction with prefabricated components, a three hinged arch is an effective structural system that can be divided into two segments linked through a hinged connection in the middle of the arch and transported to the building site. These forms are not really suitable for standardised product ranges because the curvature of the structural components is not constant. Single concrete arches cast in situ are made in segments on a re-usable falsework that can be lowered and adjusted. Tensile suspended roofs are a special form of hall construction and are usually prestressed to limit crack formation.

Plane load-bearing structures

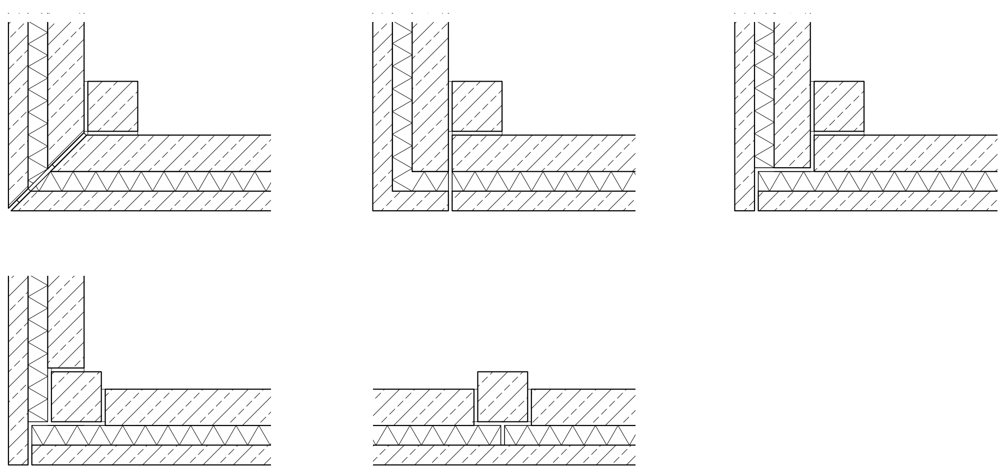
As well as standardised concrete framework structures, plane load-bearing structures are also used for halls designed for high-quality uses and are particularly suitable for roof structures that do not need to enclose space. They make it possible to build effective load-bearing systems with a wide range of forms.

Folded plate structures

Folded plate structures are plane load-bearing structures made up of discrete flat surfaces. Individual components may have only limited stiffness, but if they are integrated appropriately into a three-dimensional design, they can be highly effective load-bearing structures. Their structural form, the height of folds and the geometry of individual surfaces determine the load-bearing behaviour of folded plate structures. The individual surfaces of concrete folded plate structures cast in situ can be larger than those in plastic or steel folded plate structures because the individual surfaces are not industrially prefabricated as semi-finished parts and the problem of the buckling of individual concrete surfaces is not relevant as it is in very thin-walled individual surfaces. The prerequisite for the load-bearing capacity of folded plate structures is the transferral of loads between the edges of the individual surfaces.

Concrete folded plate structures can be both support structure and building envelope in one, so they are categorised, like concrete shells, as self-supporting building envelopes. Concrete folded plate structures take advantage of the fact that the height of the folds has a major influence on load-bearing behaviour. They are usually easier to build than concrete shells because the effort involved in reinforcing individual planar surfaces is less than that required to reinforce the double-curved surfaces of a shell. In structural terms, concrete folded plate structures are like sloping roofs. They usually require exterior insulation and sealing. In designing their geometry, it must be ensured that all the individual surfaces are properly drained. Storm water is usually drained through appropriately shaped valleys in the folded structure.

One way of categorising folded plate structures is by their form, which normally follows geometrical principles described as fold structures, such as longitudinal folding, reverse or pyramidal folding (Fig. B 4.84). Examples of reverse folds are diamond-shaped folds and fishbone folds (Fig. B 4.85). Diamond-shaped folds are made up of triangular surfaces and always produce curved forms. Fishbone folds are made up of squares and can be used to build planar and curved forms. Pyramidal folded structures, which consist of several individual surfaces meeting at a single apex, are a special geometrical case. Folded plate structures with regular, symmetrical cross sections are often analogous, from the support structure point of view,

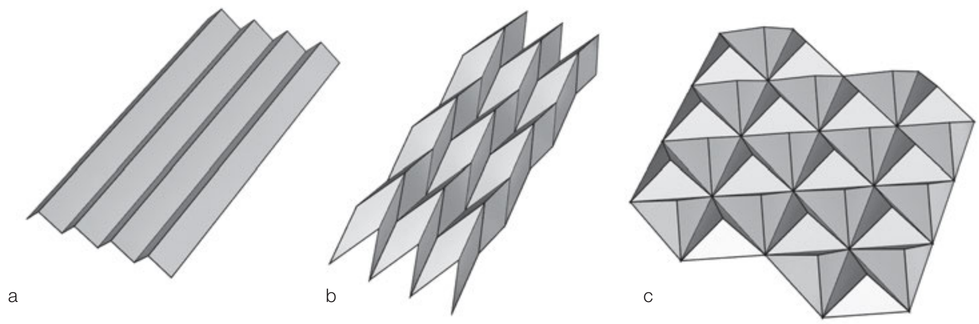


B 4.82

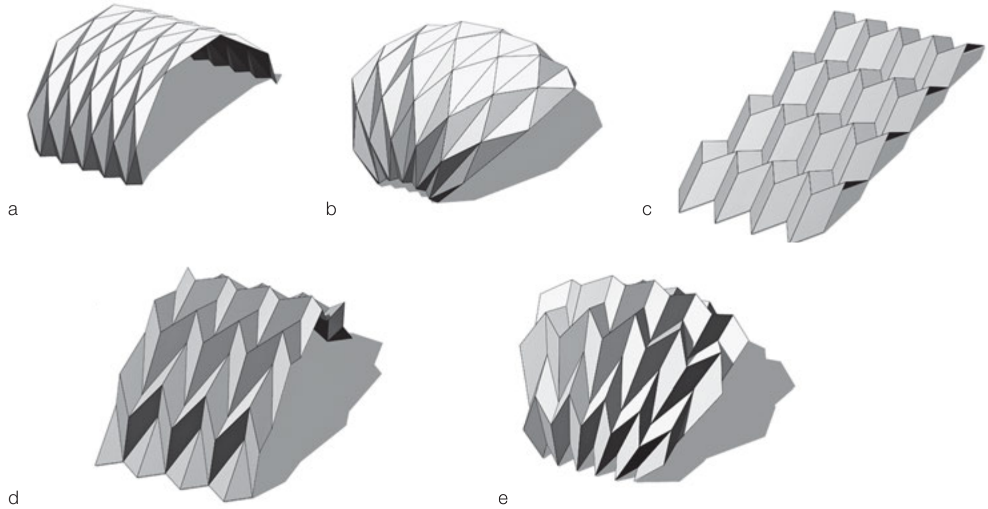
B 4.83

with familiar support systems such as beams, frames or arches. Folded plate structures can have a great diversity of forms, but it must be noted that not every folded surface has the favourable load-bearing behaviour of a folded plate structure.

Folded plate structures are mainly subject to normal forces but partly also to bending forces because the external actions normally acting on the surface are initially transferred through plate deflection in the individual surfaces to the support jointly formed by the elements' edges. The supporting forces can be transferred to the adjoining surfaces through the edges, producing normal stress in the planes of the individual surfaces. The prerequisite for load-bearing folding plate structures is a shear-resistant bond between the edges. From a structural planning point of view, the free edges of folded plate structures require particular attention because they are insufficiently restrained and can undergo major deformations. Appropriate measures may have to be taken to stabilise them. Designing folded plate structures can be very complicated because of their complex spatial geometry and the interaction of normal forces and bending loads. Numerical calculation methods and digital design tools have now increased the scope for planning complex folded structural geometries, but they have so far not yet been taken full advantage of in construction practice.



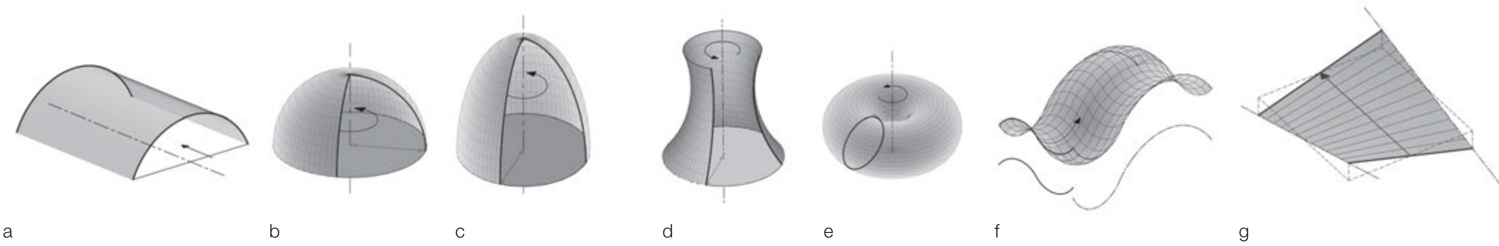
B 4.84



B 4.85


B 4.86

B 4.80 Supports for joists
B 4.81 Supports of Double Tee slabs on ceiling joists
B 4.82 Corners and column connections of multi-shell wall elements
B 4.83 Part of a hall built with precast components – with corbels and forked support
B 4.84 Folded structures
a Longitudinal folding
b Reverse folding
c Pyramidal folding
B 4.85 Examples of folds
a, b Diamond-shaped folding
c–e Fishbone folding
B 4.86 Folded-plate concrete building made of post-tensioned, precast components, sports hall, Mülimatt (CH) 2010, Studio Vacchini Architetti, Structural engineers: Fürst Laffranchi Bauingenieure GmbH (see also "Mülimatt sports education and training centre", p. 230ff.)



B 4.87

In contrast to folded plate structures made of other materials, concrete folded plate structures can be monolithic. Folded plate structures with regular fold geometry and clearly defined span directions, such as parallel folds or fishbone folds curved unidirectionally, would be suitable for concrete construction because they can be concreted in sections. Scaffolding and formwork can be lowered and moved sideways after each section hardens. Folded plate structures with irregular geometry, in contrast, must usually be built entirely on falsework. Top formwork is required for individual elements at angles of more than 30°. The edges must be reinforced so that loads can be transferred through the edges of individual elements.

Folded plate structures can also be made using prefabricated components (Fig. B 4.86, p. 101). Transport dimensions must be taken into account in designing a folded structure's geometry. Modular folded plate structures with repeating individual elements and formwork that could be reused several times would be suitable for construction with prefabricated components. Joining technology also plays a decisive role in folded plate structures made with prefabricated components, and the load bearing capacity of joints must be ensured. If the individual elements of a folded plate structure are very large, they can be prestressed. In this case, the minimum dimensions for tendon anchors must be taken into account in designing edge areas. Concrete folded plate structures make it possible to build complex spaces, expressive forms and self-supporting building envelopes with a comparatively low use of materials.

Shells

In the mechanical sense, shells are planar structural components with surfaces curving around one or two axes. Biaxial curvature can be synclastic or anticlastic. The curves result in mainly normal stresses that produce a very stiff spatial load bearing effect. Shells are highly efficient structures. They make it possible to arch over large spans without columns using minimal amounts of material. If a shell is slightly curved, the loads imposed on it will be large and the shell will not be very resistant to buckling. In designing shells subject mainly to normal forces, the issue of buckling can be a vital one, so the shell's possible imperfections, including imprecisions in manufacture, play a major role in mathematical calculations of the shell's potential buckling. As well as the shell's geometry, a shell's support is essential to its load-bearing behaviour. Edge disturbances can be avoided with continuous support in the direction of the shell that is appropriate for the shell. In practice, shells are almost always exposed to bending loads due to edge disturbances because it is often not possible to support shells appropriately for functional and spatial reasons. Attempts are often made to counteract edge disturbances with edge beams or by prestressing, but the disadvantage of such solutions is that edge members detract from a shell's slender appearance.

Concrete shells are usually designed to absorb mainly compressive normal forces. Concrete shell forms can be produced by translating or rotating conic section curves (Fig. B 4.87). Hyperbolic paraboloids (HP) are also often used to design concrete shells because they consist of straight-line generatrixes. This is of special interest in building with concrete because, with HP shells, straight formwork boards can be laid in the direction of one of the generatrixes and the straight support timbers of the scaffolding in the direction of the other generatrix. Several "hypar" shells can be assembled to make a larger form and joined along the generatrices or along curved cuts. The internal forces and moments of geometrically produced shells develop as a result of loads depending on the shell's form. Concrete shells can also be created by means of special experimental or numerical form-finding processes. An ideal distribution of internal forces can be the starting point for form finding. Form finding using soap film models can produce shell forms whose internal forces and moments are equal at every point and in every direction. To prevent cracking and make use of the material's compressive strength, concrete shells are often built so that mainly compressive stresses

B 4.88

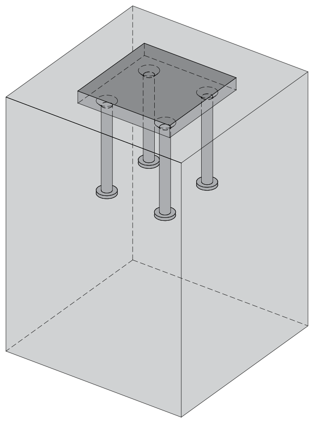
B 4.87 Shell forms (a–d rotational shells)
a Circular dome
b Paraboloid
c Hyperboloid
d Torus
e Barrel shell
f Translational shell
g Hyperbolic paraboloid

B 4.88 Elegantly curved concrete shell with monolithic transitions to the columns, crematorium, Kakamigahara (J) 2006, Toyo Ito & Associates Architects, Structural engineers: Sasaki Structural Consultants

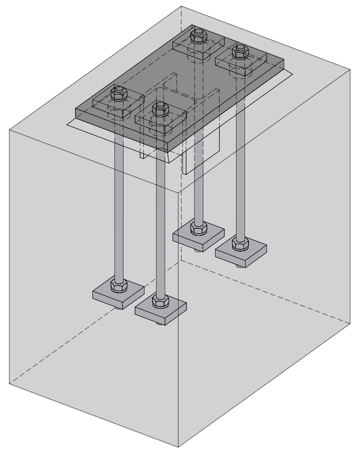
B 4.89 Built-in part

B 4.90 Structural connecting element with threaded bars

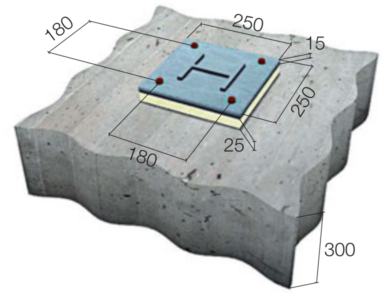
B 4.91 Dowel joint



B 4.89



B 4.90



B 4.91

occur. This form-finding process can be used to design free-formed surfaces that are geometrically very complex.
Concrete shells are usually cast in situ and only rarely produced for prefabricated construction. The prerequisite for producing concrete shells as prefabricated segments is the development of an appropriate joining technology. Pier Luigi Nervi successfully built a concrete shell in his partly prefabricated Palazzetto dello Sport in Rome (Fig. A 4, p. 12).

Shell forms are not arbitrary but are usually the result of complex form-finding processes carried out by engineers. Concrete shell construction is a form of building that 20th century architecture has enriched with a fascinating diversity of forms. Although they can be very effective structures using a minimum of materials if they are appropriately designed, few concrete shells have been built recently. One reason for this is that building formwork and reinforcement for them is labour-intensive. Another disadvantage is that the insulated roofs now required must be adapted to their curved forms. Countless ways of making it more economical to produce shells using new processes, such as pneumatic or hydraulically controlled formwork or digital production tools, have been proposed, but these approaches have not yet revived shell construction. Digital design tools make it possible to represent complex geometric forms fairly easily, so complex curved concrete structures are again being built, especially for high quality uses. The forms planned in this way are often, however, not the products of a form-finding process and usually mainly transfer loads by means of bending stresses. They very convincingly demonstrate concrete's plastic character but usually only make use of the shell's favourable load-bearing behaviour to a very limited extent.

Cast-in components and fastening technology/techniques

Concrete structures are, in many cases, connected with structural components made by different groups of tradesmen or made of other materials such as facade elements or parts of the building's technical equipment. Forces must also be transferred here. The issue of transferring forces can also arise in the area of construction joints. In certain situations, such as with stairways and balconies, concrete structures must be separated to reduce heat transfer or sound transmission. Components made by different groups of tradesmen are usually connected with steel connectors, which can be relatively small due to steel's good mechanical properties.
For standard construction situations, fastening technology offers a wide range of products for joining and/or anchoring structural components. These products are usually approved by a building regulatory authority that regulates their use.
Steel connecting parts can be planned in the form of built-in components as part of a concrete element and laid in the formwork before concreting. Concreting threaded rods or the use of dowels into steel connecting parts make it possible to subsequently attach the parts to already hardened concrete structures.

Cast-in components

Built-in components are often individually planned and designed. Depending on the loads that have to be transferred, cast-in parts have to form a load-transferring bond with the concrete through anchoring elements. (Fig. B 4.89). If loads are light, cut steel sheets can be used for anchoring. If loads are larger, components can be anchored by welding reinforcing rods onto their rear sides (to absorb tensile forces) or by shear keys (to absorb shear forces). After concreting, the steel sheets remain visible on the concrete's surface, and it is relatively easy to weld elements to them. The position of built-in components cannot be subsequently changed, so they must be planned with appropriate precision, taking construction tolerances into account.

Fastening technology

Steel columns can be joined to concrete foundations through threaded rods which are positioned in the formwork with templates and then concreted in. (Fig. B 4.90). Base plates with holes bored into them can then be connected through the threaded rods with the foundations after the concrete has hardened. The gap between the base plate and the concrete is injected with very fluid, non-shrink infill concrete in accordance with the guideline on "Production, inspection and labelling of grout and infill concretes in accordance with DAfStb guidelines".
Adhesive or expansion anchors are suitable for subsequently attaching steel connecting parts. In designing and building these dowel joints, the minimum spacing between the joints, as well as between the joints and the edges of the structural components, as specified in the technical approval documents, must be complied with (Fig. B 4.91). The load-bearing capacity of dowel joints depends on their product properties, the joint's geometry and the concrete's compressive strength, among other things. Static models of the load-bearing behaviour of dowel joints assume that compressive loads are transferred through compression in the concrete. Tensile loads and shear forces are transferred through the dowel into the concrete. Bending stresses are absorbed by a force couple consisting of the resultants of the concrete's compressive stress and the dowel's tensile force. If loads are very large and structural components slender, anchors can be passed through the component and anchored on the rear side with a counter plate. It must be ensured that loads imposed on concrete structural components are appropriately transferred.

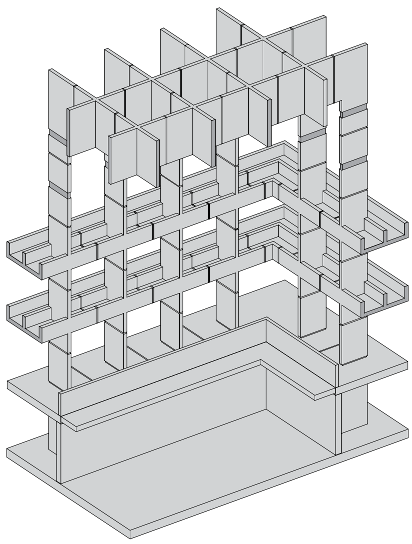
Developments

To outline some research currently being done by various scientists, some promising developments in concrete construction, not only in the area of materials but also in construction techniques, will be described below.

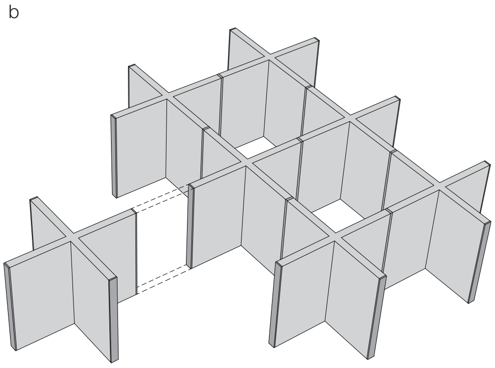
Ultra high performance concrete structures

Ultra high performance concretes (UHPC, see p. 15f. and p. 40f.) are concretes with very high compressive strengths that are due mainly to their packing densities. Because the material's elasticity modulus and tensile strength do

a



b



c

d B 4.92

not increase to the same extent as its compressive strength, ultra high performance concretes also require reinforcement. UHPC is usually reinforced with short steel fibres, sometimes in combination with other forms of reinforcement, e.g. prestressing tendons. Ultra high performance concretes make it possible to develop and design highly effective yet very slender structural components. Using the minimum amount of materials in construction is one imperative of this construction method, due in no small part to the high cost of UHPC. Thin-walled UHPC structural components look very different from ordinary concrete structural components. As well as its high compressive strength, UHPC is characterised by a high degree of resistance to environmental influences and for this reason should also have low maintenance costs. UHPC structural components are generally produced in factories. UHPC is currently rarely used in practice, mainly in civil engineering works, although UHPC structural components could also be appropriate for use in buildings. Thin-walled, short fibre-reinforced UHPC panels, which can be shaped more or less arbitrarily, are used to build curtain-wall facade structures (Fig. B 4.94). UHPC's high strength and outstanding composite properties make it possible to develop very effective joints between structural components in areas of load transfer. There are already various examples of thin-walled UHPC columns, slabs, stairs and beam structures (Fig. 4.93). UHPC structural components can also be used to build halls. UHPC is extremely suitable for thin-walled precast components that can be assembled to form load-bearing folded plate structures or to create thin-walled shell segments (Fig. B 4.95).

Joining prefabricated components

Prefabricated elements are often simply stacked on top of each other and secured in position (see "Construction using precast components", p. 78f.). In static and structural terms, this approximates a hinged joint formation. In structural design, the result is often very simple statically determined systems, especially single span girder systems that do not make use of the favourable load-bearing behaviour and redundancy of statically indeterminate systems. There remain some caveats concerning the design of transitions between structural components.

Structural components in prefabricated construction, however, can also be connected by a stiff joint that resists bending. This is usually achieved with reinforcement that extends out of the precast components and is joined with overlap joints. After adding any additional reinforcement required, the joint area is then poured with concrete in a further work operation. These joint areas will be comparatively large because of the necessary length of the overlap for the reinforcement. The subsequent concreting of joints with visible surface areas is not very suitable for exposed concrete-quality structural components because the areas the concrete has been poured onto invariably have a different surface quality and the construction joint remains visible.

One structural solution rarely attempted in practice is to combine prefabricated elements to integral concrete structures with the help of suitable built-in steel parts. By using appropriate joining technology, statically indeterminate structures, such as frames, can be constructed with flexurally rigid transitions between structural components. Integral prefabricated structures combine the manufacturing and operational advantages of building with prefabricated elements with the static and structural advantages of building with concrete cast in situ. Parts can be joined by welding them to the face of a steel element built into the prefabricated component (Fig. B 4.92). Built-in parts and weld seams must be designed to absorb the design loads. The prefabricated component reinforcement must be welded at the back to the built-in parts. Shear keys on the rear side are used to transfer shear forces. The joint pattern of structural elements joined with this technique must be an integral part of planning.

Another option is to join elements using steel casting or steel sleeves, in which the prefabricated components are placed and then injected with injection mortar. Prefabricated components can also be connected with a dry joint. Segmental construction uses post-tensioning tendons to tie precast concrete struc-


B 4.93


B 4.94


B 4.95

tural components together in such a way that the joints will only have to absorb compression forces in all possible load cases. This technique has been in use for some time in bridge building. To transfer shear forces, the webs must have a profile and elements can be joined with or without adhesive. Structures built using this technique are relatively easy to dismantle. Using this joining technique, prefabricated parts, if they are sufficiently precisely produced, can be joined with the tolerances of steelwork. Joining techniques engineered to have high load-bearing capacity that are also economical could open up new design possibilities and applications in construction with prefabricated elements.

Composite construction methods

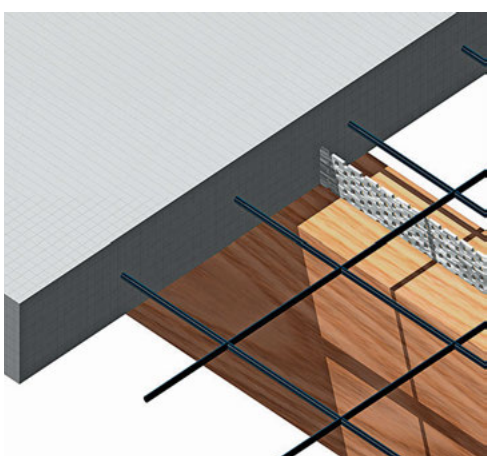
Combining structural concrete and steel to build effective composite structures is now an established and standardised construction method. Concrete can also be combined with other materials, e.g. wood or glass. The prerequisite for using composite construction methods in practice is a verifiably functioning joining technique since a composite structure's load-bearing capacity and effectiveness always depends on the stiffness of the bond between the composite materials.

Concrete and timber composite construction
The combination of concrete and wood is used mainly in composite wood-concrete slabs, which are made by adding a load-bearing layer of concrete cast in situ, usually 6 to 14 cm thick, to wooden beam or glued laminate timber slabs. One application for this is in reinforcing old wooden beam ceilings to improve their sound insulation properties, fire resistance and sway behaviour. Prefabricated elements can also be used. The composite action in timber concrete composite structures is produced by composite screws, shear connectors for timber-concrete composite structures, flat steel couplers and other composite elements (Fig. B 4.96).

Reinforcing structural elements with CFP laminates
One focus of current research into concrete construction is on reinforcement made of other materials such as carbon fibre reinforced plastics (CFP). These are currently mainly used for reinforcing and renovating structural components. This technique involves adhering CF laminate to concrete structural components such as ceilings, beams or columns. CF laminate can also be post-tensioned if necessary.

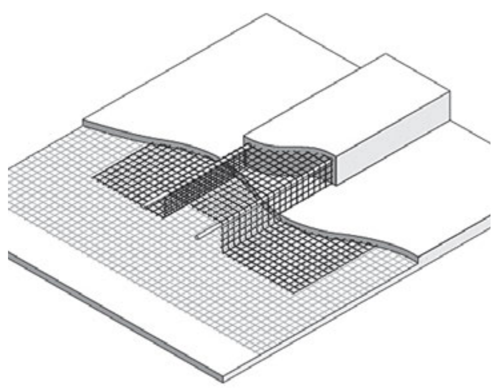
Textile-reinforced concrete construction
Another effective and promising development is textile-reinforced concrete structural components. Finely-woven textile cores made of various fibre products make it possible to create very thin-walled structural components with high levels of resistance to corrosion. The concrete cover can be greatly reduced compared with conventional steel reinforcement. Some of these textile products have already been approved by building regulatory authorities, and applications are being trialled in building and bridge construction (Fig. B 4.97).

Construction with concrete-glass composites
Research is continuing into another new form of construction combining concrete and glass, and concrete beams with I-shaped cross sections and a partly load-bearing glass web have been made. These composite beams, with their transparent webs, look much lighter than conventional beams.


B 4.96

Notes:
[1] Schlaich, Jörg; Schäfer, Kurt: Konstruieren im Stahlbetonbau; In: Beton-Kalender. Volume 2, Berlin 1998. pp. 721–895.
[2] www.fdb-typenprogramm.de (As at 18/06/2013)
[3] www.fachvereinigung-bmg.de
[4] www.leichtbeton.de

B 4.92 New central reading room of the Staatsbibliothek (State Library) Berlin (D) 2012, hg merz, Structural engineers: Werner Sobek Ingenieure
a Reading room after completion
b Monolithic, precast concrete structure consisting of intersecting, very slender concrete frames which have been assembled from small, precast concrete elements
c Individual concrete elements are joined by welding together built-in parts
d Cross-shaped, precast components with surface plates
B 4.93 UHPC stairs, Sidney Stringer Academy, Coventry (GB) 2010, Sheppard Robson
B 4.94 Filigree UHPC facade elements, Museum of European and Mediterranean Civilisations, Marseille (F) 2013, Rudy Ricciotti
B 4.95 UHPC shells, Shawnessy LRT Station, Calgary (CDN)
B 4.96 Composite timber-concrete slab
B 4.97 Structure of a textile-reinforced concrete slab


B 4.97

Digital design and fabrication methods

Tobias Wallisser

B 5.1

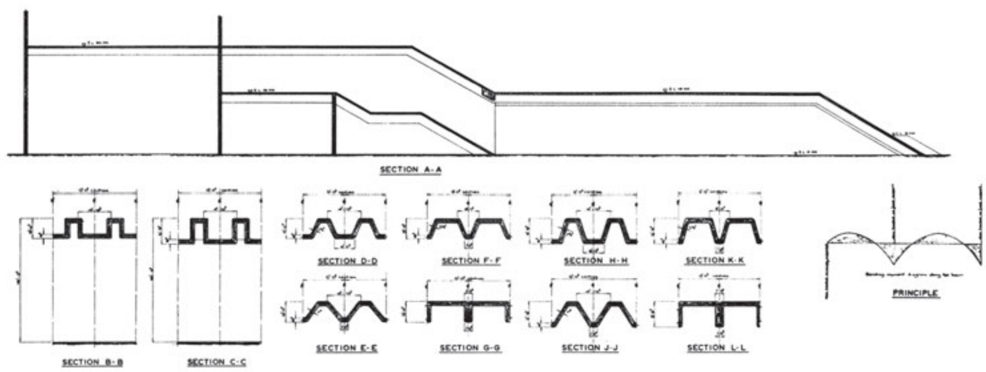
The ‘Digital Real – Blobmeister’ exhibition at the German Museum of Architecture (Frankfurt am Main, 2001) gave Thomas Assheuer occasion to write about the use of the computer in construction in the newspaper DIE ZEIT: “Used in architecture, it facilitates eccentric shapes which no sensible person would want to calculate. The computer removes the limits to our imagination and allows operations that previously would have failed due to the natural shortage of time. Without a single intermediate step, the three-dimensional design can be translated or milled directly from the screen to a model (“from file to factory”). With the digitisation of architecture, according to the Napster generation, so ends the era of mechanical construction. The revolution has begun.” [1]
In recent years, the influence of digital technologies on the conception, development and implementation of architectural designs has certainly become much more evident. While architects who experimented with digital tools were previously derided as “blobmeisters”, those who lacked a relationship with reality, it is now frequently and clearly stated that the creation of spectacular new buildings would not have been possible without the aid of the latest computer technology. Initially, complex freeform geometries were only to be found in connection with large, special constructions; however, today such ambitious designs are being found more and more in everyday construction practices. For a new generation of architects who have already worked with digital tools during their training, working with computers is simply a part of everyday life, both for design as well as for the search for suitable technologies for realisation.

Most of the projects included in the above exhibition were simple buildings with steel supporting structures. However, concrete as a building material is particularly well suited for buildings where flowing geometry and continually smooth surfaces are desired. In addition to the serial fabrication of repeating elements, two characteristics of the material concrete make it ideal for the production of individual, non-standardised structural elements: Firstly, the material does not initially have its own form and there is virtually no limit to the forms into which it can be plastically shaped; secondly, it is possible to give individual characteristics to the surface quality. Erhart Kästner aptly wrote in his book *“Aufstand der Dinge”* in 1973: “Concrete, a fantastic building material, imagination and audacity are what it needs. If it is rejected, it becomes tedious, deteriorates into the flattest platitude, then it is an affront. The affront takes place wherever imitation takes place.” [2]

Even before digital tools became widely available, two buildings illustrated how concrete could be used. Here, new ground was broken in the development of design, based on the growing technical opportunities offered by concrete construction. As a continuation of the concrete membranes developed since the 1920s by people such as Pier Luigi Nervi, Eduardo Torroja and Félix Candela, buildings have been created as technical experiments which have preceded a few of the current concepts of space. Thus, both the TWA terminal at Idlewild Airport (now John F. Kennedy Airport) in New York (1962) by Eero Saarinen (Fig. B 5.4) and the Sydney Opera House (1973) by Jørn Utzon are an expression of the search for appropriate and new architectural means of expression for public spaces. During construction of the Opera House, this led to the use of new electronic aids. For the section of the large podium, which spans the approach to the Opera House, the engineers from ARUP developed a system of undulating beams with a T-shaped profile that changes across the sine form to a U-shaped profile (Fig. B 5.2). Even at that time, computers were used to calculate the dimensioning of these rising and falling beam cross-sections. The rule-based form of the beam seems to already anticipate designs by means of flowing transformations, as emerged later through the use of animation programs [3].

In order to understand the interdependence of contemporary, computer-based design and fabrication methods, it is useful first to look briefly at the development of digital

B 5.1 Visualisation of the transfer hall, Arnhem Central, Arnhem (NL) Completion scheduled for 2014, UNStudio, ARUP
B 5.2 Undulating beams, Opera House, Sydney (AUS) 1973, Jørn Utzon
B 5.3 Phaeno Science Center, Wolfsburg (D) 2005, Zaha Hadid Architects
B 5.4 Exterior view of the TWA terminal, John F. Kennedy International Airport (formerly Idlewild Airport), New York (USA) 1962, Eero Saarinen



B 5.2

B 5.3

design tools. The computer-assisted options for the fabrication and construction of formwork will then be outlined. In conclusion, the outlook will show what new understanding of the material is possible as a result of the changing design and fabrication methods and which developments could become a reality in the near future.

From digital form generation to computer-simulated performance

In his book "The Projective Cast", the British architectural theorist and historian Robin Evans explained how the options for representation, in particular the technology of two-dimensional projection drawings, characterised the historical development of the architecture. According to Evans, the relationship between the conception and the reproduction of architectural designs is that all architectural activities (design, representation and construction) take place by means of a "projective transaction". This applies equally for all subsequent intermediate steps from the sketch and the presentation to the detailed design, so he describes design as "action from a distance", limited by the representation methods available. Digital technologies offer new possibilities at each stage: for conception, presentation and realisation. [4] The process of form finding is changing from one characterised by environmental factors (morphology) to the evolution of form as optimisation through the selection and recombination of various factors and parameters. Design alternatives are not seen as singular but as one of many possible variants. Computer-assisted technologies facilitate the simultaneous processing of the entire process chain through to the creation of prototypes while integrating technical, constructive, material and production-related limits. This enables architects to overcome traditional limits and translate almost any form into an ambitious building.

For the architects, this means a change in the design process: to develop objects where the relationships are defined between variable attributes, the so-called parameters. Parametric software makes it possible to create variations and to change elements while maintaining specified dependencies. It enables the designer to work directly on the three-dimensional object at any time. With associative geometry models, the process of development is saved along with the objects, it is stored in the construction history; this means that, despite the same outward appearance, objects are created with different characteristics and intervention options. Working with these programs requires a different understanding of relationships and dependencies as inseparable characteristics of each form. It also makes it possible to undo individual processing steps. The use of computer-based tools in design has constantly developed, as summarised in the following three stages:

- In the middle of the 1990s, free forms and complex geometry were an important focal point of digital design.
- At the beginning of the 21st century, the focus turned increasingly to the simulation of the performance qualities of the objects created, i.e. the effect of the form on its environment.
- For a few years now, materialisation and the integral search for fabrication options have been playing an increasingly important role alongside these investigations and the matter of design feasibility.

Free forms

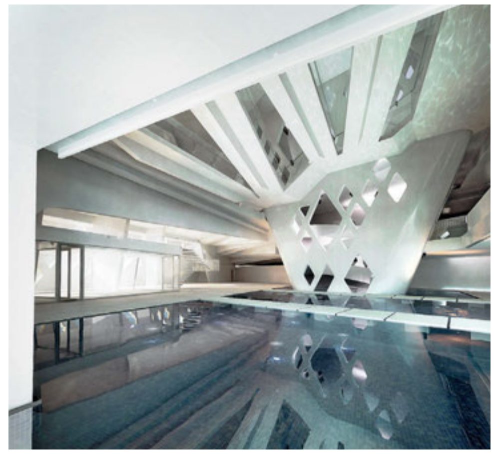
In the 1990s, architects began for the first time to examine the potential offered to architecture by the animation software used in the film industry (e.g. Maya [5]). This software enables complex forms and free geometries to be designed. Mastering these forms was possible by means of NURBS (Non-uniform rational B-Splines) [6], which were developed for use in automotive design. Greg Lynn's reference to the US film "The Blob" from the 1950s led to the projects being described as "blob architecture" [7].

An early project (planning phase began 1997, completion scheduled for 2014) where the use of concrete as a freeform material was planned from the outset was the redesign of Arnhem railway station and the surrounding area ("Arnhem Centraal", figure B 5.1) by UNStudio (Ben van Berkel) in collaboration with ARUP (Cecil Balmond). The precise geometrical description of the formwork elements and, in particular, the reinforcement configuration posed great challenges for the engineers. The experience gained by UNStudio from construction of the Mercedes-Benz Museum in Stuttgart (2006) led to a rule-based, parametric description of the geometry. Several phases of construction have already been completed; the roof of the freeform concourse is currently under construction – but partly as a steel structure.

Another example of a project where free forms have been transformed into a concrete sculp-

B 5.4


B 5.5


B 5.6

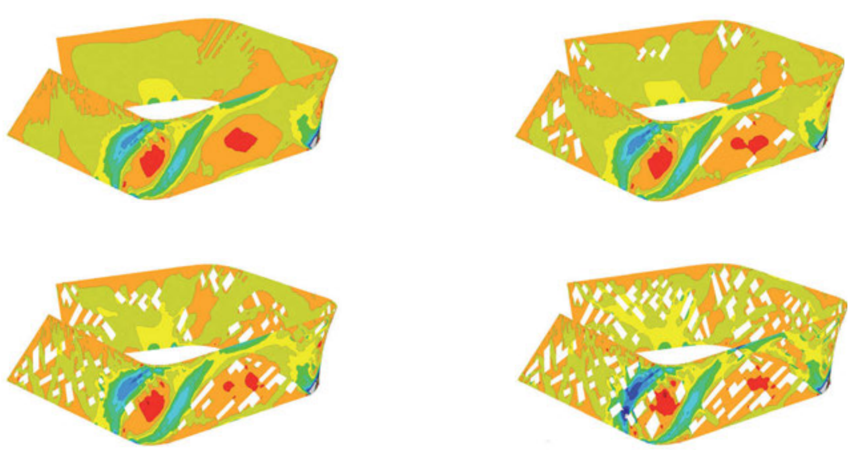
ture is the Phaeno Science Center in Wolfsburg (2005), designed by Zaha Hadid (Fig. B 5.3, p. 107). The design was developed in Maya using the simulation of physical forces as a basis. The irregular objects in the entrance level of the building were created digitally as protuberances in the overlying floor slab. The complex geometry required the use of self-compacting concrete (see “Self-compacting concrete”, p. 41).

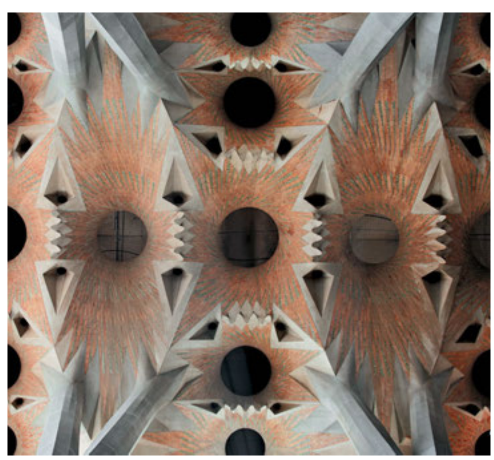
Simplicity in the midst of complexity

The development of parametric design tools since the beginning of the 21st century, such as Digital Project [8], Generative Components [9] or Grasshopper [10], has led to a stronger, rule-based definition of geometric complexity. With the already described associative definition of the form, even complex elements are easy to change parametrically. Often, individual components are developed and then, with the aid of a grid, distorted into distinct formulations over a girder geometry.
How great complexity can be achieved by means of controllable rules is illustrated by a building unusual in every respect and far ahead of its time: the Sagrada Família church in Barcelona. The most famous project by the Catalan architect Antoni Gaudí, construction began back in 1882. Gaudí changed his method of working away from the pure composition of free forms (as for the Casa Milà apartment block, also in Barcelona) to a rigid, rule-based form description. Even though he conceived the project long before the invention of the computer, it is influential as an example of a parametrical description. The design is based on a codex for extensive form generation, which generates a precise description of the geometry that is repeatable and variable within rules. With many elements, it is simply a matter of geometric ruled surfaces (Fig. B 5.8); the fabrication process influences form development, and since ruled surfaces are created with few tools, their simple developability makes it possible even to arrange reinforcement bars in double-curved concrete elements, for example. This removed the need for complex manipulation of the reinforcement, and simultaneously, it was possible to produce formwork using smooth brick. Complexity and diversity of form are created here through the superimposition of simple elements. [11]

Optimisation software

The current trend is towards the integration of additional functions into the design programs. After first improving the exchange of data between different programs and developing software for rapid communication between engineers and architects, there are now more and more parametric tools which facilitate an estimate of performance qualities even in the initial design phases, i.e. how precisely an approximation corresponds to the exact solution of an algorithm. As a result of the computing power now available, the new software is no longer reserved for expert systems; instead, there are program modules available that enable architects to receive feedback on design or energetic aspects during form finding and to incorporate it into the design process. For example, the Karamba software package [12] can be used to optimise openings in load-bearing elements or to differentiate the dimensioning of structural elements according to the load. Other software packages enable buildings to be examined with respect to daylight incidence or heating through solar gain. It is not about a perfect simulation, but about the opportunity to estimate fundamental impacts due to possible design decisions in real time. The first projects where these tools played an important part in the design process have already been completed, e.g. the Sheikh Zayed Desert Learning Centre, a visitor centre for the zoo in Al Ain (United Arab Emirates), completed in 2011 by Chalabi Architekten in collaboration with structural engineers from Bollinger Grohmann Schneider in Vienna. Here, the openings in the exterior load-bearing concrete wall have been optimised in relation to the load transfer (Figs. B 5.5 – B 5.7).


B 5.7


B 5.8

B 5.9

B 5.10

B 5.11

From CNC-produced formwork to differentiated material properties

In his report about the seminar on the opportunities of interaction between digitally designed objects and new formwork concepts for concrete, held at the State Academy of Art and Design in Stuttgart, architect Martin Schroth wrote: "As a liquid material, concrete can be formed into almost any geometry. However, one limit to this formability is the formwork. As a result, simple stereometric formwork will be replaced in the future by flexible formwork, which satisfies several requirements in terms of its applications: weight regulation during the fabrication process, implementation of different applications through orientation of the formwork, creation of structural load capacity through the deformability of the formwork." [13]
While flexible formwork is not yet part of the standard process, important correlations between the quality of concrete and its application for freeform geometries are already being defined. As concrete itself has no material-specific form and is heavily defined by the fabrication process, it is ideal for architectural projects where the focus is on sculptural formability instead of modular or additive concepts.

In contrast to steel structures, where freeform geometries are primarily produced via geometric simplification of the surface (e.g. transformation into flat subareas by means of triangulation), concrete allows for the construction of freeform elements with continual curves. However, surface quality plays an important role, with both the formwork and the reinforcement configuration being crucial. Uniform reinforcement with fibre fabrics subject to the thickness of the structural element is one option for producing continual structural elements with different properties.
What impact do fabrication processes in the digital age have on the specification of the surface and volume of concrete structures? From different concepts for formwork and new possibilities for manipulating the characteristics of concrete to a perspective on how the understanding of the material has changed due to digitisation, the impact of digital technologies is also growing with regard to cement-based materials.

Digital technologies for formwork systems

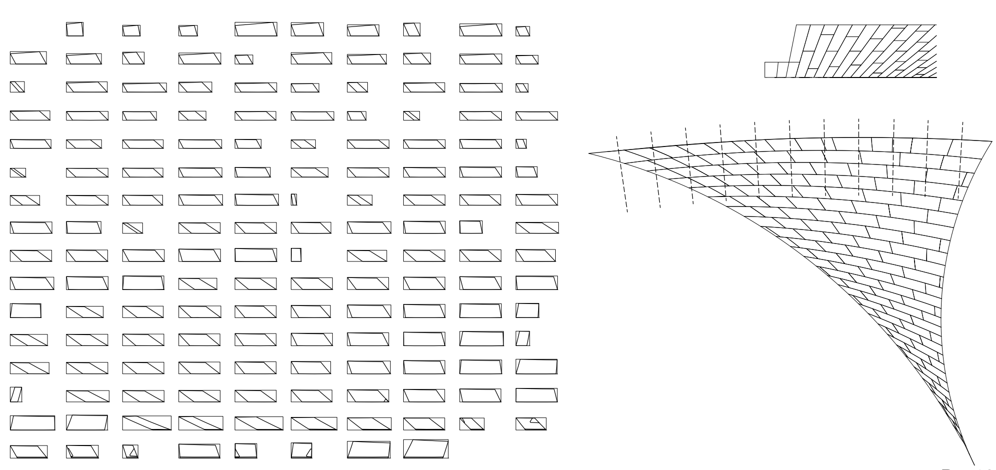
Formwork is a key factor in the surface quality of concreted structural elements. The more complex the required geometry, the greater the challenge to produce a smooth, high-quality surface. Parallel to this, it becomes increasingly difficult to determine the optimum reinforcement configuration and to fix it in the formwork.

Until the increasing prevalence of digitally supported tools in the mid-1990s, free geometries were technically limited, but often constructively optimised, based on the coherence of form and design such as the ruled surfaces in the Sagrada Família church in Barcelona. If form is initially considered separately from constructive coherence, the most important task is to find solutions for creating the necessary formwork. A commonly used type of formwork is so-called timber formwork (see "Timber formwork", p. 55f.), where individual, narrow elements are laid parallel to each other, allowing curved surfaces to be formed such as at the TWA airport terminal in New York. Factors limiting this application include the resulting characteristic surface quality and a limit on the possible curves. Computer-assisted fabrication methods for formwork are opening up new possibilities.

Double-curved formwork surfaces

"At the time of its construction (2002–2006), the [...] Mercedes-Benz Museum in Stuttgart, designed by UNStudio, posed the greatest structural challenges with respect to geometry, concrete construction and formwork technology in Germany and probably anywhere in Europe. In contrast to most reinforced concrete constructions, large-scale, multi-axis, curved structural components were to be produced with particular requirements regarding the

B 5.5 Sheikh Zayed Desert Learning Centre, Al Ain (UAE) 2011, Chalabi Architekten
B 5.6 Optimising window openings on the basis of stress distribution, Sheikh Zayed Desert Learning Centre
B 5.7 Studies on the creation of window openings, Sheikh Zayed Desert Learning Centre
B 5.8 Ceiling vault, Sagrada Família, Barcelona (Spain) Construction began 1882, scheduled for completion 2026, Antoni Gaudí
B 5.9 Digital 3D model to examine design decisions, Mercedes-Benz Museum, Stuttgart (Germany) 2006, UNStudio
B 5.10 Double-curved exposed concrete surfaces, Mercedes-Benz Museum
B 5.11 Exposed concrete surfaces with linear progression of the formwork, Mercedes-Benz Museum
B 5.12 Layout of the formwork panels for the Mercedes-Benz Museum



B 5.12

a

b B 5.13

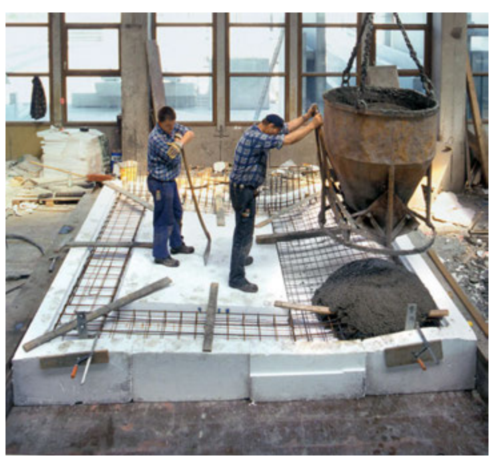
B 5.13 Terminal, Queen Alia International Airport, Amman (JOR) 2013, Foster + Partners
a Moving of the fibre-reinforced precast concrete elements
b In place as permanent formwork
B 5.14 Milling the three-dimensional formwork, Neuer Zollhof, Düsseldorf (D) 1999, Frank O. Gehry, Beucker Maschlanka und Partner
B 5.15 Fabricating the reinforced concrete structural elements, Neuer Zollhof
B 5.16 Exoskeleton wall with more than 1300 openings in a diagonal grid, O-14 Tower, Dubai (UAE) 2010, Reiser + Umemoto
B 5.17 Horizontal projection, O-14 Tower
B 5.18 Attaching the reinforcement, O-14 Tower
B 5.19 Boxing out the openings using hollow polystyrene bodies fabricated with CNC machines and inlaid in the reinforcement meshwork, O-14 Tower

surface quality. One particular difficulty was posed by the formwork for the double-curved structural elements." [14] The two-dimensional plan generation proved to be insufficient for the recording and implementation of the complex geometry, so the architects used a spatial computer model to serve as the construction documentation for all solid curved structural elements, and the design blanks were automatically generated from this data. Detailed 3D data models, which included the upper and lower shells of the elements (Fig. B 5.9, p. 109), formed the basis for the production of the formwork units. The implementation of the geometry was via prefabricated support and scaffolding structures, which, when installed, were covered with a formwork skin of inexpensive 9 mm thick, multi-layer boards. In order for a formwork design of continual lines to stand out on the curved concrete surfaces (Figs. B 5.10 and B 5.11, p. 109), the formwork panels had to be produced taking into account the material properties. To accomplish this, UNStudio worked with architect Arnold Walz from *designtoproduction* in Stuttgart to develop a special process to enable a double-curved surface to be created with the aid of elements cut on a plane that are only elastically deformed with pressure. The blank for the formwork skin was produced with a standard dual-axis CNC milling machine. This resulted in formwork panels with sharp angles and gently curved lateral edges (Fig. B 5.12, p. 109). At the same time, the milling machine also marked the positions for the screws for fixing to the formwork units and provided the box outs for penetrating supports. Planning the size of the formwork panels enabled visually smooth transitions to be achieved. The surface quality could be adjusted to the vertical structural elements in this way. In order to simplify the process used for the substructure of the Mercedes-Benz Museum, the formwork material itself had to be stable. Steel elements lend themselves to on-site formwork or the principle of master formwork; i.e. the manufacture of formwork elements in the workshop for identical elements, e.g. out of prefabricated concrete elements. Due to the high production costs for the formwork elements, this process is particularly suited for components with a serially repeating geometry, where the curved elements can be reused multiple times. Double-curved formwork elements were used for the domed ceiling vaults of the new terminal building at the Queen Alia International Airport in Amman (2005–2013), designed by Foster + Partners. Using new technology, the individual shells were produced as fibre-reinforced prefabricated concrete elements. These were then raised into position and left there as permanent formwork (Fig. B 5.13). During construction and in their finished state, these elements must bear different loads from the concrete layer applied in situ [15]. Due to their surface quality and dimensionally accurate production, prefabricated concrete elements may offer advantages for the realisation of complex geometries. However, the fabrication of double curved prefabricated concrete elements is costly, and the reusability of the formwork or moulds used is limited. Therefore, it would be advantageous to produce individual areas of free geometry using a variably adjustable formwork system. The problem with freeform designs though is in recognising recurring sections as such at all, as they often have many single or double-curved surfaces, which then require a complex design for the formwork. As demonstrated by a research project conducted by Delft Technical University with the aim of developing a flexible formwork system for prefabricated concrete elements, the division of the geometry into individual structural elements, the exchange of data between the CAD program and the controlling of adjustable, moveable elements of the formwork system are important prerequisites and are therefore being increasingly studied [16].

Fabrication of milled formwork units

The free geometry of the Neuer Zollhof project in Düsseldorf (1999) by US architect Frank O. Gehry posed a particular challenge for the supervising architects Beucker Maschlanka und Partner and the participating companies. Designed with free NURBS geometries, it was impossible to identify repetitive or rule-based geometries. The project comprises three individual buildings, with a different technical approach chosen for each. For building B, freeform polystyrene bodies manufactured with a CNC milling machine were set in square formwork boxes to create precast wall elements (Fig. B 5.15). The supervising company described the procedure as a new process that made it possible to realise the facade using a precast concrete component construction method. For this purpose, computer data from the design of the building complex was broken down into separate data sets for each storey. The modelling of the storey-high facade elements was undertaken with the CATIA software in accordance with static requirements as 18 cm thick, non-structural prefabricated segments. As there was

B 5.14



B 5.15

no formwork plan for any of the prefabricated parts of the facade, approval of the formwork plan was granted based on this data. The company examined the dimensional accuracy and precision fit of the individual prefabricated elements before giving the approval for production. The data was then used to control a milling machine, which produced the formwork for each individual prefabricated element from large-format polystyrene blocks (Fig. B 5.14). The variable parameters of appropriate milling head, possible speed and acceptable tracking distance were determined in advance. [17]
The surface of the precast concrete elements did not remain visible, with the interior finished in plaster and the exterior in stainless steel panels. The individually cut formwork units were only used once, but after stripping out they were melted down and processed into new polystyrene blocks.

Combination of digital design and fabrication technologies

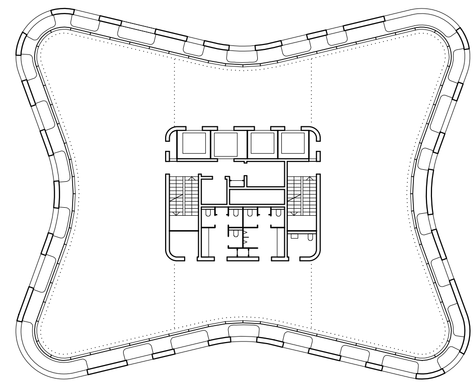
One of the most striking buildings in Dubai is the O-14 Tower office building (2010) in the Dubai Business Bay district (Fig. B 5.16). Designed by Reiser + Umemoto, its irregularly perforated concrete skin simultaneously serves as an architectural element, an intelligent shading system and the primary structural framework. This exoskeleton has more than 1,300 openings, apparently arranged in a random configuration. However, closer reflection shows that they are positioned in a diagonal grid, permitting both vertical load transfer and the absorption of horizontal forces. The plans show the facade behind this curved concrete shell at a distance of approximately 1 metre. The ceilings span freely between the core and the shell (Fig. B 5.17). The configuration of the openings in the wall shell means that the necessary starter bars for the ceilings must be at a different location on each floor. The development of the reinforcement for such a construction posed a particular challenge. This required close collaboration between the architects and structural engineers, even during the design process, and the use of a digital 3D model in which the openings were included (Fig. B 5.18). The structural engineers examined this model structurally using analysis software, and by simulating the net weight and the wind loads acting on the shell, they were able to determine the forces occurring between the openings. In consultation with the architects, the structural engineers adjusted the size and position of the openings, and optimised the flow of forces until the structural framework and the architectural design of the wall shell satisfied both parties [18].
In order to construct the perforated concrete shell, the construction company began by using a slipform technique that enabled the modular steel forms to be moved vertically upwards. This prevented the costly dismantling and setup of the formwork for the wall shell. The openings were created by inserting hollow polystyrene voids produced using CNC machines into the reinforcement mesh (Fig. B 5.19). Once the concrete cured, these voids were removed from the formwork and reused at other levels.

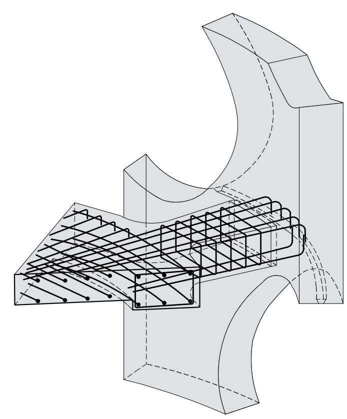
This project is characterised by the high degree of interaction between the structural engineers and architect as well as the combination of different computer-aided technologies for the formwork. It is a successful example of the seamless integration of digital tools, from design to implementation of a modern concrete construction.

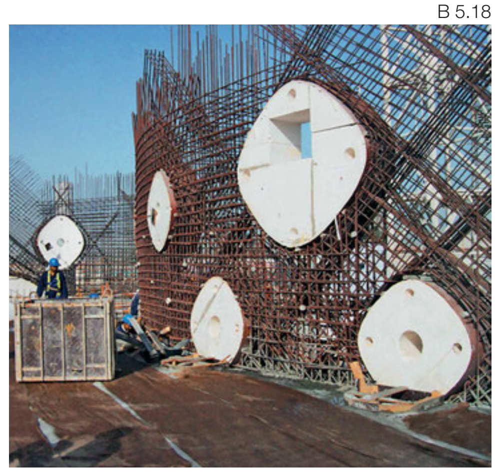
For the roof and ceiling structure of the foyer of the *Bauakademie Salzburg* [Salzburg Building Academy] (2012), the architects at soma used a virtual simulation of the behaviour of fluids to create a geometry which provides a smooth transition between the exterior and interior of the building and which differentiates the various functional areas of the multipurpose hall in the foyer (Fig. B 5.21 a, p. 112). Direction within the foyer is controlled via the guidance of the entry of light and the integration of functional elements into the roof structure. "The faceted surface structure of the concrete generates a living interplay of light and shadow which changes constantly throughout the day. […] The experimental use of concrete was also chosen in view of the teaching of the *Bauakademie,* a large proportion of which is dedicated to concrete technology." [19] The architects cooperated with the company Moldtech, which has specialised in the CNC manufacture of moulds, e.g. for the automotive industry. The computer-generated formwork elements were produced directly from 3D milling machines without any manual cutting (Fig. B 5.21 b, p. 112). In doing so, the surface structure of the formwork elements was deliberately shaped such that the traces of the milling head apparent in the polystyrene elements create a faceting, thus generating a special lighting effect (Fig. B 5.20 b, p. 112).
The project is a compelling example of how bringing together different subareas (design, lighting, control system and space planning) by means of computer-based design technologies can find its consistent continuation in the innovative manufacturing process and the new design possibilities associated with it.

Concrete elements with continual differentiation
New concrete structures should be just as delicate as they are robust. This can be achieved, for example, with an even distribution of fibre reinforcement (see "Fibre-reinforced concrete", p. 37ff.) depending on element thickness and shape. In doing so, concrete qualities can be transformed, for by using special additives, it is possible for the concrete to take on


B 5.16


B 5.17


B 5.18


B 5.19


a


b B 5.20

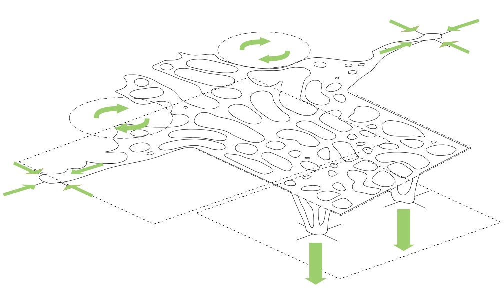
new properties; it can then also be delicate, lightweight, insulating or translucent. This represents one of the most important requirements for new material technology and construction concepts.

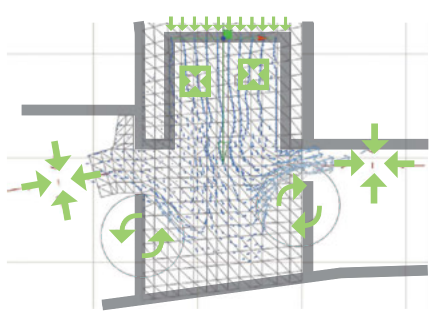
Already in the summer semester of 2010, the "Digital Design" class led by Tobias Wallisser and Martin Schroth at the Stuttgart State Academy of Art and Design examined the opportunities and limitations of design freedom and processing with concrete in conjunction with flexible formwork. This involved realising objects designed in 3D on a computer using innovative formwork concepts. The use of latex formwork made it possible to create a complex form by the simple setting of an edge geometry. When doing so, spacers limit the volume and define openings. The final form is set by the limiting conditions defined by the spacers, the alignment of the formwork and the concrete mixture due to gravity. By moving the spacers, new, complex and distinct forms can be created without having to fabricate costly new formwork. The latex formwork can be reused several times. The selection of its elasticity determines the individual surface formulation and surface finish. This overrides the often troubling contradiction of animated form on the one side and the difficulty of achieving a smooth, high-quality surface on the other. At the same time, the fabrication process for the objects remains visible due to the continually varying material strength (Fig. B 5.22) [20].

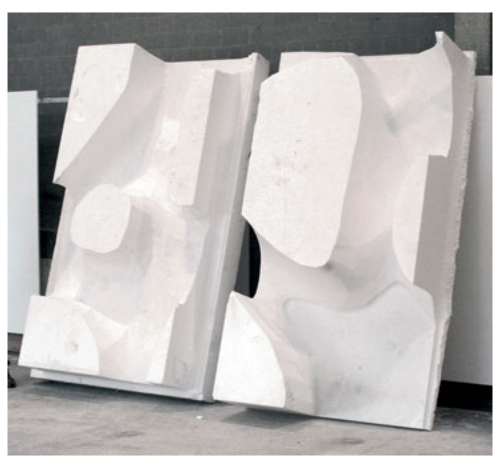
The hybrid material of reinforced concrete is based partly on the composition of different aggregates and cement, and partly on the necessary reinforcement. Through the reduction and dispersion of the reinforcement elements, it is possible for the material to have different properties in individual areas due to the nature of the processing. Thus, analogous to bionic models, the load bearing capacity can be adapted by a locally varying consistency of the material. Ultra high-performance concrete (UHPC) has a high structural density and is a diffusion-resistant, fine or coarse grain concrete with a high compressive strength (see "Ultra high performance concrete", p. 40f.). This can be used to construct very durable, high load-bearing, yet lightweight and delicate structures in an economic manner [21]. Beyond the conventional use of UHPC in civil engineering projects for bridges and high-rise buildings, its mechanical characteristics mean that completely new applications (Figs. B 5.23 a and b) such as innovative enclosure designs in mechanical engineering are also conceivable. Here, the main focus is on a geometric and physically non-linear, three-dimensional formwork formulation that, by calculating finite elements, can be transferred into a highly efficient prefabricated concrete element. Neither is conceivable without the use of computer-based technologies. The opportunities offered by this material will bring about a rethinking both in the processing and in the fabricating of structural elements or buildings.

"Digital understanding of the material" through new fabrication processes

The use of computer-assisted tools is leading from the optimisation of individual formwork elements to a closer link between the design and implementation of complex structural elements and buildings in built architecture. Also changing somewhat is the understanding of material as dead mass to a differentiable component of the whole. Cement-based materials offer many options for optimisation and engagement. Only the interplay of materials research and predominantly digitally assisted fabrication tools makes these accessible for the design and construction process. The close interaction between computer-assisted design processes, digital simulations and a seamlessly coordinated fabrication process will, in the future, define new relationships between form, mode of operation and material.
The understanding of concrete as a hybrid, non-homogenous mass could thus be regarded as a new material concept appropriate to the digital era. As such, it offers a starting point for reproducing the vision of "printed buildings" by means of a manufac-




a


b B 5.21

turing process such as that already used by Enrico Dini and his company D-shape [22] for large-scale models (Fig. B 5.24). This involves a mixture of epoxy resin and granulated natural stone being added in layers via a nozzle on a computer-controlled robot arm. Thus, digital processes of form and topology optimisation (as a rule, the development of biomorphic structures from a generative analysis) were combined with a fabrication technology. This then permitted the fabrication of geometrically complex structural elements (e.g. load-bearing structures under compression with optimised material usage), in order to integrate resource-saving aspects into a constructive and creative design function. Whether this can be fulfilled will become clear in the next few years. [23]

Notes:

[1] Assheuer, Thomas: *Das Monster kommt näher.* In: ZEITonline Kultur, 19/07/2001
[2] Kästner, Erhart: *Aufstand der Dinge. Byzantinische Aufzeichnungen.* Frankfurt/M. 1973
[3] Fromonot, Françoise: *Jørn Utzon – The Sydney Opera House.* Berkeley 1998, pp. 63–79
[4] Evans, Robin: *The Projective Cast. Architecture and Its Three Geometries.* Cambridge 1995; Moloney, Jules: Collapsing the Tetrahedron: Architecture with(in) Digital Machines. CHArt Conference Proceedings, Volume 2, 2000
[5] Maya is a professional and very widely used 3D visualisation and animation software program. It is used primarily in the film and TV industry and for the production of graphics for computer and video games. Maya is also used in other fields such as industrial manufacturing, architectural visualisation and in research & development. Maya is one of the most well-known and widely used software products in the computer animation and rendering sector. (Wikipedia, 12/04/2013)
[6] Non-uniform rational B-splines (NURBS) are mathematically defined curves or surfaces which are used in computer graphics, for example in CGI or CAD, for modelling any desired shapes. In the 1950s, mathematically precise descriptions of freeform shapes were required, particularly in automotive manufacture and shipbuilding, for the error-free reproduction of technical components. In the 1960s, it was demonstrated that NURBS are a generalisation of Bézier splines. Initially, NURBS were only used in proprietary CAD tools for automotive companies. They later found their way into more widespread computer graphics applications. (Wikipedia, 31/03/2013)
[7] Lynn, Greg: *Folds, Bodies & Blobs.* Collected Essays. Brussels 1998
[8] CATIA Digital Project is a suite of powerful 3D building information modelling (BIM) applications with CATIA V5 as the central modelling platform. http://www.3ds.com/de/products/catia/portfolio/digital-project/
[9] Generative Components (GC) is parametric CAD software. It was first introduced in 2003, became increasingly used by the architectural community in London from 2005 and was commercially released in November 2007. (Wikipedia, 18/03/2013)
[10] Grasshopper is a visual programming language that runs within the Rhinoceros 3D CAD application.
[11] Burry, Mark: *Gaudí unseen.* Lecture given at State Academy of Art and Design, Stuttgart 2007; Burry, Mark; Burry, Jane: *Gaudí and CAD.* In: The Effects of CAD on Building Form and Design Quality, ITcon 11/2006, p. 437–446, http://itcon.org/2006/32
[12] karamba3d is a freeware program for the calculation of finite elements, which enables non-experts to examine design effects. It is embedded in the parametric environment of Grasshopper. www.karamba3d.com
[13] Schroth, Martin: *Neue Formen – Flexible Schalungskonzepte ermöglichen freie Formbarkeit von Beton.* In: OPUS C, 01/2011
[14] Schmitt, Roland; Blaasch, Gerhard: *Doppelhelix – wichtiger zu erleben als zu verstehen. Das neue Mercedes-Benz-Museum in Stuttgart.* In: Tiefbau 05/2005, pp. 252–262
[15] Information about the prefabricated concrete elements from Cubus Hellas Ltd., www.cubushellas.gr
[16] Schipper, Roel; Vembersky, J. N. J. A.: Research. *A flexible mold for double curved precast concrete elements. Forschungsarbeit. Flexibles Schalungssystem für zweifach gebogene Betonfertigteile.* In: BFT International 08/2010, pp. 26–33
[17] Albrecht, Peer: *Der neue Zollhof Düsseldorf.* In: beton 09/1998
Beucker, Thomas: *Phantastische Betonteile.* Ulmer Beton- und Fertigteiltage 2000
[18] Ocampo, Jamie M.; Seinuk, Ysrael: *O-14 installment loans,* STRUCTUREmag.org, 2010
[19] Maier, Florian: *Erweiterung der Bauakademie Salzburg.* http://www.detail.de/architektur/news/erweiterung-der-bauakademie-salzburg-018952.html published 18/06/2012
[20] Sendelbach, Steffen; Rauscher, Jakob: *Latexschalung.* "Digitales Entwerfen" class, State Academy of Art and Design, Stuttgart, 2011
[21] Definition from Kirsten, Peter Ignaz: *Sachstandsbericht.* Study by the bri.dge group at the University of Kassel, 2008
[22] D-shape; www.d-shape.com
[23] Palz, Norbert: *Großformatdruck für den realen Maßstab.* In: Bauwelt 23/2011, p. 36f.

B 5.20 Extension of the *Bauakademie,* Salzburg (A) 2012, soma
a Exterior view
b Light and shadow effect created by the facetted surface
B 5.21 Extension of the *Bauakademie*
a Computer simulation of a flow pattern for determining the design
b Formwork sections, fabricated with 3D milling machines
B 5.22 Use of latex formwork, Steffen Sendelbach, Jakob Rauscher
B 5.23 Hybrid stone made from UHPC with hollow polystyrene bodies, application on a small scale
a Fabrication using polystyrene core
b Detail of the corner formation
B 5.24 "Printed" sculpture, D-shape Enrico Dini

B 5.22

B 5.23

B 5.24

Sustainable construction with concrete

Peter Lieblang

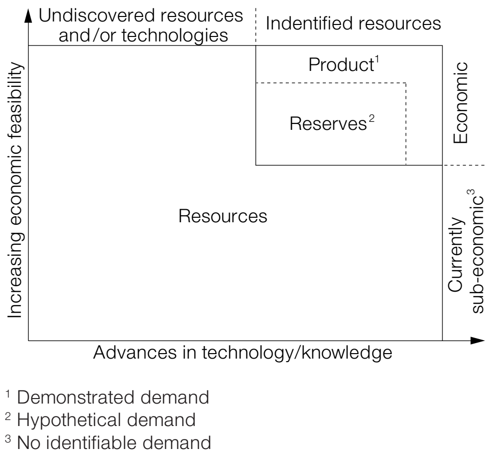
C 1.1

The expression "sustainability" has its origins in the forestry industry. It was first used in the beginning of the 18th century to describe measures in the management of woodland to secure the best possible, long-term and reliable timber yields [1]. The term was broadened and defined in the 1987 report titled "Our Common Future" from the World Commission on Environment and Development (Brundlandt Commission): "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. Sustainable building means construction, operation and use of buildings in a manner that takes all three aspects of sustainable development equally into account – the ecological, economic and the social aspects.
This definition of sustainability is based on two fundamental principles: on the one hand, it is legitimate for humans to shape and change their existing environment to meet their needs, yet, on the other hand, this is limited by the current level of technological development, social structures and finite natural resources.

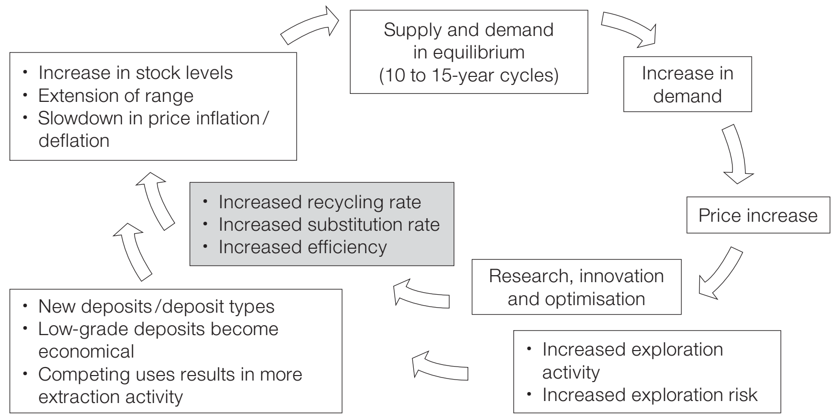
Resource efficiency as a criterion for sustainable construction

Natural resources define the ecosystem. This includes the earth's crust as a finite source of raw materials and the atmosphere with its limited capacity to absorb emissions. All natural resources are finite and therefore scarce, not only for future but for present generations. A sustainable future would ideally ensure that resources become no scarcer in the future than they are today, however, this seems unlikely. On the one hand, the availability and demand are constantly changing, and on the other, forecasts are inevitably confined to the horizon of the present generation's knowledge.
In the last twenty years, the use of natural resources has played an important role in the debate on sustainability. Yet, a distinction must be made between the energy resources and the mineral raw materials required for construction using concrete. Additionally, there is a notional distinction between resources and reserves. The former describes confirmed deposits where extraction is not currently technically and/or economically viable and the as yet undiscovered (unconfirmed) deposits where extraction is geologically feasible and available for future exploitation. The reserves form the known resources that are geologically and geographically identified and economically viable using existing technologies. The sum of the resources and the reserves is the potential remaining raw material, which can be further subcategorised by composition and origin, mineral, fossil, plant or animal. The term renewable raw material is mainly used to describe material produced from biomass in agriculture or forestry.
A decisive criterion for the sustainable use of a raw material is its scarcity. A suitable parameter is required for this concept. Often for this purpose it is defined by the quotient of the current known reserves and the rate of depletion (unit of time / extraction quantity) or as the lifetime of reserves at current consumption. This is referred to as the static lifetime and is given in years. According to the German Federal Institute for Geosciences and Natural Resources (BGR), the static lifetime for lead and zinc is 25 years, copper approx. 35 years, oil 40–45 years and natural gas 60–65 years [3]. Static lifetimes have remained fairly constant since the end of the Second World War despite continuous exploitation and an increase in extraction rates. This demonstrates that the static lifetime of reserves does not give the date of its exhaustion but rather serves as an indicator of how important it is to develop alternatives, how urgently new reserves need to be found or existing reserves used more efficiently. An evaluation of the dynamic lifetime includes projected changes to the rate of extraction and changes in the volume of reserves. The apparent contradiction that reserves increase despite continuous extraction can be explained in that mining companies increase their exploration and discover new deposits or that new technologies make exploitation of deposits with lower concentrations possible or economical. Such activities are in many cases driven by

C 1.1 Quarry
C 1.2 McKelvey diagram for distinguishing between resource and reserves
C 1.3 Supply cycle for raw materials as a dynamic equilibrium



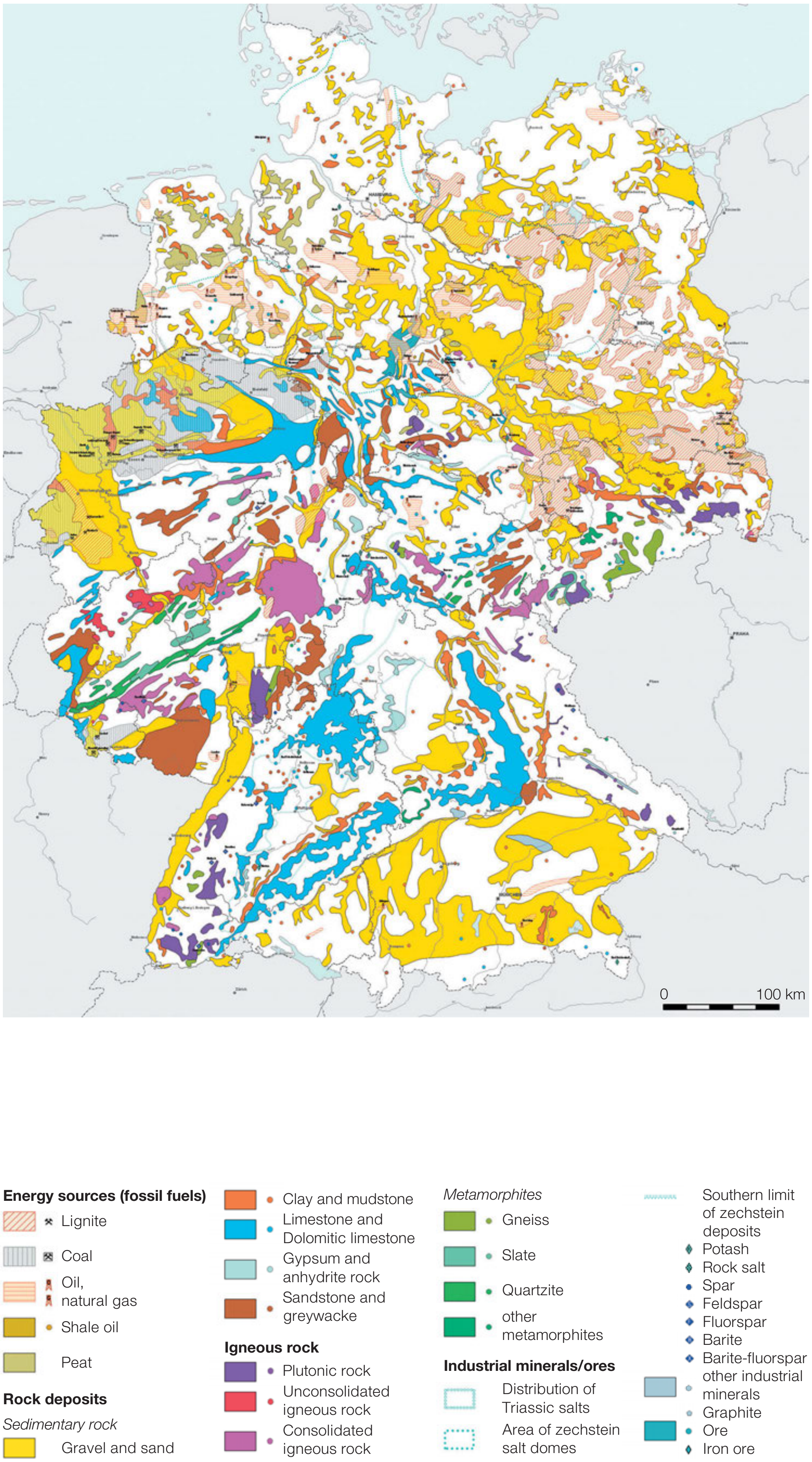
C 1.2



C 1.3

increases in raw material prices caused by real or perceived scarcity. Paradoxically, a long static lifetime can, combined with low market prices, have the consequence that a raw material becomes scarce because research and innovation into the search for new reserves, alternative technologies and potential substitutes is neglected. Leading to what is referred to as raw material cycles or commodity cycles (Fig. C 1.3).
For example, the global static lifetime reserves of all fossil fuels – coal, oil, gas and uranium – is 82 years and of the resources a further 1,232 years. Overall, even with rising consumption, global energy needs can be met. Certain raw energy resources are already scarce; oil, for example, makes up 23 % of total reserves or 2.9 % of the total of all energy resources, yet accounts for 34.2 % of all current energy consumption (as of 2010). Given a constant extraction rate at current levels and taking into account heavy oils, oil sands and shale oil – that are economically viable given a higher oil price – the static lifetime of oil reserves is 54 years; the static lifetime of oil resources is an additional 74 years. This compares to the global static life-time of coal reserves at 115 years and static lifetime of coal resources at a further 2,730 years. Furthermore, energy resources are geographically unevenly distributed. With the exception of domestic lignite deposits, Germany is especially low on energy producing raw materials and is heavily reliant on imported fuels [4].
The example of Germany shows that the availability of mineral raw materials for concrete construction is fundamentally different from that of energy producing raw materials. Domestic production covers the entire consumption of mineral resources for construction purposes. Imports and exports account for a very low proportion and are usually necessary only if there are special quality criteria or if sources of raw materials are to be found near the border. Comparatively high transport costs are a barrier, limiting the transport of mineral raw materials over long distances by road. The lifetime of domestic mineral reserves and resources cannot be accurately predicted. The structure of the sector, consisting of many small-scale businesses with no obligation to report, allows only an incomplete statistical assessment. However, there is no scarcity of mineral raw materials from a geological perspective. With enough reserves, there will be no shortage of mineral raw materials for 1,000 years – a period that exceeds human prediction time frames.
In contrast, extraction rights for many mineral quarries are granted for no longer than about a decade. It is therefore only economic pressures through competition for land use that threaten the supply of mineral raw materials. Similar to energy producing raw materials, a shortening of lifetime cycles can be overcome by changes to planning and licensing policy.
A diminishingly small proportion of the total surface area in Germany is used for mineral extraction; at 28.87 km² [5], this equates to roughly the area of the North Sea island of Norderney. Further deposits of mineral raw materials would be easily available with only a small increase in the land area for extraction. Given these circumstances, it can be concluded that Germany has sufficient mineral deposits for construction that are seemingly inexhaustible on a human time scale (Fig. C 1.4, p. 118). This conclusion holds true on a global scale, too.

This contrasts significantly with the situation of renewable raw materials such as timber. To prevent depletion in sustainably managed forests, timber production is limited to the annual growth. The annual growth is dependent on many factors such as tree species, tree density, the age of the timber stock, geographic location, climate, etc. In unmanaged forests, timber that is not extracted falls and remains as dead and decaying wood on the forest floor. There is, therefore, no net growth in natural unmanaged forests. In Germany, the mean annual growth of all timber species is 11.1 m³/ha [6]. The annual growth exceeds extraction by 10 %, meaning the German forestry industry is sustainable; this is in contrast to the global situation. According to the Food and Agriculture Organization of the United Nations (FAO) [7] the total global land area of forest is approx. 4,033 million ha (as of 2010). Although deforestation continues globally, the rate of depletion has slowed from 0.2 % annually between 1990 and 2000 to 0.13 % annually from 2000 to 2010 (Fig. C 1.6, p. 119).
At the same time, demand for renewable raw materials, including timber, continues to grow, driven, amongst other factors, by population growth. According to the FAO, the use of wood as fuel rose between 2006 and 2008 by 0.235 %; in the same period the industrial use of trunk wood increased by 5.9 %. Meeting increasing demand by depleting forests goes against the principles of sustainable forest management and results in a disproportionate reduction in the lifetime of a renewable resource. It is possible to increase the productivity of woodland by bringing natural forests into economic production, increasing yield through improved forest management of plantation woodland or using other more productive tree species. Irrespective of such measures, sustainable domestic production can meet Germany's timber requirements. However, worldwide timber production does not follow these sustainable principles. There is no unlimited supply of so-called renewable raw materials. This term simply indicates that reserves and resources have a lifetime that extends beyond the foreseeable future, just as it does for mineral raw materials. Comparisons show that the depletion of forests (3.3 % deforestation between 1990 and 2010) is many times greater than the depletion rate of mineral raw materials, where the depletion rate of resources is in the range of thousandths per year.
In principle there is no practical difference between mineral or renewable raw materials. In the light of resource scarcity, both types of raw materials are suitable for use in the construction of sustainable buildings. Two strategies can be identified. On the one hand, the use of scarce raw materials is appropriate if the buildings or building components are to meet the needs of several generations over their lifespan. This is likely to apply to all buildings that meet basic human needs and are designed for flexibility. On the other hand, the use of raw materials is not significant if there is no scarcity, if the lifetime of existing reserves extends beyond the foreseeable future or if a raw material that is currently



C 1.4

scarce will either no longer be required or even suitable to meet changing needs of future generations. In the last two cases the sustainability can only be analysed retrospectively. In all cases, a life cycle assessment is necessary.

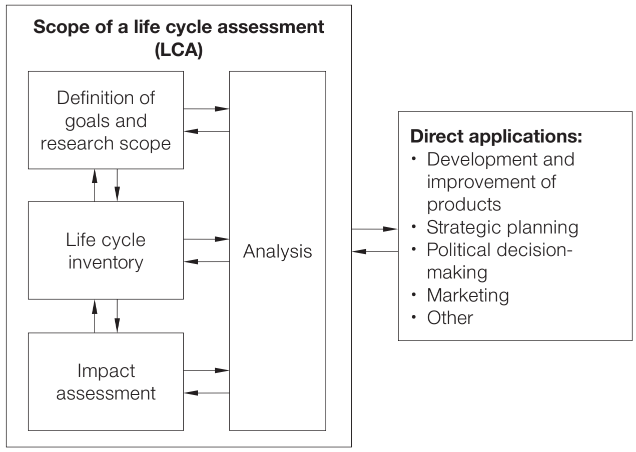
Determining the criteria for a sustainability analysis

Life cycle assessments (LCA) [8] provide a tried and tested tool to evaluate the environmental characteristics of building materials such as concrete, in that they define the criteria for a sustainability analysis. To assess the environmental impact of a product through its life-cycle as comprehensively as possible, the analysis is divided into phases (Fig. C 1.5):

- Definition of goals and scope
- Life cycle inventory (inventory of all materials and energy flows required to produce a functional unit)
- Impact assessment (using standard impact categories)
- Interpretation (including a critical evaluation)

Life cycle analyses can serve very different purposes:
- Comparison of the environmental properties of different products
- Improvement of environmental properties of a product in the different stages of its life cycle
- Identifying relevant indicators and measuring techniques for the environmental properties of a product
- Development of internal procedures for optimisation of production processes from an environmental perspective

This standardised methodology produces objective results. In all cases there is an initial inventory of all material and energy flows. However, the limits of the assessment goals can differ substantially. The type of product is of considerable significance. Although DIN EN ISO 14040 [9] uses the term “product”, this covers not only material objects but also includes intangibles (goods or services). The so-called functional unit is used as a generalised reference value for impact assessments, defined in the DIN EN ISO 14040 abstract as the “quantified performance of a product system for use as a reference unit”.
For example, a comfortable interior environment in a residential building can be achieved either with mechanical systems (heating and air conditioning), or with the adaptive and structural design of the building’s envelope, taking building physics into account. Specifying the use of particular products, such as the quality of insulation, would lead to distorted results. Instead, a definition of a functional unit in the form of a necessity (a comfortable indoor



C 1.5

C 1.4 Mineral deposits in Germany
C 1.5 Phases of a life cycle assessment
C 1.6 Changes to forest cover and managed forests worldwide
a Forest
b Commercial forests

climate), makes a more precise and objective evaluation possible. In the case of products with multiple uses – this includes most building materials – limiting the definition of the functional unit to a phase in the life cycle provides a basis for further analysis. The quantified performance of building materials – unlike the normal user evaluation of commodities – is at first sight not obvious. For example, 1 m^3 of concrete could be used to build an activation tank in a sewage treatment plant, to manufacture ornamental flowerpots or to build retaining walls in an urban excavation pit. In each specific case, the product performance is clear. However, it would be impractical to perform renewed impact analyses for each application. For this purpose, environmental impact assessment data must be made available for the evaluation of building products that may be equally suitable for many different applications. Life cycle assessments for building materials form the underlying data for the evaluation of entire buildings. DIN EN 15804 [10] refers in this context to the "declared unit".
Six impact categories have emerged, representing essential bases for human life and their consumption or scarcity as an indicator of sustainability:

- Global warming potential (GWP, given in CO_2-equivalents)
- Ozone depletion potential (ODP, given in CFC-equivalents)
- Acidification potential (AP, given in SO_2-equivalents)
- Eutrophication potential (EP, excessive accumulation of nutrients in water, given in PO_4-equivalents)
- Photochemical oxidation potential (POPC, summer smog, given in C_2H_4-equivalents)
- Consumption of non-renewable energy resources (given in MJ)

The standardised application of these categories allows a comparison since diverse impacts can be reduced to six basic units of measurement. However, the fact that an impact assessment is already implicit in the choice of the equivalent values should not be overlooked. Life cycle assessments always refer to individual cases and the results are meaningful only in relation to predetermined goals or questions. The inadmissibility of direct comparisons between individual building products on the basis of their life cycle assessment is illustrated by figures from the German Federal Ministry of Transport, Building and Urban Development (BMVBS) that give environmental profiles for building materials [11]. The manufacture of 1 m^3 solid structural timber (r = 529 kg/m^3, moisture content 15 %) requires 4,271 MJ (non-renewable primary energy), whereas 1 m^3 regular concrete (C25/30, r = 2,365 kg/m^3) requires 1,228 MJ. Structural timber contains 3.5 times the embodied non-renewable energy as the same volume of concrete; mass for mass, this ratio increases to slightly more than 15:1.

Although it might seem reasonable to use the results of the life cycle analyses for product labelling and for direct comparison, this does not work for building materials, despite identical impact categories, because the application is not known. Life cycle impact assessments of building materials offer interim values and provide meaningful results only when used as part of an assessment of an entire building. In order to avoid meaningless or improper comparisons between seemingly identical product categories, environmental product labels for various intended applications have proved useful. Compared to other products, building materials have a diverse range of applications, and only Environmental Product Declarations (EPDs) or the Type III environmental label in accordance

Region	**Forested area**			**Change**			
	Total 1990	Total 2000	Total 2010	1990–2000		2000–2010	
	[1,000 ha]	[1,000 ha]	[1,000 ha]	[ha]	[%]	[ha]	[%]
World	4,168,399	4,085,063	4,032,905	-83,336	-2.00	-52,158	-1.28
Central Asia and Middle East	126,612	121,431	122,327	-5,181	-4.09	896	0.74
North America	676,760	677,080	678,958	320	0.05	1,878	0.28
Latin America and Caribbean	978,072	932,735	890,782	-45,337	-4.64	-41,953	-4.50
Europe	989,471	998,239	1,005,001	8,768	0.89	6,762	0.68
Asia and Pacific	733,364	726,339	740,383	-7,025	-0.96	14,044	1.93
Africa	749,238	708,564	674,419	-40,674	-5.43	-34,145	-4.82

a

Region	**Productive forest (incl. plantations)**			**Change**			
	Total 1990	Total 2000	Total 2010	1990–2000		2000–2010	
	[1,000 ha]	[1,000 ha]	[1,000 ha]	[ha]	[%]	[ha]	[%]
World	1,359,883	1,375,164	1,395,294	15,281	1.12	20,130	1.46
Central Asia and Middle East	60,594	59,335	61,430	-1,259	-2.08	2,095	3.53
North America	100,205	116,944	134,667	16,739	16.70	17,723	15.16
Latin America and Caribbean	82,589	89,226	98,330	6637	8.04	9104	10.20
Europe	617,088	587,978	593,938	-29,110	-4.72	5,960	1.01
Asia and Pacific	323,149	349,982	350,403	26,833	8.30	421	0.12
Africa	222,607	215,651	201,436	-6,956	-3.12	-14,215	-6.59

b

C 1.6

1 Allgemeine Angaben

Verein Deutscher Zementwerke

Programmhalter
IBU - Institut Bauen und Umwelt e.V.
Rheinallee 108
D-53639 Königswinter

Deklarationsnummer
EPD-VDZ-2012111-D

Diese Deklaration basiert auf den Produktkategorienregeln:
PCR Zement, 11-2011
(PCR geprüft und zugelassen durch den unabhängigen Sachverständigenausschuss)

Ausstellungsdatum
16.03.2012

Gültig bis
15.03.2017

Prof. Dr.-Ing. Horst J. Bossenmayer
(Präsident des Instituts Bauen und Umwelt e.V.)

Prof. Dr.-Ing. Hans-Wolf Reinhardt
(Vorsitzender des SVA)

Zement

Inhaber der Deklaration
Verein Deutscher Zementwerke e.V.
Tannenstraße 2
40476 Düsseldorf

Deklariertes Produkt/deklarierte Einheit
1 t Zement

Gültigkeitsbereich:
Die vorliegende Umweltproduktdeklaration bildet die Ökobilanz der Herstellung eines Zements mit einer durchschnittlichen Zusammensetzung in Deutschland im Jahr 2010 hergestellter Zemente ab. Die Ökobilanz, die der EPD zugrunde liegt, beruht auf Daten von 51 der 54 deutschen Zementwerke. Diese decken ein Produktionsvolumen von ca. 95 % der Zementproduktion Deutschlands ab. Die in der Ökobilanz abgebildete Technologie kann aufgrund dieser hohen Beteiligung der Zementwerke als repräsentativ für die Zementherstellung in Deutschland betrachtet werden. Der Inhaber der Deklaration haftet für die zugrundeliegenden Angaben und Nachweise.

Verifizierung

Die CEN Norm EN 15804 dient als Kern-PCR

Verifizierung der EPD durch eine/n unabhängige/n Dritte/n gemäß ISO 14025

☐ intern ☒ extern

Dr. Eva Schmincke
Unabhängige/r Prüfer/in vom SVA bestellt

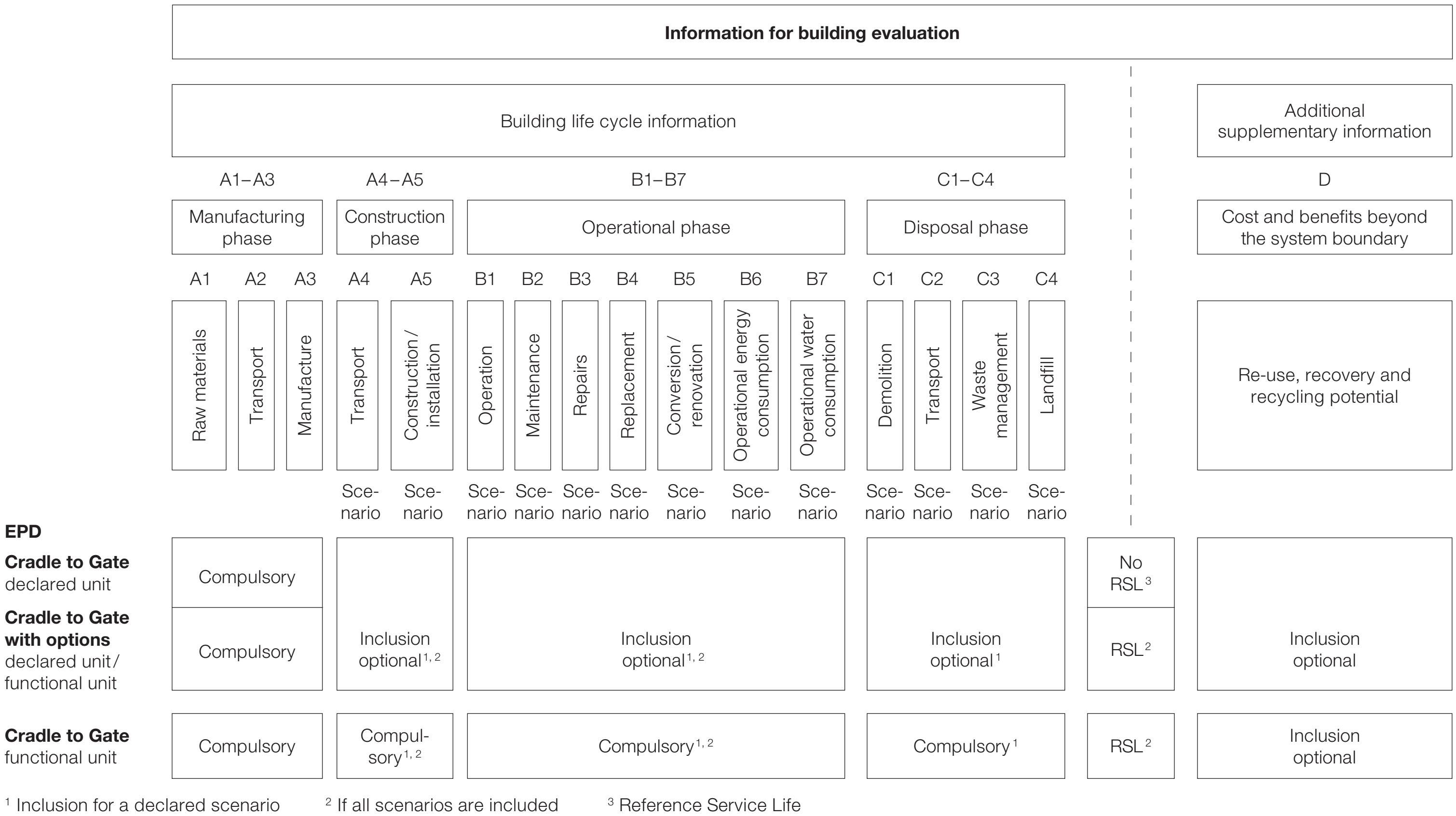
C 1.7

with DIN EN ISO 14025 (Fig. C 1.7) [12] are suitable for product identification. These are based on standardised evaluation procedures and administered through a so-called Environmental Declaration Programme. At present, the best known programme is operated by the Institute for Construction and Environment e. V. (Institut Bauen und Umwelt e. V.). Its product category rules ensure a comprehensive classification of material- and energy flows within an environmental impact assessment. DIN EN 15804 provides a type of modular conception, making it possible to determine the impact assessment data for building products (Fig. C 1.8).
Environmental profiles are now available for a large number of building products. They are available, for example, in the database "Ökobau.dat" or published in the form of EPDs cf. www.bau-umwelt.de. The other two aspects of sustainability, the economic and the social, do not feature significantly in Type III environmental labelling and are only taken into account in a holistic evaluation of a building component or an entire building.

Environmental impact assessment profile of concrete and cement

The basis for the determination of the environmental impact assessment profile for ready-mixed concrete [13] and cement in the course of a "holistic life-cycle assessment for building materials and buildings" [14] is the "cradle to gate" approach, which looks only at the extraction of raw materials, transport to the production plant and the actual production up to delivery to the factory gate (Fig. C 1.8, information module group A1 to A3). The data represents product averages and does not take manufacturer-specific factors into account. This is especially useful if the use of a specific product is associated with high transport costs, such as is the case with heavy mineral-based building materials.
One cubic metre of concrete serves as a functional unit. This takes the differing compositions of concretes with compressive strength classes C20/25 to C100/115 into account. More than 80 % of ready-mixed concrete produced in Germany falls into these classes [15]. The life cycle inventory data for the upstream supply chain – the manufacture of cement and the extraction of water and aggregates that takes place away from the ready-mix plant – results primarily from the extraction and processing of the raw materials and transport. Life cycle assessments, environmental profiles, industry-wide surveys [16] or reasonable approximations are used as a source of data. Table C 1.9 shows the environmental profile for different concretes. It demonstrates that the environmental impact increases with the concrete's compressive strength class and is related ultimately to the concrete's cement content.
An evaluation of sustainability is not possible using building material profiles alone because different compressive strength classes not only have different environmental properties but also economic consequences for the use of particular concretes. A greater compressive strength class allows thinner cross sections of components to be used within a concrete structure, which means lighter structures (with less reinforcement required and possibly less resources). Thinner cross sections reduce the concrete volume, which in turn reduces the transport costs from the concrete plant to the building site. In the case of highly stressed columns and slabs, concrete with a higher compressive strength can reduce the cross-sectional dimensions and result in a significantly greater floor area.
Ecological building material parameters should therefore be regarded as a basis for evaluating sustainability rather than the end result. They can, however, point to improvements in environmentally relevant production processes.
An impact analysis of ready-mixed concrete from 1996 and 2006 shows the primary energy required to produce 1 m³ of ready mixed concrete decreased by nearly 25 % and the global warming potential reduced by nearly 20 %. The use of secondary fuels and raw materials, such as scrap wood and used tyres, has contributed significantly to this reduction. Secondary fuels and raw materials have even completely replaced primary fuels for the operation of rotary kilns in some cement plants.
In addition the development of CEM II (blended cement) and CEM III (blast furnace cement) using other main constituents such as blast furnace slag, limestone powder, pozzolans, etc. has contributed to a further reduction in CO_2 emissions. In principle, a comprehensive, yet solely qualitative, consideration of all these environmental aspects can be carried out using the "Specification of Concrete" in DIN 206-1 and DIN 1045-2 [17]. Architects can, in theory, specify concrete with a particular cement type. However, an environmentally motivated mix design (a detailed specification of its constituent materials) is not advised. A purely environmentally motivated specification of the cement, without consideration of the technical performance of the wet and hardened concrete, can be detrimental to construction schedules (stripping times) or the durability of the resulting concrete components. Also, not every cement plant will produce all cement types, so it may be that the environmentally advantageous cement type would need to be transported great distances, with all the inherent environmental disadvantages. A knowledgeable planner can find the environmental and structural properties from the tables of cement types from cement manufactures. To begin with, there should

C 1.7 Example of a type III environmental declaration
C 1.8 Information on building evaluation according to DIN EN 15804
C 1.9 Environmental Product Declaration for 1 m³ of ready mixed concrete of compression classes C20/25, C25/30 and C30/37



C 1.8

be clarification as to whether there are other compelling structural or operational requirements that should be considered above the environmental aspects in the choice of cement type. Research from the Association of German Cement Manufacturers (Verein Deutscher Zementwerke) shows that the environmental impact resulting from the manufacture of cement and concrete has very little influence on the overall result of a sustainability assessment.

Environmental impact assessment profiles of building materials as input data in sustainability assessments

There are now many environmental product declarations (EPDs) available for the ecological evaluation of a building project, for example, for cement and concrete. These building material product profiles serve as input data for the evaluation of building sustainability with the aid of an evaluation system. They contain information on primary energy consumption and the six recognised impact categories for the evaluation of the life cycle impact assessments (see page 119). The information is broken down into primary energy consumption from renewable and non-renewable sources, use of recycled raw materials, water consumption and waste generation, which is further subdivided into overburden, domestic waste, commercial waste and hazardous waste. The methodological approach for the determination of the data was established by BMVBS in Germany in coordination with the industry prior to the compilation of the environmental product declarations. Data transferred to the database Ökobau.dat [18], which holds all environmental product declarations, is summarised in a form that ensures the compatibility between the input data and the evaluation scheme. The form summarises for reference the results described below.

The relevant publications from the cement and concrete industry give specific information on the environmental product declarations (Figs. C 1.9, p. 121, and C 1.10) including data for cement, ready-mixed concrete and building components made from ready-mixed concrete.

Recycling and recycled materials in concrete construction

Portland cement clinker is a product of a chemical and mineralogical conversion process. The most significant step in its manufacture is heating followed by a rapid cooling of the raw materials – lime, clay and (quartz-) sand – in a rotary kiln. In Germany, plants for heating and cooling cement clinker use the energy efficient semi-dry or dry processes (Fig. C 1.12). In the European cement industry, the produc-

Parameter	Unit	C20/25	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60	C55/67	C60/75	C70/85	C80/95	C90/105	C100/115
Non-renewable primary energy	MJ	1,024	1,108	1,196	1,327	1,379	1,437	1,494	1,577	1,661	1,745	1,839	2,013	2,145
Renewable primary energy	MJ	19.3	20.9	22.5	25	26	27	28	29	29	30	31	34	35
Global warming potential (GWP)	kg CO_2-eqv.	196.3	216.5	237.1	265	276	289	303	315	327	341	356	378	398
Ozone depletion potential (ODP)	kg CFC-eqv.	$5.33 \cdot 10^{-6}$	$5.80 \cdot 10^{-6}$	$6.29 \cdot 10^{-6}$	$7.0 \cdot 10^{-6}$	$7.3 \cdot 10^{-6}$	$7.6 \cdot 10^{-6}$	$7.9 \cdot 10^{-6}$	$8,3 \cdot 10^{-6}$	$8.7 \cdot 10^{-6}$	$9.1 \cdot 10^{-6}$	$9.6 \cdot 10^{-6}$	$10.4 \cdot 10^{-6}$	$11.1 \cdot 10^{-6}$
Acidification potential (AP)	kg SO_2-eqv.	0.356	0.385	0.415	0.46	0.48	0.50	0.52	0,56	0.60	0.62	0.66	0.73	0.79
Eutrophication potential (EP)	kg PO_4-eqv.	0.0501	0.0540	0.0582	0.065	0.067	0.070	0.072	0,077	0.081	0.085	0.090	0.098	0.0106
Photochemical oxidation potential (POCP)	kg C_2H_4-eqv.	0.0362	0.0394	0.0427	0.047	0.049	0.051	0.053	0,056	0.058	0.062	0.065	0.069	0.074

C 1.9

Parameter	Unit	Production phase (A1–A3)
Global warming potential	[kg CO_2-eqv.]	691.7 [1)]
Ozone layer depletion potential	[kg CFC11-eqv.]	$1{,}50 \cdot 10^{-5}$
Acidification potential for ground and water	[kg SO_2-eqv.]	0.83
Eutrophication potential	[kg PO_4^{3-}-eqv.]	0.12
Tropospheric ozone build-up potential	[kg Ethylene-eqv.]	0.1
Potential for abiotic depletion of non-fossil resources	[kg Sb eqv.]	$1.30 \cdot 10^{-3}$
Potential for abiotic depletion of fossil fuels	[MJ]	1,901.4

[1)] This figure includes 98.1 kg CO_2-eqv. from energy generation through waste incineration for the production of clinker. If the "polluter pays" principle is followed (DIN EN 15804), this should be attributed to the product system that originally produced the waste. However, this figure is not subtracted from the EPD in order to compare the global warming potential for cement beyond country borders since secondary fuels used in other countries for the production of clinker may not have the status of waste.

a

Parameter	Unit	Production phase (A1–A3)
Renewable primary energy sources, used as energy source	[MJ]	65.8
Renewable primary energy sources, used as materials	[MJ]	0
Total renewable primary energy sources	[MJ]	65.8
Non-renewable primary energy sources, used as energy source	[MJ]	2,451.3
Non-renewable primary energy sources, used as materials	[MJ]	0
Total non-renewable primary energy sources	[MJ]	2,451.3
Use of secondary materials	[kg]	167.4
Renewable secondary fuels	[MJ]	580.5
Non-renewable secondary fuels	[MJ]	1,161.1
Use of fresh water resources	[m^3]	0.18

b

Parameter	Unit	Production phase (A1–A3)
Hazardous waste for disposal	[kg]	0.008
Non-hazardous waste for disposal	[kg]	0.003
Radioactive waste for disposal	[kg]	0.180
Re-use of components	[kg]	0
Materials for recycling	[kg]	0
Material for energy recovery	[kg]	0
Energy generation	[MJ]	0

c

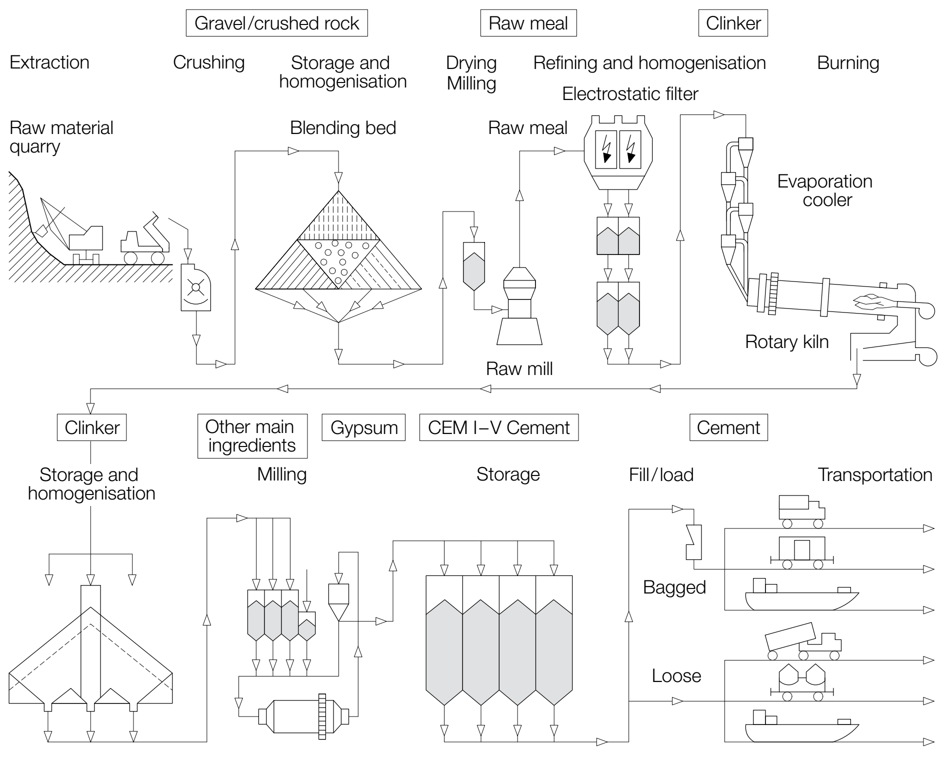
C 1.10

tion capacity of a kiln is in the region of 4,000 to 6,000 tonnes per day. The investment for a new cement plant of this type is approx. €400 million (Fig. C 1.11). Other countries, with less stringent environmental regulations, e.g. emerging or developing economies, operate small or even vertical shaft kilns. Yet in developing regions, there are large cement plants with production capacities of up to 10 million tonnes of clinker per annum. In comparison, the European industrial sector is quite homogenous in terms of process engineering and has very high environmental standards. The basic technical conditions for the efficient use of raw materials differ only in detail. All cement plants in central Europe possess a series of common characteristics that, on the one hand, are important for the composition of the raw materials and the energy use, and on the other, offer diverse possibilities for the use of recycled materials. Waste materials produced in other industrial processes are used in the production of cement in place of primary raw materials or primary energy sources. The combustion process in the production of cement is particularly suitable for the low emission co-incineration of secondary, recycled materials.
This has given rise to four fundamental strategies for the use of secondary materials for sustainable construction with concrete and cement:

- Substitution of primary energy sources with secondary sources, domestic and commercial waste or the by-products of industrial processes that have a suitable physical composition and calorific value for use in cement production (e.g. scrap wood, used tyres or waste oil)
- Substitution of primary raw materials in cement and concrete production with the by-products of other industries or recycled materials (e.g. blast furnace slag or fly ash)
- Substitution of Portland cement clinker with alternative raw materials of various compositions (e.g. foundry casting sand)
- Use of secondary materials in the form of concrete additives, e.g. fly ash

Three factors – ecological, economic and social – need to be considered when determining whether the use of a secondary material is sustainable. This can only be determined on the basis of a meaningful functional unit of the appropriate quality. To ensure good working properties, suitable for use in construction, the composition of Portland cement clinker should be 66 % by weight (wt %) calcium oxide (CaO), approx. 20 wt % silicon dioxide (SiO_2) and about 9–10 wt % aluminium oxide + iron oxide (Al_2O_3 + Fe_2O_3). Even small deviations from this optimal composition can have serious consequences for the manufacturing process and the quality and structural properties of the end product (Fig. C 1.13). Thus, a change of only 2 % in the raw material composition can affect the mineralogical composition – and thereby the structural properties of cement – by more than 40 %.
Secondary materials used in cement production fulfil nearly the same function as the primary materials. The composition of the raw materials – even when using secondary materials – must always be adequate to produce Portland cement clinker of the required quality. This can be visualised with a so-called triangle diagram, with the main constituents of Portland cement clinker as the axes (Fig. C 1.14).

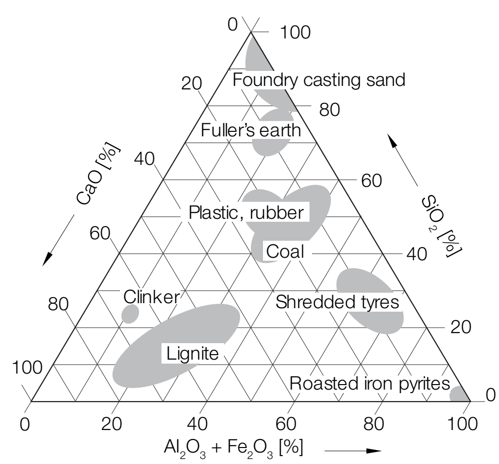
C 1.11



C 1.12

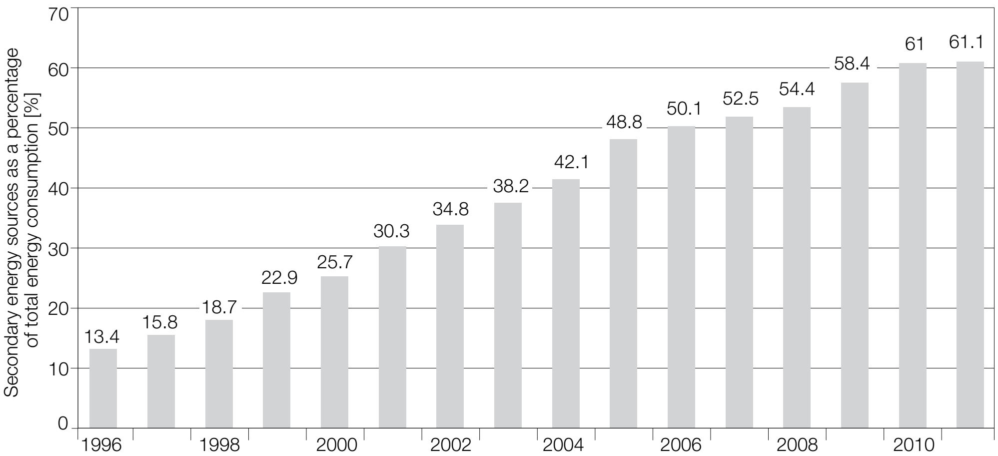
Raw materials		I	II	III
Calcium Oxide CaO	[%]	66	63	66
Silicon Dioxide SiO_2	[%]	20	22	20
Aluminium Oxide Al_2O_3	[%]	7	7.7	5.5
Iron Oxide Fe_2O_3	[%]	3	3.3	4.5
Cement clinker				
Tricalcium Silicate C_3S	[%]	65	33	73
Dicalcium Silicate C_2S	[%]	8	38	2
Tricalcium Alluminate C_3A	[%]	14	15	7
Dicalcium Ferroalluminate C_2 (A, F)	[%]	9	10	14

C 1.13



C 1.14

C 1.10 Impact potential data for 1 tonne of cement
a LCA results on environmental impact
b LCA results on resource use
c LCA results on output flows and waste categories
C 1.11 Cement plant Bernburg in Sachsen-Anhalt (D)
C 1.12 Cement production processes
C 1.13 Effects of changes to raw material composition on clinker phase
C 1.14 Triangle diagram showing composition of clinker and secondary raw materials.



C 1.15

Substitution of primary energy sources with secondary sources

The use of secondary energy sources in the cement industry is nearly always advantageous; this is because it has both energy and material benefits. When incineration releases energy from waste, the resulting ash usually needs to be disposed of; here it can be utilised within the production process and incorporated as a material component of cement. However, as with primary energy sources, the make-up of the secondary fuel, including the addition of ash, must be precisely controlled to meet the strict requirements for cement quality. Fig. C 1.16 summarises the criteria for the use of secondary fuels. It can be seen that there are no hard and fast rules for the substitution of primary energy sources, but solutions need to be found for each particular application. The German cement industry stands out in international comparisons with a particularly high use of secondary fuels, a proportion that has continued to increase in the last decades and currently averages 60 % for the sector. The reasons for this high proportion are environmental, but also the economic benefits (Figs. C 1.15 and C 1.16).

Substitution of primary mineral raw materials with secondary materials

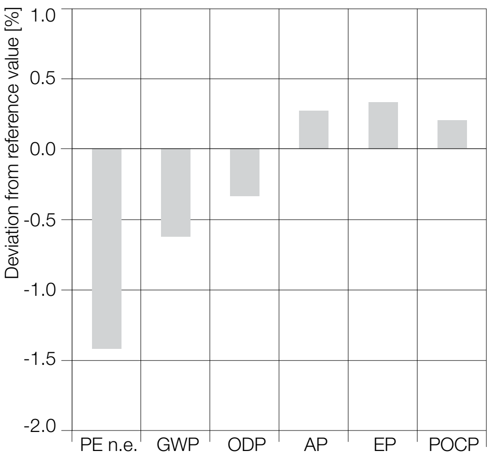
Similarly, secondary raw materials that cannot be converted into energy can replace limestone, clay or (quartz-) sand and contribute to sustainable construction with cement and concrete. Typical secondary materials used in the production of Portland cement clinker are: lime slurry from wastewater and water treatment plants, used foundry sand, pyrite cinder, fly ash, and slag and mill scale from the iron and steel industries. They replace primary materials containing lime, silica or iron, though only substitution of the latter two make up a significant proportion of the total material requirement. Although lime slurry is used extensively in water treatment plants, it does not occur in sufficient quantities to replace a large proportion of the primary lime-based materials (limestone and marl) needed for the production of cement. Additionally, all the substitutes that replace primary raw materials only (and are not also secondary energy sources) are bulky materials with high transport costs relative to their material value. It therefore only makes economic (and environmental) sense to source such materials from the immediate vicinity of a cement plant. A specific example, where the feasibility is currently under investigation, is sand from crushed concrete made in the course of the demolition and recycling of concrete structures. Crushed sands are the fine particles, with grain sizes of up to 4 mm, produced in crushers from old concrete. The properties of crushed concrete sand depend mainly on the make-up of the source concrete and the reprocessing methods, and can vary significantly. This applies to the aggregates and to the binders. While Portland cement (CEM I) was predominantly used in older concretes, more recent concretes increasingly contain Portland cement composites (CEM II). The variation in aggregates is mainly due to local availability. Aggregates could be calcite stone (limestone) or quartzite stone (shingle and sand). Sand from crushed concrete, depending on its composition, can be a substitute for limestone, clay or sand. In a similar way to secondary energy sources, these materials must be suitable and allow for production of high-quality cement with the given production conditions (input materials and engineering processes) (Fig. C 1.17).

Research by the VDZ [19] shows that appraisals of the benefits of recycled crushed concrete sand within concrete need to be made on a

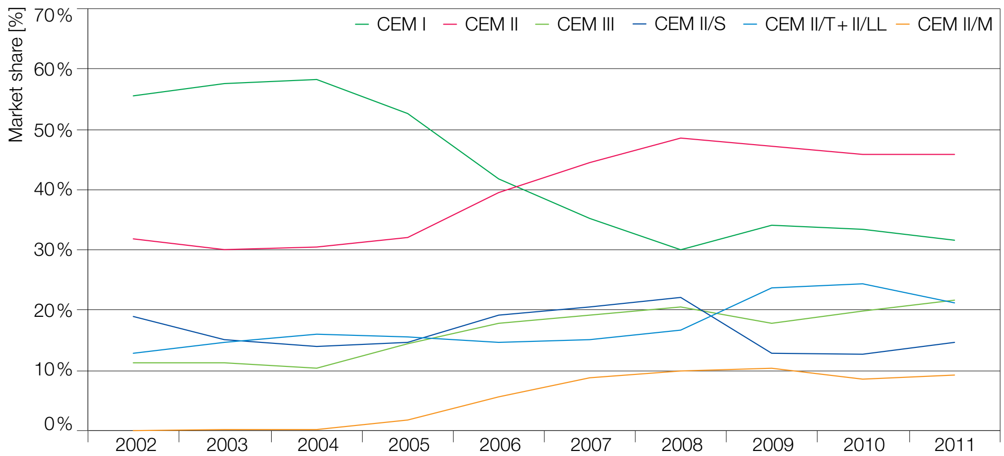
Physical properties	Chemical properties	Availability	Handling and operation
• Calorific value / moisture content • Reactivity, ignition and burning characteristics • Stability • Particle size • Dispersibility • Impurities / contaminants • Homogeneity	• Content and composition of ash • CO_2 emission factor and proportion of biogenic CO_2. • Content of recirculating compounds (chlorine, sulphur and alkalines) • Content of compounds relevant to quality (e.g. phosphate) • Fuel-nitrogen content • Trace element content (especially volatile compounds) • Total organic carbon content (TOC)	• Seasonal variations • Interruption of supply during furnace downtimes • Logistics • Alternatives	• Storage characteristics • Suitability for transport • Dosing capability • Opportunity for sampling and analysis • Health and safety • Safety related requirements (e.g. combustibility and risk of explosion)

C 1.16

C 1.15 Development of market share of secondary fuels in the German cement industry
C 1.16 Requirements for secondary fuels
C 1.17 Deviation of environmental impact indicators for primary energy from non-renewable energy sources (PE nr), greenhouse gas potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP) and photochemical oxidation potential (POCP), results of a plant-specific comparison under normal operating conditions without a reference case with the addition of crushed concrete.
C 1.18 Development of market share for different cement types



C 1.17



C 1.18

case-by-case basis. The suitability for substitution and chemical composition depends on the regionally sourced materials used within the original concrete as well as the grain size of the crushed concrete. The overwhelming majority of the crushed concrete tested was rich in silicic acid with lower quantities of calcium, allowing it to be used primarily as a corrective where raw materials are low in silica-based materials. Silica-based materials are already used in high quantities as substitutes, therefore crushed concrete can replace not only primary raw materials, but also can substitute secondary materials that might be better used in other applications. A decision on which option would make the biggest contribution to the sustainability of a concrete can only be made based on comprehensive observations that take the ecological, economic and operational/technical aspects into account:

- Regional availability in a consistent quality
- Compatibility with primary raw materials available locally
- Implications for energy use, CO_2 emissions
- Trouble-free kiln operation

The life cycle assessments carried out in this research show that the substitution of crushed concrete in clinker production is often beneficial. In the best cases, it can replace up to 3% of raw materials without adversely affecting production quality or the kiln operation. Computer simulations, confirmed by test operations in kilns, show that the use of partly deacidified crushed concrete in clinker production results in a 0.8%/t reduction in energy consumption. The resulting savings is mainly in primary fuel use. This results in a reduction of CO_2 emissions of about 0.6%. In addition, the resulting emissions of volatile organic compounds (VOC) and carbon monoxide (CO) were calculated. A reduction of less than 1% in CO emissions and a slight increase in VOC emission is to be expected compared to average emissions values from conventional raw materials. The volatile organic compounds are gases or vapours and can affect the environment in various ways. However, there are other configurations in which crushed concrete substitution exhibits better environmental performance in life-cycle assessments.

Substitution of Portland cement clinker with alternative materials

Another strategy to increase resource efficiency is the partial substitution of energy intensive Portland cement clinker with alternative materials. Clearly, these materials should not impair the technical properties of the cement. They must have latent hydraulic or pozzolanic properties such as those of blast furnace slag, fly ash, silica fume (a waste product of steel production or coal-fired power stations) or powdered limestone derived from primary raw materials. Given the right composition, CEM II and CEM III have a similar performance to CEM I. A comparison of their environmental impact using a life cycle assessment shows that a blast furnace slag content of 30% (50%) reduces impact categories by around 20% (40%). However, the indicator of primary energy consumption fell by only half as much since the energy required for clinker production is already made up from 50% secondary fuels, for which the environmental impact is already taken into account in the supply chain. On the other hand, the electrical energy required is increased because the furnace slag may, depending on particle size, need additional grinding. The environmental benefits further decrease with increased transport distances for the secondary raw materials. Overall, the market share of blended cements in Europe has risen significantly. Fig. C 1.18 shows the development between 2002 and 2011 for Germany. The market share of CEM I is not likely to shrink any further in the near future because, for technical reasons, it is not always possible to substitute CEM I and also because the availability of suitable secondary raw materials is limited.

Use of secondary materials in the form of cementitious substitution

Because of their availability and technical properties, some industrial by-products are not only used in cement production but also in the production of concrete. This applies to fly ash and blast furnace slag in particular. Whether these materials are used in cement or concrete production, the environmental impact is more or less the same. More significant for the environment is the infrastructure necessary for the use of secondary raw materials; this includes the technical conditions and the sector-specific transport logistic systems. For example, in Germany, fly ash is predominantly used in concrete production, whereas in the USA, it is used in the production of cement. In contrast, in the United Kingdom blast furnace slag is added to concrete, while in Germany it is used exclusively within cement production. Irrespective of how it is deployed, its use reduces the environmental impact and improves the workability of the wet concrete, the development of hydration heat and the hardening properties of the concrete.

All four of the strategies described can only be sensibly employed if the local conditions are favourable. There should be no systematic take-up of such strategies without a consideration of the local circumstances, as it may result in the transport of great quantities of materials over long distances.

Concrete recycling

In Germany, 580.9 million tonnes of aggregate from primary sources were produced in 2008 for use in asphalt, concrete, bricks, and road construction materials [20]. Although the existing reserves will last for many generations, it makes sense to reuse the approx. 72 million tonnes of building and demolition waste produced in Germany even if, with a recycling quota of 80%, this represents only 10% of the total annual demand (Fig. C 1.19, p. 126).

Apart from the recycling of hardened concrete, the so-called returned concrete – fresh, wet, unused concrete returned from the building site to the concrete plant, or concrete residues from cleaning mixing machinery and vehicles – is also recycled (Fig. C 1.20, p. 126). The aggregate, water used for washing and fine-grained powders are recovered and fully reused in production. Once processed, concrete from demolition is used as aggregate [21]. Depending on local conditions and its quality, the recycled material can replace up to 45% of the gravel or chippings necessary

C 1.19

C 1.20

for concrete production (see “Recycled aggregates”, p. 30) [22]. However, this does not usually result in significant energy savings. Depending on the circumstances (e.g. transport distances), the primary energy consumption for recycled concrete can even be slightly higher than for concrete made from primary aggregates.

Life cycle analysis for buildings

The principles and requirements governing the assessment of the sustainability of entire buildings in the form of a life cycle impact analysis are contained, for example in DIN EN 15643, “Sustainability of Construction Works – Sustainability of buildings”. Analogous to the life cycle assessment of materials, this set of standards uses a so-called functional equivalent to define a building’s use. All of the user requirements must be summarised to facilitate comparisons between different scenarios. They cover technical criteria such as:

- Thermal and acoustic insulation
- Fire protection
- Structural integrity
- Durability

and functional criteria such as:

- Type of use (residential, office use, production)
- Building lifespan
- Surface area and building volume
- Spatial arrangement, etc.

The methodology contained in DIN EN 15643 describes the properties of a building in regard to sustainability as comprehensively as possible. An assessment of these properties must be undertaken using a separate scheme, which, due to individual user requirements, largely prevents standardisation (Fig. C 1.21). Life-cycle analyses can be used during the planning phase and as a forecasting tool. On the one hand, they can help to provide a comparison between different planned scenarios and an estimation of the effectiveness of proposed measures. On the other hand, the element of flexibility they contain can make the formulation of a uniform methodology difficult. The current regulations for the evaluation of sustainable construction provide no standard method for incorporating a building’s life cycle. Whilst the environmental assessment and life-cycle impact analysis, as component parts of a comprehensive life cycle analysis, have been extensively investigated, there is no generally accepted instrument for the evaluation of the socio-cultural and functional aspects of a building. A concept for a simplified, context-specific and automated application of methods does not yet exist.
Initially for the construction of government buildings, “Guidelines for sustainable construction for federal buildings” was made available by the BMVBS in 2001 and based on the concept of life cycle analysis. Subsequently, the BMVBS together with other interested parties (building organisations, representatives of the building industry and building administration and academics) as part of the “Round Table on Sustainable Building” compiled a catalogue of fundamental criteria. This defines – again only for government buildings – requirements for evaluating the ecological, economic, socio-cultural and functional aspects, quality of technology and systems as well as locality.
The outcomes of a life cycle assessment of type DIN EN ISO14040 serve as a basis for an ecological evaluation and have six impact categories (see p. 119). The impact on the global and local environment, as well as the consumption of resources (at least the energy, water and land use), must also be taken into account. Input data should be sourced from recognised Environmental Product Declarations or from the “Ökobau.dat” database. Data published by the BMVBS should be used as a basis for calculating the lifespan of a building. This evaluation scenario gives the planned lifespan of office and administrative buildings as 50 years. The expected lifespan for other building types can also be calculated. An important criterion for determining the useful life of a building is its operational energy consumption and energy type, based on the respective energy saving ordinance – EnEV/ DIN V 18599 “Energy efficiency of buildings – calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting”. According to DIN 276, “Costs in the Construction Industry”, the costs categories 300 and 400 (building costs for construction and technical installations) need to be incorporated into the environmental assessment as well as the primary energy consumption (renewable and non renewable). Drinking water usage and the type of land use also need to be evaluated.

Systems for rating the sustainability of buildings

In recent years most industrialised countries have developed rating systems or certification schemes for sustainable buildings. This includes the United Kingdom (BREEAM), the USA (LEED), Germany (DGNB/BMVBS), France (HQE – Haute Qualité Environmentale), Canada (LEED Canada), Australia (Green Star), Japan (CASBEE – Comprehensive Assessment System for Building Environmental Efficiency) and India (TGBRS TERI’S – The Energy and Resources Institute, Green Building Rating System). These systems operate under the umbrella of the World Green Building Council (World GBC), whose primary aim is to promote the global exchange of information on developments in sustainable building and to make research results, standards and products available. Nevertheless, different countries base their schemes on different criteria and have their own individual rating systems. Although all systems have similar underlying objectives, the range of concepts for the implementation of sustainable building is broad and diverse. There is no consensus on a rating system.

BREEAM certification

The acronym BREEAM is made up from BRE (Building Research Establishment) and EAM (Environmental Assessment Method). With over 200,000 certified buildings worldwide, it

C 1.19 Impact crusher
C 1.20 Recycling plant for wet concrete
C 1.21 Concept used to describe sustainability according to DIN EN 15643-1

is numerically the leading sustainability rating method. Based on an evaluation of environmental features, it uses different evaluation schemes for different building typologies. There are, for example, BREEAM schemes for residential buildings, industrial buildings, law courts, prisons and for buildings in the healthcare sector. Customisation of existing rating schemes makes the evaluation of other individual building types possible. The emphasis of the nine ratings categories (Management, Health & Wellbeing, Energy, Transport, Water, Materials, Waste, Pollution, Land Use & Ecology) is on the ecological dimensions. Certified auditors award BREEAM certificates over five levels (pass, good, very good, excellent, outstanding) for new and existing buildings. There are special annual awards for buildings with the highest ratings.

LEED certification

LEED is an acronym of “Leadership in Energy and Environmental Design” and is a rating system for buildings introduced in 1998 by the US Green Building Council. Experts in different disciplines have developed the system autonomously. LEED rating systems are available for various building categories, e.g. residential, retail and schools. It is also possible to rate the building envelopes of new and renovated buildings or to evaluate town-planning schemes. The rating scheme takes the following five categories into account: sustainable site, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality and can include the bonus categories of innovation in design and regional priority. Depending on the building type, this list can be expanded to include additional criteria.

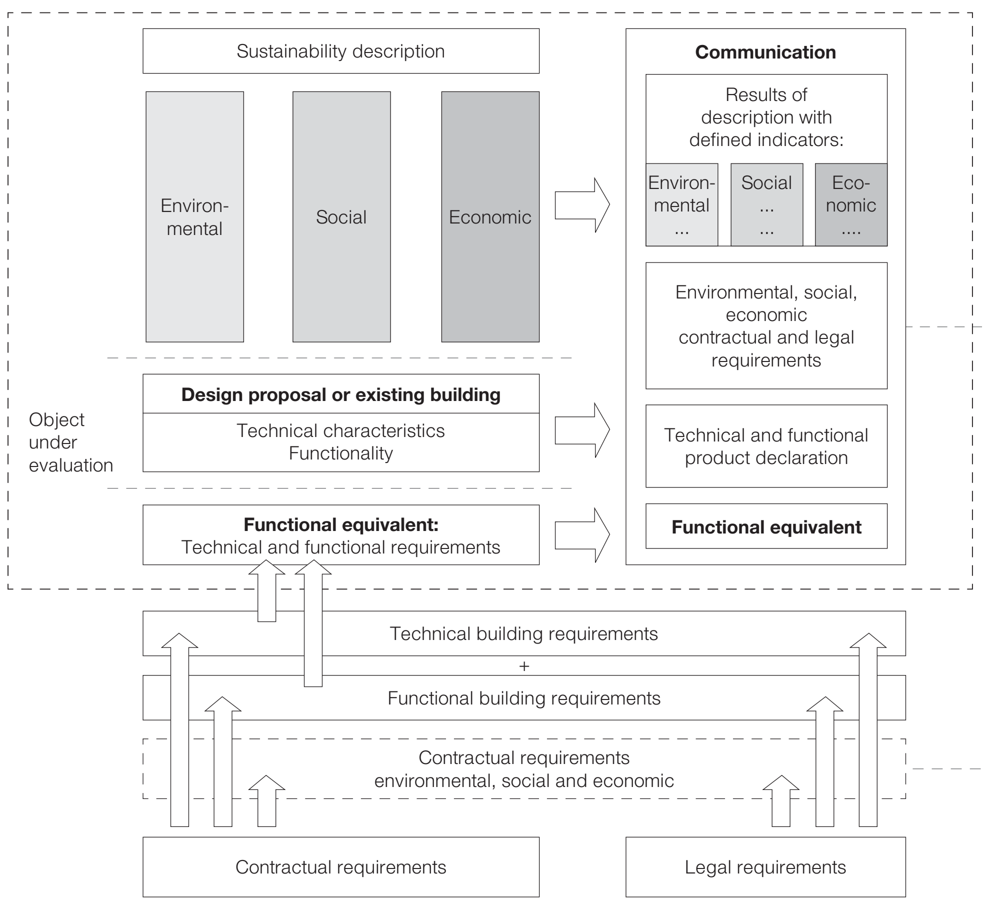
The main criteria of the DGNB/BMVBS rating systems

In Germany, the Federal Ministry of Transport, Building and Urban Development (Bundesministerium für Verkehr, Bau und Stadtentwicklung, BMVBS) has a rating system intended for non-residential buildings. The German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen, DGNB) has developed a similar scheme for residential buildings. Both rating schemes are based on open systems. To allow comparisons between the different systems and to ensure minimum quality standards, certain conditions need to be met. A sustainability analysis is carried out (a description and evaluation taking all three dimensions into account, see p. 116) using objective, detailed, clear and comprehensible parameters that lead to a (usually quantitative) evaluation. An award of the German Sustainable Building Certificate in gold, silver or bronze covers clearly defined quality levels. If the evaluation system is used for the purpose of certification, the regulatory and certifying bodies must operate a product certification system that meets the general requirements of DIN EN ISO/IEC 17 065 [23]. So-called round robin tests, in which reference buildings are evaluated, serve as a quality assurance measure.

The rating systems are based on a simple quantification of six sustainability criteria.

- Environmental quality
- Economic quality
- Socio-cultural and functional quality
- Technical quality
- Process quality
- Site quality

The minimum requirement for the evaluation of economic quality is a building-related life-cycle cost analysis (investigation, analysis,



C 1.21

Sustainability requirements			Weighting of individual criteria (% of total)	Impact factor	Weighting of criteria groups (% of total)
Environmental quality					22.5 %
Impact on the global and local environment	1.1.1	Global warming potential (GWP)	3.375 %	3	
	1.1.2	Ozone depletion potential (ODP)	1.125 %	1	
	1.1.3	Photochemical ozone creation potential (POCP)	1.125 %	1	
	1.1.4	Acidification potential (AP)	1.125 %	1	
	1.1.5	Eutrophication potential (EP)	1.125 %	1	
	1.1.6	Risks to the local environment	3.375 %	3	
	1.1.7	Sustainable logging/timber	1.125 %	1	
Use of resources	1.2.1	Non-renewable primary energy (PE_{ne})	3.375 %	3	
	1.2.2	Total primary energy use (PE_{ges}) and proportion of renewable energy (PE_e)	2.250 %	2	
	1.2.3	Fresh water usage and wastewater quantity	2.250 %	2	
	1.2.4	Land use	2.250 %	2	
Environmental quality					22.5 %
Life cycle costs	2.1.1	Building-related life-cycle costs	13.500 %	3	
Future value	2.2.1	Suitability for third-party use	9.000 %	2	
Socio-cultural and functional quality					22.5 %
Health, comfort and user-satisfaction	3.1.1	Thermal comfort in winter	1.607 %	2	
	3.1.2	Thermal comfort in summer	2.411 %	3	
	3.1.3	Interior air quality	2.411 %	3	
	3.1.4	Acoustic comfort	0.804 %	1	
	3.1.5	Visual comfort	2.411 %	3	
	3.1.6	Influence of the building's users	1.607 %	2	
	3.1.7	Building-related outdoor qualities	0.804 %	1	
	3.1.8	Safety and incident risk	0.804 %	1	
Functionality	3.2.1	Barrier-free building	1.607 %	2	
	3.2.2	Land use efficiency	0.804 %	1	
	3.2.3	Capability of conversion	1.607 %	2	
	3.2.4	Public accessibility	1.607 %	2	
	3.2.5	Convenience for bicycles	0.804 %	1	
Ensuring design duality	3.3.1	Design and urban quality	2.411 %	3	
	3.3.2	Art in architecture	0.804 %	1	
Technical quality					22.5 %
Technical execution quality	4.1.1	Acoustic insulation	5.625 %	2	
	4.1.2	Heat insulation and protection against condensate	5.625 %	2	
	4.1.3	Cleaning and maintenance	5.625 %	2	
	4.1.4	Dismantling, separation and utilisation	5.625 %	2	
Process quality					10.0 %
Planning quality	5.1.1	Project preparation	1.429 %	3	
	5.1.2	Integrated planning	1.429 %	3	
	5.1.3	Optimisation and complexity of planning	1.429 %	3	
	5.1.4	Tendering and contracting	0.952 %	2	
	5.1.5	Requirements for optimal utilisation and management	0.952 %	2	
Construction work quality	5.2.1	Construction site/construction process	0.952 %	2	
	5.2.2	Quality assurance of the building construction	1.429 %	3	
	5.2.3	Controlled commissioning	1.429 %	3	
Site quality					0.0 %
Site quality	6.1.1	Risks at the micro-site	–	2	
	6.1.2	Conditions at the micro-site	–	2	
	6.1.3	Image and status of location and district	–	2	
	6.1.4	Public transport connections	–	3	
	6.1.5	Vicinity to use-specific services	–	2	
	6.1.6	Supply lines/site development	–	2	

C 1.22

and evaluation of selected costs groups) that includes both the construction and operating costs. The decisive parameter is the present value of all costs that apply to the building's life cycle. Factors used to limit and establish an evaluation time period are published in the federal government's "Guide to Sustainable Building". Other factors, such as asset stability, financial performance and risk, can be included when evaluating economic quality.

The socio-cultural and functional quality incorporates aspects of health, comfort, user satisfaction, functionality and the creative and design quality. Specifically, this includes at minimum a building's thermal, visual and acoustic quality as well the interior air quality. An investigation of functionality must at least include an evaluation of accessibility, space efficiency, and the building's capacity for conversion. The basis for evaluating creative and design quality is given in the Guidelines for Design Competitions (Richtlinien für Planungswettbewerbe, RPW 2008) or similar guidelines. An assessment solely through a visual inspection is not sufficient.

Relevant aspects for assessing the technical quality include soundproofing, the ease of cleaning and maintaining a building and a consideration of the building's demolition and recycling potential.

Process quality assesses planning and construction. Special emphasis is placed on the development of sustainable concepts (e.g. for energy, water, reuse/recycling, waste and user-friendliness) in the early planning phase and quality control during the construction phase. If the "use phase" of a building is included, then the quality of use and operational management should be described and assessed.

As a minimum, the following aspects should be taken into account when describing site quality: risks and conditions at micro-location, transport connections and development of utility infrastructure. The site characteristics are not currently included in the evaluation because they can seldom be influenced.

In total there are 46 individual criteria (Fig. C 1.22). Each criterion is weighted with a percentage factor according to its importance. In this way, the environmental, economic, socio-cultural, and the functional and technical aspects each make up 22.5 %, while process quality makes up the remaining 10 % of the total. The 0 % weighting of the site quality is to prevent factors that cannot be practically influenced affecting the end result. Yet at the same time, a sustainability assessment must not ignore the importance of site quality. A profile is created for each of the 46 individual criteria; this specifies the objectives, aspects to be included, impact targets, methods, the relationship to other criteria, and lastly the specific requirements (Fig. C 1.23). For example, the criterion "land use efficiency" uses the ratio of built floor area to gross land area to

	Assessment levels
Z: 100	Land use efficiency factor = 0.75
90	Land use efficiency factor = 0.72
80	Land use efficiency factor = 0.69
70	Land use efficiency factor = 0.66
60	Land use efficiency factor = 0.63
R: 50	Land use efficiency factor = 0.60
40	Land use efficiency factor = 0.56
30	Land use efficiency factor = 0.52
20	Land use efficiency factor = 0.48
G: 10	Land use efficiency factor < 0.48
0	Land use efficiency factor not established

C 1.23

calculate a so-called land use efficiency factor. The planner can decide whether to improve land use efficiency by minimising traffic areas or use especially slim (in profile) building elements. This is expressed through a rating system with a maximum of 100 points. Depending on the type of criterion, sub-criteria make up the 100-point target score. The individual requirements and the sum of all the requirements are decisive. A score of 50 points represents a reference value; a sustainable building must not score below 10 points, which represents the lower threshold (Fig. C 1.22).
The rating system takes into account the key assessment principles over the entire lifespan of an object/building, as well as the results of a life-cycle analysis, to produce an evaluation.
The determination of costs related to a building not only covers the construction cost, which has in the past often been the focus of such investigations, but also the operation and running costs. The current version of the rating system does not include the cost of conversion or demolition at the end of a building's useful life, costs which can have a substantial effect on the life cycle costs.
Cost categories are:

- Build costs (construction and installation) in accordance with DIN 276, cost categories 300 and 400
- Selected operating cost categories in accordance with DIN 18960 "Operating costs in building construction"
- Imputed interest and projected price increases
- Utility costs (electricity, water, wastewater) and hourly rates for cleaning

Using the "present value method" (see "Costs and economics" p. 130ff.), compound interest is applied to the build costs and a discount rate applied to all predicted future costs during the expected lifespan of 50 years from the building's completion. The discount rate is set at 5.5 % (nominal). General price inflation for heating fuels and electricity is calculated at 2 % and 4 %. In addition, two alternative scenarios, operational lifespans of 30 and 100 years, are evaluated, thereby compensating to some extent for uncertainties in the estimation of future costs. Such scenarios reveal the extent to which certain parameters can dominate the evaluation results; the choice of construction material hardly affects the sustainability rating, whereas changes to the expected lifespan of a building have a considerable impact. The build costs in DIN 276 cost categories 300 and 400 are given in relation to the gross floor area of building (€/m^2).

The following cost categories need to be taken into account when evaluating the running costs:

- KG 311: water
- KG 312-316: oil, gas, solid fuels, district heat, electricity
- KG 320: wastewater disposal
- KG 330: cleaning and care of buildings
- KG 352/353: building inspection and maintenance/thermogravimetric analysis (HVAC)
- KG 410/420: building repairs/thermogravimetric analysis (HVAC)

Reference, target and threshold values for life cycle cost per m^2 of gross floor area serve as criteria for the evaluation of a building's life cycle costs. Higher cost values take exceptional costs of construction and/or operation into account, e.g. difficult ground conditions on site, use of especially energy-efficient but not yet economic technology, or buildings with especially high specifications in at least two of the following categories: structural stability, soundproofing, fire safety, or measures for the prevention of terrorism. To ensure that the resulting values are comparable, tables giving the standard life expectancies of materials are available in "Sustainable Construction for Federal Buildings" (Edition 2001), the VDI (Association of German Engineers) Directive 2067 or online (www.nachhaltigesbauen.de). Further detailed information on the useful lifespan of materials can be sourced either from manufacturer's information and warrantees (in so far as they are available) or from product standards and norms.
Even if the impact of a building's conversion or demolition at the end of its planned life is not included in the life cycle costs, an estimated quantitative assessment of these aspects is incorporated into the life cycle costs, as the potential for alternative uses is included in the key performance indicator of socio-cultural parameters, which is re-weighted and compared to the target, reference and threshold values. The potential for alternative use is made up of the potential for conversion at 70 %, and efficient use of space at 30 %.
The overall conclusion is that the use of life-cycle analysis to rate the sustainability of buildings represents an additional tool for planning and control. The design process, the needs of users, the relationship between location and building, the structural requirements, and thorough itemisation of sustainable architecture all continue to be of great importance.

References:

[1] Trendelenburg, Reinhard; Mayer-Wegelin, Hans: Das Holz als Rohstoff. Munich 1955
[2] World Commission on Environment and Development (pbl.): Our common future. http://www.un-documents.net/our-common-future.pdf, p. 41. accessed 15/10/2012
[3] Frondel, Manuel et al: Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen. Rheinisch-Westfälisches Institut für Wirtschaftsforschung, Fraunhofer-Institut für System- und Innovationsforschung, Bundesanstalt für Geowissenschaften und Rohstoffe. 2006
[4] Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (pbl.): Kurzstudie Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 2011. Hannover 2011
[5] Babies, Hans-Georg et al: Deutschland – Rohstoffsituation 2010. Hannover 2011, p. 28, table 3-2
[6] Polley, Heino; Hennig, Petra; Schwitzgebel, Frank: Holzvorrat, Holzzuwachs, Holznutzung in Deutschland. In: AFZ – Der Wald 20/2009, pp. 1,076–1,078
[7] Food and Agriculture Organization of the United Nations: State of the World's Forests. Rome 2011
[8] DIN EN ISO 14044: Lifecycle assessment – Requirements and guidelines. 2006-10
[9] DIN EN ISO 14040: Life cycle assessment – Principles and framework. 2006
[10] DIN EN 15804: Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products. 2012-04
[11] http://www.oekobau.dat, see http://www.nachhaltigesbauen.de, accessed 20/09/2012)
[12] DIN EN ISO 14025: Produktabbildung – Environmental labels and declarations – Type III Environmental declarations – Principles and procedures. 2011-10
[13] Verein Deutscher Zementwerke e.V.: EPD-VDZ-2012111-D from 16/03/2012 valid until 15/03/2017
[14] Eyerer, Peter; Reinhardt, Hans-Wolf: Ökologische Bilanzierung von Baustoffen und Gebäuden: Wege zu einer ganzheitlichen Bilanzierung. Basel 2000
[15] Deutscher Ausschuss für Stahlbeton (pbl.): Verbundforschungsvorhaben "Nachhaltig Bauen mit Beton". Heft 584, 2011.
[16] Löckener, Ralf: Nachhaltige Transport- und Logistikketten – Ist-Analyse der deutschen Zementindustrie. www.initiative-nachhaltigkeit.de/downloads/SUSTAIN-CONSULT_Logistik_Zementindustrie_2008.pdf. accessed 08/07/2013
[17] Bauhaus Universität Weimar (pbl.): Einsatz von Betonbrechsand in der Portlandzementklinkerherstellung, 17. Internationale Baustofftagung. Weimar 2009
[18] see reference 11
[19] DIN Fachbericht 100 "Beton – Zusammenstellung von DIN EN 206-1 Beton – Teil 1: Festlegung, Eigenschaften, Herstellung und Konformität und DIN 1045-2 Tragwerke aus Beton, Stahlbeton und Spannbeton – Teil 2: Beton – Festlegung, Eigenschaften, Herstellung und Konformität – Anwendungsregeln zu DIN EN 206-1". Berlin 2010
[20] Hauer, Bruno et al.: Verbundforschungsvorhaben "Nachhaltig Bauen mit Beton" – Potenziale des Sekundärstoffseinsatzes im Betonbau – Teilprojekt B. DAfStb-Heft 584. Berlin 2011
[21] Deutscher Ausschuss für Stahlbeton (pbl.): Beton nach DIN EN 206-1 und DIN 1045-2 mit rezyklierter Gesteinskörnung nach DIN EN 12620. Berlin 2010
[22] Bundesverband Baustoffe Steine und Erden e.V. (pbl.): Mineralische Bauabfälle, Monitoring 2010. Berlin 2013
[23] DIN EN ISO/IEC 17065: Conformity assessment – Requirements for bodies certifying products, processes and services. 2013-01

C 1.22 Evaluation matrix according to DGNB/BMVBS for office buildings
C 1.23 Assessment factors for land use efficiency, interim values should be interpolated linearly in sections

Costs and economics

Peter Lieblang

C 2.1

The principle of economic efficiency means maximising the yield of a given investment or minimising the investment needed to achieve a specific yield. Efficiency is not a goal in itself but rather a task of optimising limited resources to meet specific needs. Economic questions in concrete construction can only be dealt with on a specific case-by-case basis.

Investment analysis as a tool for determining economic feasibility

There are various investment calculations that can aid the process of deciding whether an investment makes economic sense or not, i.e. is profitable within a given time span. The relative benefits of an investment can be evaluated and alternative scenarios can be compared, which, for example, vary in respect to the land or the object to be constructed or through the use of different technical solutions or financial instruments. The investment analysis also has an application in sustainability assessments, in that the environmental or socio-cultural properties of a building can be assigned a monetary value (see "Systems for rating the sustainability of buildings", p. 126). In most cases, this calculation is based on a cash flow analysis. The timing of payments is therefore of great significance. Interest is accrued for the use of capital. Based on the interest due, the value of payments at various times can be compared using the following formula. Where interest payments are K_0 and K_n at times t_0 und t_n and the interest rate percentage is i (Fig. C 2.2):

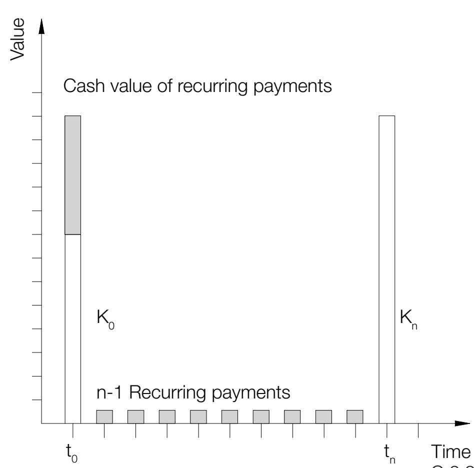
$$K_n = K_0 \left(1 + \frac{i}{100}\right)^n$$

$$\left(1 + \frac{i}{100}\right)^n$$

denotes the accumulation factor and its reciprocal value is the discount factor. The future cash value of recurring payments at specific time point t_0 can be calculated using the so-called annuity value, where n is the number of recurring payments.

$$\frac{\left(1 + \frac{i}{100}\right)^n - 1}{\frac{i}{100}\left(1 + \frac{i}{100}\right)^n}$$

The future cash value of recurring payments at specific time point t_0 can be calculated where n is the number of recurring payments. An assessment of economic feasibility is then reduced to a comparison of the cash value of various cash flows at a particular point in time. The cash value of future interest payments decreases the further the payment point lies in the future.
The Net Present-Value method (NPV) is used in most cases to assess the economic benefits of an investment. The cash value of all the expected future returns on an investment with interest discounted is compared to the acquisition costs of the object. A positive capital value indicates a rate of return that is higher than the calculation interest, whilst unfavourable investments, where the rate of return is lower than the calculation interest, result in a negative capital value (Fig. C 2.3).



C 2.2

Parameters for the economic efficiency of buildings
Buildings, when compared to other capital investments, are characterised by a very long life span. This is especially true for the use of concrete, a building material used predominantly for structural building components – the building infrastructure. As a rule, the (techni-

C 2.1 Built example of a "city building block", Estradenhaus, Berlin (D) 1998/2001, Planpopp Architektur Stadtplanung, Wolfram Popp
C 2.2 Comparison of payments made at different time points
C 2.3 Calculation example: An office building costs €10,000,000 to build. Financed with 40 % equity (discounted interest rate 5.5 %) and 60 % borrowed capital. The period under review is 10 years. The capital value of the investment is C_0 = €15,420.23, leaving a surplus after interest on equity of €15,420.23 (cash value at time of investment).
C 2.4 Reference values for standard operating life spans, with proper maintenance. The operating life span is established and defined depending on the situation in the property market.

		01/01/2014	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
	Equity capital	4,000,000.00	Committed Equity Capital (not liquid)									
Cash value at 01/01/2014	Cost of borrowing	2,035,158.97	270,000.00	270,000.00	270,000.00	270,000.00	270,000.00	270,000.00	270,000.00	270,000.00	270,000.00	270,000.00
	Rental income	6,403,626.08	900,000.00	900,000.00	900,000.00	900,000.00	900,000.00	900,000.00	900,000.00	900,000.00	0.00	1,200,000.00
	Operating costs	597,464.15	85,000.00	85,000.00	85,000.00	85,000.00	85,000.00	85,000.00	85,000.00	85,000.00	15,000.00	85,000.00
	Renovation costs	926,443.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,500,000.00	0.00
	Resale value	1,170,861.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,000,000.00
	Balance	4,015,420.23	545,000.00	545,000.00	545,000.00	545,000.00	545,000.00	545,000.00	545,000.00	545,000.00	-1,785,000.00	2,845,000.00

C 2.3

cally) useful life span of the structural building components determines the life span of the entire building, although the construction costs for the building shell (KG 300 DIN 276 "Costs in Building Construction") seldom make up more than 30 % of the total costs. Building authority requirements on safety – e.g. statics and fire safety – dictate the design and form of structural building components. This results in a high level of security against building component failure and at the same time ensures a very long life span – even with changes to a building's usage and structural loading. Changes to structural building components during building alterations are nearly always associated with a high level of cost and complexity. Technical processes play a role as does the fact that alterations to concrete structural components will require prior removal of the building fabric and are rarely localised. In extreme cases, interventions in a building's structure can be so costly that demolition and replacement with a new building is more economical. The point at which such interventions are unavoidable represents the end of a building's economic viability – the life span of a building. This can be markedly less than a building's technical life span, e.g. the point at which repair or restoration is technically impossible because of a lack of suitable building techniques. In comparison, the renovation of the non-structural parts of the building's interior or the updating of technical services is significantly less costly. In practice, this results in shorter renewal cycles for these components of a building. Yet such interventions only have a limited economic significance. It can be concluded, that while the structural building components almost exclusively determine the economic life span of a building, the interiors and technical services have only marginal implications. Because the operating life (the length of time in which cash flow takes place) is included as an exponent in accumulation, discount and annuity value factors, it will significantly influence the results of an economic evaluation. Various publications [1] provide information on the life span of buildings (Fig C 2.4) or building components consistent with the cost groups in DIN 276.

Property has an additional characteristic compared to other capital investments: the value of the site on which the building stands makes up a substantial proportion of the total investment. Land does not deteriorate. Land generates a so-called perpetual annuity and – depending on changes in demand – at the end of the life span or useful life of a building and even after demolition there is often a considerable return. Hence a more or less subjective judgement underlies the input parameters of each pre-investment analysis. The influence of these subjective judgements can be lessened, if representative data – e.g. expert appraisals for land values and land yields – are used, however, uncertainty can never be completely eliminated.

The second most important parameters are the operating costs of a building. These costs can be subdivided according to DIN 18960 "User Costs of Buildings" into:

- capital costs
- property management costs
- operating cost
- maintenance costs

The present value of these recurring expenses can be calculated to any time point within the framework of an investment evaluation. A direct link between construction methods or building materials and operating costs is only evident in some cases. For example, well-designed facades of mineral-base materials – exposed concrete or brickwork – result in lower cleaning costs than fully glazed facades (Fig. C 2.5). The facade also has an impact on a building's energy consumption for heating, air conditioning and lighting. Lastly, the importance of the facade to the appearance of the

Building type		Life span	
Detached, semi-detached, terraced houses	Standard level 1	60 years	
	Standard level 2	65 years	
	Standard level 3	70 years	
	Standard level 4	75 years	
	Standard level 5	80 years	
Apartment buildings		70 years	+/-10
Mixed-use with residential		70 years	+/-10
Retail buildings		60 years	+/-10
Office buildings, banks		60 years	+/-10
Community centres, concert halls		40 years	+/-10
Kindergartens, schools		50 years	+/-10
Residential homes, nursing homes		50 years	+/-10
Hospitals and day clinics		40 years	+/-10
Hotels, hostels, catering establishments		40 years	+/-10
Sports halls, sports centres, spas		40 years	+/-10
Supermarkets, car dealerships		30 years	+/-10
Shopping centres, department stores		50 years	+/-10
Single parking garages		60 years	+/-10
Underground and multi-storey parking garages (as individual buildings)		40 years	+/-10
Factories, workshop buildings		40 years	+/-10
Warehouses		40 years	+/-10
Agricultural buildings		30 years	+/-10

C 2.4

KG	Building component	Required time [h/m²]	Cost [€/m²]	Annual frequency	Total annual required time [h/m²a]	Annual cost [€/m²a]
334	**Glass**[1]					
	Accessibility – Easy	0.0400	0.50	2	0.08	1.20
	Accessibility – Medium	0.0500	0.75	2	0.10	1.30
	Accessibility – Difficult	0.7690	1.15	2	0.15	2.31
335	**Exterior cladding**					
	Soft natural stone	0.8696	13.04	0.25	0.22	3.26
	Aluminum, stainless steel, copper sheet, corrosion-protected steel	0.3333	5.00	0.25	0.08	1.25
	Glass	0.0500	0.75	0.25	0.01	0.19
	Artificial stone, cast stone, hard natural stone	0.1667	2.50	0.25	0.04	0.63

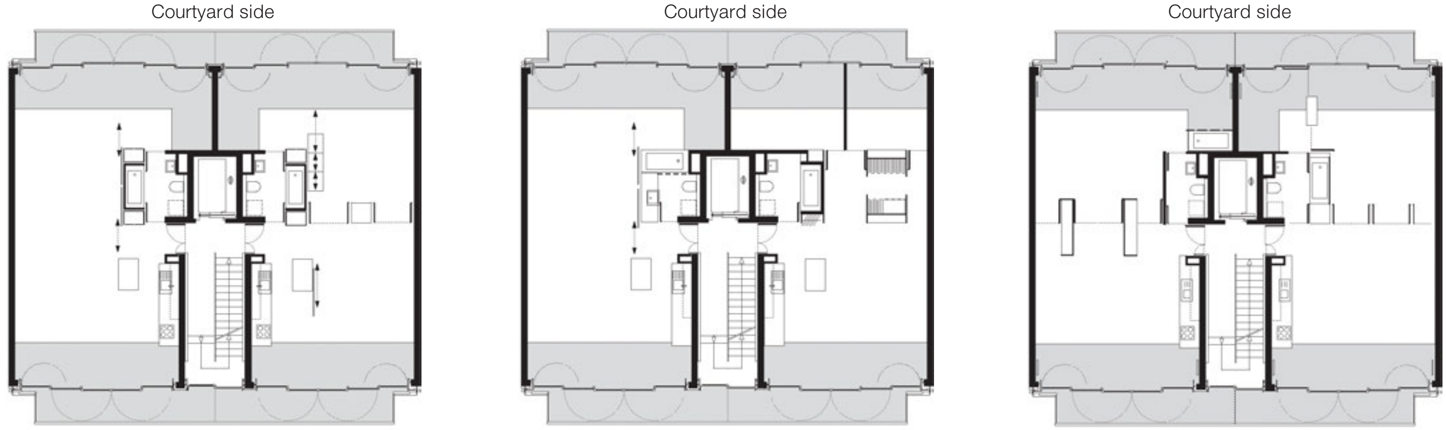
[1] Unlike exterior cladding, glass surface must be cleaned on both inner and outer faces.

C 2.5

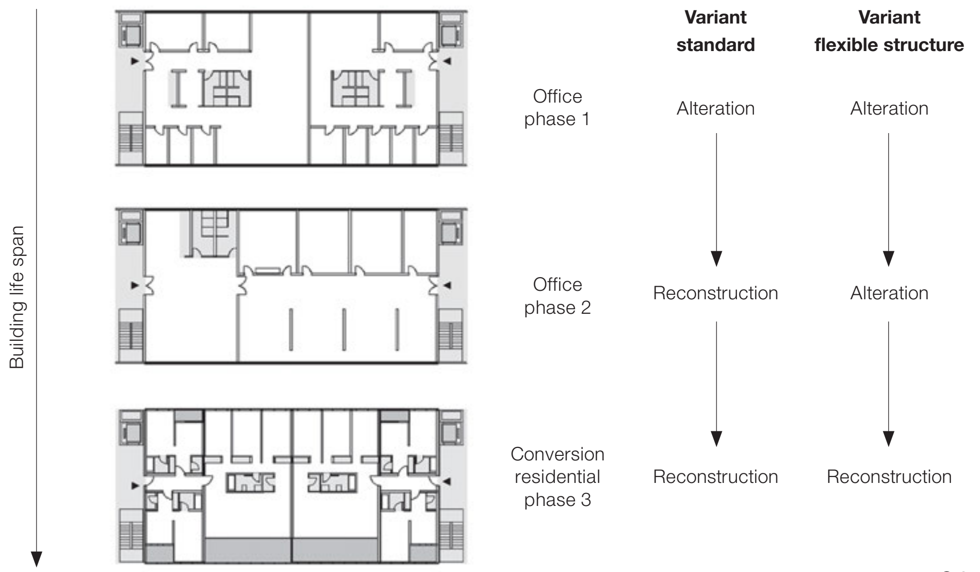
building and its surroundings should not be ignored. The dilemma for architects and developers is to balance the costs against these other aspect on the basis of information that is inevitably incomplete. A decision made on the basis of a pre-investment analysis remains subjective because assigning cash values to parameters is inevitably a value judgement. The investment evaluation aims to provide reproducible results on the basis of subjective input data.

Life cycle cost analysis

As part of a joint research project, the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF), the German Committee for Reinforced Concrete (Deutscher Ausschuss für Stahlbeton, DAfStb) and other industry and institutional partners investigated the economics of (reinforced) concrete buildings using a life cycle analysis. To obtain representative results, the research project used a reference building unit, the so-called "city building block", a multi-storey building with six floors above ground level and two underground parking garage levels. With a floor to ceiling height of 2.80 m for each storey, the building was still under the height limit for high-rise buildings. The floor plan measured 30 × 16 m, giving a footprint of 480 m² (Fig. C 2.8).
This represents a building model where the structural shell provides an infrastructure for varied uses. All other tasks – the installation of room divisions, acoustic and thermal insulation, fire-proofing and technical building services – are designed to suit the specific usage. A recent notable example of this type of building is the Estradenhaus (Figs. C 2.1, p. 130 and C 2.6). The structural elements are reduced to a minimum and consist of pre-stressed, hollow core slabs of concrete with a clear span of approx. 6.50 m, supported by only three walls. The architectural concept of the building resembles a shelving unit that can be filled to suit the user's requirements without needing to interfere with the permanent structure. The completed building showed that – due in part to the open structure of the building – construction times could be reduced, and the absence of solid internal dividing walls led to a 25 % reduction in the cost of the building shell.
This "city building block" building allowed the definition and comparison of the economics of both the construction and operational phases for a variety of practical scenarios. These scenarios represent realistic use profiles for urban buildings within a nominal time period of 100 years. Initially, the building is used for office cubicles, then reconfigured into an open-plan office and finally, after a bigger intervention, converted to residential units with three different floor plans (Fig. C 2.7). This is compared to a second scenario where the conversion from an office to a residential building involves demolition and new construction. The experimental building has a flexible structure, allowing considerable alteration to the floor plan without the need for substantial building measures. In particular, when compared to the standard structure, the ceiling spans are greater with fewer supporting walls and columns. This is achieved through the use of a prestressed construction, a high degree of steel reinforcement in concrete components (approx. 2.3 times the amount of reinforcing steel) and the use of concrete with a higher compressive strength (up to compressive strength class C50/60 instead of C25/30). This flexible construction method also results in fewer columns and walls in the basement levels, a reduction in



C 2.6

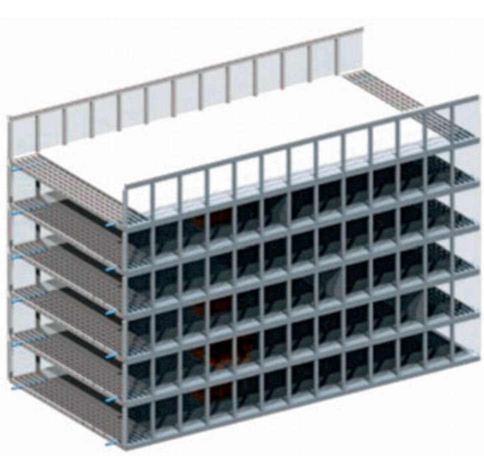


C 2.7

the dimensions of the foundation as well as a floor slab with only minor variation in thickness, which in turn contributes to an overall reduction in building costs.
A life cycle cost analysis was carried out based on current policy and legal requirements. The estimated key cost values were sourced from the Information Centre for Construction Costs (Baukosteninformationszentrum, BKI). The investigation in to the "city building block" provided information on:
- the impact of the design, building material production and dimensions on the economic and ecological costs of buildings with concrete structures
- the cost of the concrete structure as a proportion of the life cycle cost of a building
- the sensitivity of a life cycle cost analysis to changes in the input parameters at the level of building components, structure and the entire building.

The scenarios investigated in the "city building block" are in principle transferable to other residential and office buildings made of concrete, in conurbations or metropolitan regions, which go through different phases of usage. Two variants of the flexible building were compared to assess the impact of the costs of energy for heating, air conditioning (HVAC), hot water and lighting. The energy consumption of a design that met the Energy Performance of Buildings Directive (EnEV) 2007 served as a reference value. A variant with an optimised heating requirement of 15 kWh/m^2a, similar to Passive House standards, served as an alternative. (Fig. C 2.9) The improvement to the energy standard was almost exclusively due to a reduction in the U values of the facade (opaque components and windows). Cost for technical services (KG 400) remained unaltered.
The life cycle costs are calculated on the basis of an operating life of 100 years, discounting accrued interest from the time of the investment. The calculation assumes price inflation for energy costs of 4 %, 3 % for water costs and 2 % for all other costs. The discounted annual interest rate is taken as 5.5 %. The life span or useful life of building components from KG 300 is taken from the "Guidelines for Sustainable Construction for Federal Buildings" and for KG 400 from the "Directive Association of German Engineers" (VDI) [2]. The construction costs are based on values from the Information Centre for Construction Costs (BKI) [3].

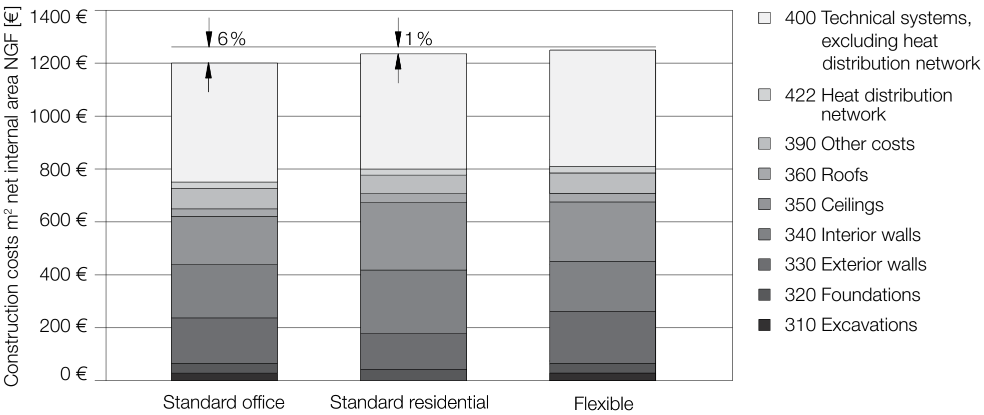
Construction and operating costs
The construction costs of the reference building (standard structure) are approx. 1,200 €/m^2. Nearly 60 % of these costs are from KG 300 and 40 % are from KG 400 (Fig. C 2.10, p. 134). Improving the building's energy performance from Energy Performance of Buildings Directive (EnEV) standard to Passive House standards increases the construction costs by about 8 %. The additional costs for the experimental building are, in the main, a result of improved thermal insulation to the building's envelope (including windows), whilst the cost of technical services remains unchanged. Concrete components make up about 30 % of KG 300 (Fig. C 2.11, p. 134). This proportion is dependent to a considerable extent on the building's specification and decreases accordingly as the specification standard increases. Changes to the building's structure, with the aim of improving the potential for conversion for alternative uses, also increases the construction costs.
An examination of the life cycle can determine the discounted cash flow at the time of the investment. Fig. C 2.12 (p. 134) shows a breakdown of the total costs for the flexible building structure built to conform to


C 2.8

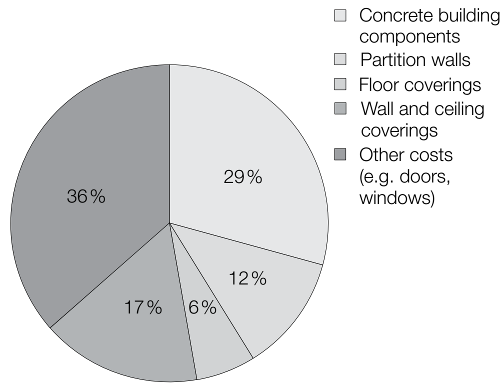
	Supporting structure	Energy consumption [kWh/m^2a]		
		Office I	Office II	Residential
EnEV 2007	Standard	109.6	122.4	68.2
	Flexible	109.1	122.0	68.2
HWB15	Standard	74.0	86.3	57.8
	Flexible	75.6	85.6	57.8

C 2.9

C 2.5 Cleaning costs and key cost values for glass surfaces and facades in Germany
C 2.6 Floor plan variants, Estradenhaus, Berlin (D) 1998/2001, Planpopp Architektur Stadtplanung, Wolfram Popp
C 2.7 Usage scenarios, "city building block"
C 2.8 Reference building "city building block" as the subject of a comparative life cycle cost analysis in a joint research project.
C 2.9 Energy consumption of "city building block" building types with energy standard EnEV 2007 and HWB15 dependent on use



C 2.10



C 2.11

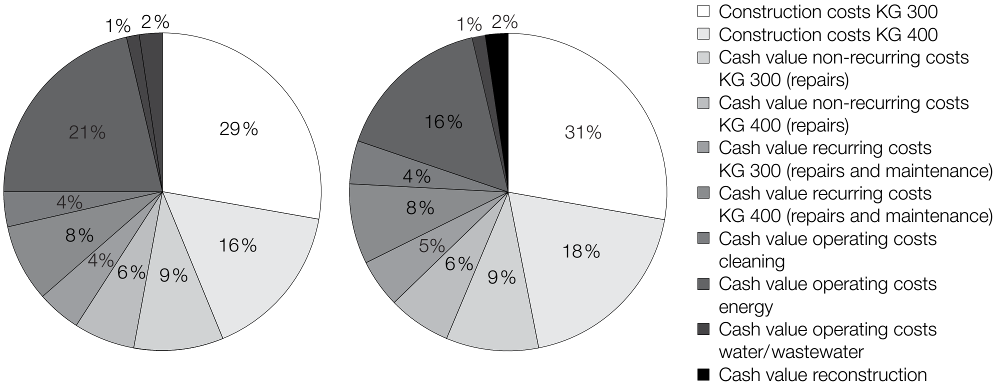
Energy Performance of Buildings Directive (EnEV) standard. The construction costs at 44 % are the largest single item. Repair and maintenance – this includes irregular maintenance – during the 100-year operating life amount to 27 %, whilst conventional operating costs are 26 %. In summary, this shows that, with current standard building practices, construction makes up almost half of the total life-cycle costs. Improvements to energy standards are likely to further reduce consumption-based costs. However, increases in energy efficiency are associated with higher construction and maintenance costs. These days, the maintenance of buildings equipped with air-conditioning units has led to a noticeable increase in life cycle costs. Only future experience with this construction method will show whether or not the reduction in operating costs from improvements to energy efficiency can compensate for the increase in construction and maintenance costs and raw material consumption.

There is considerably more experience in the evaluation of energy consumption for detached houses with different energy standards. The exponential relationship between expenditure and returns from energy-saving measures – at least with heat loss prevention measures – results in a limit to economic efficiency. A limit determined predominantly by the cost of energy, but also by the additional construction costs of the energy-saving measures.

The energy consumption of a residential building with energy standards that exceed the Energy Performance of Buildings Directive 2009 (EnEV 2009) reliably achieves values of less than 40 kWh/m^{2}a. Further reduction through heat loss prevention is usually uneconomical. Additional investment in solar systems or heat exchangers can make further contributions to the energy balance of buildings. Whether or not the use of solar or geothermal energy is economical, depends on the specific circumstances. It is also decisive for the calculation of economic viability whether or not the conditions at the time of the initial investment remain unchanged for the whole life cycle. This assumption is uncertain, at least when it concerns state subsidies to promote the generation of electrical power with renewable energy. The same applies for the value of the primary energy factors, against which the use of renewable raw materials for energy production is assessed.

Maintenance

Maintenance describes all the technical and administrative processes that ensure a building or building components are maintained and remain functional during the operational life of a building. Maintenance encompasses cleaning, painting, repairs and replacement of parts of a building (see DIN EN 15 643 "Sustainability of Construction Works – Sustainability Assessment of Buildings"). Remedial work is an established term in the field of concrete construction to describe the restoration of the sectional dimensions and properties of damaged concrete building components. The terms maintenance and remedial work are not strictly demarcated. Typically the maintenance of concrete building components includes measures to protect the concrete's surface. The application of a surface protection system (see "Calculating durability", p. 23) prevents corrosive substances – e.g. salts or acids – from penetrating the concrete and diminishing its durability. Interior concrete components are, by virtue of their ambient conditions, practically maintenance-free. External concrete elements and surfaces that see heavy traffic use need to be regularly maintained and their surfaces treated. In the example of the "city building block", many different scenarios for the maintenance of concrete surfaces were trialled in the underground parking garages (see "Restoring underground car parks", p. 168). These differed in the type of binders used in the manufacture of the concrete, the size of the treated surfaces and the renewal cycles for the surface protection system. In particular, the impact of monitoring systems on the life-cycle costs was investigated. The systems monitored the condition of concrete components, especially in vulnerable areas with built-in sensors – e.g. anode conductors – to indicate when maintenance is required. By monitoring the concrete's condition accurately, the system can reduce material usage – and the associated environmental impact – and costs compared to a scenario with a rigid maintenance cycle. However, the benefits are only evident in the last third of the total operational life of 100 years. This again demonstrates that the amortisation of higher construction costs through savings in the cost of operation and maintenance largely depends on the realisation of the predicted lifespan and is therefore uncertain.



a b C 2.12

Influence of re-use

The re-use of buildings has a dual meaning from an economic perspective. Alternative potential uses following the planned operational life of a building are a primary considera-

tion in a sustainability evaluation for new buildings. The cost of a building's eventual demolition makes up approximately 2 % of the total life cycle costs and does not play a major role. A reduction in the predicted life cycle costs, if the building under investigation has residual value at the end of its planned operational life, is of greater influence. But the re-use of existing buildings that are no longer needed or functional has by far the greatest economic significance. The structural substance of very old concrete buildings is sufficiently robust that, after the necessary testing and repair, they can still meet today's demands. Even after decades, particularly in residential buildings, concrete components show few signs of deterioration. In many cases, the re-use of old buildings and building components is hindered less by the actual condition than inaccurate assessment of their condition, inadequate information on the properties of the building components or an incompatibility of the older building type with the current technical standards and legal requirements. The obvious contradiction between the actual low level of re-use currently taking place and the expectation that future generations will make substantial use of the re-use potential of existing buildings is deliberately ignored.
However, numerous examples can be found of follow-on uses for existing concrete buildings that are both practical and functional. Even for structures where economic benefits from re-use at first seem unlikely, creative solutions can still be found. Examples include the conversion of the air raid shelter "Reichsbahnbunker Friedrichstraße", built in 1942 in Berlin Mitte, into a private museum with the construction of a residential unit (Fig. C 2.13). The site remained vacant until 2003 as the cost of demolishing the shelter, with its 4 metre thick concrete roof slab, exceeded the value of the land, making a new building uneconomical. The new owners, together with architect Jens Casper, devised a solution that combined and re-used the existing bunker within a new building. Today the bunker serves as a private museum with over 3,000 m^2 of exhibition space; in addition, the 1,000 m^2 roof space has become a penthouse with a terrace and roof garden, in a sought-after residential location. Architect Gerhard Spangenberg used a similar strategy in the conversion of the Exzenterhaus in Bochum (Fig. C 2.14). For the conversion to be successful, it was essential that the design retained the character of the listed building. The circular bunker built in 1942, with a solid central core and conical roof, stood disguised as a town tower on an arterial road. The continued development of the city and its transport infrastructure led to the tower's unusual location – on a traffic roundabout. However, the high-rise concept, incorporating the bunker as a base and using the space above the seventh storey, is ideal for the site, with its many disadvantages, precisely because it solves the problem of spatial separation and provides the required spacing between buildings, and between buildings and roads. In this way 15 upper floors of offices were built. By housing the building's technical services in the bunker's six windowless lower floors and extending the bunker's core as structural support for the high-rise, rentable space makes up 77 % of the new building's floor area. Again this shows how the economics of construction is decisive in the design of a building.
One hundred years after it was built, Cologne's first large-scale reinforced concrete building – colloquially referred to as the "Seven Mountains" because of its imposing western gables – was converted to flats, re-using the concrete structure. The building was originally built in 1909 as a grain store. The architect Hans Verbeek divided the facade facing the city into two stair towers and seven gable structures, a reference to the predominance of medieval buildings along the panorama of the Rhine. The facade contrasted with, what was at the time of construction, a ultra-modern, reinforced concrete frame structure with spans of 5 m between columns. A structure that was adequate for new, alternative uses. The ground floors were converted to high-value offices, and a total of 138 flats were built in the upper floors. It was possible to retain nearly the entire envelope of the building, which was only partially opened for illumination and for patios.
In summary, the economic viability of a building is determined in the first instance by the architect. This applies in greater measure to the re-use and conversion of existing buildings than it does for new buildings since the site, with its already standing building, is far more complex. Pre-investment analysis and life-cycle costs analysis provide valuable tools and a quantitative aid to decision making in the design process.

Notes:

[1] Gondring, Hanspeter (ed.): Immobilienwirtschaft. Munich 2004; Sachwertrichtlinie vom 05.09.2012, Bundesanzeiger AT, 18.10.2012 B1 Bundesministerium für Verkehr, Bau und Stadtentwicklung (pbl.): Leitfaden Nachhaltiges Bauen bei Bundesbauten. Berlin 2011
[2] VDI 2067: Wirtschaftlichkeit gebäudetechnischer Anlagen – Grundlagen und Kostenberechnung. Berlin 2012
[3] Baukosteninformationszentrum Deutscher Architektenkammern (pbl.): Baukosten. Published regularly

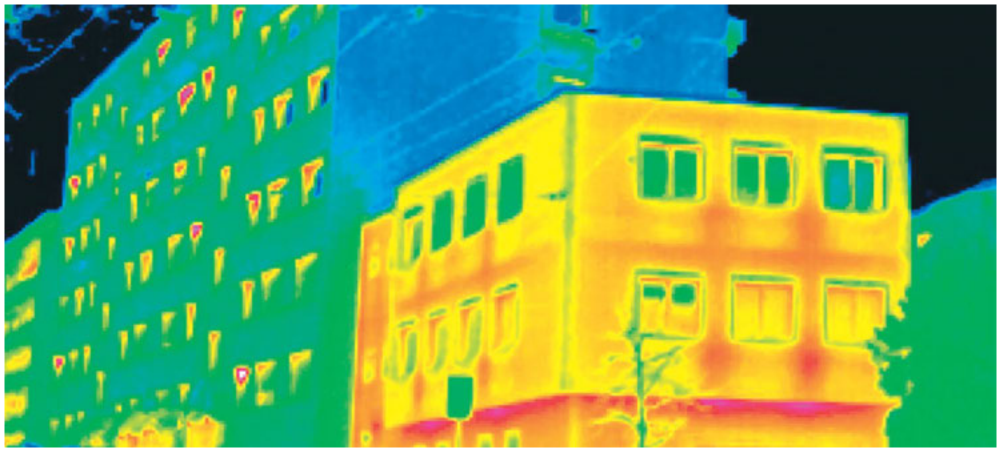
C 2.13

C 2.10 Comparative construction costs for the flexible and standard variants
C 2.11 Cost allocation of building materials KG 300
C 2.12 Cost comparison over 100 years for the "flexible structure"
a Variant EnEV standard
b Variant Passive House standard (HWB 15)
C 2.13 "Reichsbahnbunker Friedrichstraße"/Sammlung Boros, Berlin (D) 2008, Realarchitektur
C 2.14 Exzenterhaus, Bochum (D) 2013, Gerhard Spangenberg

C 2.14

Thermal building physics and energy efficiency

Peter Lieblang



C 3.1

C 3.1 Infrared thermography detects and displays infrared energy radiating from a surface, e.g. a building facade
C 3.2 Thermal conductivity

Thermal building physics

Thermal building physics essentially describes the transport and storage of energy (heat) in buildings. These processes are important for two reasons: Firstly, the interior climate of a building should be comfortable for the majority of users and as constant as possible throughout the year, despite changes in the outside environment. Secondly, the control of a building's temperature is associated with considerable energy consumption, with environmental and economic consequences. There are established models and methodologies to describe thermal processes.

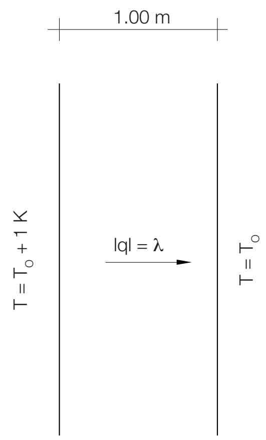
Heat and heat-transfer processes

Heat is a manifestation of energy, just like energy stored in movement or chemical bonds. It may not be perceived directly, but the warming or cooling of objects causes observable phenomena, such as changes to the volume of solids, liquids and gases, as well as changes to the electrical resistance or optical properties (e.g. colour) of materials. Heat is never present without a material. It is perceptible as the kinetic energy (movement) of atoms and molecules. These movements are completely random and non-directional. This conceptual model (the kinetic theory of heat) explains numerous phenomena that occur with changes in temperature. This is made clear with the example of a gas, where variations in the state of individual particles cannot be recorded but are apparent as pressure and temperature.
Temperature T is a measure of the random (stochastic) movement of atoms or molecules, from which materials are made. Heat and temperature are linked by the ability of a material to store heat – the heat capacity C. The absolute heat capacity C, when taking into account the mass m of a material, gives the material's specific heat capacity c.
This relationship applies to all states of matter, i.e. for gases, liquids and solids:

$$Q = C \cdot \Delta T = c \cdot m \cdot \Delta T$$

Q heat [kJ]
C heat capacity [kJ/kgK]
c specific heat capacity [kJ/kgK]
m mass [kg]
ΔT change in temperature [K]

The heat capacity of a building material determines how much the temperature changes when heat (energy) is absorbed or released. The specific heat capacity is only to a lesser extent dependent on the density of a material, the type of molecular or atomic bonding has a far greater influence. As a result, metals have a relatively small specific heat capacity. The specific heat capacity of mineral building materials is approx. c = 1 kJ/kgK. Water has a high specific heat capacity of 4.2 kJ/kgK, which means the moisture content of a building material can have a significant indirect effect. It can be said that the capacity of a building to store heat is proportional to the gross density of its raw materials since: the dimensions of standard ceilings, walls and columns only vary to a small extent; all mineral building materials have a specific heat capacity of approx. 1 kJ/kgK; and the temperature range of components in buildings, for reasons of comfort, is limited to a few Kelvin. Concrete, with a gross density of approximately 2,350 kg/m^3 is a good thermal reservoir. Without evidence to the contrary, it can be assumed that the effective heat capacity of concrete structures averages around 45 Wh/m^{3}K. A typical one-family detached residence of solid construction can therefore store up to 100 kWh without raising the temperature of the building to levels that might be uncomfortable. In comparison, DIN 4108 "Thermal protection and energy economy in buildings" gives the heat capacity for lightweight buildings as 15 Wh/m^{3}K, one third of the heat capacity of a solid construction.
Temperature as a measure of heat is quantified by comparison to a reference. The absolute reference point is the (in reality unachievable) zero point on the thermodynamic temperature scale (Kelvin scale), at which point the random movement of the elementary particles in a body or system ceases. In practice, the temperature of two bodies is compared by bringing them into contact and observing changes in their physical sizes – e.g. the volume of a gas or liquid in a thermometer – as heat is transferred



C 3.2

between the two bodies. There are various scales used to measure temperature. The Celsius scale, named after the Swedish mathematician Anders Celsius, is applied most commonly as it uses the freezing and boiling point of water (at atmospheric pressure) as reference points. The Kelvin scale, internationally recognised in 1990, is offset by 273.15 compared to the Celsius scale, thus a temperature of 0 °C equates to 273.15 K.
Generally, temperature is known as a value that is directly experienced through human temperature perception. For this reason, one speaks of "sensible heat". There are also changes in the amount of heat in a body that cannot be detected by sense perception. In this case, one speaks of "latent heat", noticeable only through changes in the aggregate state or the crystal structure of the material. Both phenomena can be described as phase changes, and can be utilised, through the addition of phase change materials (PCM) to plaster, rendering mortars, or to concrete, to regulate interior temperatures, for example.

Three different processes adequately describe heat transfer mechanisms:
- Thermal conduction
- Thermal radiation
- Convection

Several of these mechanisms often occur simultaneously.

Thermal conductivity
Conductivity is based on the interaction between individual atoms / molecules within materials, independent of their aggregate state. It occurs equally in gases, liquids and solids, but not in a vacuum. The conceptual model uses heat as a macroscopic quantity representing the average kinetic energy of atoms and molecules. Hence thermal conductivity can be described as the spread of this kinetic energy via collisions between neighbouring particles. This explains firstly how heat is conducted from warmer to colder areas and never in the opposite direction and secondly that the process is highly dependent on the properties and structural composition of the materials.

Since nearly all building materials are inhomogenous on a micro-structural level, heat transfer rarely occurs solely through conductivity. In fact all mineral building materials contain pores of varying sizes and these pores can be filled with gas (as a rule air) or liquid (mostly water), other transfer mechanisms also come into play. How far the actual conditions deviate from the ideal condition of pure conductivity depends on multiple factors, e.g. the geometry, distribution and contents of the pores and surface characteristics, etc. Air-filled pores are poor thermal conductors and also reduce the density of the building material, thus the raw density of a building material correlates with its thermal conductivity. This is clearly demonstrated in the conductivity values for (lightweight) concretes of differing densities and the low conductivity of insulating materials. The value λ gives the heat flux density of a building material of 1 m thickness with a temperature difference between the two surfaces of 1 K (Fig. C 3.2).

Most processes in the field of thermal building physics can be described with a simple equation, assuming that the heat flux is one-directional and perpendicular to the building component under observation and if the capacity to store heat and any heat sources or heat sinks within a building component are ignored. Under these conditions, thermal gains and losses of a control volume are in equilibrium. The basic equation for thermal conductivity at steady state is:

$$q = \frac{\lambda}{d} \cdot \Delta T$$

q heat flux density [W/m²]
λ thermal conductivity [W/mK]
d building component thickness [m]
ΔT temperature difference between inner and outer surfaces [K]

Here the term λ/d is called the coefficient of thermal conductivity. The reciprocal value of thermal conductivity is thermal resistance.

$$R = \frac{1}{\Lambda} = \frac{d}{\lambda} \quad [m^2 \cdot K/W]$$

The rate of heat flow through a building layer decreases as the thermal resistance increases (or as the thermal coefficient decreases).

Thermal radiation
Apart from conductivity, heat transfer can also result from radiation. This is transfer of energy through electromagnetic waves, and it is not reliant on the presence of materials, i.e. it takes place in a vacuum, too. The strength and wavelengths of thermal radiation depend on the temperature of the radiating body.
A so-called ideal radiator is called a "black-body". It completely absorbs incident radiation of every wavelength and is perceived visually as black. At the same time, the emissivity of any wavelength is at maximum; for a black-body, this is 1. The sun can be approximated to a black-body radiator. Its maximum radiation occurs at a wavelength of approx. 500 nm, within the range that is visible to the human eye. In contrast, the wave length of thermal radiation emitted from the earth's surface or buildings and building components is longer than 700 nm and is outside the visible range.
The Stefan-Boltzmann Law gives the energy radiated from a black-body relative to the absolute temperate, the surface area and the energy emitted:

$$P = \varepsilon(T) \cdot \sigma \cdot A \cdot T^4$$

ε emissivity ($0 \leq e \leq 1$)
σ Stefan-Boltzmann Constant ($\sigma = 5.6704 \cdot 10^{-8}$ [$Wm^{-2}K^{-4}$])
A surface area of the emitter [m²]
T temperature of the emitter [K]

The net radiant energy emitted from a body to its surroundings through radiation is expressed as:

$$P_{net} = e \cdot \sigma \cdot A\,(T^4 - T_0^4)$$

T_0 ambient temperature

If the temperature and the emission coefficients of the energy exchanging body are

Heat transfer resistance	Heat flow direction up	horizontal	down
R_{si}	0.10 m²K/W	0.13 m²K/W	0.17 m²K/W
R_{se}	0.04 m²K/W	0.04 m²K/W	0.04 m²K/W

C 3.3

Building materials	Heat penetration coefficient [J/m² · K · s^1/2]
Concrete (ρ = 2,350 kg/m³)	2,400
Concrete (ρ = 1,800 kg/m³)	1,600
Lightweight concrete (ρ = 1,000 kg/m³)	650
Aerated concrete	250
Glass	1,500
Wood	300
Sand lime brick	1,100
Glass and mineral wool	35
Polystyrene (EPS/XPS)	35
Steel	13,000
Brick	1,100

C 3.4

Activity	Metabolic rate [W/m²]	[met]
Leaning	46	0.8
Sitting, relaxed	58	1.0
Sitting activity (office, home, school, laboratory occupation)	70	1.2
Standing, light activity (shopping, laboratory or light industrial occupations)	93	1.6
Standing, medium activity (retail occupation, housework, operating machinery)	116	2.0
Walking on flat ground		
2 km/h	110	1.9
3 km/h	140	2.4
4 km/h	165	2.8
5 km/h	200	3.4

C 3.5

C 3.3 Calculated values of heat transfer resistance according to DIN EN ISO 6946
C 3.4 Heat penetration coefficients for different building materials
C 3.5 Metabolic rate of the human body related to activity level, according to DIN EN ISO 7730
C 3.6 Examples of the heat transfer resistance of different clothing (I_{ce} = clothing insulation value) according to DIN EN ISO 7730
C 3.7 PPD-value relative to PMV-value

not very far apart, the net radiant energy is approximately proportional to the temperature difference.

$$P_{net} = \varepsilon \cdot \sigma \cdot A \cdot 4\,T_m^3 (T - T_0)$$

T_m Mean value of ambient temperature and temperature of the body

With use of this approximation, the heat transfer through radiation can be formally described, in the same manner as heat conductivity, by using a temperature difference T and a coefficient h_r:

$$q = \varepsilon \cdot \sigma \cdot 4T_m^3 \cdot (T - T_0) = h_r \cdot \Delta T$$

Infrared thermography uses thermal radiation to make the temperature difference of building components visible (Fig. C 3.1, p. 136). During colder parts of the year, it can be used to localise and identify buildings with higher surface temperatures (thermal bridges).

Convection
Apart from conduction and radiation, heat is also transported through the movement of matter. This process is especially relevant in gases (above all in air) and liquids. Convection is a transport process by which heat is moved together with matter from one location to another. This occurs, as does thermal radiation, on the surface of building components and can be described by the coefficient h_c. The heat flux ($\dot{Q}$) is proportional to the flow velocity at the surface of the building component.

$$\dot{Q} = \frac{d}{dt}(m \cdot c) := h_c \cdot A \cdot \Delta T$$

Convection occurs especially on the external surfaces of buildings, but also to some extent in inhabited spaces and in the voids between building components, e.g. within vented facades or roof space. Building ventilation is also a convection process because heat is carried to the outside with the extracted air.

Heat transfer
These processes, at boundary layer of gases, fluids and solid bodies – at the surfaces –, are especially influenced by the transport mechanisms of radiation and convection and are described using so-called thermal transfer resistances. Formally, this resistance is dependent on the properties of the air layer bordering on the solid body. The surface heat transfer resistance R_s is defined as:

$$R_s = \frac{1}{h_c + h_r}$$

h_c convection transfer coefficient (c)
h_r radiation transfer coefficient (r)

The values for the transfer coefficients h_c on the interior surface of a wall are entirely dependent on the orientation of the heat flow. They are, according to DIN EN ISO 6946:
- h_{ci} = 5.0 W/m²K for an upwards orientation of the heat flow
- h_{ci} = 2.5 W/m²K for a horizontal orientation of the heat flow
- h_{ci} = 0.7 W/m²K for a downwards orientation of the heat flow

On the outer surface of a wall, the convection transfer coefficient can be calculated using the wind speed v [m/s] across the building's surface:

$$h_{ce} = 4 + 4 \cdot v$$

Where there are no exceptional circumstances, the values for surface heat transfer resistances R_{si} (surface, interior) and R_{se} (surface, exterior) given in Fig. C 3.3 apply for flat building components. The tables are based on the following assumptions:

- emissivity ε = 0.9
- T_M = 20 °C for the calculation of R_{si}
- T = 0 °C for the calculation of R_{se}
- wind speed across the exterior surface v = 4 m/s

Other divergent conditions can be described using the equation given to calculate h_c and h_r.

Thermal comfort
Thermal comfort is defined in section 7 of DIN EN ISO 7730 as "the condition of mind which expresses satisfaction with the thermal environment". Human temperature perception is the measure of thermal comfort. Temperature is felt mainly through the stimulation of the skin's thermoreceptors. Apart from the absolute skin temperature, thermoreceptors are sensitive to the rate of temperature change and the area of stimulation. There are different receptors for the perception of warmth and cold. As long as both receptors send impulses of the same intensity, the individual is indifferent to temperature – it feels neither too hot nor too cold. If perception of warmth or cold goes beyond certain limits, a regulatory loop is set off that holds the body's temperature fairly accurately at 37 °C. When the temperature is too low, the body's energy consumption increases and body heat is produced through metabolic activity; at higher temperatures, body heat dissipates via the additional cooling effect of sweat evaporating on the skin until equilibrium is reached and thermal balance achieved.

The idiosyncrasies of perception, together with the physical properties of materials, explain how concrete is perceived as a "cold material" and wood as a "warm material", even at the same temperature. Touching a part of a building with a temperature that differs from body temperature causes a heat flow through the body that is proportional to the temperature difference and the heat penetration coefficient $b = \sqrt{\lambda \cdot c \cdot \rho}$. This value, a combination of thermal conductivity and the specific heat capacity, is five times greater for concrete than for wood (Fig. C 3.4), so the experience and stimulation – despite the same temperature difference – is perceived as five times as intense. This phenomenon also takes place when parts of a building are above body temperature, in which case concrete is perceived as the "warmer material", but goes unnoticed because the temperature of building components is usually less than 32 °C (human skin temperature).

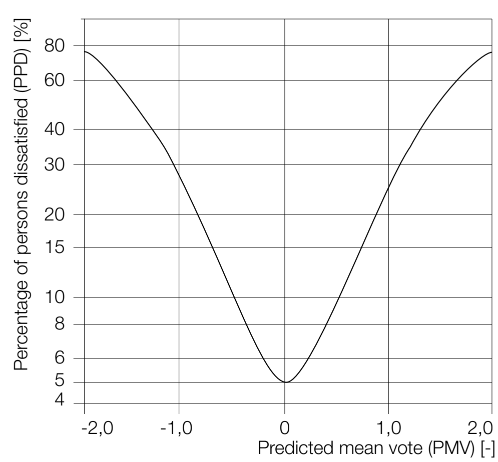
The thermal balance of the human body includes above all energy from metabolic activity M (as well as the external contribution W). The metabolic rate of a person sitting at rest serves as a unit (reference value). This unit – 1 met – equals 58 W/m² (Fig. C 3.5). This value can easily treble with physical exertion. Thermal energy transfers to the environment through evaporation (Q_e), respiration (Q_{res}) and heat flow through clothing. This value will depend primarily on the thermal transfer resistance of clothing (Fig. C 3.6). If the control volume is limited by the boundary layer between clothing and air instead of the skin surface, the transmission losses are the sum of radiation (Q_r) and convection losses (Q_V). The thermal transfer resistance of normal office clothing (a business suit) serves as a reference. This unit – 1 clo – has a thermal transfer resistance of 0.155 m²K/W. Heat losses and gains must be balanced if an environment is to be perceived as comfortable.

$$M + W = Q_e + Q_{res} + Q_r + Q_V$$

Because the amounts of thermal energy produced by the body or gained from external sources and heat given up to the environment by the body are variable, each individual experiences many different states of equilibrium as thermally neutral. Given the same conditions, heavy physical exertion or sporting activities requires lighter clothing than stationary activities. The level of activity, clothing and the interior climate are all therefore decisive parameters for the perception of thermal neutrality. Age, sex and acclimatisation to a particular climate influence thermal perception less, as shown in comprehensive investigations [1]; however, inter-subjective differences play a significant role in the appraisal of climatic boundary conditions.
The function of the interior spaces within a building – and therefore the level of physical activity and the clothing of the users – is normally precisely predetermined. The metabolic rate of a typical (seated) office activity is about 1.2 met, which is the equivalent of 70 W/m². At the same time, office workers normally wear clothing with a thermal transfer resistance of 0.155 m²K/W, or the equivalent of 1.0 clo. In these conditions, the air temperature, the temperature of the interior surfaces, the relative humidity and the air speed all determine whether the condition – in this case the office climate – is thermally neutral and hence feels comfortable. For practical reasons, the mean radiation temperature of a room's surfaces and the air temperature are often aggregated to a cumulative parameter, e.g. the operative temperature that can be measured directly. To identify how the interior climate is experienced for specified uses, the so-called PMV-index (predicted mean vote) can be calculated. Values lie between -3 (cold) and +3 (hot), where PMV = 0 is perceived as thermally neutral. Due to differences in individual perception, extensive sampling produces a characteristic distribution function that also shows the percentage of persons dissatisfied (PPD). Fanger's research results [2] show that the PPD value, with pre-existing met and clo values, does not fall below 5 % (Fig. C 3.7), even with unlimited variable parameters. These remaining dissatisfied users have no alternative than to wear different clothing.

Work clothing	clo	I_{cl} m²K/W	Standard clothing	clo	I_{cl} m²K/W
Underwear, overalls, socks, shoes	0.70	0.110	Underwear, t-shirt, shorts, light socks, sandals	0.30	0.050
Underwear, overalls, shirt, socks, shoes	0.80	0.125	Underwear, short sleeved shirt, light trousers, light socks, shoes	0.50	0.080
Underwear, shirt, trousers, dust coat, socks, shoes	0.90	0.140	Underwear, underskirt, stockings, skirt, shoes	0.70	0.105
Underwear, shirt, trousers, jacket, socks, shoes	1.00	0.155	Underwear, shirt, trousers, socks, shoes	0.70	0.110
Long underwear, insulated jacket, socks, shoes	1.20	0.185	Underwear, shirt, trousers, jacket, socks, shoes	1.00	0.155
Underwear, shirt, trousers, jacket, quilted jacket and overalls, socks, shoes, cap, gloves	1.40	0.220	Underwear, stockings, blouse, long skirt, jacket, shoes	1.10	0.170
Long underwear, shirt, trousers, jacket, quilted jacket and overalls, socks, shoes	2.00	0.310	Underwear, shirt, trousers, pullover, jackets, socks, shoes	1.30	0.200
Long underwear, insulated jacket and trousers, parka with thick quilting, overall with thick quilting, socks, shoes, cap, gloves	2.55	0.395	Underwear, shirt, trousers, vest, jacket, coat, socks, shoes	1.50	0.230

C 3.6



C 3.7

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Cologne	Temperature [°C]	2.4	1.9	4.9	9.0	13.4	15.6	17.9	17.9	14.4	11.1	6.0	4.1
	Relative humidity [%]	83.3	76.5	73.8	71.5	69.7	75.2	69.4	76.2	79.6	84.3	85.1	84.3
Berlin	Temperature [°C]	1.9	0.3	5.4	8.3	14.0	17.6	19.1	18.5	15.0	10.2	4.4	2.4
	Relative humidity [%]	80.4	80.5	77.8	69.8	63.8	64.5	63.1	65.5	70.6	76.8	83.0	86.6
Sydney	Temperature [°C]	24.3	24.0	21.6	18.7	16.2	15.6	12.5	13.7	15.9	18.8	19.1	20.5
	Relative humidity [%]	68.9	69.1	66.2	64.6	76.0	67.3	63.6	49.4	53.1	62.1	61.2	68.7
Hong Kong	Temperature [°C]	16.1	16.3	19.0	22.6	26.1	27.9	28.9	28.4	27.5	25.3	21.5	17.1
	Relative humidity [%]	75.0	80.1	82.2	84.2	81.7	84.6	79.6	81.5	80.8	72.2	69.1	66,6
Stockholm	Temperature [°C]	-3.5	-0.8	0.3	4.5	11.7	14.5	17.0	16.0	11.3	6.7	1.6	-1.9
	Relative humidity [%]	90.7	78.6	84.3	65.4	63.5	68.0	73.0	72.3	81.8	85.8	88.2	88.5
Washington	Temperature [°C]	-0.6	1.5	5.8	10.9	16.4	22.6	24.5	23.7	20.4	13.9	7.9	1.7
	Relative humidity [%]	66.0	71.0	56.6	60.3	60.4	66.4	71.3	72.9	66.9	70.9	66.4	67.2
Riyadh	Temperature [°C]	14.0	16.7	20.3	25.9	32.1	35.2	36.2	36.4	33.0	27.6	21.6	14.9
	Relative humidity [%]	43.3	33.8	30.3	23.5	14.7	12.0	8.5	10.5	15.7	21.0	24.1	57.1
Moscow	Temperature [°C]	-6.8	-7.6	-0.9	7.3	13.4	16.6	19.1	15.9	10.9	5.7	-2.7	-5.7
	Relative humidity [%]	86.0	77.7	70.2	68.7	68.0	70.0	73.2	80.0	82.4	82.5	83.8	85.1
Dakar	Temperature [°C]	20.2	20.3	20.9	21.3	23.0	25.1	27.0	27.3	27.7	27.5	25.9	23.1
	Relative humidity [%]	64.9	72.7	79.1	83.6	85.0	83.3	78.8	84.8	81.6	79.7	76.3	70.6
Lima	Temperature [°C]	22.5	23.2	23.1	20.9	19.2	18.5	17.0	16.6	17.1	17.8	19.3	21.4
	Relative humidity [%]	76.8	80.1	79.2	81.1	81.1	81.3	80.1	84.8	83.3	83.5	80.2	76.5

C 3.8

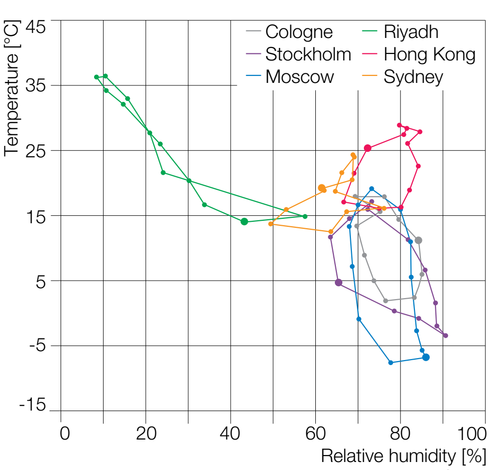
The term local discomfort indicates a phenomenon that only occurs at particular points within a space and causes individuals to feel uncomfortable, although the space as a whole meets the criteria for comfort. This includes:

- Draughts (especially around the neck or ankles)
- A pronounced vertical air temperature difference
- A floor that is too warm or too cold
- Asymmetric radiation exchange due to differing surface temperatures

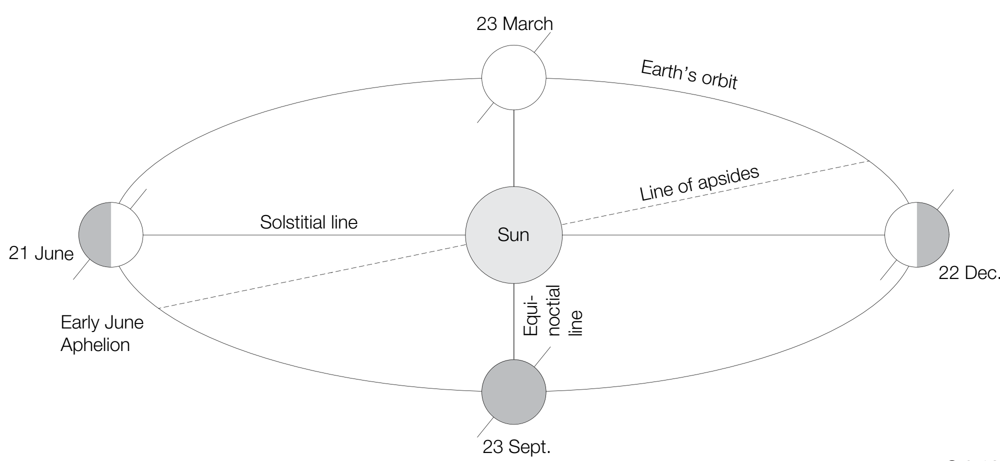
The decisive parameters – air temperature, mean radiation temperature, relative humidity and air speed – determine the PMV values for comfort perception. These parameters are influenced by the exterior climate and, at the same time, are closely linked to a building's construction and technical services. This relationship is explained in brief below.

Climatic conditions

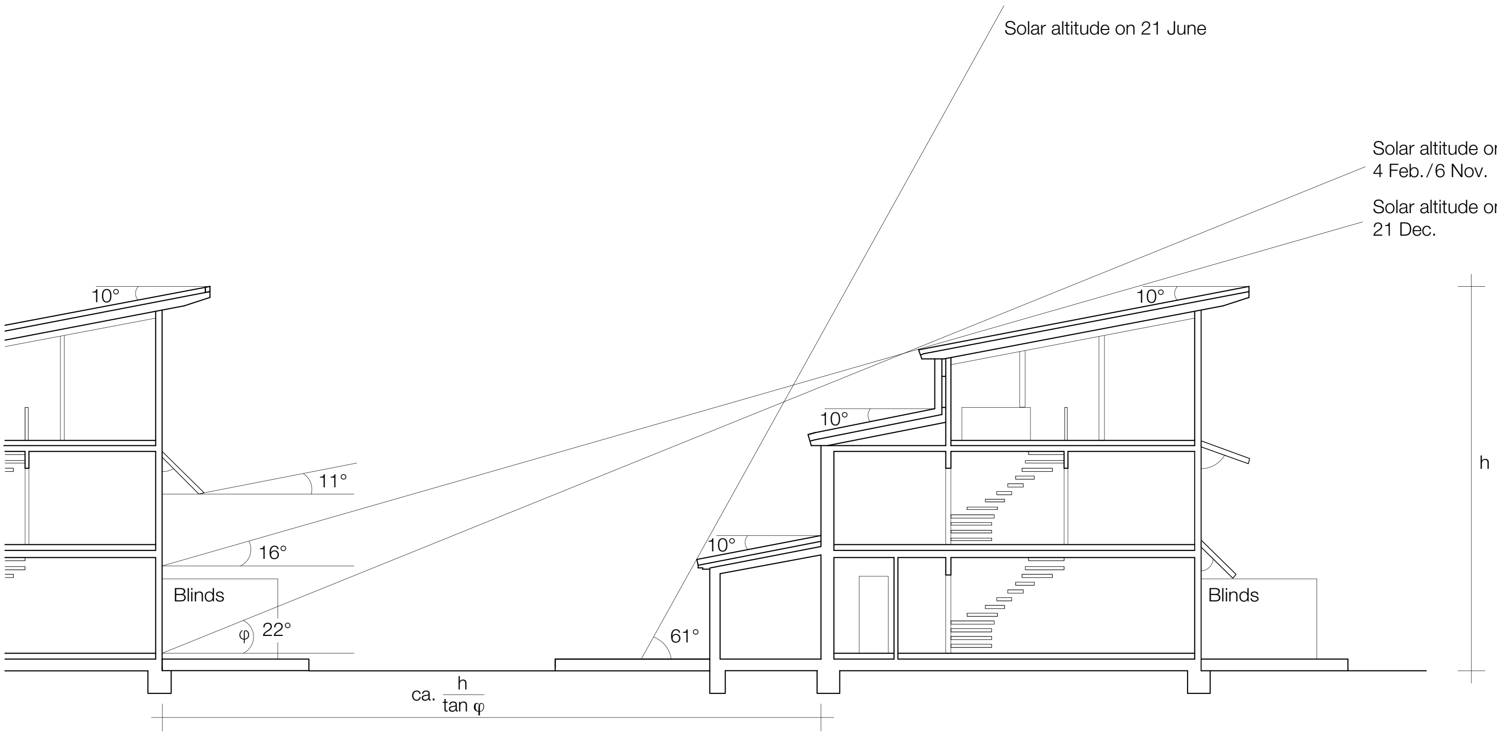
On the whole, the European climate is regarded as temperate and has typical seasonal variations. At the macro level, the climate is subject to the movement of large air masses and is influenced by the capacity of the earth's surface and sea to store heat as well as by solar radiation. Germany belongs to the mid-latitudes with a moderately warm and rainy climate. The north-west is subject to oceanic influences, while the climate becomes increasingly continental toward the south-east. Seasonal changes bring a relatively mild winter and a summer that is not too hot. To gauge the impact of the climate on the heating requirements of buildings, climate data is available in the form of long-term mean values. The temperature and radiation values are most relevant. DIN V 4108-6, for example, gives monthly averages for outdoor temperatures and radiation intensities for 15 climate zones in Germany. As part of a simulation programme, the United States Department of Energy also provides climate data (Fig. C 3.8 and 3.9). The climate in Central Europe means that interior spaces can only be kept comfortable through the input of energy and through the use of technical systems. The temperatures in winter are so low that the heat flux density from warm interiors to cold exterior is, depending on the energetic standard of the building's envelope, between 4 and approx. 10 W/m². In the summer as well, the average difference between the temperatures of interior spaces and the outer air temperature means heat flow is to be anticipated. However, for the same



C 3.9



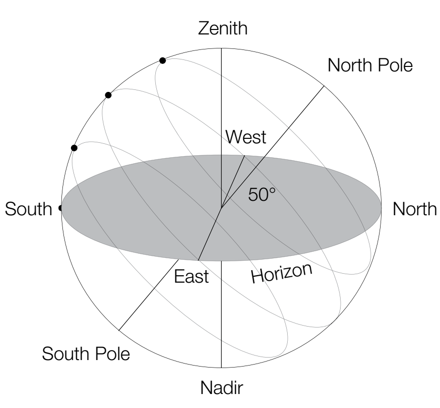
C 3.10



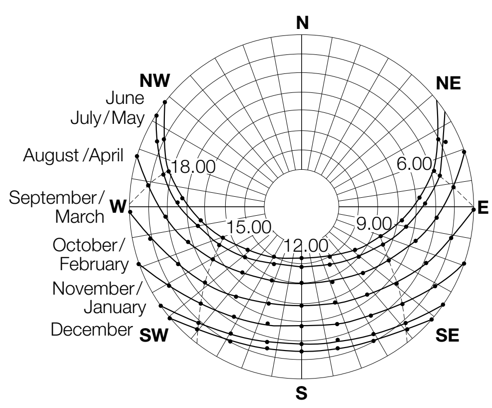
C 3.11

U-value, the heat flux density is only around 20 % than in colder months. Additionally, the difference between the maximum and minimum daily temperatures in summer is much greater than in winter, so at times the direction of the heat flow, at least on the exterior surfaces, reverses.
Apart from the temperature, solar radiation also constitutes a climate parameter. The radiant power of the sun is given as the so-called solar constant. This is 1,367 W/m², of which – depending on the season, latitude and atmospheric conditions – approx. 740 W/m² reaches the earth's surface. Germany's geographic location stretches more or less between the latitudes of 48° and 52° north. Because the earth's axis of rotation tilts by approx. 23.5°, solar radiation varies considerably through the year (Fig. C 3.10). At a latitude of 50° north, the sun reaches a high point of around 66° in midsummer and around 17° in midwinter (taken as the angle from the horizon). It is possible to determine the path of the sun for every point on the surface of the earth as a function of time, which can be represented in a sun chart (Figs. C 3.12 and C 3.13). With floor-to-ceiling glazing of a height h and without shading, the sun's rays will reach up to a depth of h · cot φ into a room, where φ is the angle of the sun (Fig. C 3.12). In the summer months (May until August), more solar radiation passes through the vertical surfaces into a building's interior on the eastern and western facades than on the southern facades. However, this is more than made up during the remaining months of the year. The sun's path determines both the minimum distance between neighbouring buildings in relation to their height if the sun's rays are to reach interiors spaces or systems that utilise solar energy.

The interaction between buildings and climate can be observed and categorised according to different levels of scale. The influence of buildings on the macroclimate is not recognisable. However, there are signs of a shift towards higher annual mean temperatures. It is expected that global warming will lead to a reduction in the need for heating during the winter months. For non-residential buildings, this can also mean an increase in the requirement for cooling and air conditioning in the summer. In any case, it would seem prudent to consider these developments in the planning and construction of new buildings with operational life spans of more than 50 years; this means attaching more importance to summer sun protection.
The mesoclimate is determined by regional characteristics. At this level, there is an interaction between the topography, areas of water,



C 3.12



C 3.13

C 3.8 Mean daily temperature and humidity values for selected regions
C 3.9 Annual variations (running clockwise) in temperature and humidity for six selected cities, the large dot denotes January values
C 3.10 Elliptical orbit of the earth around the sun
C 3.11 Overshadowing by neighbouring buildings and the position of the sun
C 3.12 Annual apparent path of the sun for a location 50° north latitude
C 3.13 Sun position chart for 51° north latitude (position on the 21st day of each month)

Cross section	Exterior Passive House	Exterior KfW-Efficiency House	Exterior wall new building	Exterior wall WSVO 1995	WSVO 1981/ triple glazing sealed units	Double glazing sealed units	Older double glazing, brick wall 36.5 cm	Ventilated double glazing/case-ment windows	Single glazing
U-value [W/m²K]	0.15	0.2	0.3	0.5	0.8	1.2	1.8	2.5	6.0
Air temperature interior/exterior [°C]					**Interior surface temperature [°C]**				
18/-10	17.5	17.3	16.9	16.2	15.1	13.6	11.4	8.9	-3.8
20/-10	19.4	19.2	18.8	18.1	16.9	15.3	13.0	10.3	-3.4
22/-10	21.4	21.2	20.8	19.9	18.7	17.0	14.5	11.6	-3.0
18/-5	17.6	17.4	17.1	16.5	15.6	14.4	12.6	10.5	0.1
20/-5	19.5	19.4	19.0	18.4	17.4	16.1	14.2	11.9	0.5
22/-5	21.5	21.3	20.9	20.2	19.2	17.8	15.7	13.2	0.9
18/0	17.6	17.5	17.3	16.8	16.1	15.2	13.8	12.2	4.0
20/0	19.6	19.5	19.2	18.7	17.9	16.9	15.3	13.5	4.4
22/0	21.6	21.4	21.1	20.6	19.7	18.6	16.9	14.9	4.8

C 3.14

vegetation, housing developments and climate. The level of solar radiation, for example, is related to the aerosol content in the air (e.g. dust particles and salt crystals) and to an area's elevation profile. Vegetation and topography can noticeably affect the air temperature and humidity. For the purpose of building design, the mesoclimate can be regarded as an unalterable, although changes to urban and spatial planning may have an effect in the medium to long term.
The microclimate, i.e. the climatic conditions in the immediate surroundings of a building site, is of great significance for the design and construction of a building. Exterior temperature, humidity, solar radiation and wind speed can vary greatly and can themselves be influenced by the building, e.g. the colour of the facade material, the roof type and the design of the outside areas. As part of the statutory requirement for planning approval and to meet legal conditions, which for understandable reasons are standardised, the design of a building must not ignore the microclimate and its relationship to the specific location. The necessary climate data is available from the German Weather Service or from relevant literature [4] or electronic media [5].

Interactions between building components and interior climate

Interiors must be heated during periods of persistently low temperatures. Generally, the interior air is kept at a constant temperature, via convection or radiation from heated surfaces, of at least 20 °C. The temperature of the building's interior surfaces should not drop below a minimum temperature to avoid the build-up of condensation and to keep the room feeling comfortable. With conventional heating systems (radiators), the temperature of the building's interior surfaces is always lower than the ambient room temperature during the heating period. The difference to the air temperature is a result of the heat flow resistance and the heat transfer resistance, and is largely dependent on the direction of the heat flux (Fig. C 3.3, p. 138). Surface heating (under-floor heating or wall surface heating) is particularly suitable for heating systems with a low supply temperature. The surface temperature of these building components is slightly higher than the air temperature of the room. This has a positive effect on the perception of comfort. Assuming a steady state, the temperature in a cross section of a building component can easily be determined since the temperature change through a homogenous building component is linear (see "Basic equations of thermal conductivity", p. 137). For building components with different layers perpendicular to the thermal flux, the total heat transfer resistance R_{tot} is the sum of the individual resistances

$$R_{tot} = R_{si} + \sum_n \frac{d_n}{\lambda_n} + R_{se} = R_{si} + \sum_n R_n + R_{se}$$

Heat transfer resistance is inversely proportional to the thermal conductivity, the U-value :

$$U = \frac{1}{R_{tot}}$$

At the same time and due to

$$q = \frac{\Delta T_{tot}}{R_{tot}} = \frac{\Delta T_i}{R_i}$$

the temperature distribution can be calculated from the resistances and the overall temperature difference:

$$\Delta T_i = \frac{R_i}{R_{tot}} \Delta T_{tot}$$

In a steady state, the temperature of the interior face of exterior building components can be derived from the equation:

$$T_{si} = T_i - \frac{R_{si}}{R_{tot}} \Delta T_{tot}$$

Fig. C 3.14 shows how lower U-values correlate with higher interior surface temperatures, which aids the exchange of thermal radiation between the building's occupants and the interior surfaces. The radiation temperature can have a similarly large effect on the comfort of a room as the air temperature. Window surfaces demand special attention as they nearly always have a higher U-value and a lower surface temperature than opaque building components. This can easily lead to radiation asymmetry. In extreme cases, the temperature difference with old double-glazed units, casement windows and single-glazed windows is so great that it can be mistakenly perceived as a draught, although it is actually radiation asymmetry.
During the summer months, heating is not generally necessary in building interiors. Heat from the building's normal operations contributes to maintaining a comfortable interior temperature. In addition, there is heat gain from solar radiation through glazed surfaces. Because of the high heat capacity of buildings of solid construction, the interior air temperature does not differ considerably from the temperature of the building's internal surfaces, even on days with strong solar radiation. The solar gain is buffered by a moderate increase in the temperature of the building components, i.e. they store the heat, and the interior climate remains at a level that the majority would find comfortable

Energy efficiency of buildings

Currently the operation of building services and systems makes up the largest part of a building's energy consumption. These services and systems maintain a comfortable interior climate, keeping the undesired effects of the changing exterior climate at bay and limiting fluctuations to the interior temperature. If the energy balance of a building were the only consideration in its design, the building envelope would resemble a thermos flask, isolating

C 3.14 Correlation between U-value and surface temperature
C 3.15 System boundaries for evaluating heating requirements, showing the losses through the plant and technical systems
C 3.16 Insulation thicknesses required for exterior concrete components to achieve the U-value of the reference building (EnEV 2009)
C 3.17 Production of sandwich panels in a precast concrete factory

the building's interior almost entirely from the outside world. But for good reason, there are many other considerations that need to be incorporated into the design of a building. In this part of the world and regardless of location, buildings are heated during the winter months and – especially office buildings – cooled in the summer. This requires a substantial amount of energy, which can be calculated as the balance of all energy flows through the material balance envelope. Energy inputs are made up of a combination of the primary energy supplied (solid, liquid or gaseous fuels, electricity, district heating), direct and indirect solar gain and even the heat emitted by the building's users. In assembly rooms where large groups of people congregate, the occupants can emit so much heat that high-powered air conditioning is required to limit the increase in temperature. The input of energy generated in and on buildings, e.g. through the use of photovoltaic or solar thermal energy systems, or wind turbines, should be taken into account. Energy loss is practically solely due to heat loss; this covers heat lost through planned and unplanned ventilation, radiation and transmission as well as heat lost in the exhaust gases of combustion or in wastewater. The basic model for the energy balance is shown in Fig. C 3.15. Ignoring the capacity of the building itself to store energy, the energy inputs and losses should balance out at any point in time, resulting in – just as in the human body – a steady state (assuming heat storage capacity is not taken into account). Whether these assumptions represent a useful approximation, is largely dependent on the subject under investigation. When calculating the annual heating requirement, an assumption of a steady state will give adequately accurate results. However, if the change in the interior temperature of a room exposed to strong sunlight over the course a day is to be investigated, the assumption of a steady state will distort the results significantly.

Energy efficient heating

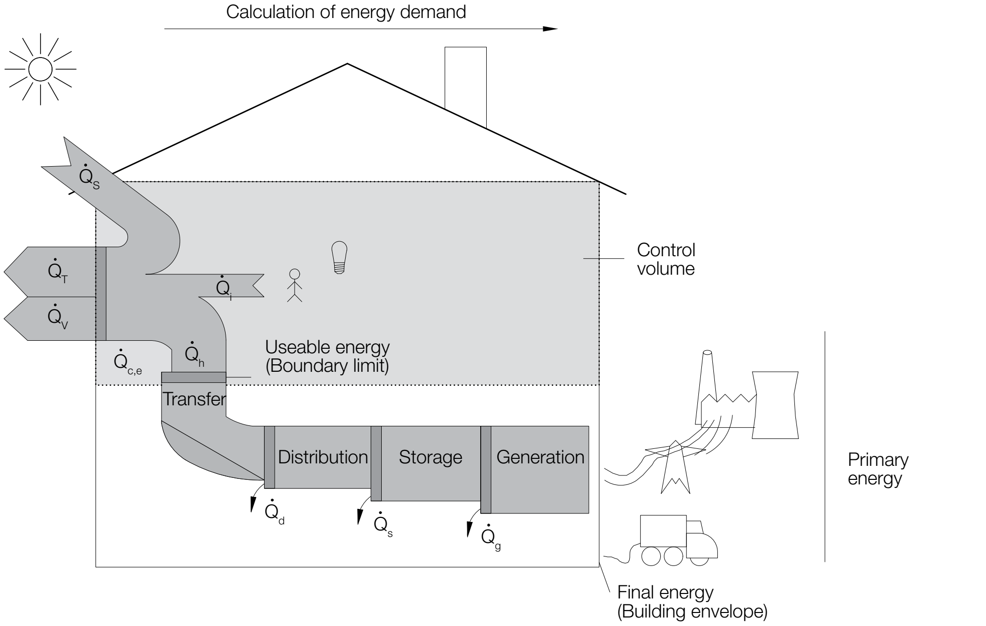
There are three principle prerequisites for the efficient use of energy during the heating period:

- A well-insulated building envelope that prevents transmission losses
- Interior building components with a sufficiently high heat storage capacity to buffer solar heat gain by increasing component temperature – especially in spring and autumn – and which allow the stored heat to be released back into the interior over several days
- The design and implementation of air tightness in conjunction with controlled ventilation and heat exchange to minimise airborne heat loss

Effect of thermal insulation

Concrete as a building material is employed in all opaque areas of a building envelope. Standard concrete has a relatively high thermal conductivity and can therefore not be used for exterior building components without the addition of thermal insulation. For this reason, concrete layers within a multi-layered construction have no practical bearing on the heat transfer coefficient (U-value). Fig. C 3.16 gives the minimum thickness of the insulation layer for the reference building to meet the current Energy Saving Ordinance standard. The need for thermal insulation does not exclude the option of designing exterior concrete walls: rendered facade surfaces, cladding suspended on a substructure and facade layers from exposed concrete are all possible. However, casting insulated exposed concrete facades in-situ is technically complex, as the exterior facade layer needs to be cast against the insulating and the structural layers. It is simpler to manufacture the insulated concrete facade as pre-cast sandwich elements for installation on site (Fig. C 3.17). In situations where additional thermal or acoustic insulation is necessary – e.g. for facades bordering on busy roads – a low density insulating layer is required (see, "Building acoustics", p. 152ff).

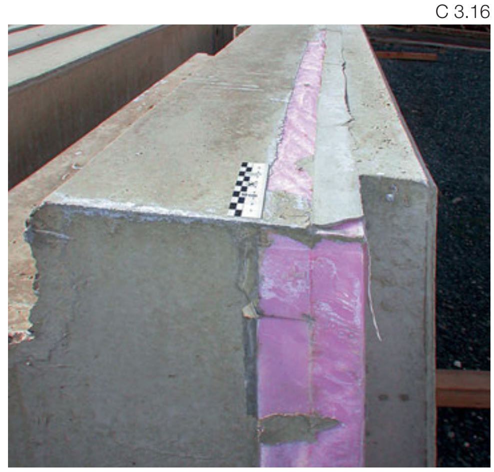
A monolithic construction is possible for external building components using lightweight concrete without additional insulation. Lightweight concrete and steel reinforced lightweight concrete for structural components have a calculation value for thermal conductivity in relation to their gross densities of between λ = 0.39 W/mK for ρ = 0.8 kg/m^3 and λ = 1.6 W/mK for ρ = 2.0 kg/m^3. Depending on the composition of the lightweight concrete and the block geometry, the calculation value for thermal conductivity of lightweight concrete blocks can be reduced to as little as λ = 0.09 W/mK. Detailed information can be found in the building authority approvals for specific block types.
Occasionally, the total thickness or the thickness of individual layers changes abruptly, e.g. around stiffening building components or in an area around installations. As long as the thickness of the insulation layer in this area remains unchanged, it has a negligible influence on the U-value and consequently on energy efficiency. If the sectional dimension changes result in a significant increase in the U-value, it is useful to estimate the impact according to DIN EN ISO 6946. For this purpose, an assumed network of orthogonal isotherms and heat flux lines with equidistant interval values is used to calculate the upper and lower limits of the U-values [6]. In principle, this is a model of resistances connected in series and parallel, with the values



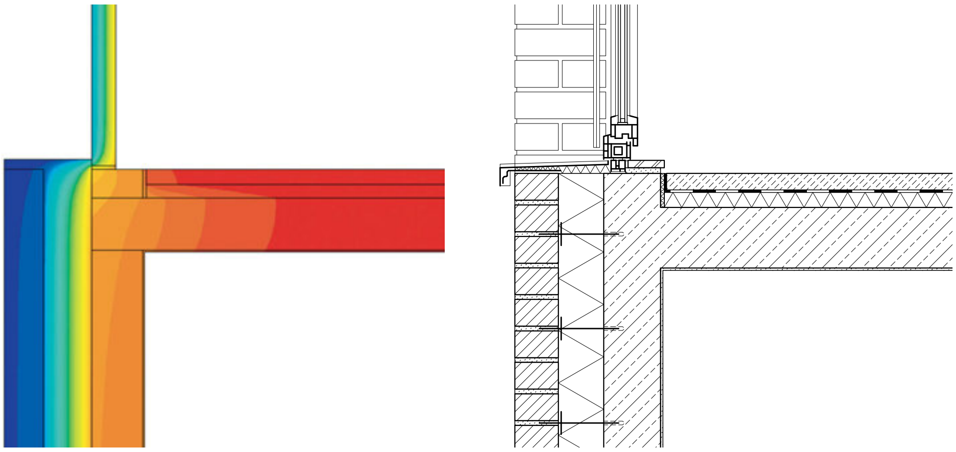
C 3.15

λ	Building element: Ceiling /roof	Wall	Floor slab
0.030	14	10	8
0.032	15	11	8
0.035	17	12	9
0.037	18	12	10
0.040	19	13	10

C 3.16



C 3.17



a b C 3.18

C 3.18 Thermal bridge at the base of a building
a Examples of isotherm curves
b Detail, scale 1:20
C 3.19 Anchor types for the production of sandwich panels
C 3.20 Measuring the natural air exchange rate using the tracer gas method

$$R_{m,n} = \frac{s_n}{\lambda_{m,n}}$$

Using the surface area proportion $f_m = A_i/A_{tot}$ the upper limit of the thermal resistance can be determined:

$$R'_T = \left(\sum_m \frac{f_m}{\underbrace{[R_{si} + \sum_n R_{m,n} + R_{sa}]}_{\text{Resistance of the section m}}} \right)^{-1}$$

The lower limit of thermal resistance can be calculated using:

$$R''_T = R_{si} + \sum_n \underbrace{\left[\sum_m \frac{f_m}{R_{m,n}} \right]^{-1}}_{\text{Resistance of the layer n}} + R_{se}$$

As long as $R'_T \leq 1.5 \cdot R''_T$, the mid-point between the lower and upper values can be used as a reasonable approximation of the actual thermal resistance:

$$R_T = \frac{R'_T + R''_T}{2}$$

In all other cases, the isotherms and heat flux lines form a curvilinear network, indicating a thermal bridge (Fig. C 3.18 a). The impact of such thermal bridging can be calculated precisely or estimated using tables [7].

The connections between the load-bearing layer and the exterior facade layer, as well as the design of the joints between panels, are especially important for the U-values of insulated concrete sandwich panels. If, for example, these junctions are sealed with an airtight expansion joint, there is little likelihood of an increase in the U-value. The various types of anchors used to create a connection are normally made from stainless steel (Fig. C 3.19). They form a classic thermal bridge, and their high thermal conductivity ($\lambda_f \approx 50$ W/mK) has an effect on the U-value. The impact on the heat transfer resistance can be approximated from appendix D of DIN EN ISO 6946. Here, an allowance of ΔU_f is applied, which is dependent mainly on the properties of the anchors – quantity (n_f), cross section (A_f), thermal conductivity (λ_f) – the thickness of the insulation layer (d_0) and the relationship between the heat transfer resistance of the insulating layer (R_T) and the heat transfer resistance of the sandwich panels ($R_{T,h}$):

$$\Delta U_f = 0.8 \cdot \frac{\lambda_f \cdot A_f \cdot n_f}{d_0} \left(\frac{R_1}{R_{T,h}} \right)^2$$

This allowance is then added to the U-value to calculate cases in which the insulation layer is not penetrated:

$$U_c = U + \Delta U_f$$

Glazed areas have considerably higher U-values than opaque surfaces. This has not changed significantly, despite the development of high-performance multi-layered insulating glazing with U-values from 0.6 to 1.1 W/m²K. The proportion of glazing in a building facade varies. The orientation of the facades' surfaces (to the sun), the building's use (internal heat gain and required light levels) and design decisions are all important considerations. Generally, glazed surfaces should not make up more than 30 % of a facade.

Influence of the heat storage capacity
The effective capacity of a building to store thermal energy greatly influences the interior temperature and its energy efficiency. The heat capacity of a building component increases as its mass increases in relation to its surface area, if a building material is chosen with a higher specific heat capacity or if the difference between the temperature of the component and the ambient temperature increases. Therefore, concrete building components have a very high storage capacity in comparison to components made of lighter building materials, thanks to their heat storage capacity in relation to the component's surface area (see "Heat and heat-transfer processes", p. 136ff):

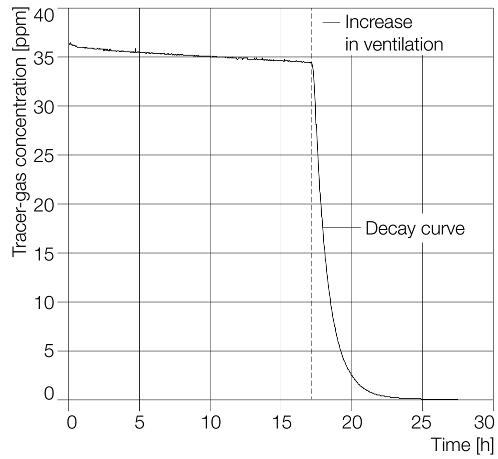
$$C' = \rho \cdot d \cdot c$$

If the building component borders the interior air space directly and is not separated behind a layer of insulating material, it can store large amounts of heat in the short term. An increase in air temperature above the temperature of the building component initiates a heat flux towards the inside of the component. If the building component has a very high heat capacity, the increase in air temperature is limited to just a few degrees Kelvin. If this is followed by a fall in air temperature back below that of the building component, the building component releases its stored heat. This is a transient and therefore a time-dependent process, requiring some effort to describe with mathematical formula and then only applicable to a limited number of cases. For practical purposes, it is sufficient to approximate the phenomena in terms of a time constant, determined by the relationship between heat storage capacity $C_{eff.}$ and thermal conductivity H (given as the transmission heat loss coefficient):

$$\tau = \frac{C_{eff.}}{H}$$

This effect ensures the interior temperature of solid structures remains within a range of a few Kelvin, even with considerable energy gains. In addition, energy inputs (gains) within the building envelope can be stored and used when needed to provide heat for the interior. For this concept to function there must be both a sufficiently high effective storage capacity (taken from the thermal conductivity coefficient) and good thermal insulation on the exterior surfaces of the building component (in the form of a low U-value).
In buildings constructed from concrete, practically all structural building components – solid columns, wall and ceiling slabs – are effective as active thermal storage. Their high density and high thermal conductivity mean their capacity to absorb and store thermal energy is significantly better than brick or block-built constructions. The full effect on the interior climate is achieved if the air in the room comes into direct contact with the concrete surfaces. Especially in offices and administration buildings, schools, theatres and cinemas or venues where the interior thermal gain increases rapidly during occupation,

C 3.19



C 3.20

concrete storage mass can be particularly beneficial if the interior surfaces are not clad with insulating material for acoustic reasons, for example.

Influence of convection

For health and hygiene reasons, a minimum air exchange is required in buildings. This will depend on the level of pollutants and odours and the oxygen consumption of the occupants. The rate of air exchange should be at least $n \approx 0.5\ h^{-1}$ in normal recreational rooms, (e.g. lounges, common rooms). Where there is greater air consumption, e.g. in kitchens, bathrooms and production facilities, a higher air exchange rate should be provided for. Air exchange involves heat flow (convection). During the heating period, the exchange of used air from a building's interior with exterior air leads unavoidably to a heat flow to the outside that can be reduced but not reversed through the use of heat exchange equipment. In the summer months, the heat flows in the reverse direction. During the day, heat is transported into the building with outside air; night-time ventilation takes heat with air from the interior to the exterior. Air has a specific heat capacity of $c_p \approx 1.4\ kJ/m^3K$, which is comparatively low in relation to its volume. If the temperature changes at constant air pressure, 2,000 m^3 of dry air can store the same amount of heat as 1 m^3 of concrete. Despite this, the energy transferred with a relatively high rate of air exchange is not insignificant. Heat flows linked to air movement must be regulated to meet the needs of the occupants. A basic prerequisite is that there is no leakage of interior air, through gaps and unsealed junctions, in the case of a pressure difference between the interior and exterior. Characteristically, concrete constructions have few joints and seams. This also applies to the use of precast concrete components, where joints are filled and/or sealed with tape. Openings and junctions require special attention. At these points, an air-tight layer in the form of sheeting or sealing strips, properly installed and inspected, is important. As a quality control procedure, air exchange in a building can be measured. In smaller buildings this takes place using the differential pressure system (blower door) according to DIN EN 13829. For larger interior spaces, the measurement of the differential pressure is difficult. In such cases, the air exchange rate can be calculated at normal pressure, using the so-called tracer gas test, by adding tracer gases to the interior air and measuring their decay curve (Fig. C 3.20). The results of these two test methods more or less correlate.
The simplest way of controlling ventilation is to use conventional user-operated windows, either opening directly to the outside on one side of a room or creating cross-ventilation with other windows in the room. This has the advantage of a high degree of user-acceptance, which is based primarily on habits and reinforced by the direct connection with the outside world. The disadvantages are the reliance on wind pressure and the direct inward flow of air from the outside, which can be very cold especially in winter. Shaft or roof ventilation, relying on warm used air rising, is another natural ventilation method. Here too the air exchange can, because of the external or internal conditions, come to a standstill or go into reverse and require the occasional use of supplementary fans. High interior spaces and other particular building shapes require a mechanical ventilation system to supplement or replace the natural ventilation. Additionally, mechanical ventilation systems are able to increase the air exchange rate specifically to expel heat that could only be buffered by accepting uncomfortably high interior temperatures. Lastly, heat exchangers give the option of tempering the cold incoming air using the warm exhaust air.

Influence of thermal radiation

Solar radiation brings a considerable amount of heat into buildings. Transparent building components reduce short wave UV radiation only moderately. Whereas infrared radiation with a longer wavelength (thermal radiation) is for the large part absorbed and/or reflected by transparent surfaces, this is known as the green house effect. The application of a vapour-deposited metallic film alters the radiation characteristics of window glass, optimising the balance between transmission and reflection. Solar control glass uses this process. However, these functional coatings always affect the transmittance of radiation in the visible range and lead to noticeable darkening. The heat transfer through radiation results in direct thermal gain in buildings because the solar energy passes through the transparent surfaces and is absorbed by the interior of the building. In order to make the best possible use of this gain, those building parts exposed to solar radiation must have a sufficiently high effective heat storage capacity. If this is not the case, the interior temperature will increase beyond comfortable levels, and solar thermal gain will need to be expelled through ventilation (convection) to the outside. Solar radiation raises the temperature of the opaque external parts of buildings. Because the heat flux density is directly proportional to the temperature difference, the heat transmission losses are reduced during the heating period.

Internal gains

Nearly all buildings contain a variety of electrical devices and equipment. Electrical energy used to operate equipment remains as heat in the building. In residential buildings, these internal thermal gains are around 8–10 W/m^2, whereas for office buildings this can be as much as 30 W/m^2. In individual cases, in addition to the energy used for lighting, the operation of office machinery plays a part. In the future, with the increased use of energy-efficient lighting technologies, these internal gains are likely to decline. Furthermore, the building's occupants are a heat source – depending on the level of physical activity ("Thermal comfort", p. 138) – contributing around 100 W per person to the building. This fact plays an important role in office buildings and much more in buildings where a large number of people congregate, e.g. theatres, assembly and concert halls.
All these influencing factors and their interactions need to be considered in the design and construction of energy-efficient buildings by quantifying the individual losses and gains.

Summer heat protection

The construction of building envelopes with U-values of less than 0.2 W/m²K has significantly reduced energy exchange through thermal conductivity. Heat transfer between the inside and outside still takes place through radiation and convection (ventilation). During the summer, the thermal gains through solar radiation and the operation of electrical equipment and appliances are so high that they exceed the night-time losses through thermal conductivity and the (negligible) radiation losses. Office buildings, with a high level of daytime occupancy combined with the heat from illumination and electrical equipment, are especially affected. Additionally, facades of non-residential buildings often feature a high proportion of glazing to provide daylight for the working areas. A simplified calculation of the summer heat protection (according to DIN 4108-3) can be made using solar transmission values. This takes account of the climatic region, the relationship between the surface area of windows and the surface area of the relevant rooms as well as the quality of the windows.

Alternatively, the internal temperatures of the individual rooms or zones of a building can be determined using thermal building simulations with temporally variable (transient) system boundary conditions by modelling the specific physical and technical parameters of a building and then simulating energy flows over a given time period. The boundary surfaces of the cuboid example (Fig. C 3.21) are thermally insulated externally to Passive House standards, so the heat capacity of the building components can be used as a buffer. Wall and roof construction have the same U-values. Windows make up 13.5 % of the total wall area and are arranged equally on all four faces. Thermal transfer occurs through the surface of the outer envelope (system boundary) in the form of thermal conductivity, radiation and convection (ventilation). Other heat sources or sinks (heating, building equipment technology or similar) are not present. The daytime air exchange rate is $n = 0.5\ h^{-1}$ and can be increased to $n = 5.0\ h^{-1}$ during the night. Heating or cooling systems are not active during the simulation [8].

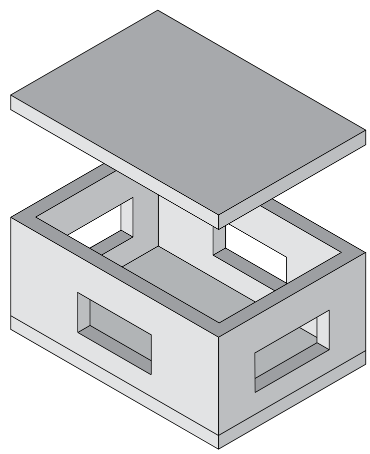
Fig. C 3.22 shows the changes to the exterior and interior (operative) temperatures over the simulation period. It is clear that the exterior temperature shows periodic fluctuations. At the same time, variations over several days (warming and cooling) are identifiable. In principle, the interior temperature follows the course of the exterior temperature. However, the interrelation between the course of the operative temperature and the effective heat storage capacity of the building structure is evident. With a lower heat storage capacity, the operative temperature shows pronounced fluctuation and follows the movement of the exterior temperature closely. With no heat storage mass, the building heats up markedly during the daytime; the peak temperatures become so high it is no longer comfortable and consequently the space has to be air-conditioned.

With greater effective heat storage capacity, the amplitude of the operative temperature compared to the exterior temperature is reduced considerably, and the room temperature oscillates in a narrower range, which is still perceived as comfortable. Under these circumstances, cooling or air-conditioning is not required. These results lead to the general conclusion that, given Germany's climate, the installation of air-conditioning is not necessary if heat influx can be restricted through the use of effective solar protection measures – e.g. external window shading – and building components with effective heat storage capacity to store incoming heat. The temperature of the thermal store at the start of the sun's irradiation should be as low as possible so that – proportional to the temperature difference – heat transfer is maximised and the temperature of the component after storing incoming thermal energy does not exceed approx. 26 °C. This strategy requires the removal of the heat gained in building components during the day through convection to the outside (ventilation) in the cooler night hours, even in the midsummer months. This leads not only to a reduction in a building's primary energy consumption, but also reduces the investment and operating costs for equipment and systems.

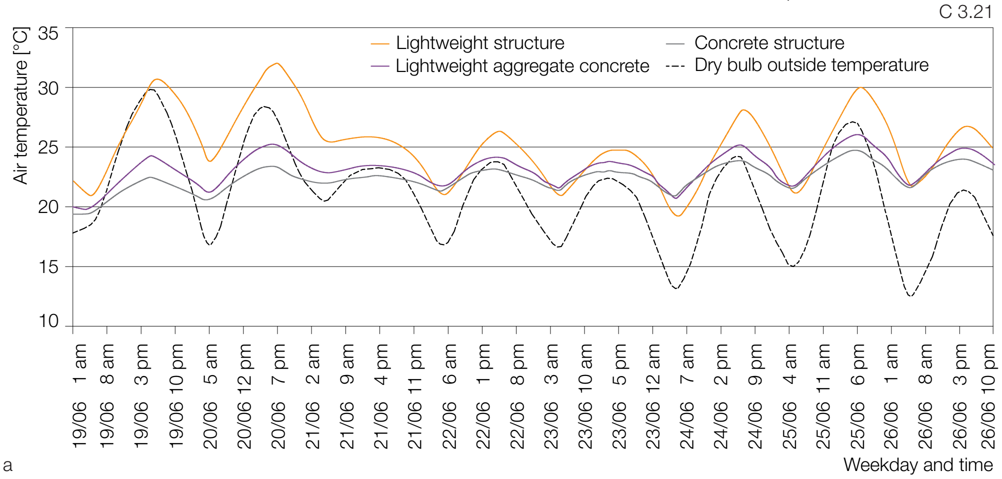
C 3.21 Room example to simulate the interior temperature

C 3.22 Weekly variation in the operative room temperature at midsummer (21 June) with an air exchange rate of $1.0\ h^{-1}$
a With nighttime ventilation of $3.0\ h^{-1}$
b Without nighttime ventilation

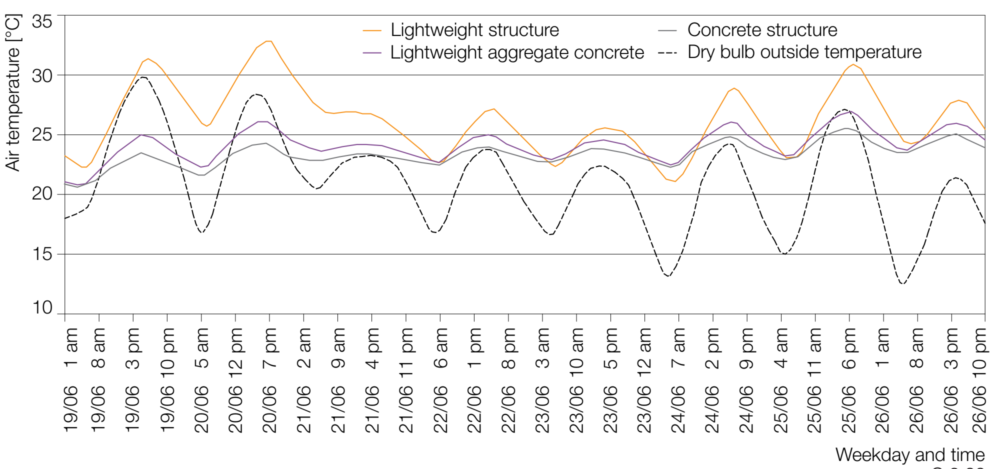
C 3.23 Total system efficiency depending on the size of the building and the annual energy demand for heating in relation to the surface area of the building
a Low temperature boiler 70/55 °C
b Condensing boiler combined with solar thermal to heat water
c Heat pump system



C 3.21



a



b

C 3.22

Systems engineering

Heating and cooling systems ensure buildings are always thermally balanced. If the heat available within a system decreases – and with it the temperature – under a lower limit, heating systems make up the shortfall from a reservoir. If the heat inside the control volume rises above an upper limit, it is discharged to a reservoir outside the system boundary. Heat exchange using technical systems is never without energy loss, as energy is necessary for the operation of the systems. The ratio between energy cost and benefit (inputs and outputs)represents the total system efficiency, expressed by a single value e.

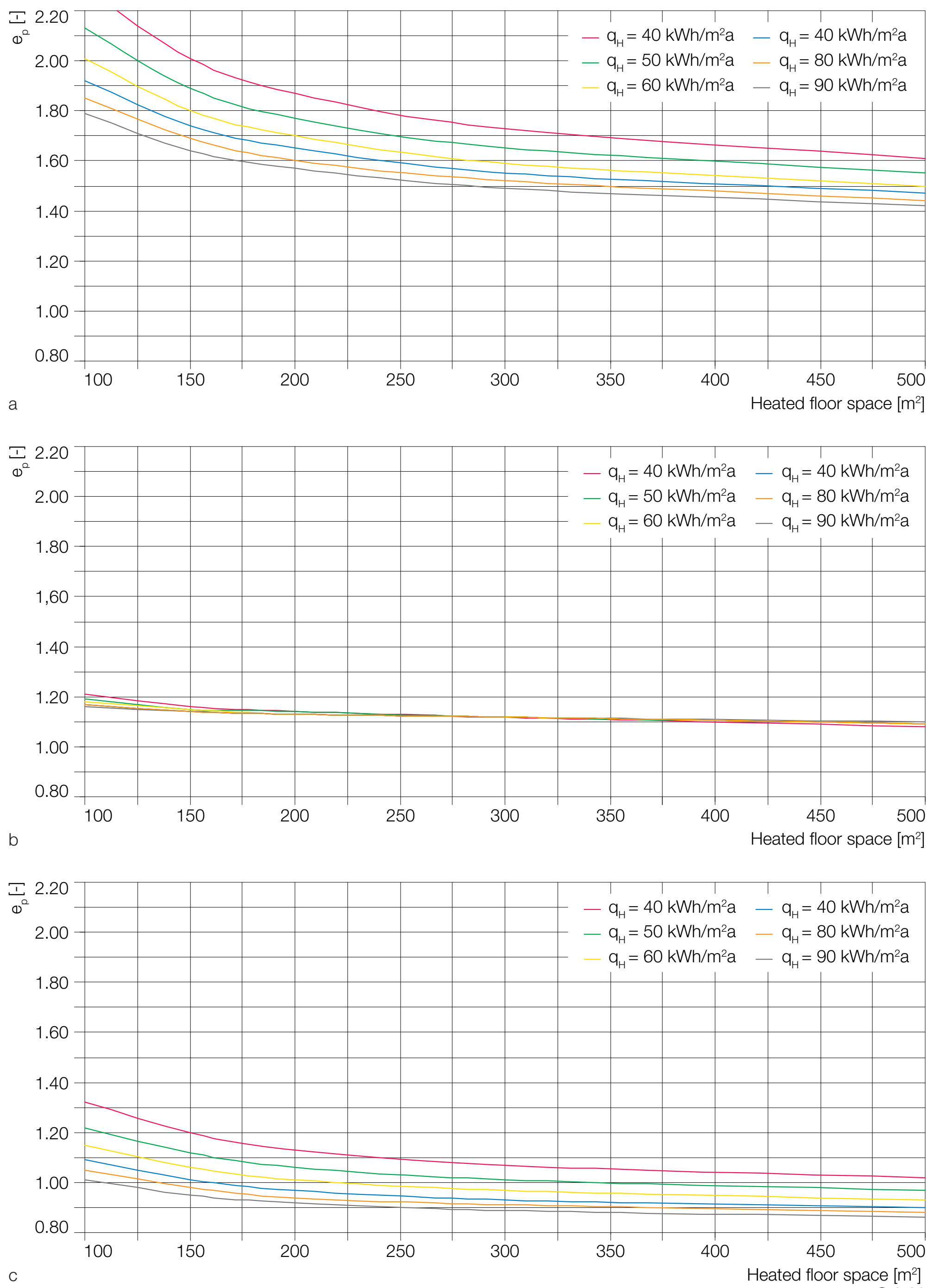
For conventional heating systems, which use energy from fossil fuels such as coal, oil or gas, the total system efficiency is given by e_p, taking the total energy required for extraction and preparation of the primary energy resource from the earth's crust [9]. This takes all the stages in the provision of usable energy as heating or warm water into account: extraction, storage, distribution and delivery (Fig. C 3.15, p. 143). To establish the reference value, DIN V 4701-10 offers two simplified processes using diagrams or tables to obtain e_P. A detailed observation of systems engineering that takes the specific values of all components into consideration is also possible. The diagrams clarify the main parameters influencing the efficiency of heating and ventilation systems.

Conventional heating systems

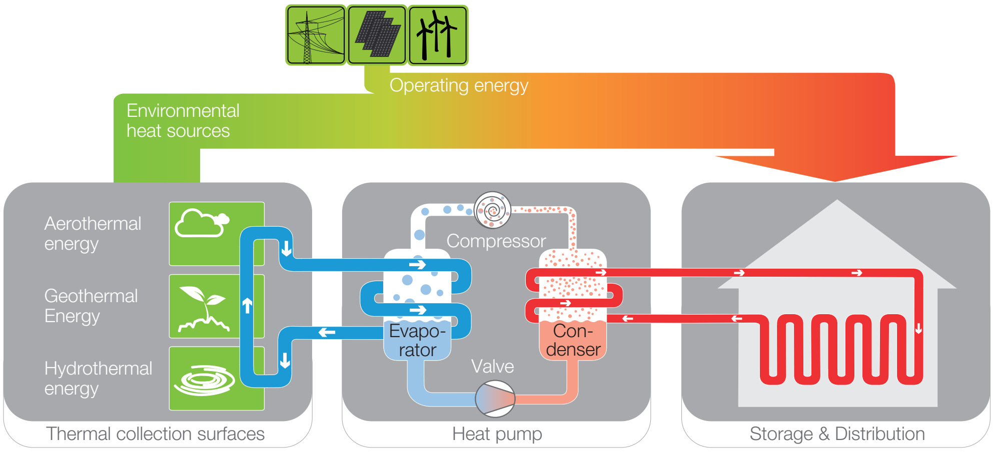
A typical system often found in existing buildings is the low-temperature boiler with 70 °C flow and 55 °C return temperatures. Such systems have a total system efficiency of $1.3 \leq e_p \leq 2.3$, depending on the size of the building (expressed as A_N) and the annual energy demand for heating in relation to the surface area of the building in use q_H. A system's total system efficiency e_p falls as the floor space and net energy demand q_H and rises with lower annual energy demand (Fig. C 3.23) since boiler output, and with it a significant part of the system losses in buildings with smaller floor spaces, is determined by the hot water requirement. Outside the heating period, heating systems are used solely for the preparation of hot water. The lower the annual energy demand, the longer this situation continues. Condensing boilers, which use the latent heat contained in exhaust gases, are more efficient and have a better total system efficiency than low-temperature boilers. With the addition of a solar water heating system for domestic hot water, the boiler can be shut down completely outside the heating period, making the performance coefficient practically independent of the annual energy demand or the length of the heating period (Fig. C 3.23 b, p. 147). Further reductions in the performance coefficient are achievable only by utilising heat from the environment or from renewable energy sources, such as with heat pumps systems.

Systems for the utilisation of geothermal and environmental heat sources and renewable energy

In order to use alternative heat sources for heating and cooling buildings, they must be long-lasting, available in sufficient quantities and have low investment and running costs. Depending on the type of system to be installed, there are also requirements for temperature levels and the heat capacity of the thermal reservoir. In addition, the operation of the system must allow phases of sufficient length to regenerate the reservoirs. The heat pump is a tried and tested system that uses a compressor to take heat from the environment and bring it up a level sufficient to heat buildings through the so-called Carnot cycle (Fig. C 3.24). Heat pumps operate with low initial feed temperatures, normally no higher than 55 °C, supplying distribution systems with large surface areas such as radiators and radiant wall and floor heating systems. In contrast to boilers, heat pumps only require primary energy to operate the compressor. This can be seen in their very low e_p-value, which under favourable operating conditions and with large areas to be heated, can be as low as 1.0. A basic distinction can be made between monovalent and bivalent heat pump systems. A bivalent system is a combination of a conventional system and a heat pump system. This combination is especially suitable



C 3.23



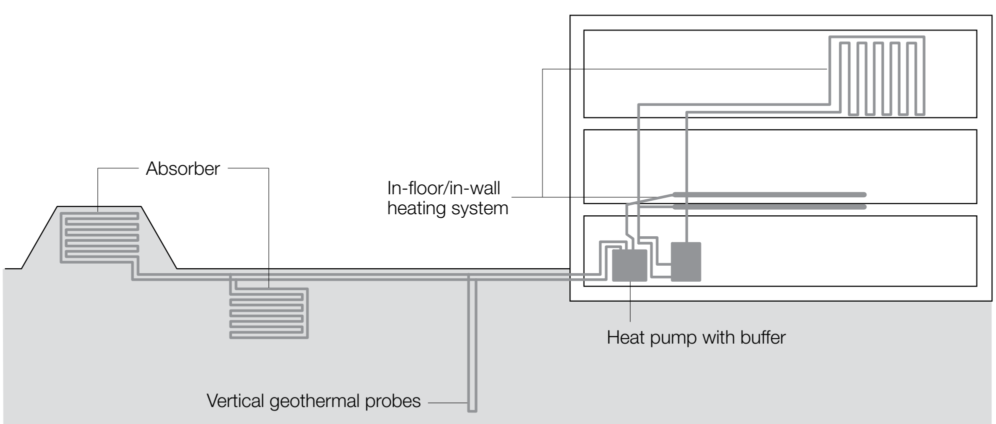
C 3.24

for upgrading the energy efficiency of heating systems in existing buildings. Monovalent systems are preferable for new buildings as the heat pump provides all the required thermal energy.

Heat pumps can be used to exploit reservoirs with relatively low temperatures e.g. (ground) water, earth and air. The near-surface heat absorbed by these systems (to a depth of up to 20 metres) is renewed mainly through solar radiation and seepage water (rain) and can be considered renewable by today's standards. At depths greater than 20 metres, heat flux from the earth's core becomes more significant.
Unlike conventional heating systems, the difference between the flow and return temperatures for heat pump heating systems is just a few degrees Kelvin because the temperature level of the heat source is low. It follows that both the thermal collection surfaces at the heat source and the systems for the storage and distribution of heat within the building must have large surface areas for heat transfer. Other potential heat sources suitable for controlling building temperature are water, wastewater and exhaust gases from industrial or building services and systems. Depending on the temperature level, the heat from these processes can either heat or cool water or air directly or be used in a heat pump. In areas where a large number of heat pumps are installed to collect near-surface ground source heat, there is the danger of phases where the heat source is overexploited. In these cases, it can be prudent to install supplementary solar thermal systems to feed thermal water reservoirs so that the latent heat released in the phase transition between water and ice can be extracted when needed (Fig. C 3.26). A water tank containing 5 m^3 can store approx. 460 kWh of latent heat.

The use of alternative energy sources
Near-surface geothermics use the relatively constant ground temperature at depths of up to 200 m for heating and cooling with geothermal heat exchangers. These are either laid horizontally below the surface as ground heat collectors or installed vertically as geothermal probes or energy piles. Brine is used as the thermal transfer fluid, a weak saline solution that can be cooled to below 0 °C without freezing. The near-surface temperature of the earth's crust, at a depth of 10 m, is almost constant. At greater depths, the temperature increases at a rate of approx. 3 °C per 100 m. Ground source heat collectors rely nearly exclusively on heat derived from solar energy from seepage water. At depths of less than 10 m, there are seasonal variations in temperature. A system's performance depends on the heat capacity, thermal conductivity and the density of the ground, which all changes with the moisture content.

Horizontal ground heat collectors are made up of meandering pipes, which extract heat from a large surface area. Indirect systems consist of a brine circuit for heat transfer and a refrigerant circuit in a heat pump process. As a rule, these systems are characterised by low installation costs, but require a circulation pump to operate, whereas direct collection systems have pipes filled with refrigerant, thereby forming part of the heat pump process. This version invariably exhibits improved performance, yet this increased efficiency comes with increased material and installations costs. Regulations to protect groundwater also come into play. Constant heat extraction can lead to local ground frost that can potentially disrupt vegetation. The installation depth of single pipes or pipe networks with intervals of more than 0.60 m should be no less than 1.50 m. The moisture content of the ground determines its thermal conductivity and therefore the extraction performance of a system.
Energy piles and geothermal probes – vertically orientated elements made of concrete – are installed at greater depths. They make use of a thermal transport system using either brine or a glycol solution, which, depending on the time of the year, extracts heat from the ground or feeds heat into the ground. Generally, depths of up to 100 m are sufficient for cooling systems; high-performance thermal extraction systems require depths of between 100 and 200 m. Due to the great



C 3.25

C 3.26

a b c C 3.27

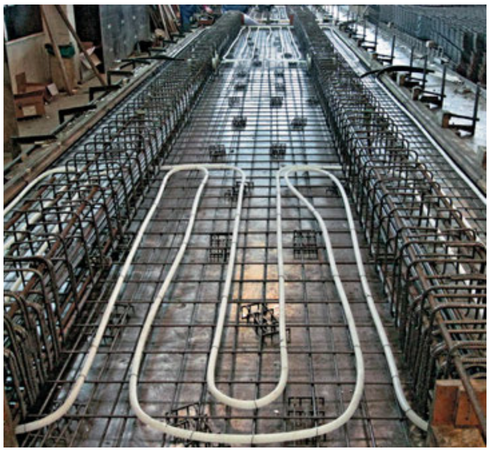
distances from the earth's surface, these systems can use the ground for seasonal heat storage. A hybrid system of energy piles and geothermal probes or geothermal probes of differing lengths can provide year-round coverage for heating and climate control. Compared to ground heat collectors, these systems require less space and a smaller total surface area, as temperatures fluctuate little at greater depths. Energy piles are especially advantageous if a building needs deep foundations anyway and the system is to mainly provide cooling in the summer. Depending on the ground's stratification and the building's structural foundations, piles extend 20 to 30 m into the ground and can be cast in situ, or precast driven piles with integrated probes can be used.
Groundwater heat pumps can also provide thermal energy. Groundwater – because of its constant temperature – offers an excellent source of heat, and its natural circulation replenishes extracted heat quickly. These systems consist of an extraction well and an injection well. Groundwater is extracted in the direction of flow, and fed into a heat exchanger or a heat pump and subsequently returned to the same groundwater layer via the injection well located at a suitable distance from the extraction well. The use of ground water as a source of heat is not always possible and requires authorisation for environmental protection reasons.

Radiant heating
The high emission coefficient of radiation exchange of exposed concrete makes it especially suitable for radiant heating surfaces. Radiant heating surfaces with large surface areas are well suited for heating systems operating at lower temperatures. A heat pump with under-floor heating is a typical combination and can reach a heat flux density of around 50 W/m^2 at a temperature differential of 5 K. Radiant wall heating surfaces are also possible, although not suitable for external walls. Hot water pipes are normally laid into a floating floor screed and for wall heating the pipes are installed under a thin layer of plaster. The large surface area and uniform temperature distribution prevent the occurrence of localised areas of thermal discomfort.
With the right layout, radiant heating systems can influence the operative temperature and contribute to a slight reduction in the thermal energy requirement as the temperature difference of external building components is reduced. Wall-hung concrete panel radiators are an exception and function as conventional convection heaters or radiators (Fig. C 3.28). According to DIN EN 442, panel sizes of up to 85 cm wide and 200 cm high can have standard heat output values of up to 1096 watts. This represents 40 % of the output values of a tube radiator of comparable dimensions.

C 3.24 Operating principles for a heat pump
C 3.25 Schematic diagram of a system for utilising environmental heat sources
C 3.26 Ice storage as a (latent) thermal reservoir for a heat pump system
C 3.27 Installation of geothermal probes
a, b Drilling the bore-hole in stages, lining with pipe sections
c Filling the annular gap with special building materials
C 3.28 Concrete panel radiators

Thermally activated building systems
These days, nearly without exception, floor slabs are made from steel reinforced concrete. If heating coils are laid, not in the floating floor screed but directly in the solid slab, it is referred to as thermal activation, concrete core temperature control or as a thermally active building system. A liquid medium is circulated through a network of pipes laid into the concrete's core between the upper and lower reinforcement layers (Fig. C 3.29). Temperature control is achieved through regulation of the flow rate and the input temperature. The operating temperature is limited by the temperature of the heat source and the temperature that is comfortable for the building's occupants. Heat transmission occurs through radiation and convection and relies on exposed surfaces of the floor and ceiling slab. Cladding or coverings to the underside or floating screeds to the upper surfaces of the slab impede thermal transmission. Suspended thermal ceiling panels can alleviate acoustic problems and at the same time increase the heat-dissipating surface. In rooms with thermally activated elements, the temperature distribution and the thermal radiation is perceived as very comfortable because the heat is emitted or absorbed uniformly. This prevents localised areas of thermal discomfort from occurring. Thermally activated building elements can replace radiant heating systems in buildings with very low heating requirements

C 3.28



C 3.29

	Heat transfer [W/m²K]	Emission [W/m²]
Floor, cooling	7	21
Floor, heating	11	33
Ceiling, cooling	11	33
Ceiling, heating	6	18
Cooling total	18	54
Heating total	17	51

C 3.30

and sufficient heat storage capacity if the interior temperatures fluctuate so little that the difference between the room temperature and the temperature of the heating (or cooling) surfaces is sufficient to regulate the room temperature. The heating and cooling performance of thermally activated building systems in relation to floor area is shown in Fig. C 3.30. If necessary, pre-heating the building's air intake, increasing the flow rate or the installation of supplementary conventional radiators can compensate for the low heat output of thermally activated heating systems.

The large surface area of thermally activated concrete makes it suitable for passive cooling and operation without a refrigeration compressor. There are various options. For example in the summer, energy piles absorb thermal energy from thermally activated floor slabs and heat exchangers. Cooling performance can be greatly improved if groundwater flows around the piles, effectively avoiding a steady warming of the ground through the continuous cooling as the heat is distributed further by the groundwater and the thermal storage capacity of the ground is fully utilised. Ground cooling can also be supported by a fluid heat transfer medium within the building's foundation slab, whereby the cooling performance of the foundation slab is limited. With a foundation slab of sufficient mass and depending on the cooling requirements, systems are possible where heat is not absorbed into the ground but almost entirely stored within the building to be recovered in winter. In this case, a thermal separation from the surrounding ground in the form of perimeter insulation is necessary. Surplus heat is fed successively into different zones of the foundation slab until thermal saturation of all building elements is reached. If further cooling is required, a ground system can be used in addition.
The highly effective thermal storage capacity of concrete building elements enables a considerable phase shift between the interior and outside air temperatures. In the summer, heat is absorbed during the day and is released in the cooler night hours by increasing the air exchange rate. A thermally activated floor slab supports concrete's self-regulating effect and during extremely hot periods, prevents a build up of the interior temperature to uncomfortable levels. The same circulatory system is used in winter to heat a building's interior.

Energy Performance of Buildings Directive
Since its introduction in 2002, the German implementation of the Energy Performance of Buildings Directive (EPBD) has been amended several times. A new revised version, soon to

	EFH in Passive House standard	KfW-Efficiency House 70
Floor slab	• Water-resistant concrete, 250 mm On foam glass, 400 mm	• Concrete, 250 mm, insulation, 20 + 60 mm
Walls	• Basement: triple wall system from water-resistant concrete, 240 mm perimeter insulation between slab and soil, 240 mm • Ground/upper floor: solid precast steel reinforced concrete walls, 180 mm, composite insulation, 260 mm	• No basement • Ground/upper floor: load-bearing brickwork, 150 mm, cavity insulation, 180 mm, exterior shell, 115 mm
Roof	• Steel reinforced concrete, 200 mm • Insulation in roof pitch, 320 mm in the middle	• Shallow pitched roof with nail plate trusses • Mineral wool insulation, 240 mm
Windows	• Argon-filled triple glazing • Insulated wooden window frames, aluminium exterior	• Argon-filled triple glazing • Plastic windows
U-values	• Exterior walls to outside air: 0.119 W/m²K • Exterior walls to soil: 0.129 W/m²K • Flat roof: 0.115 W/m²K • Floor slab: 0.140 W/m²K • Windows (total installed): 0.85 W/m²K	• Exterior walls to outside air: 0.169 W/m²K • Roof: 0.165 W/m²K • Solid ceiling to the outside air: U = 0.204 W/m²K • Floor slab: 0.193 W/m²K • Windows: (total installed): 0.90 W/m²K
Ventilation	• Ventilation with heat recovery, preconditioned with ground source heat, 50 m	• Natural window ventilation
Heating and hot water	• Heat pump power consumption 1.15 kW, total system efficiency 4.2 • Ground source heat collectors with brine, 1.80 m deep, installed horizontally • Water reservoir, 150 l • Under-floor heating	• Heat pump power consumption, 2.79 kW, total system efficiency 4.4 • Two ground source heat probes, 95 m deep • Water reservoir, 1,250 l for hot water and heating • Under-floor heating
Photovoltaic system	• Output 5.08 kWp, installed on a flat roof	• Output 5.16 kWp, installed on a shallow pitched roof
Energy consumption[1]	• 13.4 kWh/m²a	• 34.3 kWh/m²a

[1] Energy consumption was calculated using non-climate-adjusted user data (meter readings).

C 3.31

C 3.32

come into force, is expected to reduce the limits for annual primary energy consumption in two stages each of 12.5 % and area-related transmission heat loss in two stages of 10 % [10]. In combination with the European EPBD [11], the European building directive [12] will be implemented and the Very Low Energy House will become established as the standard for new buildings by 2020.
According to European directives, a Very Low Energy House is "a building that has a very high energy performance. The very low amount of energy required should be covered to a very significant extent by energy from renewable sources" [13]. For this purpose, the EnEV contains three essential requirements for new buildings:

- The annual primary energy consumption for heating, hot water, ventilation and air conditioning must not exceed the primary energy consumption of a reference building of the same geometry, floor area and comparable technical specification.
- Maximum limits are defined, depending on the type and use of the building, for the level of heat transmission losses relative to the building's heat transferring envelope.
- A requirement of protection against summer overheating, either by controlling solar ingress according to DIN 4108-2 or by limiting the hours of excess temperature; this can be demonstrated using a thermal building performance simulation.

The use of renewable energy as an energy source e.g. biomass, wood logs, pellets or wood chips or district heating results in the total system efficiency $e_P < 1$, so that even buildings with unfavourably high energy needs are able to meet the requirements. Whether buildings heated with electrically driven heat pumps comply with a low annual primary energy consumption requirement, will depend on future developments in the proportion of renewable energy in the electricity supply.

Very Low Energy, Passive and Energy-plus houses

Passive houses are defined by an especially low heating requirement of about 15 kWh/m^{2}a. Such low values are achieved by minimising heat losses (transmission and ventilation) and by maximising the beneficial gains (solar radiation, internal gains, storage capacity). To a large extent, controlled ventilation with heat recovery ensures sufficient heat exchange. Heat pumps are usually installed to provide hot water and winter heating. Fig. C 3.31 compares the value for two built examples. Measurements of energy consumption show that a reduction in the U-value of exterior building elements below U = 0.15 W/m^{2}K does not result in significant energy savings. Instead, controlled ventilation with heat recovery and the use of renewable energies make a greater contribution to a building's energy efficiency. This includes primarily solar thermal and photovoltaic systems. Combined heat and power plants can also operate with renewable energy sources. Even in urban areas, buildings of a suitable height in favourably windy locations can be equipped with small wind generators, producing up to 10 kW (Fig. 3.32). To operate such systems as efficiently as possible, storage capacity is required for excess electricity, e.g. in the form of thermal storage. When compared to thermal storage that uses sensible heat exclusively, the capacity of such storage can be significantly increased through the use of phase changing materials (PCM), such as waxes and salt hydrates. By selecting a suitable changing point (phase transition temperature), latent energy storage can also be integrated into buildings. Currently, the high cost of PCMs is preventing their widespread application, e.g. as a concrete additive.

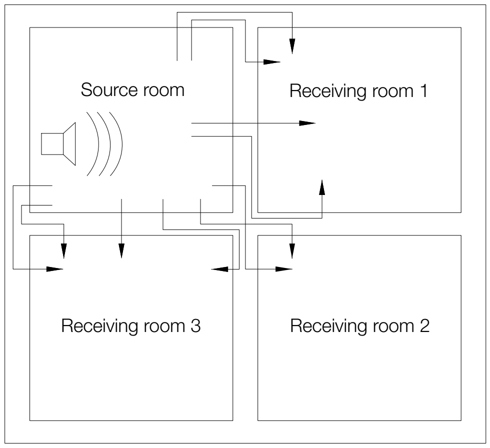
C 3.29 Installation of pipe work within thermo-active concrete building elements
C 3.30 Surface-related power of thermo-active ceilings at a constant surface temperature of 23 °C
C 3.31 Comparison of the characteristics of two single-family houses
C 3.32 Small, vertical-axis wind turbine

Notes:

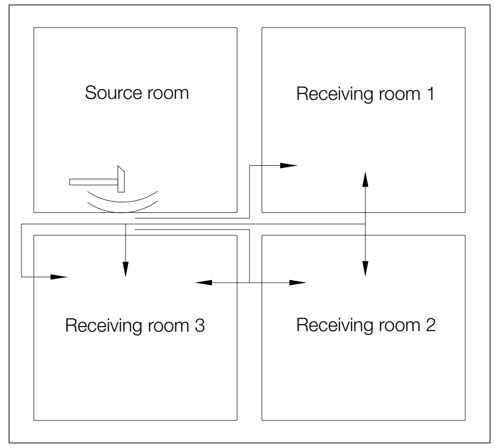
[1] Brüel & Kjaer (pbl.): Thermal Comfort. Technical Review 02/1982
[2] Fanger, Poul Ole: Thermal Comfort. Analysis and Applications in Environmental Engineering. New York 1973
[3] http://www.dwd.de
[4] Palz, Wolfgang; Greif, Jürgen: European Solar Radiation Atlas. Berlin 1996
[5] http://www.weatherbank.com
[6] Hill, Rodney: Elastic Properties of Reinforced Solids: Some Theoretical Principles. In: Journal of the Mechanics and Physics of Solids 05/1963, pp. 357–372
[7] http://www.planungsatlas-hochbau.de
[8] University of Bochum / Stephan Eilers: Thermische Gebäudesimulation für ein massives Beispielgebäude
[9] DIN V 4701-10 Energy efficiency of heating and ventilation systems in buildings – Part 10: Heating, Domestic hot water, Ventilation. 2003-08
[10] Draft of second legislation to amend Energy Saving Ordinance 15/10/2012
[11] Draft of fourth legislation to amend Energy Saving Ordinance
[12] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (revised)
[13] Ibid

Building acoustics

Peter Lieblang



C 4.1



C 4.2

Sound is the propagation of waves through a compressible medium. In buildings, two categories of sound are present – airborne sound takes the form of speech or music, whereas impact sound is caused by human activity such as walking or the vibrations of the building's services and systems. Two purely physical parameters characterise these vibrations: amplitude and frequency. Here, amplitude is given as the geometric mean of the sound pressure change in Pascal (Pa) (the subscript $_{eff}$ is often omitted for simplicity) and the frequency is given in Hertz (Hz). The effective sound pressure is defined as:

$$p_{eff} = \frac{1}{T}\int_0^T \sqrt{p^2(t)}\,dt \quad [Pa]$$

Apart from the physical properties of sound, human perception – the field of psychoacoustics – is of great significance for building acoustics. The perception of sound is a complex process, which is still not fully understood. Essentially, the eardrum receives vibrations in the air that are then transmitted through a series of bones in the ear (stirrup, hammer and anvil) to the inner ear. From there, the stimulations are passed electrochemically through the nervous system to the brain, where sensory perception takes place. Individuals with normal hearing can perceive sound in a frequency range of ten octaves between approximately 20 Hz and 20 kHz. The auditory threshold, i.e. the level of the effective sound pressure at which sound can be perceived, varies with frequency. In its most sensitive range – between 2 and 4 KHz – the auditory threshold of the human ear is approx. $2 \cdot 10^{-5}$ Pa. The effective sound pressure of the auditory threshold increases sharply, especially at lower frequencies. Above a value of approx. $2 \cdot 10^{2}$ Pa (10^{7} times greater than the auditory threshold), sound is perceived as painful. Because human perception covers a wide range of effective sound pressures, a scale is used to describe the logarithmic relationships using the pseudo-unit decibel (dB). This sound pressure scale derives from the decadic logarithm of the ratio of the effective sound pressure p and the effective sound pressure at the auditory threshold p_0 of a pure tone at a frequency of 1000 Hz:

$$L_p = 10 \cdot \lg\left(\frac{p}{p_0}\right)^2 = 20 \cdot \lg\left(\frac{p}{p_0}\right) \quad [Hz]$$

The use of the logarithm has two advantages. Firstly, it leads to manageable values; the scale has a maximum value of 140 dB and does not normally go lower than 0 dB. Secondly, the scale reflects the relationship between changes in the logarithmic magnitude of stimulus and sensory perception, described by what is commonly known as the Weber-Fechner Law. Especially at lower sound pressure levels, actual perception deviates from idealised values. In order to illustrate actual sound perception, the reference value of effective sound pressure $p_0 = 2 \cdot 10^{-5}$ Pa from the auditory threshold to the pain threshold in relation to frequency is presented on a graph. Curves of the same loudness (isophones) are shown on this graph, which covers the so-called hearing range (Fig. C 4.3). The value of the sound pressure scale at a frequency of 1,000 Hz is defined as loudness and is given by the unit phon. By definition, the values of the scale and the loudness level are identical for a pure tone with a frequency of 1 kHz. For tones of other frequencies, the perceived loudness does not correspond to the sound pressure level. At the limits of audible frequencies, the perceived loudness is lower than the sound pressure level. For example, DIN ISO 226 "Acoustics – Normal Equal-Loudness Level Contours" shows that at a frequency of 100 Hz, a level of approx. 50 dB has a loudness of 20 phon, whereas a level of 100 dB corresponds to a loudness of 90 phon. A comparison of two different levels shows that change to perceived loudness is about double the sound level difference, especially at lower frequencies. This non-linearity means that the absolute sound pressure levels and loudness values are not capable of providing an adequate indication of the subjective auditory perception.

An additional value for loudness has been established, the "sone". The ear senses whether the perceived sound is "louder" or "quieter". "Louder" means that the perceived effective intensity of the sound in the ear or on the eardrum has increased, "quieter" means

C 4.1 Airborne transmission
C 4.2 Airborne transmission
C 4.3 Audible range

there is reduction in the perception of sound intensity. The reference value for loudness is a pure tone with a frequency of 1 kHz at 40 dB. Above 40 dB, the loudness doubles with an increase of 10 dB. Reducing the sound level below 40 dB causes the loudness to drop progressively. A reduction of the sound level from 10 to 8 dB halves the loudness. In contrast to a sound level meter with a linear reading over the whole measurement range, ear sensitivity adapts to the sound level. The ear is more sensitive at lower levels than at higher sound levels. This adaption, with its possible evolutionary advantages, is an inconvenience from the perspective of building soundproofing. For example, background sound levels in urban residential areas are higher than in quiet rural areas. Despite identical building construction, high background sound levels mask sounds that may be noticed in a quiet environment. This phenomenon should be considered in the specification of soundproofing measures. Even this condensed summary illustrates how challenging it is to develop a realistic description of the processes involved in soundproofing for construction. Above all, the spectral distribution of the acoustic signals is an important parameter for perception. An analysis of the entire audible frequency spectrum quickly becomes impractical. Because the frequency of sound in buildings lies mostly between 100 and 3,150 Hz, and since, for simplicity's sake, the isophones in this audible range can be considered as geometrically similar (affine), the sound levels in this frequency range can be summarised into what is called a single value statement containing all the essential information. Reference or weighting curves describing the frequency-dependent auditory perception of sound are used to approximate the single value statement. The best-known reference curve is the A-weighting curve, indicated next to the isophones in the audible range (Fig. C 4.3). The A-weighted sound (pressure) value $L_p(A)$ can be calculated using the level addition values $L_{pi} + \Delta L_{pi}$ from the individual frequency bands:

$$L_p(A) = 10 \cdot \lg \left(\sum_i 10^{(L_{pi} + \Delta L_{pi})/10} \right)$$

A-weighting gives less emphasis to the lower frequencies than the higher frequencies, corresponding more or less to human auditory perception.

Characteristic values for sound insulation in buildings

The decisive factor for sound insulation in buildings is the sound arriving at the receiver (the hearer); human hearing is the yardstick. In order to describe building sound insulation objectively, units are used that can be measured or calculated. The reference is the sound (pressure) level at a receiver, simulated by a sound source with predetermined properties. This can either be airborne noise or, if the building is vibrated directly, structure-borne sound. The soundproofing concepts for airborne noise in the DIN 4109 standard are based on the use of what is known as a pink noise source emitted from a dodecahedron loudspeaker. Pink noise is an acoustic signal with zero information content (containing random frequencies across the entire audible spectrum). As the frequency increases, the sound level drops by 3 dB per octave. A standardised instrumented hammer or specific services and systems in the building are used to generate structure-borne sound. In Germany, information on sound insulation for airborne sound is derived traditionally from a comparison between the levels of sound at the source and receiver. This is the weighted sound reduction index R_w. For walking noise and noise from building equipment impacts, such as noise made by lifts, compressors, ventilators, heating systems, etc., the normalised impact sound pressure level $L_{n,w}$ or the A-rated maximum sound level $L_{AF,max}$ is used. Figs. C 4.1 and C 4.2 illustrate the principle of sound transmission through buildings that are fundamental for the characteristic values. Sound normally travels in multiple routes (vibrating building components) from sender to receiver. It is not absolutely necessary for the spaces where sound is emitted and received to be separated by a common dividing element (wall or ceiling); diagonal acoustic transmission is also possible. To identify this, the existing values within the building – taking transmission paths into account – are assigned an apostrophe. The building sound insulation value describes a building's airborne sound insulation between two rooms and is calculated using the following formula:

$$R' = L_S - L_E + 10 \cdot \lg \frac{S}{A} \quad [\text{dB}]$$

L_S and L_E are the source and reception sound levels in rooms, S is the surface area of the dividing building component, A is the equivalent absorption surface. If there is no dividing building component in relation to the standardised sound level difference, D_{nT} is used in place of R'. Taking normalised impact sound pressure level from all transmission paths into account,

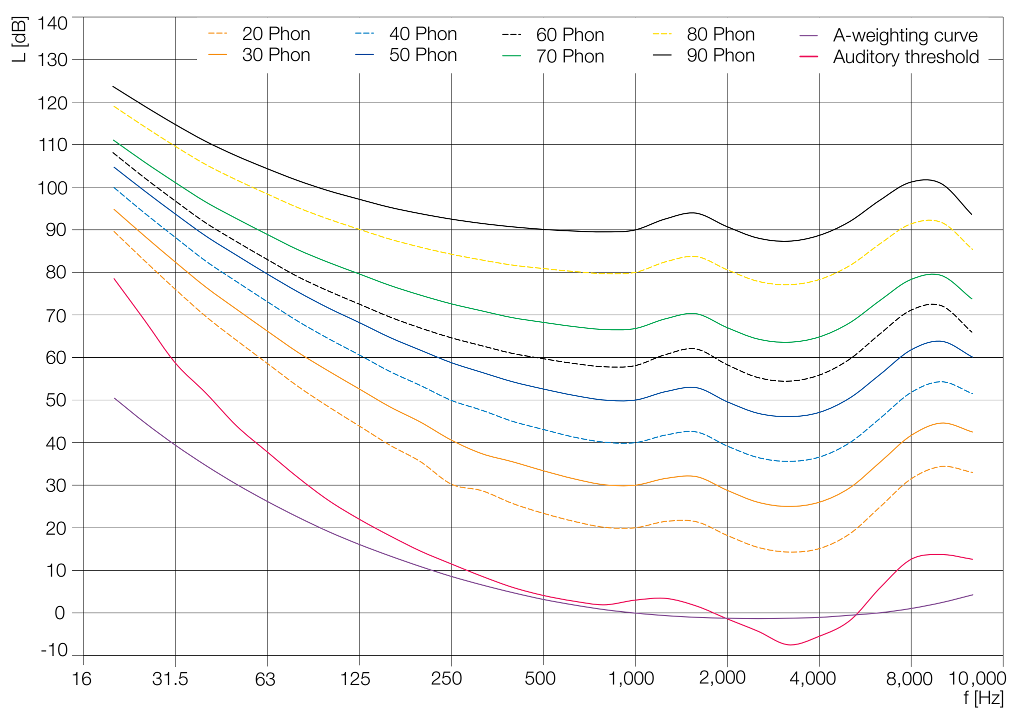
$$L'_n = L_E + 10 \cdot \lg \left(\frac{A}{A_0} \right) \quad [\text{dB (A)}]$$

describes a standard reception level on a reference absorption surface $A_0 = 10\ \text{m}^2$. Sound levels emitted by a building's technical equipment, plumbing or through commercial operations can be established with a sound level meter using the A-weighting curve and the time constant "Fast". These levels are given in decibels as the value $L_{AF,max}$.

For clarity, the 16 third-octave bands between 100 and 3,150 Hz relevant for acoustics in buildings are combined – similar to the A-weighting – into single value statements: the sound reduction index R'_w and the normalised impact sound pressure level $L'_{n,w}$. The frequency evaluation is compared to nominal and reference curves, corresponding to human auditory perception as defined in DIN EN ISO 717 (Fig. C 4.4).

Regulations concerning sound insulation in buildings

Sound insulation serves to protect occupied areas within buildings from the effects of undesired noise and to prevent danger to life and health in a manner that is appropriate to



C 4.3

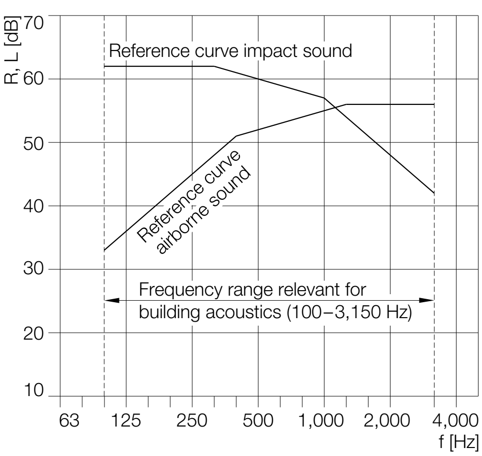
a building's usage. DIN 4109 "Sound insulation in buildings" has been introduced as a technical requirement in all of Germany's federal states and serves as a guide for most planners and architects. A new revision of standards DIN 4109 is in preparation and is to be published soon. In addition to the current content of DIN 4109, this chapter describes forthcoming changes to the publication. There are many additional rules and regulations concerning sound emissions that cannot be covered individually here (technical instructions on noise abatement, regulations on aircraft noise, etc.). The "Pocket book of technical acoustics" contains an overview of the relevant laws and regulations [1].

Requirements for sound insulation in buildings

Requirements for sound insulation are governed by building and planning law and in most cases supplementary contractual arrangements between the parties involved in a building's design and construction. In Germany, DIN 4109 covers planning and building inspection requirements. This applies to all building projects requiring permission from government planning departments. For this purpose, an estimate of sound insulation is calculated using the methods described in Supplement 1 of DIN 4109, which then becomes part of the project documentation. This proof should be performed or approved by a state recognised appraiser to assure it complies with building regulations. Despite these measures, it cannot be assumed that external sound or sound from neighbouring apartments or commercial units will not be audible; building regulations are primarily health and safety requirements. The regulations are not exactly concerned with the prevention of damage to hearing but with "the protection of people inside buildings from unacceptable levels of transmitted sound from external residential and commercial areas" [2]. The assumption is that these are rooms with normal levels of sound, i.e. rooms with considerate neighbours and without exceptional levels of noise. In many cases, building regulations are not sufficient to meet the expectations of the occupants. Of course, the parties involved in a building project have the option of agreeing to greater levels of sound insulation. Differing interpretations of such agreement between contractual partners means many building-related legal cases concern sound insulation [3]. From a legal position, sound insulation measures should be included in the contract. This task is made easier if soundproofing is described for each individual room requiring sound insulation using the numerical values R'_w, $L'_{n,w}$ and $L_{AF,max}$. If numerical values are not included in a contract, the values can be calculated using generally recognised codes of practice from the detailed specifications of the proposed construction. These algorithms are contained in Supplement 1 of DIN 4109. The values are considered contractual.

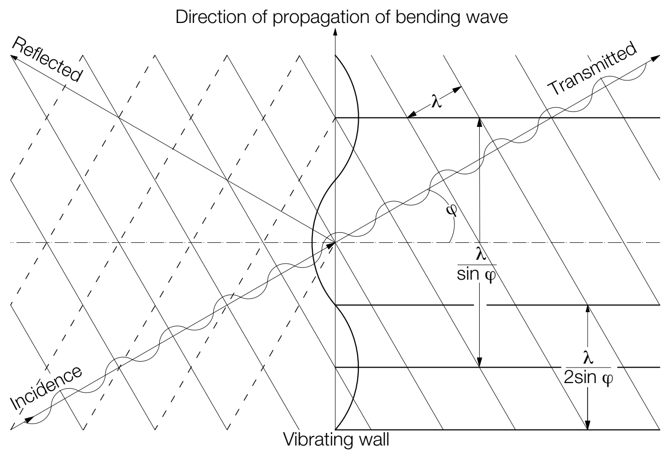
In the absence of information on design details, an agreement can be reached on the properties of a building, for example, via "explanatory and precise descriptions of the contractual parties, other contractual circumstances, the physical relationship of a building to its surroundings, qualitative customisation, its purpose and functionality" [4]. This can mean, for example, that any planned apartments or offered units must comply with the higher requirements for sound insulation. If there is a total lack of detailed information concerning sound insulation, this can be inferred from the intended use of the building or the sound insulation of comparable buildings on which the owner or occupants have based their expectations. In this case, generally recognised codes of practice are to be observed [5].

The question is whether the specifications for sound insulation in buildings should be based on the physical performance of the building or the perception of the occupants. The acoustic properties of buildings can be determined reliably and objectively. The uncertainties for mathematical evaluations or quality control tests are normally no greater than 2 dB. Furthermore, the processes for determining building performance are in both cases not greatly affected by uncertainties such as variations in the background noise or transmission levels. In contrast, the human perception of sound is subjective in several respects. Specifications based on acoustic perception are only meaningful if the frequency dependent background noise levels at the point of reception (immission point) are defined. By calculating the loudness according to DIN 45613, it can be shown that at background noise levels of 25 dB structural measures which go far beyond generally accepted practice have to be used in order to reduce the subjective loudness by 50 % [6]. The division of residential buildings into sound insulation levels as proposed in the technical literature is only useful if the background noise levels are sufficiently low to allow the difference in these levels to be perceived [7]. For the designer, this means that a higher specification for sound insulation is necessary for quieter residential areas than in inner cities and/or noisier zones. The building planner should explain this situation to the building's owner and occupants.

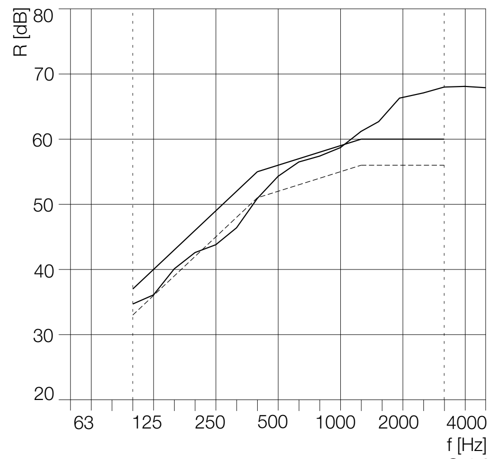


C 4.4

C 4.4 Reference curves for airborne and impact sound (one-third octave values) according to DIN EN ISO 717. Frequency dependent values are shown as dashed lines in all diagrams.
C 4.5 Coincidence effect of sound waves with an oblique angle of incidence
C 4.6 Sound insulation values of a single layer 200 mm thick concrete wall



C 4.5



C 4.6

Estimation of sound insulation in buildings (solid construction)

The estimation for sound insulation can either follow national standards or the simplified calculation method in DIN EN 12354 "Building acoustics – Estimation of acoustic performance of buildings from the performance of products" that serves as the basis for DIN 4109.
The current edition of DIN 4109 assumes an approx. mass of 300 kg/m² per unit area for the solid construction of flanking building elements. Given this assumption, the sound insulation level can be calculated directly using the mass per unit area of the dividing components. For flanking elements with a low mass per unit area, sound insulation values must be adjusted. In the same way, the weighted normalised impact sound pressure level for a solid floor can be calculated from the tabulated values for the equivalent normalised impact sound pressure levels of a concrete floor slab and adjusted to account for the floating screed and/or a suspended ceiling. The weighted sound reduction index of the building or normalised impact sound pressure levels are the sum of the energetic transmission paths (partition walls and flanking walls). The evaluation uses, for example, the appendices in DIN EN 12354 or an appropriate computer programme.

Acoustic properties of concrete building components

A building's construction method does not influence the generation/stimulation of sound or human sound perception. Rather, it is the task of the building's structural design and building components to effectively reduce the transmitted sound on route from sound source to sound receiver. To meet this objective, there are, in principle two mechanisms: firstly, sound attenuation, whereby the energy of sound waves is converted into thermal energy (dissipated) through a friction process. Porous materials, such as mineral wool, are ideally suited for this process. Lightweight and aerated concretes also have sound absorbing properties. Secondly, sound reduction occurs through the reflection of sound waves from the surfaces of building components. High levels of sound reduction occur if the impedance of the materials on either side of a boundary layer differs markedly. The impedance is the ratio of sound pressure to sound velocity and indicates the resistance to the propagation of sound waves. Heavy building parts that are not too rigid are most suitable for airborne sound insulation. Lighter insulation layers are used to insulate impact sound (impact on floors).

Airborne sound

Airborne sound is understood as sound emanating from an emitter and initially propagating through the air in the form of (longitudinal) pressure waves. In buildings, these airborne waves meet the room dividing and boundary surfaces of various materials and cause these parts of the building to vibrate. Sound waves are then conducted as structure-borne sound to the next boundary surface of the receiving space, where they are once again radiated from the surface of the building component to a receiver as airborne sound. Practically all parts of a building – walls, ceilings, floors, windows, doors, etc. – play a part in the transmission of airborne sound. Additionally, sound waves can travel directly between rooms via air vents, pipes and similar open connections. A distinction is made, when calculating the propagation of airborne sound, between single and double-layer building parts because their mechanics of sound transmission differ.

Single-layer building components

Single-layer building components, e.g. plastered walls or ceilings without an insulating layer, vibrate as a single plane. The attenuation of sound transmission occurs mainly based on the principle of sound reflection – the surfaces of the building components reflect a large proportion of the airborne sound waves due to the differing densities and impedances of air and the material of the building components. However, sound waves meeting the wall at oblique angles – as always occurs in practice – result in a resonance effect as first described by Lothar Cremer in 1942 [8]. This is the so-called coincidence effect, where the wavelength of the sound waves meeting the building component at an oblique angle is equal to the bending wavelength of the vibrating building component, resulting in a break in the sound insulation (Fig. C 4.5). The coincidence effect only occurs at a particular frequency. This frequency f_g is called the critical frequency and is given in Hertz. This can be calculated for sound at an oblique incidence with an airspeed of c, density of ρ, a Poisson's ratio of μ, a modulus of elasticity of E, and a plate thickness of d; the following applies for concrete:

$$f_g = \frac{c^2}{2\pi \cdot d}\sqrt{\frac{12 \cdot \rho\,(1 - \mu^2)}{E}} \approx \frac{6.4 \cdot 10^4}{d}\sqrt{\frac{\rho}{E}} \approx \frac{18.4}{d}$$

The plate thickness d used is an approximation and is given in meters. As the angle of incidence increases, the critical frequency also increases. Below this frequency, the sound insulation of the single-layer building components is not influenced by the angle of incidence of sound waves, above this frequency it increases by approx. 6 dB per octave. The coincidence frequency of single-layer concrete building components with thicknesses greater than 20 cm is less than 100 Hz. However, for building acoustic purposes, frequencies above 100 Hz are relevant. This is the point at which single-layer concrete building components begin to exhibit high sound insulation values (Fig. C 4.6). A fixed reference curve for the weighted sound reduction indices (as a single value statement) in relation to the mass per unit area of a single-layer solid building element can be derived from this context (Fig. C 4.8) [9]. The weighted sound reduction index R_w for single-layer building components made from (standard) concrete with a mass per unit area between 65 and 720 kg/m² can be determined using:

$$R_w = 30.9 \cdot \lg\left(\frac{m'}{1\ \text{kg/m}^2}\right) - 22.2 \quad [\text{dB}]$$

The mass per unit area m' is the product of the thickness of the building component and the density of the building or composite building material. For calculation purposes, the density of unreinforced standard concrete can be taken as ρ = 2,350 kg/m³ and for steel reinforced concrete as 2400 kg/m³ [10]. Lightweight concrete, cast in-situ or precast, is divided into density classes with a range of $\Delta\rho$ = 200 kg/m³. In addition, there are many different bricks and blocks from concrete and lightweight concrete in density classes ranging from 0.45–2.40. For these building materials, a weighted average is used to compensate for the influence of the mortar. The weighted sound reduction index of single layer solid building components can be estimated simply by using a so-called nomogram, based on the information in Supplement 1 of DIN 4109. It contains guidelines for walls made of standard concrete (with a density of 2,300 kg/m³ for calculation purposes) for wall thicknesses of 10, 20, 25 and 30 cm (Fig. C 4.7).

Single layer building components made of lightweight concrete have two special characteristics. Numerous measurements under test conditions have shown that lightweight concrete walls have a 2 dB higher weighted sound reduction index than other solid walls of the same mass per unit area (Fig. C 4.9). This is due to the structure of the lightweight concrete and the lightweight aggregates e.g. pumice, expanded clay, shale or glass. As sound waves have to transverse several boundary surfaces between these materials and the air trapped within the porous structure of the building component, a higher proportion of the sound energy is dissipated than in homogenous, non-porous building materials. The results for lightweight concrete, with an applicable mass per unit area of between 140 kg/m² and 480 kg/m², are expressed in a special mass curve:

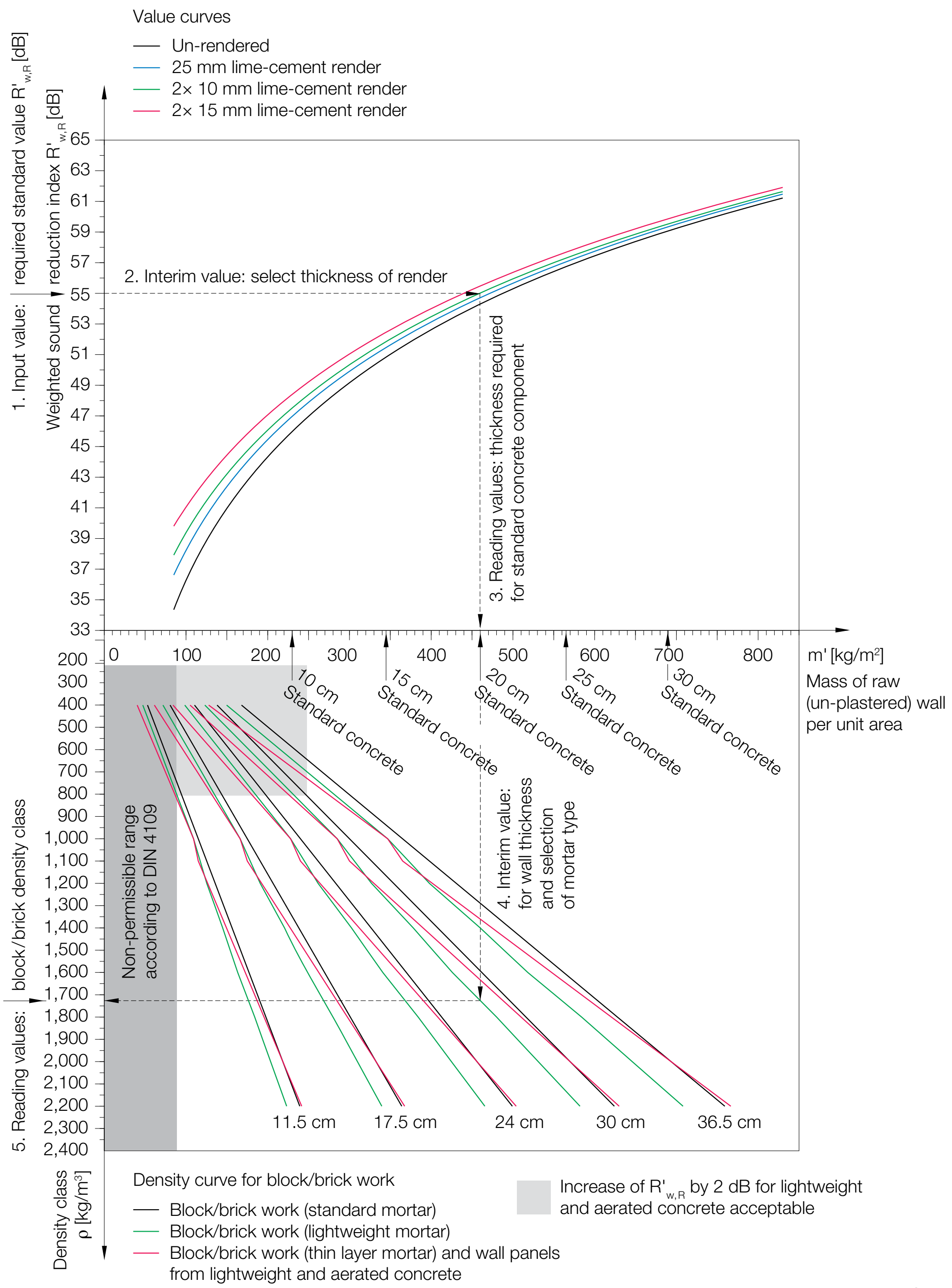
$$R_{w,\,LC} = 30.9 \cdot \lg\left(\frac{m'}{1\ \mathrm{kg/m^2}}\right) - 20.2 \quad [\mathrm{dB}]$$

In contrast, walls made of hollow, lightweight concrete blocks with multiple cavities, the same as all hollow building blocks, may have lower sound insulation values than homogenous building components with an equal mass per unit area.

Double layer construction
Multi-layer components vibrate as a system of plates, as if linked with springs. As a rule, multi-layer concrete constructions are formed of two volumes (the layers); the void between the layers is filled with air or an insulation material that behaves like a spring or dashpot. In an ideal model, the two layers are completely mechanically separated for the transmission of structure-borne sound, allowing only airborne sound to pass through the cavity. Sound waves must pass through several boundary surfaces, and reflection from these surfaces contributes to a high level of sound insulation. Dissipation of sound energy within the insulation layer also adds to the sound reduction. However, cavity walls can also resonate, resulting in a decrease of sound reduction. The value of the resonance frequency f_0 can be estimated using the mass per unit area of both layers m_1' and m_2' and the dynamic rigidity of the insulation material:

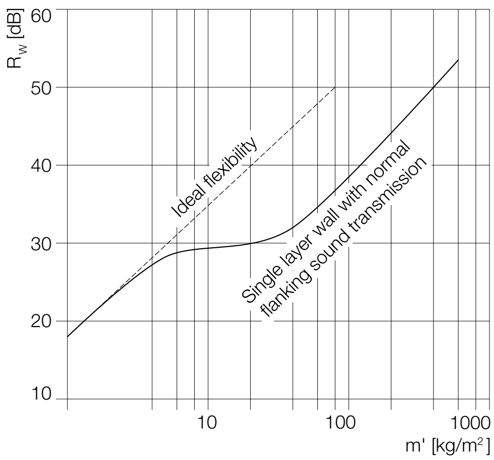
$$f_0 = 160\sqrt{s'\left(\frac{1}{m_1'} + \frac{1}{m_2'}\right)} \quad [\mathrm{Hz}]$$

Below this frequency – given the same mass per unit area – there is practically no difference between the sound reduction index of single and double-layer building components. However, above this frequency, double-layer building elements are significantly better sound insulators than single-layer building components of the same weight – the sound insulation value increases by approx. 12 dB per octave. In practice, double-layer concrete components are used mainly as partition walls, thermally insulated exterior walls and solid floor slabs with a floating screed. In order to achieve a high sound reduction index, the resonance frequency should lie outside the frequency zone relevant for building acoustics.

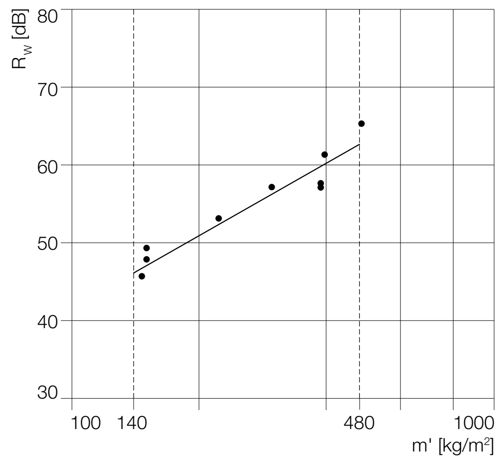


C 4.7

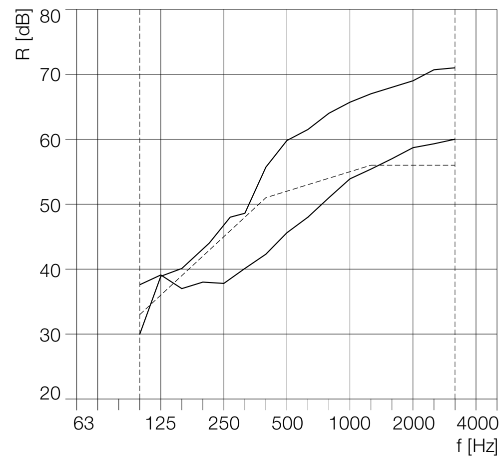
C 4.7 Nomogram for roughly estimating a building's weighted sound reduction index according to Supplement 1 of DIN 4109
C 4.8 Sound insulation values of single layer wall (Berger's mass law)
C 4.9 Values for lightweight concrete with sampling points
C 4.10 Sound insulation of composite thermal insulation system (bottom curve: structural layer, upper curve: complete wall mounting)



C 4.8



C 4.9



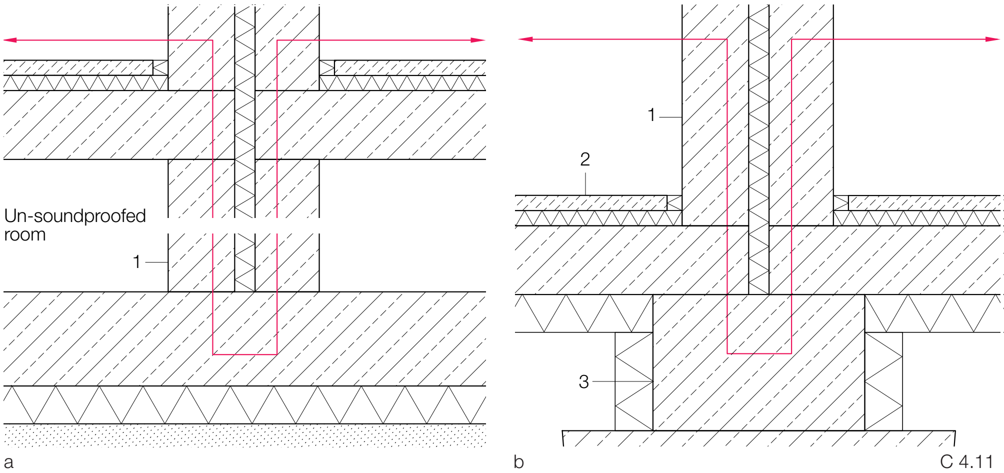
C 4.10

If sufficient soft insulation material is used within the cavity and the individual layers are as heavy as possible, the resulting resonance frequency can be kept below 100 Hz (low tuning). Although for traffic noise with lower frequencies, the target should be a resonance frequency of below 50 Hz.
Layers of plaster or render applied directly to insulation material, together with the supporting wall, form a double layer construction, e.g. external composite thermal insulation systems. This system consists of two layers (supporting wall and rendered layer) with an intermediate separating "spring" (thermal insulation). A low resonance frequency is achieved with soft insulation material, e.g. mineral wool, and a sufficiently heavy mineral render at least 10 mm thick. Fig. C 4.10 shows the frequency-dependent sound insulation values of a heavy solid wall (m' = 369 kg/m²), with a composite thermal insulation system made up of a 12 cm insulation layer with a dynamic stiffness of s' = 6 MN/m³ and 15 mm of lightweight render. In comparison, the resonance frequency of composite thermal insulation systems, consisting of rigid foam panels (expanded polystyrene boards) and a thin plaster layer of only 2–3 mm, lies within the frequency range that is relevant for building acoustics and is often perceived as disturbing.
The weighted sound reduction index of double-layer partition walls (separating two houses) can be evaluated using Supplement 1 of DIN 4109. Initially, just as with single-layer walls, the sounding insulation value $R'_{w,R}$ can be ascertained from the sum of the mass per square unit of the individual layers. For double-layer construction with a continuous void, 12 dB is then added if the mass per unit area of the individual layers is at least 150 kg/m² and if the individual layers are separated by a void of no less than 30 mm and covered with mineral insulation sheets with shiplap edges. DIN 4109 allows for an air void between individual layers with a minimum mass per unit area of 200 kg/m², but the use of an uninsulated intermediate void is not recommended for thermal insulation reasons (thermal bridging at connection points between the external and internal layers) and the risk of sound bridging. If such a design is actually used, the void must run the entire height of the flanking exterior wall and be sealed with plastic stripping or a permanently elastic sealant. In practice, the influence of the weight of the solid layers is often given too much significance and the width of the void between the solid layers too little importance. The improvement to the sound insulation as the width of the void between solid layers increases can be estimated according to Karl Gösele as follows:

$$\Delta R = 20 \cdot \lg \frac{t}{30} \quad [\mathrm{dB}]$$

ΔR improvement to the sound insulation value [dB]
t width of void [mm]

However, the separation of the layers is never perfect. Structure-borne sound will always be transmitted via sound bridges of various types. These can be continuous walls, floor slabs, base layers or a shared foundation connecting the individual layers. Particularly in buildings without basements, the achievable level of sound insulation is largely determined by the construction of the joints between partition walls and floor slab or foundation slab; in concrete construction, these have particular characteristics. The floor slab is largely decoupled from the ground by perimeter insulation and a capillary break, so in the absence of insulation against structure-borne sound, its sound insulation values will not differ significantly from a ceiling slab of a similar weight. A complete separation of the lower flanks at ground level is not possible without a basement. Even if a gap is used to separate the foundation (not recommended, as it results in an uneven loading of the foundations and difficulties sealing the building against water ingress), sound is still transmitted through the base layer. Furthermore, unavoidable construction tolerances, e.g. when casting floor slabs and foundations, affect sound transmission at the flanks. This is not quantifiable due to insufficient data. In this case, the greater the difference between the impedance of the partition wall and the floor slab/foundation, the more beneficial it is in this situation. This occurs between block work walls and concrete ceiling/floor slabs due to their differing densities, but cannot be quantified. Buildings constructed solely of concrete do not have this impedance differential because the density and impedance of the wall and floor slabs are the same.
Due to these influences, the values predicted in DIN 4109 for the sound insulation of double layer partition walls in buildings without basements are often not achieved in practice. No significant improvements can be made through the physical separation of the foundation and the base slab with an expansion joint since sound is transmitted through the ground over this short distance (acoustic short circuit).
The literature shows that without a basement, the actual sound insulation value can be up to 5 dB lower than the predicted values [11]. Gösele points out that double-layer concrete walls on a continuous slab can result in lower sound insulation values than a single-layer concrete wall of the same weight [12]. Without a basement, the calculated value for $R'_{w,R}$ in Supplement 1 of DIN 4109 should be adjusted upwards by 4 dB to ensure the required level of sound insulation. If a higher level is needed, a basement is unavoidable. In view of the additional technical complexity involved in the construction of double-layer concrete partition walls, it would seem that in the particular case of buildings without basements, single-layer partition walls with a sound insulation value of 62 dB can be specified, although this diverges from the recommendations of the German Acoustical Society (DEGA) [13]. Single-layer constructions with a sound insulation value of 62 dB to meet DEGA's building regulations BR 0101 can be produced more economically than double-layer concrete constructions. The client should be informed of these particular details, and, if necessary, single-layer partition walls could be specified in the building contract. Semi-detached and terraced houses built on a shared basement without bituminous sealing are linked by a design-related sound bridge. These constructions are impermeable structures in which the concrete has both a structural and waterproofing function. The separation of the building parts is complex because



C 4.11

1 Steel reinforced concrete 150 mm
Expansion joint, mineral insulation material 50 mm
Steel reinforced concrete 150 mm
2 Cement floor screed 40 mm
Separation layer PE-membrane
Impact sound insulation 40 mm
Floor slab, steel reinforced concrete 160 mm
Perimeter insulation 100 mm
3 Foundation

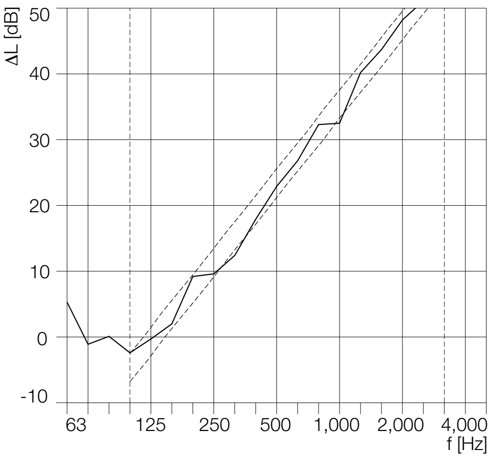
they are made without junctions or joints: the base slab and basement walls form an impermeable layer. Thus, the double layer partition walls at basement level abut the continuous flanking elements (external basement walls and floor slab) and are friction-locked. Acoustic bridges are formed at the points at which the partition walls, ceilings and external walls meet. The infrequent practice of notching the external flanking basement walls to the height of the maximum groundwater level is inadvisable as it considerably increases the risk of cracks and fissures forming. Systematic research has shown that basements built using this technique do not reduce the sound insulation values of the ground floor level as long as a continuous joint runs the entire width of the building [14].

Advice on constructing concrete partition walls

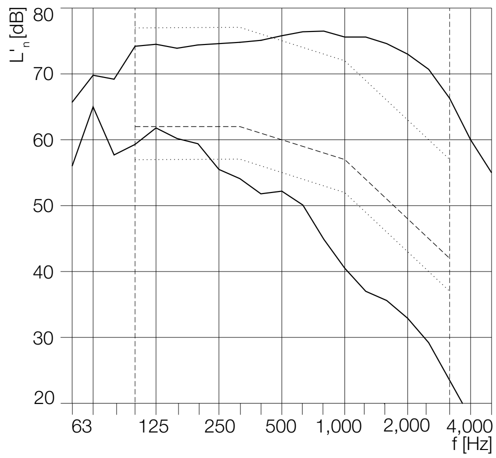
Double layer partition walls can be precast or cast in-situ. Particularly with precast elements, the joints between individual components must be carefully sealed to avoid direct airborne sound transmission through small gaps. This method allows the fabrication of individual walls with thicknesses no more than 10 cm, reducing the overall thickness of the partition wall to 26 cm.
The use of concrete cast in situ is possible if attention is paid to the practical and operational aspects of construction: First, the formwork for the first wall is erected, reinforcement laid and concrete poured. For thin concrete walls (equal to or less than 18 cm thick), the concrete pump hose must be able to fit easily through the reinforcement layers. The maximum diameter of the concrete vibrator should be 40 mm. It is also recommended that the largest aggregate size be restricted to 16 mm. Initially, the formwork is only removed from the side facing the internal cavity. Partition panels of mineral wool, which are able to withstand the loads of the concreting process and have continuous shiplap joints along all edges, are glued to these exposed surfaces. The shiplap edges of the mineral wool panels effectively prevent penetration of cement paste as long as the joints between the panels are sufficiently tight. The concrete pour rate must be adjusted to suit the permissible loads of the mineral wool panels. Using class F1–F4 concrete, with a normal setting time, at standard temperature and a permissible fresh concrete pressure σ_D of 50 kN/m^2 for the panels, the appropriate concrete pour rate is approx. 2 m/h. The mineral insulation panels then form the “lost” formwork for the second concrete wall.
There are two methods for ensuring the fresh concrete pressure is withstood when casting the second layer. In the first method, the formwork from the first side of the wall is left in place and is used to support the formwork for the second layer. In this method, sufficiently long tie rods are passed through tie holes, the wall and the insulation panels. A load spreading plate (approx. 15 × 15 cm and 4 mm thick) braces the spacer sleeve and tie cone against the insulation panels. A hole matching the nominal diameter of the tie rod is drilled into the centre of the plate, which is then threaded on to the tie rod with a rubber washer, spacer sleeve and cone. To prevent sound bridges forming through the leakage of cement paste, the inside diameter of the rubber washer should be slightly smaller than the diameter of the tie rod and the outside diameter larger than the diameter of the cone. After the reinforcement is laid, the formwork is erected and anchored with brackets to the formwork of the first wall. Once the concrete has set, the tie holes are carefully sealed with fibre-reinforced cement plugs to prevent airborne sound transmission through the openings.
The second method is to use a so-called single-sided formwork. In this method, bracing frames transfer the pressure of the fresh concrete out of the formwork and into the substructure (floor slab or ceiling slab). At the same time, the previously erected wall and the partition panels, which together act as formwork, must be supported as they are not capable of retaining the pressure without additional support. A standard ceiling height of 2.6 m and a fresh concrete pressure of up to 50 kN/m^2 results in a moment of approx. 70 kNm/m. Bracing frames on the formwork of the first wall transfer the resulting load to the substructure during the concreting process. Alternatively, the first layer can be produced using single-sided formwork. After the concrete in the first wall has set, only the formwork from the cavity side is stripped and the opposing formwork remains for the second pouring without the need for additional bracing or support.
Single-layer partition walls present fewer construction or practical difficulties. The use of non-recoverable ties prevents airborne sound transmission through small openings as the tie holes on the face of the concrete can be sealed completely and permanently with a very low failure rate.
Protective casing is used at the butt joints between the partition walls and the flanking exterior basement walls in waterproof concrete construction. As this is primarily secondary reinforcement, the starter bars can easily undergo reverse bending.

Impact sound

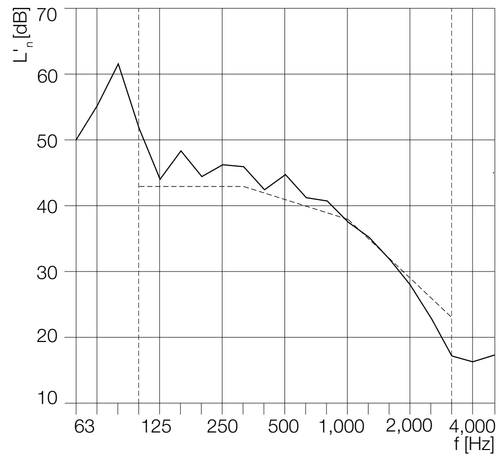
A building’s floors and ceilings are especially prone to direct vibration. The resulting sound, known as impact sound, stems not only from footfall on floors, but also from the movement of furniture, falling objects and other similar occurrences. Impact sound is transmitted through the building’s structure and then emitted from boundary surfaces of the receiving room, finally reaching the receiver as airborne sound. Although there are many factors influencing impact sound – e.g. the weight and shoe type of a building’s occupants, floor coverings, the material and construction of ceilings/floors, etc. – building acoustics measures and calculates the impact on the floor with a standardised instrumented hammer, a device with five 500 g hammers hitting the floor at a predetermined speed.
Solid floors exposed to impact sound are usually multi-layer, with a floating screed. Sound is transmitted as in other double-layer building components (see p. 156ff.) and is tuned to the same frequency so that the resonance normally falls under 100 Hz. To evaluate a floor/ceiling construction, the normalised impact sound pressure level $L_{n, w, eq}$ of the floor/ceiling is used – in some cases, the standardised impact sound pressure level is used – and can be determined for all other typical solid floor/ceiling constructions from their mass per unit area:



C 4.12



C 4.13



C 4.14

$$\Delta L_{n,w,eq} = 163 - 35 \cdot \lg\left(\frac{m'}{1\ kg/m^2}\right) \quad [dB]$$

The effects of floating floor screed and other possible additional floor coverings are taken into consideration with the improvement factor ΔL; this depends primarily on the weight of the screed, the rigidity of the insulation layer and, to a lesser extent, the screed material and the material of the floor coverings. For simplicity, the resonance frequency of the system can be derived solely from the mass per unit area of the screed:

$$f_0 = 160 \sqrt{s'\left(\frac{1}{m'}\right)} \quad [Hz]$$

If f_0 is known, the frequency-dependent reduction in impact sound can be estimated.

$$\Delta L = 40 \cdot \lg \frac{f}{f_0} \quad [dB]$$

Strictly speaking, this relationship only applies to infinitely large areas of screed. However, for well-damped screeds – where the sound level drops quickly with increasing distance from the impact point – the formula gives a very good estimate of the level, and a reasonable estimate for less well-damped screeds (Fig. C 4.12). In principle, the curve of the normalised impact sound pressure level across frequencies is similar for all solid floor/ceiling slabs (Fig. C 4.13, top curve) and reaches levels in excess of 70 dB in practically all third octave bands. Concrete floor/ceiling slabs do not meet the requirements for sound insulation on their own. A floating screed on a soft insulation layer reduces the impact sound levels, particularly in the higher frequencies where the human ear is especially sensitive (Fig. C 4.13, bottom curve). However, it also follows that the evaluation of impact sound pressure levels according to DIN EN ISO 717-2 exceeds the reference curve in the lower frequencies – in some cases considerably – and can occasionally be perceived as a disturbing low frequency drone.

It is critical that sound bridges are avoided when laying a floating screed. A single mortar bridge can increase the impact sound pressure levels by 10 dB or more. Sound bridges with floating screeds occur all too often in practice. For this reason – particularly for ceramic floors fixed with mineral-based adhesives – DIN 18353 "Floor Screed Works" and DIN 18365 "Floor Covering Works" recommend that perimeter insulation strips are only cut back after floor coverings are laid, which is regarded as a separate contractual task. Because the floor screed contractor does not want an additional trip to the building site, the perimeter insulation strip is often cut back before the floor tiles are laid, causing the tile adhesive to meet the adjoining walls directly and resulting in sound bridges.

Generally, little attention is paid to sound insulation in concrete buildings and concrete construction; it is assumed that the sound insulation is good because of the high mass per unit area. However, concrete construction demands good detailed planning to avoid the effects of resonance and the propagation of structure-borne sound.

Notes:

[1] Müller, Gerhard; Möser, Michael (pbl.): Taschenbuch der technischen Akustik. Beurteilung von Schallimmissionen – Vorschriften – Normen – Richtlinien. Berlin 2004, pp. 103–148
[2] DIN 4109 Sound insulation in buildings. 1989-11, p. 2
[3] German Supreme Court (BGH): judgement 14/05/1998, VII ZR 184/97
judgement 14/06/2007, VII ZR 45/06, etc.
[4] Higher Regional Court Stuttgart: judgement 17/10/2011, 5 U 43/11
[5] For general definition of technical standards see: Reichsgericht: judgement 11 October 1910, IV 644/10, RGSt. 44,76 (79)
[6] Alphei, Henning; Hils, Thomas: Welche Abstufung der Schalldämmmaße sind bei Anforderungen an die Luftschalldämmung sinnvoll? In: wksb 59/2007, pp. 26–31
[7] German Acoustical Society (DEGA) Schallschutzausweis VDI 4100
[8] Cremer, Lothar: Theorie der Schalldämmung dünner Wände bei schrägem Einfall. In: Akustische Zeitschrift 07/1942, pp. 81–104
[9] Berger, Richard: Über die Schalldurchlässigkeit. Dissertation TH München, 1911
[10] Lieblang, Peter: Wirtschaftlicher Schallschutz bei nicht unterkellerten Häusern. In: Beton 05/2006
[11] Peters, Hans: Schallschutz mit Ziegeln. In: Bauhandwerk/Bausanierung 03/2001, pp. 32–36
[12] Gösele, Karl: Schalldämmung von Doppelwänden mit steifen Wandschalen. In: Betonwerk + Fertigteiltechnik 05/1978, pp. 248–253
[13] German Acoustical Society (DEGA)-Memorandum BR 0101 "Die DIN 4109 und die allgemein anerkannten Regeln der Technik in der Bauakustik", 08/2005
[14] Schallschutz von Haustrennwänden. Mitteilungsblatt Nr. 210 der Arbeitsgemeinschaft für zeitgemäßes Bauen e. V. 03/1998. 3rd Edition 2002

C 4.11 Sound transmission paths (red), double layer partition wall
a With basement: longer transmission paths over multiple junctions
b No basement: shorter transmission paths over fewer junctions

C 4.12 Improvement factor for a floating floor screed on a solid floor slab (continuous line: measured values; dashed line: estimate based on above approximation of resonance frequencies for 125 and 160 Hz)

C 4.13 Normalised impact sound pressure level for a solid floor slab (top curve: floor slab: bottom curve: prefabricated concrete floor with floating floor screed or floor coverings)

C 4.14 Normalised impact sound pressure levels for typical residential floor construction – 200 mm thick, steel reinforced concrete slab with floating cement floor screed and parquet flooring

Renovation and restoration

Arthur Wolfrum, Christoph Dauberschmidt

C 5.1

About a third of all construction permits in Germany are issued not for new buildings, but for work on existing buildings. If you add to this the large number of building projects that do not require approval, the great importance of construction work on existing buildings now becomes clear. Projects involving buildings listed as protected, in which there is no alternative to working with existing buildings, make up only an insignificant number of such projects.

Conversion is often less expensive than demolishing an existing building and building a completely new one. The growing consideration of ecological criteria also makes the conversion of existing buildings attractive, especially in terms of their "grey energy", i.e. the energy used to build a building. This consideration becomes even more significant when a permanent concrete load-bearing or shell structure that has not yet reached the end of its "life cycle" still forms part of the building's substance.
As well as desired changes to a building, simple and ideally ongoing repair and maintenance plays an increasingly important role in this context because it can help maintain a building's value, which is of concern given the increased importance of real estate as a long-term investment.

Although concrete has been a central building material for a long time, current renovations are particularly focusing on concrete buildings built in the 1960s and 1970s. Concrete structures built more recently are also being repaired, but increasing numbers of concrete buildings from this earlier period, which also saw a major building boom, are showing early signs of corrosion damage. In the 1970s in particular, concrete exposed to the weather was used more than it had been before. The large number of these buildings, as well as defects in the execution of their construction, is now making repairs and restoration necessary.

Almost every part of a building can be built in concrete. The frequency, necessity, and expense and effort involved in renovations may, however, vary greatly, even within the same structure. Mistakes made during construction, a lack of careful maintenance and subsequent changes to structural elements often make renovation necessary. A still-intact concrete structure may have had to meet requirements when it was built that are different from those it is facing now, especially issues concerning sound insulation and fire safety, but also possibly involving higher standards of comfort.

Building permits

Renovations often have consequences for a building's permit situation, which is not always obvious at first glance. Thorough research of these issues in advance is just as important for building regulation law aspects as it is for construction aspects.
Before the consequences of new plans are assessed, the existing structure's permit and approvals situation should first be examined. If the building's owners are not able to provide building and planning permissions in text and plan, planners must request copies of these documents from the authority issuing them.

It often turns out that an existing structure diverges significantly from its building and planning permit, even before any new planning. This divergence must not necessarily be of a structural nature. On the contrary, one of the most common and serious divergences of reality from the approved building situation is the use of the building or parts of it in ways not necessarily indicated in the plans. Only knowledge of the existing building's permit and approvals situation will enable a planner to determine whether a building regulation law procedure will be necessary before any technical measures can be taken.
The range of regulatory requirements, whose breach would result in such a procedure, is too large to be exhaustively described here, but the main and, in practice, most frequently encountered issues include:

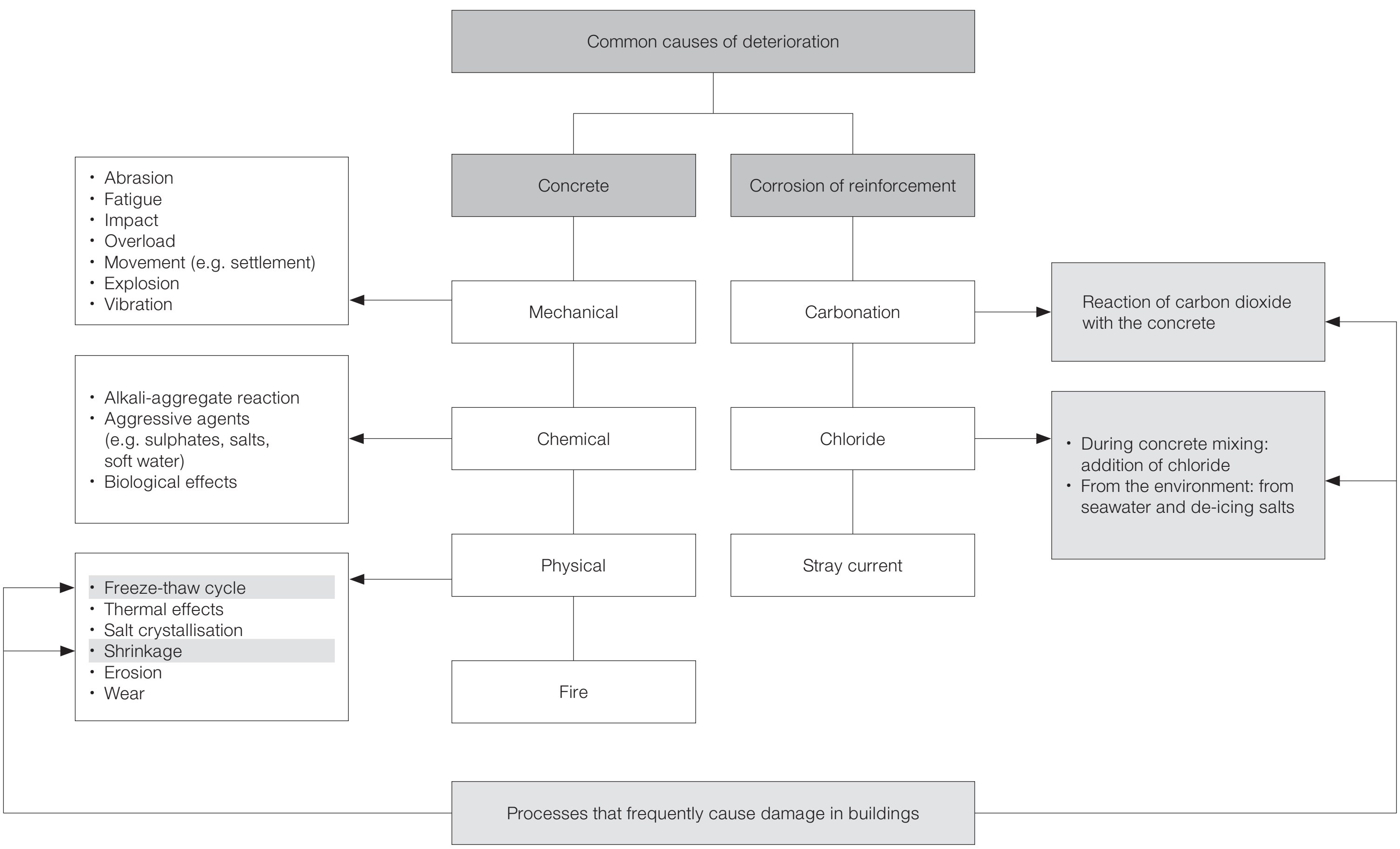
C 5.1 Scuola Media, school, Locarno (I) 1963, Dolf Schnebli
C 5.2 Common causes of damage showing frequent damage processes in buildings

- Usage: Even if an intervention does not involve structural alterations (as in a purely conservative restoration), a building regulation law procedure can become immediately necessary if usage of the structure changes. The consequences may be serious. New traffic loads may overburden a support structure or a different number of car parking spaces may entail settlement fees. Current fire protection and sound insulation requirements may mean that extensive structural or technical retrofitting is required. Beyond building regulation legal issues (in Germany, the various state (Länder) building regulations are authoritative), the building law and regulatory consequences (development planning) of a change of use must also be examined.
- Interventions involving changes to the load-bearing and bracing components of a structure usually require a regulatory procedure.
- Changes to a building's cube shape relevant to spacing, and not only the "classic" added storeys or additions. Such changes are a frequent result of renovations carried out to improve insulation, such as new exterior insulation for a solid concrete building or additions to attics as part of the refurbishment of a flat roof.
- Major changes to floor space: such as the removal of non load-bearing walls or the extension of interiors by the installation of a new facade projecting further out after renovations carried out to improve insulation.
- Changes to the structure's appearance: In these cases, it must be ascertained in each case whether the respective building regulations, design regulations or development plans specify requirements for which non-compliance would involve additional regulatory procedures.

The specifications of the various state building regulations are authoritative. In case of doubt or in the many grey areas, it is advisable and in the architectural planners' own interest to enter into dialogue with the authorities that issue and regulate building permits as early as possible and to document proceedings.

"Grandfathering"

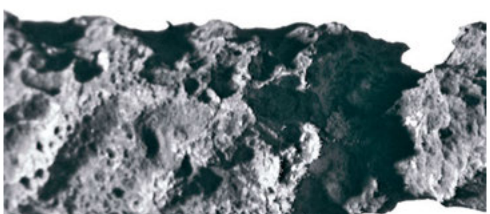
One of the most important concepts for the client in this clarification process is "grandfathering" or a permit to continue operating a non-compliant structure "as is". It is, however, issued for a previously approved structure, so it does not automatically apply to the structure now existing in fact.
If an approved structure is modified substantially, the right to continue operating it can be revoked. This will especially be the case if the changes are so extensive that they will require an additional regulatory procedure. Here it must be checked in each case whether the most recent construction measures have objectively changed the fundamentals and assumptions on which existing approvals and the current permit situation is based, especially where a permit to continue operating a non-compliant structure is being relied on. Emergency exit stairs that were built in compliance with regulations but that now no longer meet current statutory fire protection requirements will usually be able to be used unchanged if they are renovated and their usage does not change, for example. If, however, the number or mobility of persons who may have to use the stairs is significantly different from that specified in the old building permit, an existing permit to continue operating it will no longer be an adequate argument against the current protective goals of fire safety regulations.
Historic buildings listed for protection require special management in parallel to the usual building regulation legal processes. Very different requirements can be made depending on whether a historic protection order has been imposed on the whole building, its external appearance or also its interiors. Here too, the relevant authorities must be involved as early as possible.



C 5.2

C 5.3

C 5.3 Carbonation causes corrosion of the reinforcement. The greater volume of the corroded metal causes bulges and/or spalling above the corroding reinforcement.
C 5.4 Chloride-induced corrosion
a Deep corrosion pits on rebar
b Loss of substance of reinforcement of an underground car park ceiling around cracks
C 5.5 Frequent inspection methods and their goals
C 5.6 Potential mapping of an underground car park floor slab to locate reinforcement corrosion
a Carrying out measurements
b Exemplary presentation of results



a

b C 5.4

Damage processes in reinforced concrete buildings

Reinforced concrete in buildings is subject to incremental damage, depending on the type and intensity of existing corrosive influences. Fig. C 5.2 (p. 161) shows common types of corrosion and causes of deterioration to reinforced concrete, emphasising the damage processes that can be expected to most frequently affect buildings.
Concrete's high level of alkalinity protects the steel reinforcement in concrete from corrosion. With typical pH values in excess of 12.6, the concrete's pore solution forms a very thin but stable passive film on the steel's surface and prevents the steel in concrete from corroding when the concrete is permanently damp. The steel reacts chemically like noble steel.
The processes most damaging to buildings (carbonation and chloride permeation) destroy the reinforcement's protection, making it susceptible to corrosion. In conditions favouring corrosion (the presence of moisture and oxygen), the reinforcing steel is attacked and gradually disintegrates over time, which can significantly reduce reinforced concrete's load-bearing capacity.

Carbonation

Carbonation is a process in which the concrete's pore solution reacts with carbon dioxide from the ambient air, causing the concrete to lose its high level of alkalinity. The so-called "carbonation front" (the depth at which the concrete is no longer alkaline and thus the passive layer on the rebar is removed) moves over years from the surface into the inside of the structural component. If the carbonation front reaches the reinforcing steel, it destroys the reinforcement's protection from corrosion. The permeation of carbon dioxide and the chemical reaction of carbonation only take place in fairly dry concrete. Damaging corrosion of steel in carbonated concrete requires enough moisture to be present, so structural elements that are alternately wet and dry are mainly at risk (e.g. reinforced concrete facades).
Carbonation-induced corrosion is mainly a problem in temperate latitudes where concrete coverage is very slight, which it often was in reinforced concrete buildings built from the late 1960s and into the 1970s. The rust produced by the corrosion process has a much greater volume than the intact reinforcing steel, which can cause burst pressure within the concrete cover and subsequent spalling (Fig. C 5.3). The cross section loss of substance of the affected reinforcement rods is, however, usually so slight that the structure's load-bearing ability is not necessarily endangered.

Chloride-induced corrosion

Chloride in buildings usually comes from de-icing agents, which vehicles bring into the building (see "Restoring underground car parks", p. 168ff.) or in coastal areas from salt water. It permeates wet concrete through diffusion and, when it reaches the reinforcing steel in high concentrations, can destroy parts of the alkaline passive film and cause localised pitting corrosion. Usually, it takes chloride several decades to reach the reinforcement in uncracked concrete depending on the concrete cover's density and thickness. Chloride can, however, penetrate much faster through cracks and corrode reinforcement in just a few months (Fig. C 5.4 b).

Chloride-induced corrosion is an especially serious attack because it is not usually visible on the surface – the concrete cover does not typically spall, as with carbonation – and because very high rates of corrosion often occur in local areas of corrosion, which can quickly reduce the substance of the reinforcement.

The freeze-thaw cycle

The repeated freezing and thawing of water in the pore system of concrete can cause concrete close to the structure's surface to flake off (spalling). Horizontal components of buildings directly exposed to weather, such as balcony slabs, pergolas, porches, the tops of walls and parapets, are particularly at risk of this kind of damage, although the frequency and intensity of damage caused by freezing tends to be low.

Shrinkage

Concrete shrinkage is a natural property of the material that does not itself cause corrosive damage to structural elements, but it can result in planned crack formation. Depending on environmental conditions, there is then a risk of the cracks becoming weak points in the corrosion protection inherent in the type of construction used to build the structural component. The reduction in volume leads to a slight contraction in the structural component when the concrete hardens due to its drying. If this shrinkage deformation in the installation position of a structural element is prevented, cracks can occur, which can be problematic, especially if high demands are made on the appearance of surfaces (e.g. exposed concrete) or on serviceability (e.g. a "white tank" foundation). Crack widths can be limited by using crack width-limiting reinforcement or an appropriate concrete mix, but cracks cannot usually be entirely prevented.

Building diagnosis

Current regulations [1] define building diagnosis as the assessment of existing damage or visible weak points, their extent (classification) and causes, and an evaluation of the safety and load-bearing capacity (and thus public safety) of a structural component before restoration begins. Only if the causes and extent of damage are known before restoration begins, can it be planned so that success is assured. There have been many practical examples of restoration going wrong due to the omission of a building diagnosis, resulting in an accelerated damage process. A targeted building diagnosis before restoration also increases the stability of mass and thus cost certainty of the measure.

Since safety and load-bearing capacity aspects are evaluated, building diagnosis is a typical task for engineers, one which according to the technical rule for the protection and repair of concrete structural elements (Richtlinie für Schutz und Instandsetzung von Betonbauteilen [2]) should be carried out by an expert concrete restorer (verified through certification). Fig. C 5.5 shows the most frequently used investigation methods. As already explained, damage from chloride contamination can hardly be seen or assessed from the outside, so areas more likely to be subject to corrosion should be examined using a non-destructive method through a so-called potential mapping (Fig. C 5.6). The process of identifying reinforcing steel corrosion [3] is explained in the data sheet (Merkblatt) for electrochemical potential mapping “Merkblatt für elektrochemische Potentialmessungen”. Those tendering for a potential mapping can be referred to the data sheet to ensure appropriate quality.

If the methods described above do not lead to a verification of load-bearing capacity of the structural component investigated, an assessment or verification of load-bearing capacity can be made by carrying out a load test on a structural element on site. This will require comprehensive structural investigations in advance to prevent spontaneous failure or permanent damage to the structural element during testing. Such load tests are often carried out on vaulted support structures and other historic load bearing ceilings and walls [4].

Inspection method	Inspection goal
On-site inspection and assessment by an expert engineer	Locating and ascertaining extent of flaking, corroded reinforcement, cracks, efflorescence, impurities, sanding, inspection of drainage, sealing and coatings
Knocking off a concrete surface	Locating of cavities
Magnetic process	Determination of concrete cover, distribution of reinforcement
Electro-chemical potential mapping	Locating areas with increased probability of reinforcement corrosion
Rebound hammer (Schmidt Hammer)	Non-destructive test of compressive strength (in justifiable cases also in combination with destructive testing by taking drill core samples)
Phenolphthalein test	Identifying the depth of carbonation in concrete
Drill dust analysis	Determining chloride content at various depths

C 5.5

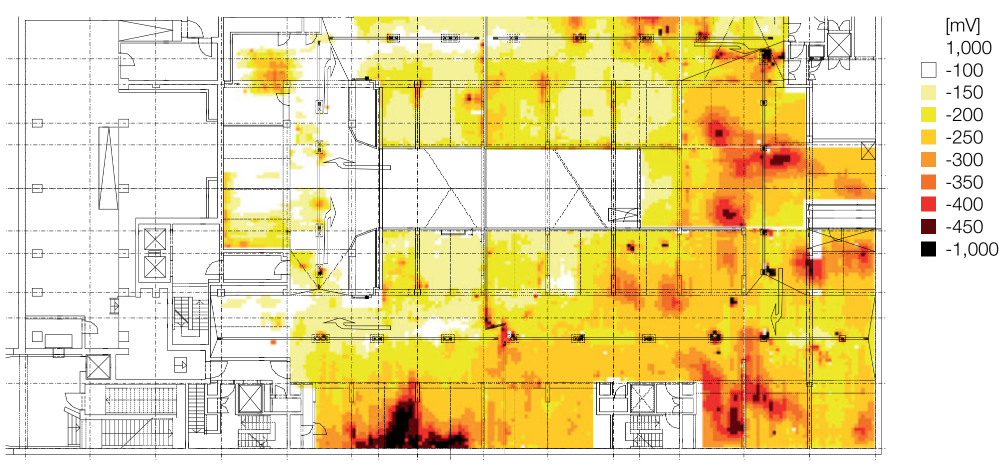
Restoration planning – maintenance

German building regulations require the application of the technical rule for the protection and repair of concrete structural elements (“Schutz und Instandsetzung von Betonbauteilen” – RL-SIB) issued by the German Committee for Reinforced Concrete (Deutscher Ausschuss für Stahlbeton – DAfStb, 2001) in the restoration of concrete structural components whose stability is or may be compromised. The European series of restoration standards, EN 1504, has only been partly implemented as building regulations, and there are also so-called supplementary standards [5].
The RL-SIB must therefore be applied in planning the restoration of structural elements relevant to load bearing capacity in Germany. It regulates the following protective and restoration work:

- Providing permanent corrosion protection of reinforcement if the concrete cover is insufficient
- Restoration of the permanent corrosion protection of already corroded reinforcement
- Renewal of concrete in areas near its surface (surface areas) if there is damage from external influences or corrosion in the reinforcement
- Filling of cracks and cavities
- Providing additional preventative protection for structural components from the permeation of substances that attack concrete and steel
- Increasing the resistance of structural component surfaces to frictional wear and abrasion

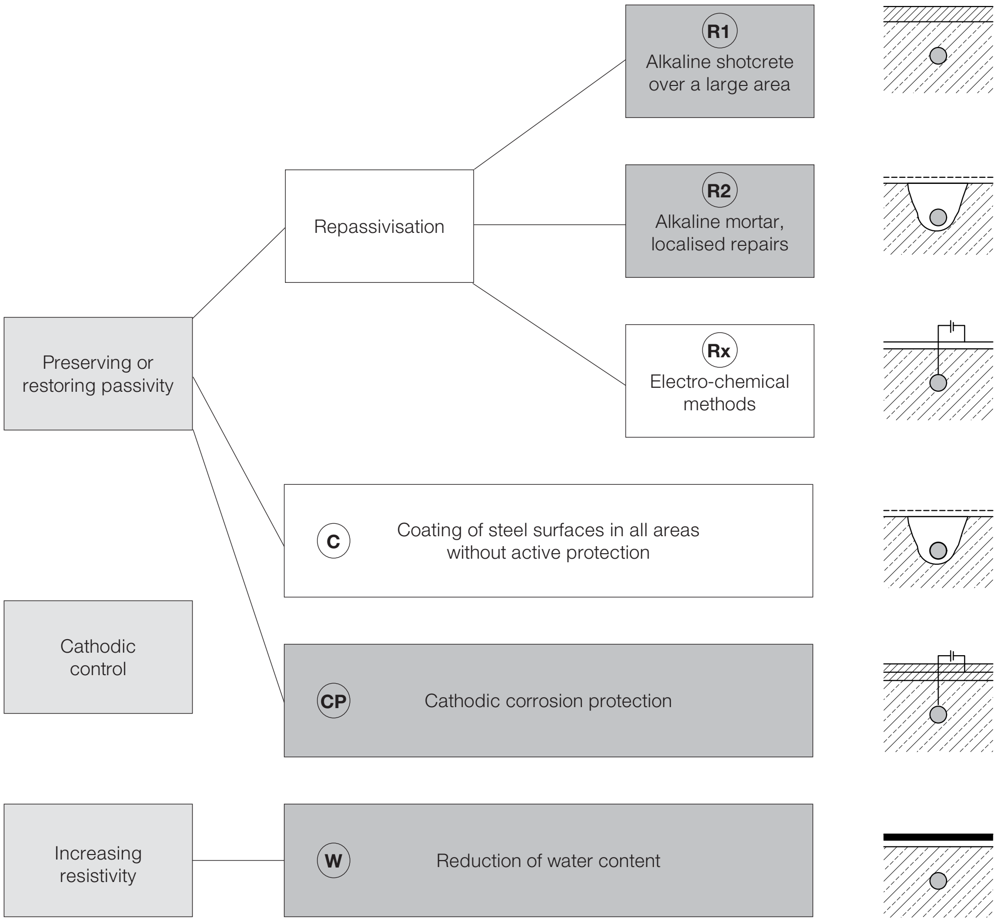
The RL-SIB provides detailed restoration concepts for restoring corrosion protection during the restoration of carbonated and chloride-contaminated structural elements. Fig. C 5.7 (p. 164) shows a summary of principles of corrosion protection for structural components contaminated by chloride. Applying the usual restoration principles R1 and R2, it calls for the removal of chloride-affected concrete. In practice, this often involves extensive shoring and support measures as well as high levels of dust and noise pollution. Examples of applications are provided in the section on “Restoring underground car parks” (p. 168ff.).
Beyond restoration, physical structures (i.e. all buildings) must be regularly inspected, maintained and kept in good condition to comply with building regulation law and civil law and for economic reasons: The building regulatory laws of the states state that a building’s owner is responsible for its stability. The obligation to keep buildings and physical structures safe is part of the liability for the safety of premises under sections 823, 836–838 of the German Civil Code (BGB). Owning, using and operat-

a



b

C 5.6

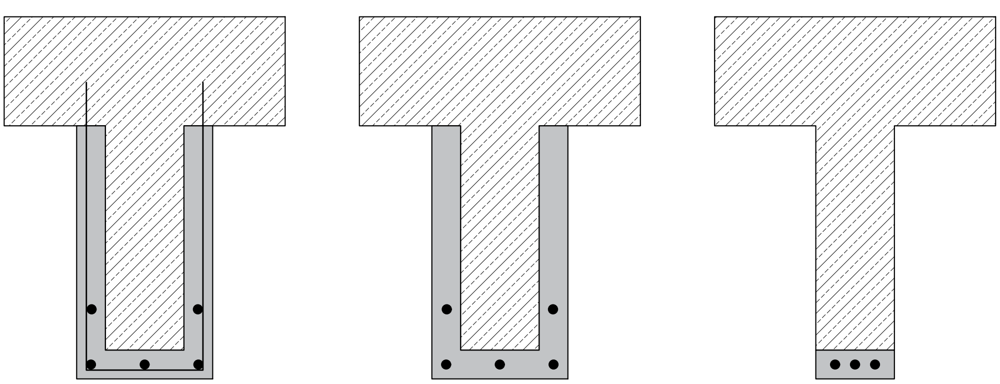


C 5.7

Criterion		Sprayed concrete	CFRP sheets Adhered	CFRP sheets Set in	Textile-reinforced concrete
Technical properties	Basic rule	Standard	National test certificate		Building inspection approval in individual cases
	Increase of load-bearing capacity	++	+		++
	Anchoring	++	-	+	++
	Additional own weight	--	++	++	+
	Protection of the reinforcement from corrosion	+	++	++	++
Production	Preparation of the substrata	-	--	+	-
	Sensitivity to weather	+	--	-	+
	Effort involved in application	-	++	+	-
	Subsequent treatment	-	++	++	--
	Additional fire protection	+	--	--	++

++ very positive/very slight cost and effort
+ positive/slight cost and effort
-- very negative/very high cost and effort
- negative/high cost and effort

C 5.8


C 5.9

ing buildings can cause danger to life and limb, impinge on other rights of persons and damage the environment, so legislators have made property and building owners or others charged with the maintenance of buildings responsible for taking all required and reasonable measures to avoid or reduce danger or injury [6].
For German federal (and state or Länder) government buildings, the guidelines for the monitoring of German federal government buildings and structures (Richtlinie für die Überwachung der Verkehrssicherheit von baulichen Anlagen des Bundes – RÜV) [7] prescribes a regular inspection of buildings, with annual surveys and any closer inspections required in consequence. If a possible danger is identified, further investigation is required. The guidelines of the Association of German Engineers (Verein Deutscher Ingenieure – VDI) 6200 contain more information on this topic [8].

Demolition – strengthening – retrofitting

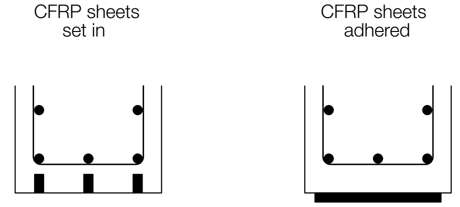
Concrete's excellent load-bearing properties can be a handicap when subsequent changes to the geometry of concrete structural components are made. The removal of concrete structural elements, even those that are not load-bearing, is fairly costly and time consuming. The cutting and core drilling of concrete are however now so common and affordable that even in new building construction, (smaller) openings are often now no longer formed, but core drilled after pouring. Noise, dirt and water (for cooling saw blades) can cause problems during renovations. The classic tool for small-scale removal of concrete is the jackhammer. Special machines are available for the large-scale removal of entire reinforced concrete building components. Using high-pressure jets of water to remove only the concrete in a structural element may also be an interesting method because the reinforcement remains. A "hand lance" is used for small areas, with the addition of robots for large areas. One factor inherent in this system is the use of large amounts of water, and its high technical complexity is reflected in its cost.


C 5.10

A classic problem in conversions of reinforced concrete buildings is the replacing of columns or joists whose geometry is not compatible with the new usage. As well as the concreting techniques described below, it can be advisable to resort to steel beams or columns. Usually, these steel structural elements must subsequently be enclosed in a fire-resistant coating, which is relatively complex and costly, but they are often geometrically easier to install, allowing the formwork and setting times involved in concrete alternatives to be dispensed with. Details in restricted spaces can mean that it is sometimes almost impossible to properly place and compact concrete. It can also be difficult to ensure a monolithic bond with an existing overlying structural component, such as a reinforced concrete joist subsequently attached to an existing ceiling, whereas a steel beam can be precisely adjusted and remaining joints filled in with pack mortar to form integral bonds.
The following technical methods of strengthening reinforced concrete structural elements are often used in practice (Fig. C 5.8):

- Sprayed concrete: The sprayed concrete or shotcrete method is suitable for retroactively strengthening reinforced concrete structural components to improve their load-bearing capacity and for re-profiling them during restoration (Figs. C 5.9 and C 5.10). It must be noted, however, that the application of sprayed concrete also increases a structure's own weight, which works against the strengthening, especially in reinforced concrete structural elements, such as ceilings, that are subject to bending loads. Using sprayed concrete to strengthen structures is also beneficial in terms of fire protection. A decisive factor for success in strengthening a slab is the bond between the old and new layers of concrete, which will require special measures to ensure the strength of the bond. A layer of strengthening sprayed concrete is usually applied to the underside of a slab. It may be structurally possible in some rare cases to apply a top layer of reinforced concrete.
- CFRP sheets: Carbon fibre reinforced plastic sheets (CFRP sheets) can be used to strengthen inadequately load-bearing structural elements, bear loads and transfer loads during the creation of apertures and demolitions, with a distinction made between bonded sheets and those bonded into slots (Fig. C 5.11). Carbon fibre sheets are pultruded epoxy resin laminates with a minimum carbon fibre proportion of approx. 70 %. The sheets are usually 1.2 to 1.4 mm thick, but can be made up to a maximum thickness of 2.8 mm. The sheets are 50 to 150 mm wide. Only approved reactive resin system adhesives, mainly epoxy resin-based adhesives are suitable for bonding them [9]. In verifying the structure's load-bearing ability, only tensile forces can be assigned to the sheets in planning. Depending on the shear force loading, steel mounting brackets or carbon fibre laminate bonded to resist shear forces must also be built in.
- Textile-reinforced concrete: Textile-reinforced concrete is a relatively new construction material. As with reinforced concrete, the concrete absorbs compressive forces, while the reinforcement (here a textile layer) absorbs tensile forces (Fig. C 5.12). Using textile-reinforced concrete in restoration increases load-bearing capacity due to the textile reinforcement, which strengthens the reinforced concrete and improves its "advance notice behaviour" (the formation of large or many cracks or sagging indicates, for example, imminent failure).

a



b C 5.11

Fire protection

Most of the protective goals of fire protection apply to concrete buildings in the same way as they do to other buildings, although in terms of flammability and fire resistance, the situation for structural elements is different. Reinforced concrete is not combustible, so a concrete structure cannot form part of the fire load and cannot become a source of smoke and heat. In assessing the fire resistance rating of a structural component, however, it must first be determined whether it functions as a load bearing and/or as an enclosing element. In the new European standards, these functions are represented by the letters "R" for load bearing capacity (Résistance) and "E" for spatial enclosure (Étanchéité).

Inadequate spatial enclosure is the rule rather than the exception in existing buildings, especially where service ducts are involved. This also goes for subsequent openings for installations. During renovation, these must be closed in compliance with the regulations of the relevant fire resistance class of the perforated structural element and the utilities sealed off in conformity with the approval in the same class.

Since relatively few technical problems related to fire protection occur with reinforced concrete buildings, the material in existing buildings is often simply assumed to have the

C 5.7 Corrosion protection principles in accordance with the RL-SIB, with designation of the principles under which chloride-contaminated concrete does not have to be removed.
C 5.8 Evaluation of strengthening measures
C 5.9 Possibilities for subsequent strengthening of the tensile zone with sprayed concrete
C 5.10 Strengthening a slab with sprayed concrete, reinforcement installed before the application of sprayed concrete
C 5.11 Subsequent strengthening of the tensile zone with CFRP sheeting
a Joist strengthened with bonded CFRP sheeting
b Schematic cross section
C 5.12 Textile-reinforced concrete
a Typical dimensions of textile-reinforced concrete, depending on the number of layers
b Integration of textile reinforcement

a

b C 5.12

C 5.13

appropriate fire protection quality because it is almost impossible to see with the naked eye what fire resistance a steel reinforced concrete structural component has. One of the first and most elementary tasks in renovating a reinforced concrete building, therefore, is to have a structural planner investigate load-bearing structural components as well as their fire resistance.

A reinforced concrete building's sensitivity to fire results from the rapid decline in the structural load-bearing ability of steel exposed to the heat of fire at temperatures above about 350 °C. The concrete cover initially protects the steel, but if very high temperatures affect the structural component within a short time, inner vapour pressure can burst the concrete cover. A temperature of just 90 °C is critical in renovations using bonded CFRP sheets, as this is the point at which the adhesive will fail. Thus, structures strengthened with CFRP sheet bonding must have separate fire protection.

Load bearing concrete structural elements with inadequate fire resistance usually cannot easily be replaced, so possible solutions for their technical retrofitting for fire protection purposes are as follows:

- Prevention of fire close to the structural component
- Cooling of the structural element in the event of impact from high levels of heat
- Absorption of the heat by chemically or physically reactive protective cladding
- Insulation or an increase in the mass of the structural element to deflect heat for the duration required according to its fire resistance rating or to distribute the heat over a larger mass of the structural component

Considerations should not be limited to the individual structural element being renovated, but should cover its task in the context of protective goals. In many cases, a holistic fire protection concept can avoid unnecessary construction and technical cost and effort. This especially applies to sprinkler systems, which provide fire protection and even cooling as mentioned above, but are often not considered because they are a very costly and complex solution to install and maintain.
The usual way to renovate reinforced concrete structural components with inadequate fire resistance is to encase them in additional layers of fire protection materials approved by building regulatory authorities, usually panels or a plaster coating. The most important materials used for this purpose are:

- Mineral wool for insulation
- Plasterboard or gypsum fibre board to absorb heat (The water in the plaster vaporises when heated, cooling the board.)
- Calcium silicate (As a board or moulded element, it combines insulation and absorption properties.)

Floor and ceiling slabs

The fire resistance of reinforced concrete floor and ceiling slabs often has to be upgraded during renovation or conversion. Errors that must be rectified can also be made in construction, such as insufficient reinforcement or an inadequate concrete cover on the slab's underside. Because of their large surface areas and minimal cross sections, ribbed ceilings are especially sensitive to fire. For a long time, it was standard practice not to remove their relatively complex timber formwork on the underside, which then became part of the fire load and also made visual inspection during renovation more difficult.
In most cases, the impact of fire on the top of a slab is less serious because the layer of screed, concrete and reinforcement usually found here provides additional protection, and the main thermal effect of fire always develops above the blaze, so it affects the slab's underside. If, however, a slab must be renovated to provide fire protection on the top side, an additional layer of screed or dry screed can achieve the required fire resistance class. The disadvantages of these measures (increasing the structure's own weight, necessary adjustments to doors, joints) are described in the chapter on "Steel reinforced ceilings" (p. 167).

If the building is not reduced to its shell during renovation, every rising wall subsequently installed will break into the new upper protective layer. Larger cavities (in drywall construction) can represent weaknesses in the structure's fire protection and must be dealt with separately.

This problem of penetration can also arise on the underside of a slab if each wall touching the ceiling breaks into a potentially new protective layer on the underside. This protective layer can be built in the form of additional layers of plaster or approved sprayed plaster. This will require a building site that can accommodate dirt and water, but such coatings are very quick and easy to install and especially suitable for structures with complicated geometries such as ribbed ceilings or joists. Another benefit is the lack of inherent problems with suspended ducts for utilities and services. This method cannot, however, usually be used in renovations carried out while the structure is in use because of the dirt and damp involved. Sprayed plaster will have an inherently large surface and a very rough, uneven appearance, so it is not suitable for areas subject to heavy mechanical stress.

Alternatively, the underside of a slab can be clad with drywall panels of the approved fire resistance class. The joints between the panels are then filled, and if they remain visible, are sanded smooth ready for painting. Every protrusion in the slab's geometry will, however, involve more cost and effort. The additional material required also results in a much thicker type of structure than is produced with plaster. Pre-existing suspended elements and utility ducts can also pose further difficulties for this method.
In contrast to the techniques described above, an approved suspended fire protection ceiling does not provide close fitting fire protection for the building's shell. This solution is often the only possible if there are installations on the slab's underside. The precondition for a suspended fire protection layer is adequate ceiling height after the measure is completed. In this case, there are no penetration problems because all the cables are in a protected cavity, although the cables themselves can

C 5.13 Test core drilling of a steel reinforced concrete slab with bonded screed
C 5.14 Noise insulation renovation of a steel reinforced concrete slab with bonded screed by the placing of a layer of floating dry screed


C 5.14

become a hazard if they become part of the fire load or if their suspension fails in a fire and the cables fall onto the suspended ceiling and break through it. A fire protection casing must therefore be built around combustible structural elements. There are also approved fire protection wraps in which electrical and data cables can be wound. Both types of measures are, however, labour-intensive and expensive.
What all suspended ceilings with approved fire protection have in common is that they have clearly defined framework conditions governing the maximum spacing in the suspended element and sub-structure that often conflicts with existing service and utility cabling. Construction managers should carry out a partial acceptance inspection of such ceiling systems before they are concealed under cladding.
Another frequent problem with ceiling slabs with high levels of installations for equipment in existing buildings is a lack of space for the suspended elements of a fire-protected ceiling and of workspace for drills. Free-spanning, suspended ceiling systems with appropriate approval are suitable for such small spaces.

Sound insulation

Concrete's high material mass means that concrete structures are less subject to airborne noise problems than other materials, which is directly due to the concrete itself. Generally, the most important measures to improve airborne noise insulation are:
- The closing of openings of all sizes in sound-absorbing structural elements. This prevents sound from spreading unimpeded into adjacent spaces.
- The use of sound-absorbing surfaces to reduce airborne noise reflection, which can reduce the quantity of sound waves hitting the sound-absorbing structural elements.
- Increasing the mass of sound-absorbing structural elements so that the relatively low-energy airborne noise will no longer cause heavier structural components to vibrate.
- The building of heavy, multi-layered structures with each layer of a variable weight, so that it can react to a greater range of frequencies, is best.

Conflicts around structure-borne noise (usually footfall sound) occur frequently during the restoration of concrete buildings. Classic concrete buildings are poured almost entirely without joints in one piece, so they offer an ideal path for spreading structure-borne noise. The main potential improvement measures are:
- The isolation of transmission paths.
- The removal of all acoustic bridges that short-circuit this isolation.
- The absorption of airborne noise that reaches the ear as a result of structure-borne noise.

Reinforced concrete ceilings

Ordinary, steel reinforced concrete ceilings have a large mass, giving them good sound insulation properties. The appeal of certain lightweight construction methods (lightweight concrete, gas-aerated concrete), ribbed ceilings or hollow core slabs, lies precisely in the reduction of this mass, thereby increasing the structure's efficiency. This, in turn, results in inferior sound insulation.
Even strong reinforced concrete ceilings, however, can have significant sound insulation problems if screed is not floating, but bonded (Fig. C 5.13). This method was used in the construction of residential and administrative buildings until well into the 1980s and is still common in many European countries today. All structure-borne and airborne noise effects on the screed are transferred, undiminished, to a ceiling slab and thus to the space below it because the screed and ceiling slab merge to form a monolithic structure for purposes of sound insulation.
The use of a good sound-absorbing floor covering, such as carpet, is the easiest renovation measure, yet when used alone, not nearly enough to ensure the required sound insulation levels.

A key and often unavoidable measure is the placing of additional floating screed. The screed layer must be isolated on all sides from the ceiling slab with soft materials and from all rising or penetrating structural elements. Floor structures not properly connected, pipe breakthroughs that are not acoustically isolated and insulation strips incorrectly laid along edges can very quickly result in acoustic bridges that negate any good acoustic insulation levels in these surfaces.
Adding a new, often second screed layer to a slab also changes all the floor heights. All the building's connecting points (ramps, thresholds, connections to stairs) and all existing doors usually have to be adjusted. The new screed also increases the structure's own weight and brings lots of moisture into ongoing construction operations in what may often otherwise be a relatively dry building renovation site. Both these problems can be minimised by using dry screed panelling material (Fig. C 5.14).
To improve sound insulation from top to bottom, a false and flexible as possible ceiling can also be hung. This is, however, ineffective against flanking transmission via the walls and is much less effective than floating screed.

Unintended interior insulation

Insulating materials are often used for interiors in renovations involving sound insulation, even though their insulating properties may not be not necessary.
If a vapour pressure gradient is expected in the installation situation (in all structural elements in the building envelope), each succeeding layer must be checked for the formation of condensation. Thermal insulation installed for sound insulation reasons is also subject to all the risks of classic interior insulation (see "Exterior walls", p. 168).

Replacing steel reinforced concrete facade cladding

Over the course of thermal renovations, it can be advisable to replace un-insulated or barely insulated (prefabricated) concrete elements as weatherproof cladding in the facade. This, however, can sometimes lead to conflict because the new layers may insulate much better after renovation, but the original building will have lost a great deal of mass. This can significantly diminish airborne noise insulation,

C 5.15

which must be mathematically checked or technically measured if exterior noise levels are high and facade elements are light.

Building equipment and technology

The practically joint-free construction typical of many concrete buildings makes them ideal for transmitting structure-borne noise. Incorrectly installed building equipment and technology elements, especially water pipes, pumps or lifts, can cause disruptive noise. Machines or drive units can often be relatively easily decoupled from a concrete structure, the sound insulation renovation of partly or completely concreted-in pipes is, however, usually not possible or possible only to a limited extent. In this case, it is the building equipment and technology that is renovated and not the concrete structure.

Heat insulation

Heat insulation regulations, which have become more stringent in the past 20 years, mean that almost every building renovation also demands an upgrade of the insulation on the building envelope. This is especially often the case with older concrete buildings. The goal is to reduce the energy consumed in controlling the building's temperature while increasing its comfort and protecting structural elements, especially from condensation. To increase the heat insulation of the building envelope, its overall thermal conductivity must be significantly reduced. In parallel, it must become more airtight as considerable quantities of heat are lost through open joints due to convection, while uncontrollable flows of moisture can compromise the structure. A generally better insulated envelope, however, does not solve the problem of localised thermal bridges. If individual structural elements conduct heat much better to the exterior than adjoining insulated elements, they will be much cooler and their interior temperature will fall below the dew point, allowing condensation to form.
Before a thermal renovation plan is drawn up, a precise survey of the existing building is indispensable. Since, as mentioned above, planning documents for the existing building do not always reflect reality, trial openings are strongly recommended (Fig. C 5.15). As well as the geometry, the vapour permeability of the various layers of the existing structure must be taken into account, especially around connections to adjoining structural elements. The more thorough the survey, the lower the risk of unforeseeable surprises in the subsequent construction process and in costing.
Similar types of problems occur repeatedly in individual structural components when renovating steel reinforced concrete buildings:

Flat roofs

The most frequent reason for renovating flat concrete roofs is usually insufficient or damaged insulation on the roof surface. In most cases, this is accompanied by extensive ageing of the sealing layer and its connections, so that the entire flat roof needs to be replaced. If, during the removal of the existing structure, it is determined that water has permeated through it, the ceiling reinforcement must be checked for damage. While renovating a roof's flat surface is usually unproblematic, there may well be difficulties with the connections of rising structural elements and the attic. Geometric forces from the existing building often prevent construction in accordance with the authoritative flat roof guidelines. Special solutions, often involving liquid sealants, are then unavoidable.

Exterior walls

Un-insulated or inadequately insulated exterior concrete walls, concrete sandwich pre-cast elements with insufficient core insulation and rear-ventilated facades with non-bearing, curtain-type precast concrete weatherproofing elements are the structural elements most frequently in need of thermal renovation. The wealth of possibilities always requires an individual examination of the situation on site, during which the following tips may be helpful:

- External insulation should be preferred to interior insulation because of its much better structural and physical properties, including in renovations. External insulation also involves fewer connection problems because the insulation encases all the structural elements, apart from balconies, porches etc.
- Existing core insulation cannot usually be replaced. A building physicist can help to determine what layers of additional insulation of what thickness would be best. The temperature profile for each planned wall structure must be mathematically checked.
- Interior insulation reduces floor space, which must be especially taken into account around connections to ceilings and interior walls. Interior insulation should not be so thick that the temperature on its outside falls below the dew point. There are two different approaches to solving the problem of the transport of moisture from the inside to the outside: Either a material is chosen that can absorb moisture from the space to a certain extent and allow it back into the space during the warm months of the year, or an attempt is made to prevent moisture permeating the inside by using vapour dampening or vapour blocking coatings. The latter method demands very high-quality execution of construction. A moisture-adaptive vapour barrier combines the two principles. Its vapour diffusion resistance depends on ambient moisture levels. It usually functions like a classic vapour barrier, but if the insulation becomes soaked, its vapour diffusion resistance declines, allowing the interior insulation to dry out.
- Cavities in the existing facade that cannot be inspected (such as behind prefabricated concrete cladding) must be avoided. If they cannot be filled with insulation, the relevant layers should be removed and replaced with new ones.
- Concrete exterior cellar walls are particularly subject to damp. Often in these cases, the moisture input from the space is not only especially high (the basement laundry room is a classic case), but the effect of moisture from the earth penetrating from the outside also has to be taken into account.
- A structural-physical inspection of the sequence of layers in a sample field and around joints is indispensable in each case.

Balconies and porches

Concrete balconies and porches projecting from existing buildings are often not thermally separated. It is better if they can be supported by corbels at various points. Corbels however, are usually not insulated and are integrated into the monolithic concrete structure. Using solely interior insulation provides a geometric advantage for renovations (Fig. C 5.17 c). For external insulation and most mixed forms, these penetrations of the insulation are, however, a problem (Fig. C 5.17 b). The best solution in terms of building physics is to remove the projecting structural elements and replace them with self-supporting structures that are statically and thermally independent of the building, such as a balcony on new, separate supports.
This is, in many cases, impossible for reasons of cost. Alternatively, it must be then mathematically ascertained whether insulation on the underside of the ceiling, as well as any existing top-side footfall sound insulation along the facade, is necessary or not. The surface of an insulated exterior wall will, however, cool in the area around the projection, and thermal bridges that are almost impossible to overcome by modifying the structure's geometry remain, such as those around tied-in interior walls (Fig. C 5.16).

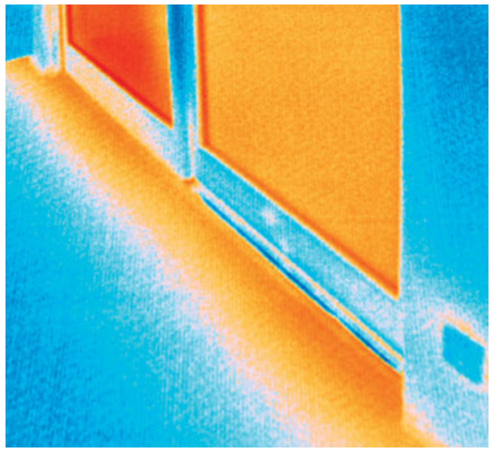
Restoring underground car parks

While restoring parts of the concrete structure of ordinary residential and non-residential buildings almost always involves general renovations, including thermal, noise insulation and fire safety renovations, the restoration of underground car parks involves mainly typical, and sometimes serious, corrosion damage to the steel reinforced concrete structure or parts of it. The main damage, as mentioned before, is the chloride-induced corrosion of reinforcing steel. If restoration is necessary, an overall renovation for economic reasons is also always possible. The renewal of a structure's coatings usually required over large areas also opens up the possibility of refreshing its colours and improving its orientation. Since restoration, in any case, often necessitates the removal and replacement of large parts of the (existing) lighting and drainage systems and gates and doors, it may also be practical to optimise the ergonomics of the building's use during this work.

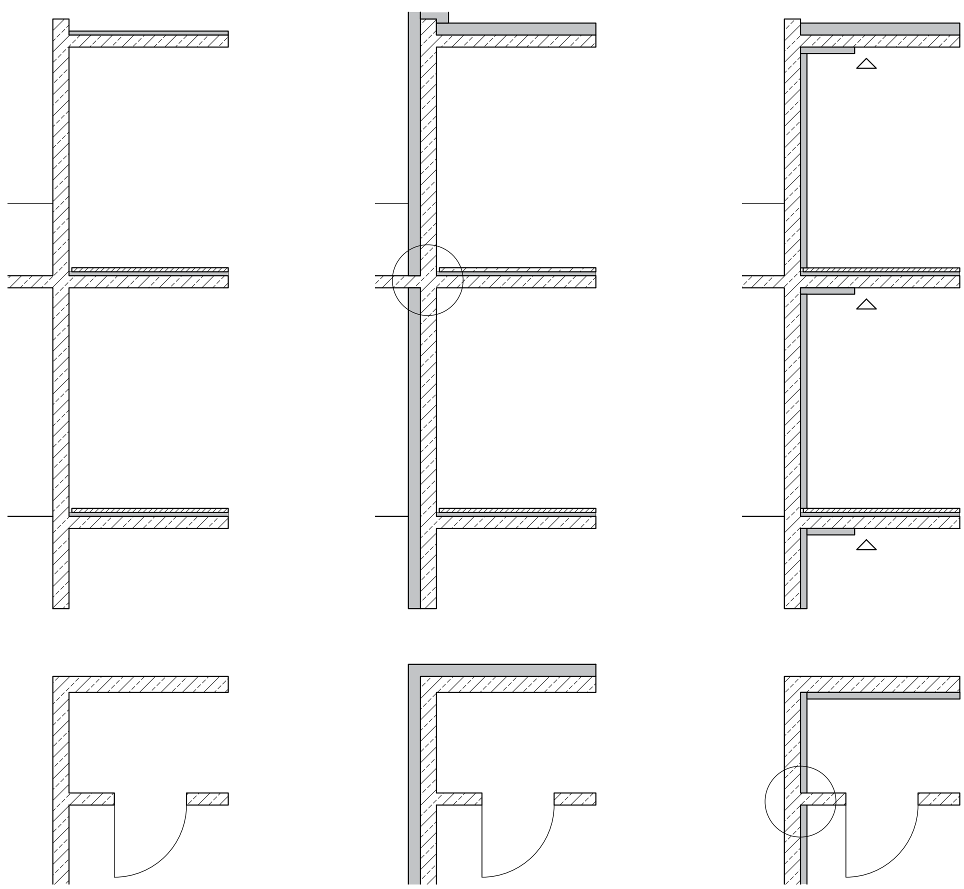
The assessment and restoration of the steel reinforced concrete of car park buildings and underground car parks is a fundamental engineering task that requires profound concrete restoration expertise. Yet this kind of work is often assigned as part of the performance of an overall renovation to a planner responsible for organising all measures, who subsequently employs appropriate expert planners to work on individual sections of the project, e.g. for an underground car park's renovation or restoration.

Underground car parks and car park buildings require particular care and attention to ensure their durability because of their usage. They are often damaged due to exposure to chloride. Cars bring de-icing substances containing chloride into the buildings (often in the wheel hubs), and the substances then reach the insides of load-bearing steel reinforced concrete structural components by means of diffusion. If a critical concentration is exceeded, chloride-induced corrosion can cause significant loss of the reinforcement's substance (Fig. C 5.4, p. 162).
This shows clearly that structural components with inadequate durability concepts have been built for decades. Chloride-induced corrosion often causes extensive damage to load-bearing structures and thus very complex and costly restoration. The following areas of existing underground car parks are often extensively damaged, especially if the structure is not coated (Fig. C 5.18, p. 170):

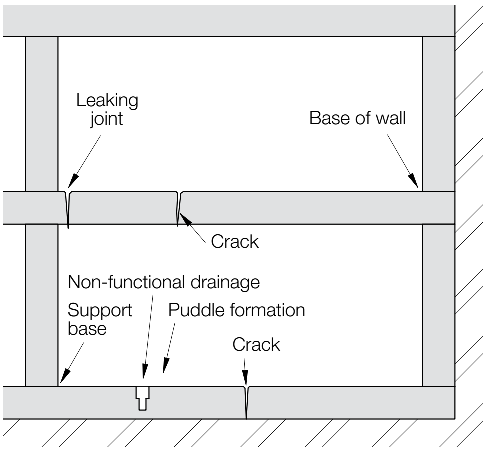
- The feet of columns and walls: Water containing chloride often flows directly around the feet of columns and walls, which are likely to contain voids and have a thin concrete cover because of the way they are made. This enables the chloride to quickly penetrate to the inside of the concrete and start corroding the reinforcement.
- Cracks and leaking joints: Chloride can penetrate through cracks in concrete almost unhindered and cause the reinforcement under the crack to corrode. Penetrating cracks or leaky joints on the underside of suspended ceilings can cause extensive corrosion and spalling of the concrete cover, which diminishes the structure's traffic safety.
- Reinforced concrete suspended ceilings are usually designed as flexible structures with a planned formation of flexural cracks, but the possibility of separating cracks due to the action of forces cannot be excluded. As well as the risk of corrosion to reinforcement described, cracks and leaky joints in a suspended ceiling limit its serviceability since water dripping from the ceiling becomes highly alkaline after contact with the concrete and can damage the surfaces of parked cars.
- A decisive factor for uncoated floor slabs, exposed to the risk of corrosion, as well as the concrete cover and quality of the concrete, is whether accumulating water is quickly drained away. Cracked areas in floor slabs that do not slope or have functioning drainage are at very high risk of corrosion because chloride can quickly reach the reinforcing steel and cause corrosion with high loss of substance.
- Double car parks: Walls and the floor slabs of the pits of double car parks are often not coated and hard to inspect visually.
- Steel reinforced concrete structural elements under paving can often be profoundly impacted by chloride without the impact being visible from the outside.


C 5.16

C 5.15 Trial opening in a facade with a pre-cast exposed-aggregate concrete element before renovation
C 5.16 Thermal image of a balcony slab (not thermally separated) from the outside. The orange area in front of the window indicates substantial heat loss.
C 5.17 Unrenovated existing building (a), renovation with external insulation (b), renovation with internal insulation(c), thermal bridges are circled. The triangles indicate ceiling insulation reducing heat loss.



C 5.17



C 5.18

C 5.19

Building diagnostics for underground car parks
The degree of damage to a load-bearing structural element in an underground park can be estimated by a visual inspection. If the questions posed in Fig. C 5.20 (p. 170) are answered in the affirmative, an increased probability of corrosion must be expected. If there are indications of an increased risk of corrosion, an expert restoration planner must carry out a building diagnosis and a step-by-step inspection concept is advisable: In the first step, an engineering survey and random testing of concrete cover and of the chloride contamination of various structural elements and potential mapping are carried out. From this, the necessity of restoration can be deduced and a rough plan drawn up. It is then advisable to carry out a detailed building diagnosis to ensure stability of the mass and assess the economic efficiency of alternative restoration concepts. Experience has shown that the costs invested in a detailed building diagnosis usually result in far less expensive restoration, leading to considerable savings over the entire restoration process.

Restoration planning
The restoration of chloride-contaminated structural elements relevant to a structure's stability should be carried out in accordance with the DAfStb protection and restoration guideline (RL-SIB). The removal of chloride-affected concrete and subsequent re-profiling – the refilling of areas from which concrete has been removed – has become the established restoration concept. In recent years however, the restoration principle of cathodic corrosion protection (CP) has been increasingly frequently used (see "The principle of CP" in Fig. C 5.7, p. 164). It stops the corrosion process with an anode (e.g. a mixed-metal oxide-coated titanium mesh) attached to the concrete's surface, which a low current attached from the outside permanently polarises (Fig. C 5.21). The great advantage of this method is that chloride-affected concrete can remain in the building, which significantly reduces the dust and noise of restoration. The prerequisite for use of cathodic corrosion protection is that the building has sufficient remaining load-bearing capacity (Fig. C 5.22).

The DAfStb "protection and restoration" guideline prescribes the corrosion protection principle W (Fig. C 5.7, p. 164), which, if chloride is present, may also be referred to as W-Cl. This corrosion protection principle is based on keeping water away from a structural component by applying a coating to the concrete surface so that it dries out over time and stops the corrosion of reinforcing steel. The coating of chloride-affected structural elements alone, however, involves a high technical risk since, due to its chloride content, the concrete is hygroscopic, i.e. the concrete retains water and does not really dry out. This means that existing corrosion processes are barely stopped by a coating. The restoration guideline therefore contains an explicit warning that the W-Cl principle should only be applied after prior proof of suitability (through a trial installation) and a warning of the high technical risk.

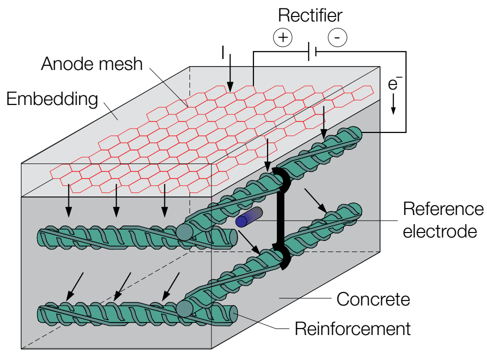
Preventing further damage
To prevent further damage in underground car parks, the following should be taken into account if possible during their construction or restoration (the relevant DBV data sheet provides further information [10]):
- Creation of a gradient and effective drainage for horizontal structural elements that are directly driven on (floor slabs, storey slabs)

Bases of columns and walls	Are the load-bearing steel-reinforced concrete structural elements not coated?	Increased risk of corrosion
	Is water flowing around rising structural elements?	
	Is discolouration and efflorescence visible on rising structural elements?	
	Are vertical cracks visible at the bases of columns?	
	Are there voids or flaked off areas over the reinforcement?	
Suspended ceilings	Is the ceiling not coated?	Increased risk of corrosion
	If there is a coating, are there cracks in it?	
	Are puddles forming?	
	Are there gaping cracks through which water can penetrate?	
	Is brown discolouration visible around cracks in the underside of a structural element?	
	Are voids or flaked off areas visible on the underside of the ceiling?	
Floor slabs[1]	Is the floor slab not coated?	Increased risk of corrosion
	If there is a coating, are there cracks in it?	
	Are puddles forming?	
	Are voids or flaked off areas visible on the underside of the floor slab?	

[1] With floor slabs the risk of corrosion is apparently often difficult to detect

C 5.20

a



b C 5.21

- Ensuring a high nominal concrete cover of 35 mm (coated bases of walls and columns) up to 55 mm (steel-reinforced concrete structures that are directly driven on, with and without coating)
- Avoidance of cracking or the use of a crack-bridging coating
- Coating of the bases of columns and walls and double car park pits
- Sealing of structural elements under paving

Underground car parks must be regularly maintained, so it can be advisable to draw up a maintenance plan as part of planning, which can be given to the client before final acceptance.

Notes:

[1] DAfStb-Richtlinie – Schutz und Instandsetzung von Betonbauteilen (RL-SIB). Berlin 2001-10
DIN EN 1504-9: Products and systems for the protection and repair of concrete structures – definitions, requirements, quality control and evaluation of conformity. Part 9: General principles for the use of products and systems. 2008-11
[2] DIN EN 1504-9: Products and systems for the protection and repair of concrete structures– definitions, requirements, quality control and evaluation of conformity. Part 9: General principles for the use of products and systems. 2008-11
[3] Merkblatt für elektrochemische Potentialmessungen zur Ermittlung von Bewehrungsstahlkorrosion in Stahlbetonbauwerken (B3) Published by the Deutsche Gesellschaft für Zerstörungsfreie Prüfung e. V. Berlin 2008
[4] DAfStb-Richtlinie – Belastungsversuche an Betonbauwerken. 2000-09
[5] Hintzen, Wilhelm: Bauaufsichtliche Regelungen zur Umsetzung der Normenreihe DIN EN 1504. http://www.dafstb.de/akt_normenreihe.html. (accessed on 03/02/2013)
[6] Richtlinie für die Überwachung der Verkehrssicherheit von baulichen Anlagen des Bundes RÜV. Published by the Federal Ministry for Transport, Building and Urban Development (Bundesministerium für Verkehr, Bau und Stadtentwicklung – BMVBS). 2008 version
[7] ibid.
[8] VDI 6200 – Standsicherheit von Bauwerken – Regelmäßige Überprüfung, 2010-02
[9] Allgemeine bauaufsichtliche Zulassung Z-36.12-73: Verstärken von Stahlbetonbauteilen durch in Schlitze verklebte Kohlefaserlamellen Carboplus. Bilfinger Berger. 03/2011
[10] DBV-Merkblatt Parkhäuser und Tiefgaragen, 2. überarbeitete Ausgabe. Published by Deutscher Beton- und Bautechnik-Verein e. V. Berlin, 09/2010

C 5.18 Typically problematic areas of uncoated underground car parks
C 5.19 Removal of chloride-affected concrete, base of a column blasted free
C 5.20 Checklist for evaluating the visual inspection of underground car parks
C 5.21 Cathodic corrosion protection of steel in concrete
a Restoration of a suspended ceiling using anode strips
b Sketch of the principle
C 5.22 Common measures for restoring structural elements in underground car parks

Structural element	**Typical restoration**	**Cathodic corrosion protection**
Bases of columns and walls	• Installation of bracing or supports • Removal of chloride-affected concrete down to levels below the reinforcement using high-pressure jets of water • Laying of new reinforcement, if necessary • Re-profiling of columns/walls • Coating of the bases of walls and columns, creation of grooves • Removal of bracing or supports	• Uncovering of cavities and their re-profiling if required • Preparation of the substrata • Installation of anodes • Embedding of anodes • Wiring and installation of the rectifier • Coating of the bases of walls and columns, creation of grooves
Suspended ceilings and floor slabs	• Installation of bracing or supports if required • Removal of chloride-affected concrete down to levels below the reinforcement using high-pressure jets of water • Laying of new reinforcement, if necessary • Re-profiling • Coating of the top (to bridge cracks) • Removal of bracing or supports	• Uncovering of cavities and their re-profiling if required • Preparation of the substrata • Installation of anodes • Embedding of anodes • Wiring and installation of the rectifier • Coating of the top (crack bridging not absolutely essential)
Cracks and expansion joints in suspended ceilings and floor slabs	• Installation of bracing or supports if required • Removal of chloride-affected concrete 10 cm around both sides of the crack with high-pressure jets of water • Laying of new reinforcement, if necessary • Re-profiling • Coating of the top (to bridge cracks) • Removal of bracing or supports	• Preparation of the substrata • Installation of anodes • Embedding of anodes • Wiring and installation of the rectifier • Coating of the top (crack bridging not required)

C 5.22

Interiors, design, vision

Ulrike Förschler

C 6.1

In order to reduce the consumption of materials and to lower transport costs in the future, a number of studies are being undertaken in the field of structural engineering on the subject "lightweight construction with concrete". In contrast, with reference to interiors, there are other more creative themes relating to the subject of concrete that affect clients, architects, interior designers and product designers.

Developments in the creative use of concrete

Since approximately 1890, pioneers in the use of reinforced concrete have been daring to leave concrete surfaces visible in factory buildings and warehouses, and even when building churches. Some of the most important examples in the history of interior concrete include buildings by architects such as Le Corbusier, Louis Kahn, Gottfried Böhm and Walter Förderer dating from the 1950s to 1970s. At that time, concrete was formed using rough timber formwork. The result was a deliberately harsh and uncompromising representation of the structural concrete in the interiors as well.

In the 1980s and 1990s, interior surfaces were increasingly being executed with a purist-looking, smooth exposed concrete, as non-porous as possible, with ordered formwork joints and planned fixing holes on interior surfaces. More recently, exposed concrete is increasingly being augmented with other materials such as wood, textiles, leather, plastic, metal, lighting elements and even organic materials as well as green plants – materials that, by emphasising the characteristics that concrete clearly does not possess, create a vision, for example an ornamentation, which hints at the spirit of the place, a shiny or sparkling concrete, a soft and folding concrete, a concrete that brings a green area to life, or flowing, shaped concrete.

Ornamentation

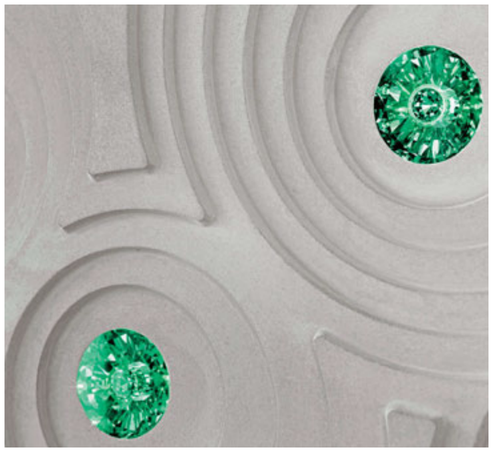
The use of concrete for interiors evolves into a game with the surfaces, which come into being and gain their character in different ways. The example of the Atelier Bardill in Scharans by Valerio Olgiati demonstrates how relief ornamentation, which does not just cover individual structural elements, but the concrete surface of all the interiors and external facades, makes a significant contribution to the overall effect of the building. A decoration on an old chest belonging to the client gave the architect inspiration for the rosettes, three different sizes of which were carved into the softwood timber formwork as depressions (Fig. C 6.2). When the formwork was removed, these produced embossed rosettes on the concrete surface. The architect achieved the bold terracotta colour of the exposed concrete by adding colour pigments and additional rock flour (Fig. C 6.1). The choice of an artisanal method, as in this case, implies a renunciation of modern techniques such as computer-controlled milling and pixel graphics or the use of pattern matrices (see "Matrices / matrix formwork", p. 56f.), additional formwork moulds, photo concrete (see "Photo concrete", p. 59), retarder paper (see "Washed concrete surfaces", p. 59) or laser engraving. The carving process itself is very time-consuming but does deliver a distinctive character.

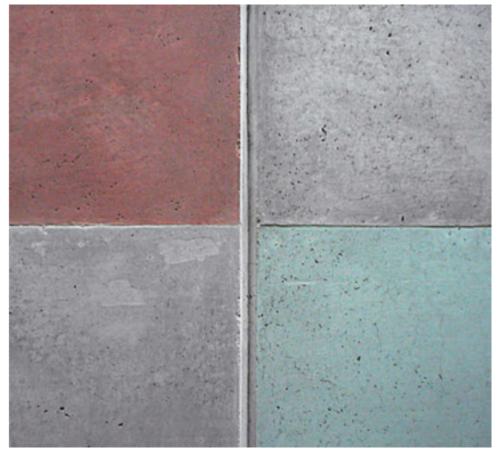
Inlays and surface coating

The appearance of concrete can also be upgraded with the addition of different types of inlay, such as polished glass stones, or by subsequent surface coatings, for example with precious metals. Wall surfaces can be given an extravagant look by fixing micro glass beads or polished crystals in the formwork. Prefabricated panels are used in this way as facing formwork or as load-bearing panels for wall construction in upscale interior construction (Fig. C 6.3). The finish of both cement home accessories and interior wall tiles can be refined by using the traditional craft of gilding to apply gold and silver leaf. This creates a powerful contrast between the dull, velvety concrete and the glossy metal surface (Fig. C 6.5). However, tiles with such a costly finish should not be used for splashbacks, but are intended for use as ornamental wall and interior decorations. As with other gilded items, they require very careful cleaning and maintenance.

C 6.1 Atelier Bardill, Scharans (CH) 2007, Valerio Olgiati
C 6.2 Carved rosette in softwood and the carving tool used, Atelier Bardill
C 6.3 Crystals inserted in the formwork are tapered on the visible side. A coating on the back of the stones ensures sufficient adhesion. After the concreting operation and the formwork have been removed, the crystals remain visible, reflecting incoming light.
C 6.4 Coloured concrete glazes highlight the character of the material.
C 6.5 Refining concrete through the subsequent application of gold leaf and silver leaf
C 6.6 Stitching as a means of connecting textile impregnated with concrete, Stitching Concrete Chair (Germany), Florian Schmid
C 6.7 Coloured textile concrete for covering furniture, etc.


C 6.2


C 6.3


C 6.4

Coloured concrete

Concrete as a material has long had a rather cold and austere image. Most people, when they think of concrete, automatically imagine the colour grey. However, concrete can be selectively coloured by adding colour pigments. In order for the colour to have lasting effectiveness, they must be light-fast and stable in the cement stone. The pigments are added in the form of powder, granules and pearls. The intensity of the colour depends strongly on the concrete base materials, the concrete composition and the quantity of pigments added. When using grey cement, the shades are muted, while with white cement they are, in contrast, purer and brighter. Colour pigments are inorganic additives comprising metal oxides, carbon or carbon black. Different oxides provide the following colour results:

- Yellow: oxides of titanium, chromium, nickel, antimony
- Blue: oxides of cobalt, aluminium, chromium
- Green: oxides of cobalt, nickel, zinc, titanium, aluminium
- Red, yellow, brown, black: iron oxide
- White: titanium oxide

According to DIN EN 12878 [1], colour pigments may be used as additives if proof is provided that the concrete has been properly manufactured and processed. As a rule, they do not affect the mechanical properties of the concrete.

Colour on the concrete surface

The particular charm of exposed concrete lies in the effect of the surfaces as unique creations that are the result of a number of influences. Concrete glazes are ideal for bringing colour to areas of exposed concrete without destroying this character. Glazes have also proven particularly useful for the cosmetic treatment of surface defects (Fig. C 6.4).
Other methods of lending colour to grey concrete include paints and coatings as well as pigmented waxes.

In combination with textiles

The interplay of concrete with textile materials is being tried out for furniture and wall surfaces, and so-called concrete veneers are being created on a trial basis. A textile fabric impregnated with cement sets, when moistened with water, as a thin, tough, waterproof and fire-resistant concrete surface, in a similar way to a plaster cast. The material is primarily used in civil defence for the stabilising of trenches and pipes, in the construction sector, but also in furniture design. The joining techniques used are overlapping, stitching or covering. With the Stitching Concrete Chair, for example, the textile material is 5–13 mm thick and reinforced on the underside with a fabric mesh and incorporated synthetic fibres as well as coated with PVC on the rear, whereby the scattered cement powder is retained (Fig. C 6.6). The flexibility lasts for a few hours after being moistened, allowing surfaces to be deformed in one direction or opposing directions, before it hardens after approximately 24 hours. The textile surface feels soft and warm, with the hardened concrete layer located beneath.
Another method is the combination of textiles such as fibreglass or carbon fibre with concrete. As a two-dimensional material, it retains its stability through formations such as pimples, pillows, waves, etc., and in furniture construction, it is classically set into a frame or mounted as a wall covering. In this case, the material is only a few millimetres thick (Fig. C 6.7).

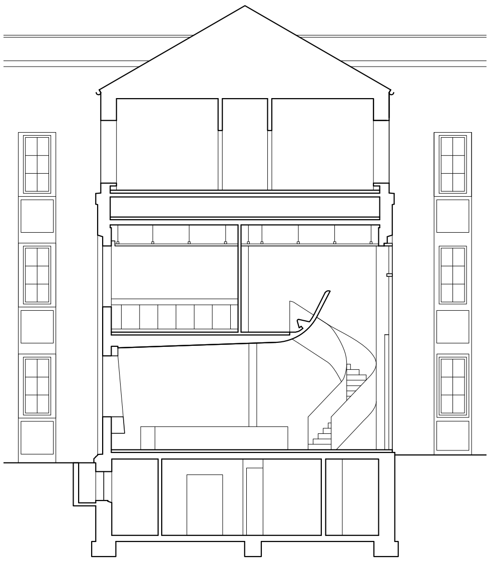
Parameterisation

The increasing use of state-of-the-art computer technology in the design of buildings and interior spaces, as well as the direct translation of data records into the fabrication of formwork sections, makes it possible to execute multiple and oppositely curved structural element geometries in concrete. Such complicated geometries were created at the Roca Gallery in London by Zaha Hadid (see p. 218ff.). For stabilisation and to reduce the net weight, aluminium honeycombs are used here as wall cores and reinforcement. A specially developed concrete recipe appropriate for the application guarantees that the concrete and aluminium form a frictional connection with each other. Mixed polymers increase the


C 6.5


C 6.6


C 6.7



C 6.8

C 6.9

C 6.8 Sectional view, scale 1:250, remodelling of the student services centre at Braunschweig University of Technology (Germany) 2009, DODK Architekten
C 6.9 Remodelling of the student services centre at Braunschweig University of Technology
C 6.10 Presenhuber holiday home, Vnà (Switzerland) 2007, Andreas Fuhrimann, Gabrielle Hächler
a A view of the living room
b Floor plan first floor
c Floor plan second floor
C 6.11 *"Sitz für Garten und Strand",* 1954/2000, Willy Guhl, appropriate use of fibre cement in loop form as self-supporting design
C 6.12 Poli House, Coliumo (Chile) 2005, Pezo von Ellrichshausen

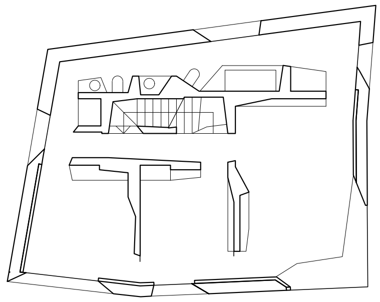
plastic deformability of the concrete of the thin-walled elements, thereby helping to prevent the formation of cracks during transportation and installation.
Another option for the fabrication of three-dimensional shaped formwork elements is the use of rigid foam blocks created by CNC milling machines. These blocks are either used as formwork themselves or applied to corresponding formwork panels for stabilisation. The rigid foam panels can also be reinforced with GRP laminate and then smoothed and sealed, which also guarantees that they are non-porous. This technique creates a reproducible, smooth surface for subsequent formwork oil treatments.

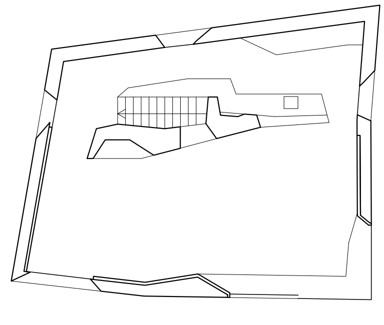
Various institutes, including the Centre for Architectural Structures and Technology at the University of Manitoba, are currently researching the effects that flexible, elastic formwork concepts, such as three-dimensional, rubber-elastic plastic formwork or textile membranes, can have on the free formability of concrete. The object only achieves its desired form and size through the expansion of the formwork during the casting process in accordance with the laws of gravity. Complex geometries can always be better calculated and benefit from the qualities of the concrete material: the individual shaping of the surface and the almost unlimited plastic formability.

Concrete in interiors

The purist and "modern" effect of concrete has led to it becoming very popular with clients as a design element for walls, ceilings and stairs. As a rule, concrete is used in interiors for load-bearing structural elements, which are created in exposed concrete with no plaster, wallpaper or paint applied. Both concrete cast in situ and prefabricated elements are suitable for this. Frequently, non-absorbent formwork with ordered joints is selected and transferred onto orthogonal geometries. This shows off the pristine and vibrant surface to its best advantage – and every surface is unique. Both the composition of the concrete and the selection of the formwork skin determine the result. Steel formwork provides a smooth surface with sharp edges while rough-sawn timber boards produce a coarse wood grain in the surface of the concrete. The industry supplies a number of different formwork materials, formwork systems and installation matrices for different textures. Through the careful selection of aggregates, such as gravel, crushed stone, granite, quartz and granules as well as colour pigments, it is possible to influence the composition of the concrete and consequently its subsequent appearance. The precise configuration of formwork and construction joints, as well as the positioning of fixing holes, determines the appearance of the surfaces. Once the formwork has been stripped away, the surfaces can be further treated, e.g. by grinding and polishing or by means of artisanal techniques, such as those used by a stonemason: bush hammering, tipping, nidging, bossing, etc. (see "Stonemasonry finishes" p. 60f.).
When fabricating exposed concrete, every influence from the construction process and/or from the ambient conditions, both positive and negative, remains identifiable, and subsequent changes are usually very costly. Consequently, a prior careful, accurate and expert specification of the work to be carried out and the selection of an experienced contractor, as well as their cooperation with the concrete factory, all have an important role to play.
The remodelling of the student services centre at the Braunschweig University of Technology undertaken by DODK Architekten is a successful example of the design-determining use of an arched ceiling parapet element in exposed concrete with smooth, non-absorbent formwork (Figs. C 6.8 and C 6.9). A section of an existing ceiling between the ground floor and upper floor was opened up for design and functional reasons and had to be completely removed due to construction difficulties. The new soaring balustrade cast with the gallery platform in smooth exposed concrete now forms a striking structural sculpture, providing attractive visual links between the two levels. The new "implant" brings a new lightness to the "heavy" architecture of the Nazi era.
A very different approach to the use of exposed concrete in interiors is demonstrated by the architects Pezo von Ellrichshausen in the Poli House on Chile's Culiumo Peninsula. Here, they used rough-sawn timber formwork comprising boards of equal length (Fig. C 6.12). The building functions as both a private holiday home and a cultural centre. The rooms are not assigned any specific use and are arranged around a central hall in the centre of the building. The exterior walls and a large proportion of the interior walls were created completely from exposed concrete. The formwork boards used were later recycled to line the walls, as sliding shutters for the large square window openings and for the built-in furniture flush with the walls. A coat of white paint on the interior walls and wooden elements draws together the different materials of the same texture, enabling them to appear as a unified whole.
The focus is also on a homogenous appearance at the Presenhuber holiday home in Vnà in the Lower Engadine, Switzerland, designed by architects Andreas Fuhrimann and Gabrielle Hächler (Fig. C 6.10). Here, the external impact is crucial for the overall appearance of the locality. Over time, several fires destroyed the wooden houses in the area and stone houses have become typical. Concrete, the primary construction material used in the holiday home, takes into account the stone character of the village. The interior also impressively highlights the use of concrete. Only the living room and bedrooms have been lined with plywood


a


b


c

C 6.10

panelling to increase warmth and comfort and as an approximation of the traditional atmosphere of a "mountain hut". Also traditional is the cohesion of the ground floor. On a constructive level, the use of insulating concrete deals with the archaic, as it facilitates a homogenous wall without layering. The resulting substantial wall thickness closely approximates the character of a traditional building method and permits the typically bevelled window reveals. Arranged according to interior criteria, these give the facade an unceremonious appearance typical of the old houses. Finally, the traditional and modern elements of the sculptural construction blend into a unified whole [2].

Fixtures and fittings in concrete

The use of concrete for furniture and accessories in the home and office sectors is proving to be very versatile, in kitchens and bathrooms as well as for radiators and fireplaces. Cement-bonded materials are even being increasingly used in jewellery and fashion design.

Concrete furniture

In German, the word for concrete furniture – Betonmöbel – is itself a paradox, because the word Möbel comes from the Latin word mobilis, which means moveable. Far from being deterred by this seeming contradiction, designers and architects are continually coming up with new approaches for realising their ideas in concrete.
One of the classics of the 1950s is the fibrated concrete Loop Chair by Swiss industrial designer and furniture designer Willy Guhl. Intended for outdoor use, his furniture and objects are characterised by their curved form, visual lightness and low material thickness (Fig. C 6.11).
The subject of weight must not be underestimated with respect to moveable interior design and furniture. Despite this, bold designers still dare to create shelving, stools and chairs in concrete. For example, designer Konstantin Grcic developed his Chair_ONE in aluminium with a concrete base, which adds a significant weight of around 40 kg to the scales. Both with respect to the static loads of the ceilings as well as the structural consequences with respect to the floor area, it is recommended that clients and owners with a desire for concrete furniture consult appropriate specialist engineers early in the planning stage. A structural engineer should definitely be involved in the case of older buildings and large concrete objects.
Less heavy furniture is produced using a combination of textiles and concrete. More recent developments are moving in this direction. The option of shaping a textile material and applying a thin layer of concrete to create the stiffness is characterised in the following examples: The folded Stitching Concrete Stool by designer Florian Schmid is reminiscent of the aesthetics of origami with solid coloured thread. They appear light, soft and even suggest elasticity. The material used is called Concrete Canvas, a textile fabric impregnated with cement, which once shaped is soaked with water and allowed to harden, ultimately retaining the desired shape (Fig. C 6.6, p. 173).
The design firm werkform uses a similar principle to stabilise textile fabric with concrete. However, it uses the new material flat, as a lining for doors or panels for side walls with furniture. The material is given additional rigidity by a kind of impression in its surface. The textile structure and the concrete create a unit. In this case, the material is not used to support loads, but is applied to a supporting material – thus creating a smooth door or a furniture frame.

Concrete bathrooms

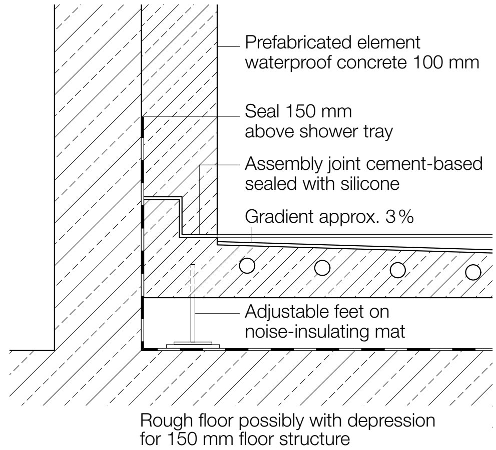
An ensemble of a moulded recliner bench and a rectangular bath sunken into a blue tiled plinth, with only a curtain partitioning off the recess, this is the bathroom of Le Corbusier's Villa Savoye in Poissy in all its simplicity.
More and more clients today are expressing a desire for this classic simplicity of fixtures and fittings in the bathroom – whether it be in the style of washbasin, e.g. a countertop washbasin reminiscent of the bygone days of washbowls and water jugs or a full-width vanity surface with a sunken basin (Fig. C 6.13); in the choice of bath in a box-shaped or round, organic design; or shower trays installed flush with the floor (Fig. C 6.15). A few companies supply standard products for the bathroom sector. However, it is also possible to form and cast the concrete for bathroom fixtures and fittings individually on site.
Designed completely in exposed concrete, the bathroom in the Presenhuber holiday home has a very unique appeal (Fig. C 6.14), with the overall impression of the room cool and austere. The floor, walls, ceiling and bathroom were monolithically constructed and interpreted as an ensemble unit. Only a light curtain in front of the window filters the light and protects against prying eyes. On the one hand, the reduction in the materials used impresses in this elongated space, on the other hand, some guests feel slightly chilled and welcome the integrated floor heating in the floor slab.


C 6.11


C 6.12

C 6.13

C 6.14



C 6.15

Concrete in kitchens
Around one hundred years ago, sinks and basins made from terrazzo found their way into our kitchens and washrooms. However, over the decades, more low-maintenance materials such as enamelled steel basins, stainless steel sinks and worktops, as well as modern plastics, have pushed these fittings out of our kitchens. Today, this artificial stone in simple and attractive designs is experiencing a renaissance amongst kitchen designers. Some use it rather cautiously, just creating the worktop or sink in concrete perhaps, while others use it to produce an entire kitchen block as a freestanding sculpture or an ensemble oriented towards a wall. In the Presenhuber holiday home mentioned above, the kitchen units, the half-height partition wall to the living room and a continuing wall with integrated fireplace and staircase form the centrepiece of the room. Living and eating are focused around this central block, which both divides and unites (Fig. C 6.10, p. 175).
In principle, concrete is suitable for use in kitchen areas (Fig. C 6.16): It is sufficiently heat-resistant and food-safe but is not resistant to acids. Neither is it suitable for cutting and, with an untreated surface, must be maintained in a similar way to natural stone. New methods of surface treatment, such as grinding, polishing, waxing, impregnation and even sealing, offer a wide range of options for protecting the concrete according to its requirements. However, these treatments wear out and need to be renewed repeatedly. It is also recommended that manufacturers' care instructions be followed, in particular with respect to cleaning, as acids and bases may react involuntarily with the concrete. Sometimes, it is the small blemishes that make the concrete distinctive. However, it is quite rare to find roughly-formed exposed concrete. A special concrete recipe and previously used formwork are responsible for holes and shrinkage cavities.
Kitchen worktops are often reinforced to protect them against damage during manufacture and transport or to ensure that when placed in their final position they can stretch for several metres or even protrude without support. Reinforced worktops are generally at least 6 cm thick. They require a substructure designed to accommodate their weight. When considering installing a concrete kitchen, a structural engineer must always be consulted with respect to the necessary structural requirements.

Concrete floors and floor coverings
In addition to concrete surfaces on walls and ceilings, there are also a number of options for creating floors or floor coverings with concrete. Besides cast varieties with a monolithic construction or the use of terrazzo, floors can be laid in the form of slabs and tiles.

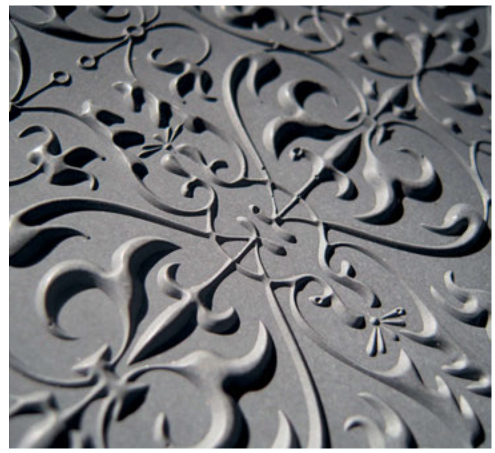
Concrete tiles and slabs
Concrete can also be used to create tiles and slabs, which are then used as decorative elements. The choice of decoration ranges from plain via pseudo-historical to modern, from graphically geometric to baroque and floral in relief (Fig. C 6.17). Concrete tiles are available in an almost unlimited variety of patterns, formats, surfaces and colours – both for interiors and for use on terraces and balconies. The tiles and slabs are very often reinforced with glass or plastic fibres, enabling them to be manufactured as thinly as possible, thus saving weight and making them easier to lay. Products with a material thickness of up to 12 mm are referred to as tiles, any thicker and they are known as slabs. Reference must be made to the respective manufacturer and installation guidelines when considering the different applications. A significant portion of these elements is custom-made according to the specifications of the client. The format sizes range from 5 × 5 cm to 125 × 200 cm.
Each concrete element exhibits typical characteristics. For instance, textures, pores, striations, cloudiness, colour variations, small shrinkage cracks and edge roughness with small ruptures may occur. These are all characteristic of the innovative material concrete and are therefore generally tolerated if not actually desired outright.
Some patterns and decorations follow historical examples and are suitable for use in listed buildings. Some manufacturers will also produce custom orders according to old templates. Different surfaces are available, ranging from oiled, waxed and polished to a concrete impregnation. Particularly expensive are tiles which are subsequently coated with gold or silver leaf, but a link with plants is also readily chosen as a theme (Fig. C 6.18).

Concrete floors – monolithic construction
Various manufactures supply floor systems suitable for a monolithic construction, i.e. for a floor consisting exclusively of concrete and with no coating. These concrete floors are usually ground several times or polished in up to seven grinding steps. The appearance of unground concrete surfaces is characterised by surface deposits of cement paste, which tend to disintegrate during use. In contrast, ground concrete surfaces are even suitable for industrial buildings with strict requirements regarding mechanical and chemical resilience. Today, private clients are also frequently seeking to use them in homes. The method used to compile and work the concrete defines its subsequent appearance. By using white cement or by adding coloured pigments, surfaces can be produced in all colours. As with classic terrazzo, the aggregate is of special significance with this floor system because after the final surface treatment, it has a significant influence on the appearance of the floor. In addition to industrial and private buildings, public institutions, such as museums, hospitals and exhibition halls, are also typical areas of application for concrete floors.

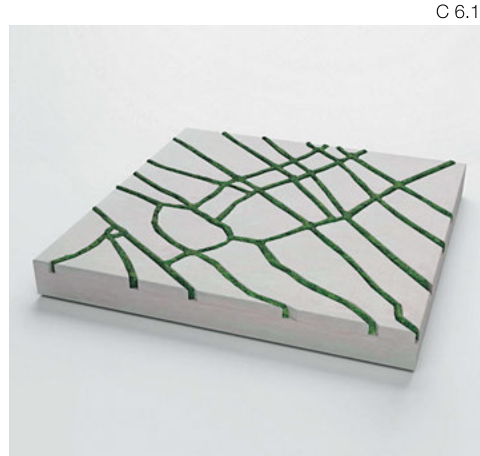
Terrazzo
Terrazzo describes a surface-finished floor covering, manufactured from a mixture of approximately equal amounts of white and coloured aggregates such as marble, porphyry, tuff and other types of stone as well as cement and water (Fig. C 6.19).
The first terrazzo floors were found in the villas of Ancient Rome. Centuries later, wealthy Venetian merchants enjoyed these ornate floors in their magnificent palazzos. The spreading of this decorative craft throughout Europe and America followed, beginning from Friuli in northern Italy, but not until the begin-

C 6.16

ning of the 19th century. Classic terrazzo is also called Pavimento alla Veneziana. Despite its popularity, it was superseded by other floor coverings due to reasons of time and cost. However, the reputation of this exclusive material and its design quality remained intact, and these floors have been experiencing a real renaissance in recent years, although only a few craftsmen still possess the art of its production today.
Terrazzo is created on site and fabricated according to DIN 18353 [3] in two layers, the base concrete and the visible facing layer. The latter must be at least 15 mm thick. The strength of the terrazzo flooring fabricated in a composite with the load-bearing substrate must correspond to the specifications of preliminary standard DIN V 18500 [4]. Laid as floating floors, terrazzo floorings must also fulfil the specifications for cement screeds as stipulated in DIN 18560-2 [5].
Using terrazzo floors offers a variety of artistic and creative opportunities. Individual colour creations can be produced by adding coloured aggregate. In addition to homogneous surfaces, patterns and borders of mosaic tiles can also be incorporated. For design reasons, larger areas can be subdivided with metal rails, e.g. made from brass, and then filled with different coloured terrazzo compounds. The cement mixture applied to the substrate surface can then be smoothed, tamped and rolled with heavy rollers. The most important stage is the rolling of the entire area in order to achieve the stability of the mass. This process presses the excess cement slurry onto the surface, where it is swept away and collected. After a drying time of approximately one week, and in accordance with DIN V 18500, the area is wet-ground, levelled, ground once again and polished in several stages until the maximum grain size is visible. The abrasive wear of terrazzo floors may not exceed the values specified in this preliminary standard. With rolled terrazzo, building joints are to be applied and field boundary joints are to be included with metal rails that can be sanded. The fields should be ≤ 4 m^2, but may also be planned larger with special measures.
A terrazzo floor is very durable, can be reground because of its thick wear layer and has proven to be very easy to maintain. Depending on the size of the area, several weeks may be required for its fabrication. If working temperatures are too low, the hardening process will be slowed down significantly; if the temperatures are too high and drying takes place very quickly, so-called shrinkage cracks may appear. In order to be able to work under controlled ambient conditions, terrazzo can also be prefabricated in a factory as flooring slabs and steps – known as factory terrazzo or cast stone. Cooperation with experienced terrazzo producers is to be recommended in each case.



C 6.17



C 6.18

C 6.19

C 6.13 Washbasin, Ravensburg Museum of Art (Germany) 2012, Lederer Ragnarsdóttir Oei Architekten
C 6.14 Bathroom in concrete, Presenhuber holiday home
C 6.15 Detail of a concrete shower tray, Villa Rocca, scale 1:10
C 6.16 Kitchen island manufactured from just 8 mm thick concrete, with special additives. The precise formwork for shaping and the costly surface treatment (grinding, polishing) are done by hand. The surface is then optionally waterproofed and oiled or sealed with polyurethane. Steininger Designers
C 6.17 Concrete tile with embossed floral relief
C 6.18 Concrete slabs for wall design with fine impressions, which, when laid together, form a geometry of small channels covered with moss. 2010, Ivanka Design, Kriszta Balázs
C 6.19 Aggregates for terrazzo

C 6.20

C 6.21

Concrete in town and country

When the southern Hungarian university town of Pécs was selected as European Capital of Culture in 2010, Ivanka Design created a new design for the public square in the centre of the town. An angular concrete bench was installed in the square. During the day, the bench has the character of a sculptural, monolithic object. By night, it is lit from within, the light escaping outwards through many fragmented glass strips. From a distance, it appears to shimmer, but the closer the observer comes to the bench, the clearer the pattern of small glass inlays becomes, like a luminous swarm of glow worms cast in the concrete. Transforming concrete into a material that people no longer associate with the brutalist and blotted grey of the Communist era in Hungary, but instead recognise its potential and aesthetics, was one of the motives of the designer (Fig. C 6.20).

Pedestrians in Halle an der Saale also stumble unexpectedly across an accessible floor installation that can be sat on. On the site of a demolished six-storey prefab building, the artist Dagmar Schmidt has faithfully followed the floor plan with chest-high surrounding walls, furnishing the interiors with small sculptures made from concrete: The former basement walls now form the exterior walls. The installation reveals an entire apartment complex, in the truest sense of the word, in the form of a normal storey with six apartment units.

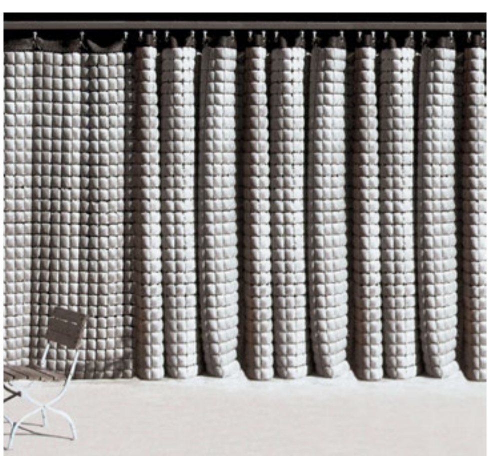
Sofas, chairs, bathrooms and kitchen units were standardised and cast in concrete. The sculpture broaches the issue of the shrinking prefabricated housing estate, incorporating the aesthetics of the surrounding prefabricated architecture and transforming them artistically. Firstly, it recalls a past building culture and, secondly, the style of living still current in many places, which is immortalised here. Too high a density of residents and the desire for more open spaces was probably the original reason for tearing down the prefabricated building. Where new buildings are usually enhanced with art, in this case, the art is a metaphor for the disappearance of buildings and towns (Fig. C 6.21).

The breaking up of rigid structures is also the theme of the designer group memux. When thinking of concrete, most people imagine rigid and solid structures. Instead, these designers dared to develop a moving curtain in concrete. Intended as a sun, wind and privacy screen for use indoors and outdoors or as a divider, the curtain has excellent sound-absorbing and heat-absorbent properties. The use of a geotextile as a flexible and UV-resistant carrier material gives the object characteristics that support free formability. The attraction of this design object is primarily in the unexpected. The form of the individual cushions and the flexibility make the curtain into a tactile and acoustic experience thanks to the creaking and scraping noises created by movement (Fig. C 6.22).

Research and teaching projects

Architects do not just require expertise with and knowledge of technical properties and design rules, but also the necessary sensitivity to work with concrete in an artistically meaningful and ambitious manner, especially since in recent years the presence of concrete as a means of design has passed from structural elements to interior architectural elements (Fig. C 6.23).

In this respect, in addition to developing designs, realising them as prototypes on a scale of 1:1 can help students to obtain a flair for concrete as a construction material. With this practical measure, working with formwork and reinforcement, as well as the construction process, is of importance, and in addition to the development of special forming designs, the surfaces in particular play a role. Instruction in this field offers a test area where the most diverse of materials can be combined. At Rosenheim University of Applied Sciences, for example, 20 students designed seating and reclining solutions for the Regional Garden Show in Rosenheim 2010 [6].



C 6.22

C 6.23

C 6.20 New design for town square featuring glass concrete bench, Pécs (Hungary) 2009, Ivanka Design
C 6.21 *"Grabungsstaedte"* floor installation, Halle a. d. Saale (Germany) 2005, Dagmar Schmidt; Sofas, chairs, baths and kitchen units cast in concrete broach the issue of the shrinking prefabricated housing estate and illustrate it artistically.
C 6.22 Concrete curtain, Andelsbuch (A) 2006, memux
C 6.23 *"Beton Minimal"* lounger in textile concrete, student project at the Faculty of Architecture at RWTH Aachen University (Germany) 2006; Manufactured using spraying process with alternate layers of 3 mm thick concrete and reinforcement inserted into the formwork.

C 6.24

C 6.25

C 6.26

Research projects frequently involve emphasising or overriding the characteristics of a material. Concrete is associated with many preconceptions, such as it is hard, artificial stone, lifeless, dull, etc., with which a visually soft concrete cushion plays. The combination with plastic (Fig. C 6.24), wood, steel, organic and inorganic materials also offers interesting possibilities here – the future knows virtually no bounds.
The type of formwork used offers further surface designs, with everyday materials such as plastic film or bubble wrap, old fabrics made from velvet, perforated hardboard and aluminium foil producing astonishing results (Figs. C 6.25 – C 6.27).

Concrete as a shaping material

Until it solidifies, not yet set plasticised concrete will take on almost any shape desired. Only the formwork of the concrete defines its shape. Consequently, construction using concrete is in stark contrast to modular and additive design principles such as construction using bricks.
Concrete has no predefined texture. Again, it is the composition of the components, the formwork, the selection of aggregates and the treatment of the surface that determine the appearance of the objects. The surface textures of concrete can achieve very different tactile and visible means of expression, which the designer is able to use specifically. The shaping allows for everything from very fine, smooth, shiny and matt surfaces to rough and course concrete where the fabrication process remains visible.

This issue of the variety and countless design options has occupied architects and designers for many years and they are always reinventing it, interpreting it and thinking about it in different ways.
Every time they do this, requirements are obviously made of the material and the material cooperates patiently – because there will be new themes and tasks to solve with concrete today and in the future. In this trusted but not completely comprehensible material, architects, engineers and designers always see a challenge in finding new solutions for construction and in design.
Designers are always being confronted with the task of finding answers to creative, social and cultural questions using the formable material concrete. As concrete has no geographical reference to a region, such as with the Norway spruce, Sollnhofen limestone or hand-made, peat-fired bricks from Wittmund, this leaves the designer free – as demonstrated by the building designed by Valerio Olgiati (Fig. C 6.1, p. 172) – to instil the concrete with this reference or even the spirit of a place.

Notes:

[1] DIN EN 12878: Pigments for the colouring of building materials based on cement and/or lime – Specifications and methods of test. 2006-05
[2] Cf. www.afgh.ch/index241.htm
[3] DIN 18353: German construction contract procedures (VOB) – Part C: General technical specifications in construction contracts (ATV) – Laying of floor screed work. 2012-09
[4] Preliminary standard DIN V 18500: Cast stones – Terminology, requirements, testing, inspection. 2006-12
[5] DIN 18560-2: Floor screeds in building constructions – Part 2: Floor screeds and heating floor screeds on insulation layers. 2009-09
[6] Director Prof. Ulrike Förschler, Rosenheim University of Applied Sciences, with support and technical consultation from Beton Marketing Süd, Munich, as well as from H. Egenter, Freiburg, and professional practical implementation by the cement works in Rohrdorf.

C 6.24 Circular plastic discs inserted in absorbent concrete let the concrete shine. *"45 × 45 – flach"* concrete slab, student project at the Faculty for Interior Design at Rosenheim University of Applied Sciences (Germany) 2007/2008
C 6.25 Velvet with historical pattern inserted in formwork, *"höher als breit"* concrete column, student project at the Faculty for Interior Design at Rosenheim University of Applied Sciences (Germany) 2010/2011, Magdalena Prankl
C 6.26 Bubble wrap inserted in formwork, *"höher als breit"* concrete column, student project at the Faculty for Interior Design at Rosenheim University of Applied Sciences (Germany) 2010/2011, Anne Hüttinger
C 6.27 Floral decoration made with plastic film inserted in formwork, *"höher als breit"* concrete column, student project at the Faculty for Interior Design at Rosenheim University of Applied Sciences (Germany) 2010/2011, Susann Lehman

C 6.27

House

Zurich, CH 2007

Architect:
Christian Kerez, Zurich
Assistants:
Jürg Keller (Project Manager), Andreas Skambas, Fumiko Takahama,
Dirk Massute, Ryuichi Inamochi
Structural planning:
Dr. Joseph Schwartz, Zug

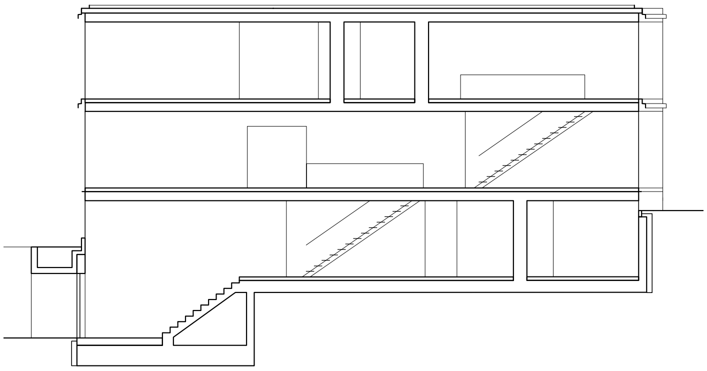
Site plan
Scale 1:2,000
Cross section •
Floor plan
Scale 1:250

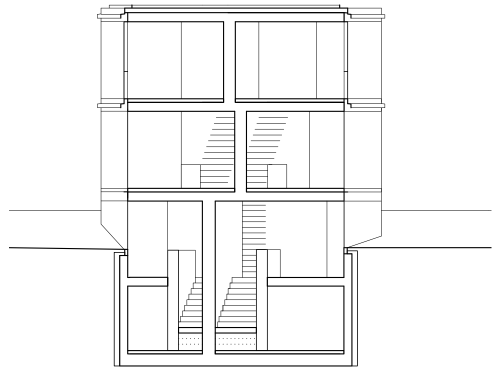
1 Entrance
2 Workspace
3 Living/dining areas
4 Bedrooms

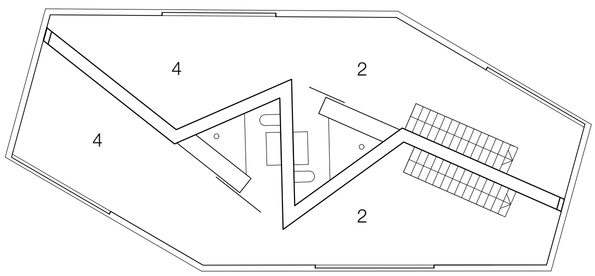
This two-family house was built on an exclusive sloping site on the south-eastern edge of Zurich. Despite the narrow site, both residences have a clear view of Lake Zurich because the building is divided lengthwise, with each unit extending over three floors. A "single-wall house" design concept has been consistently implemented here. A 40 centimeter thick, steel-reinforced concrete wall separates the two homes and supports the projecting ceilings. It runs in a different form through each of the three storeys, bending sharply in places. These bends brace the building, while their projections and recesses define its floor space. The bathrooms and their installation shaft, for example, are integrated into triangular niches in the wall, hidden behind sliding doors. The wall's varying course results in a differentiated and obverse layout of the two homes' interiors on three levels, connected by open, single-run steel stairs. Despite their restricted floor space, the homes are surprisingly spacious.

Since the wall and the floors and ceilings form the house's load-bearing and bracing structure, no facade supports were necessary. The aluminium frames of the glass facade were installed flush with the ground and the building's floor and ceiling slabs. Floor-to-ceiling glazed areas link the inside and outside space apparently seamlessly, giving residents the feeling of living on a sheltered terrace, separated from the environment only by an almost invisible glass shell. Every second glass element along the building's length can be completely opened. In spite of their size, 3.50 × 2.50 metres, the sliding doors are easy to move because they are pneumatically sealed using a special system, so they do not require a lifting device or additional sealing, which would make it harder to open the doors.

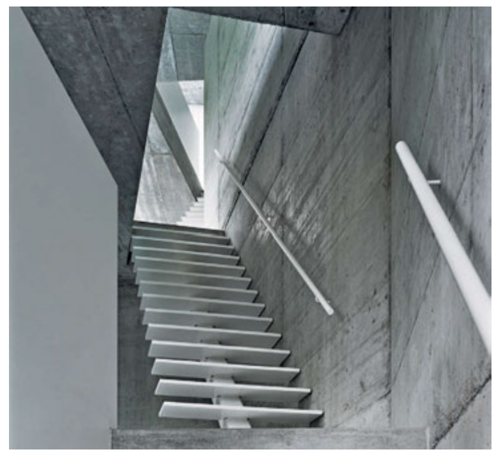
As well as the exposed concrete surfaces of the floors, ceilings and walls, the floors are also covered with a 1 centimetre thick layer of impregnated hard aggregate screed throughout. This deliberate reduction to just a few elements and materials is also reflected in the facade's design. Narrow horizontal aluminium bands, carefully finished and profiled, frame the glass elements, cladding the floor and ceiling slabs and roller blind casings.

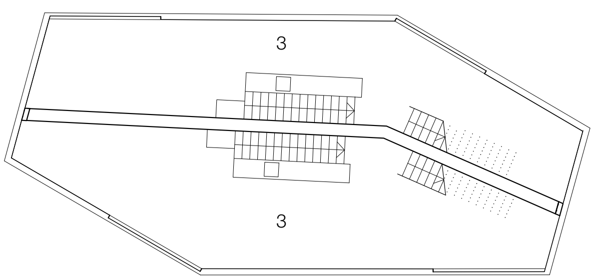

aa


bb

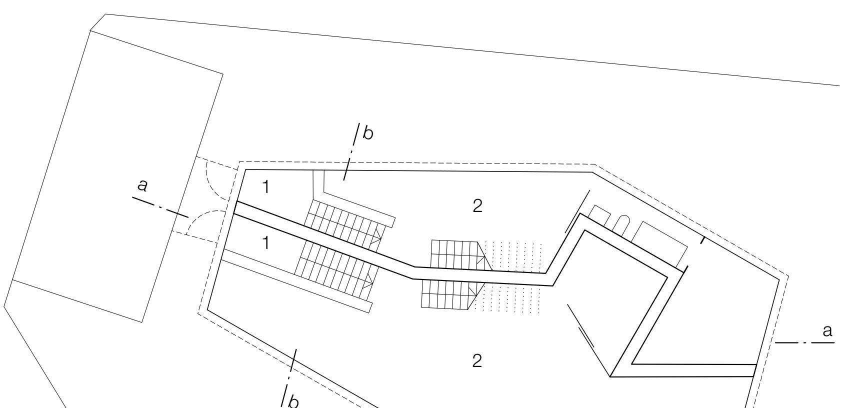


1st floor

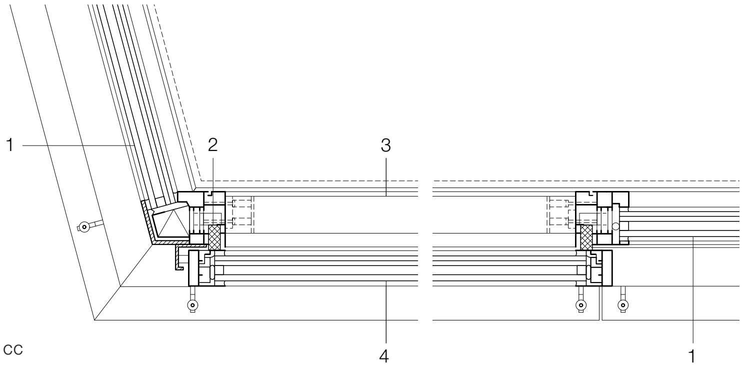


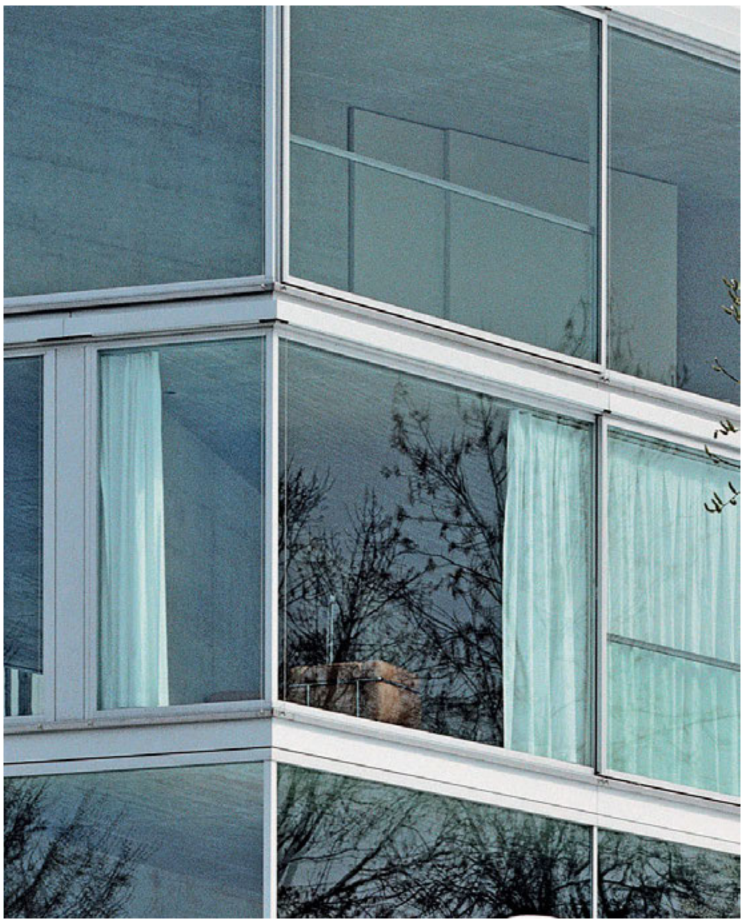


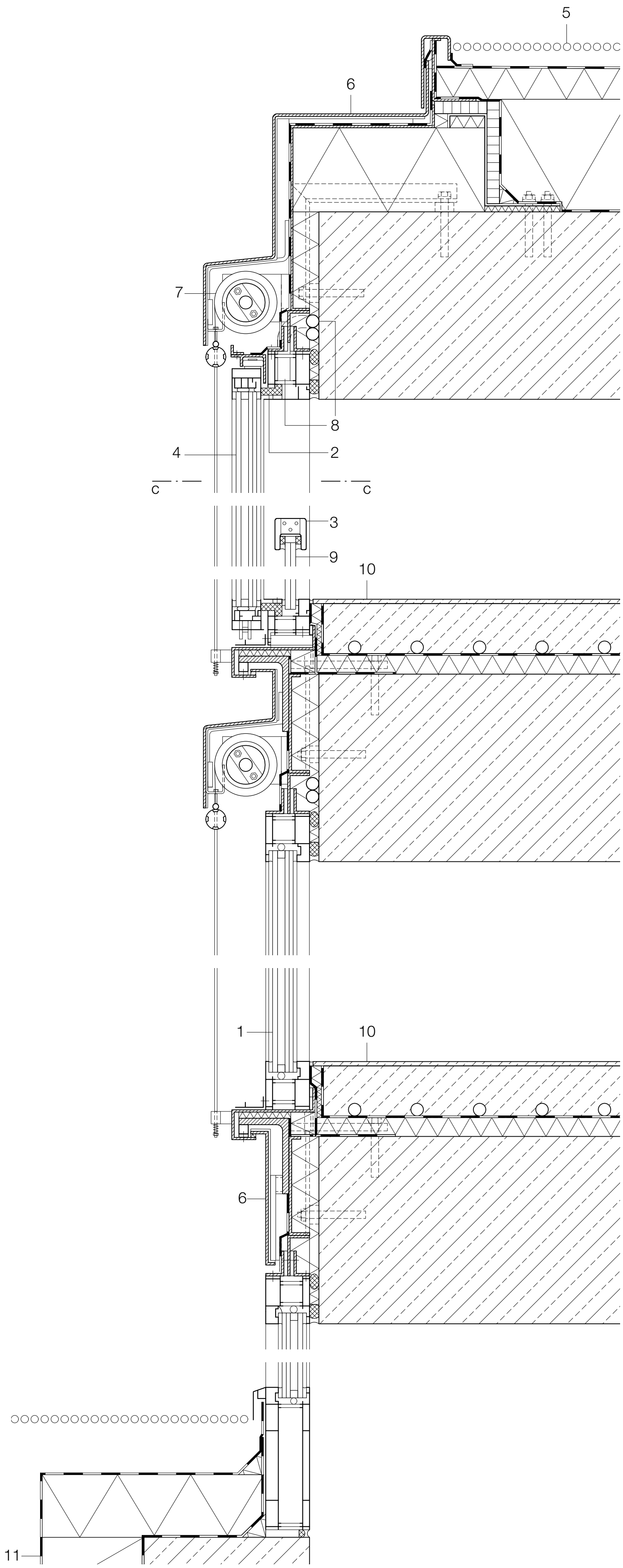
Ground floor



Basement







Horizontal cross section • vertical cross section
Scale 1:10

1 Fixed insul. glass, float glass 8 mm + between panes 12 mm + laminated glass 13 mm, U = 1.1 W/m²K, element size, 3597/2534 mm, in alum. frames
2 Circumferential pneumatic frame sealing
3 Stainless steel profile, burnished 50/50/2 mm
4 Sliding element, insul. glass, float glass, 8 mm + between panes 12 mm + laminated glass 13 mm, U = 1.1 W/m²K, element size, 3551/2528 mm in alum. frames, rail-mounted on roller bearings
5 Gravel fill, 30–40 mm
Fleece
Sealing, bitumen sheeting, two-ply
Insulation XPS, sloping
Insulation XPS 160 mm
Vapour barrier
Reinforced concrete 300 mm
6 Alum. sheeting 4 mm
7 Solar protection roller blind, synthetic fibre
8 Air supply to pneumatic frame sealing
9 Parapet, laminated glass 2× 8 mm
10 Hard aggregate screed, impregnated 10 mm, load distributing slab, hard aggregate screed with floor heating 70 mm
Separating layer, PE foil
Sound insulation, 30 mm
Reinforced concrete 300 mm
11 Sealing, bitumen sheeting
Insulation XPS 160 mm
Vapour barrier
Reinforced concrete 265 mm

Residential complex

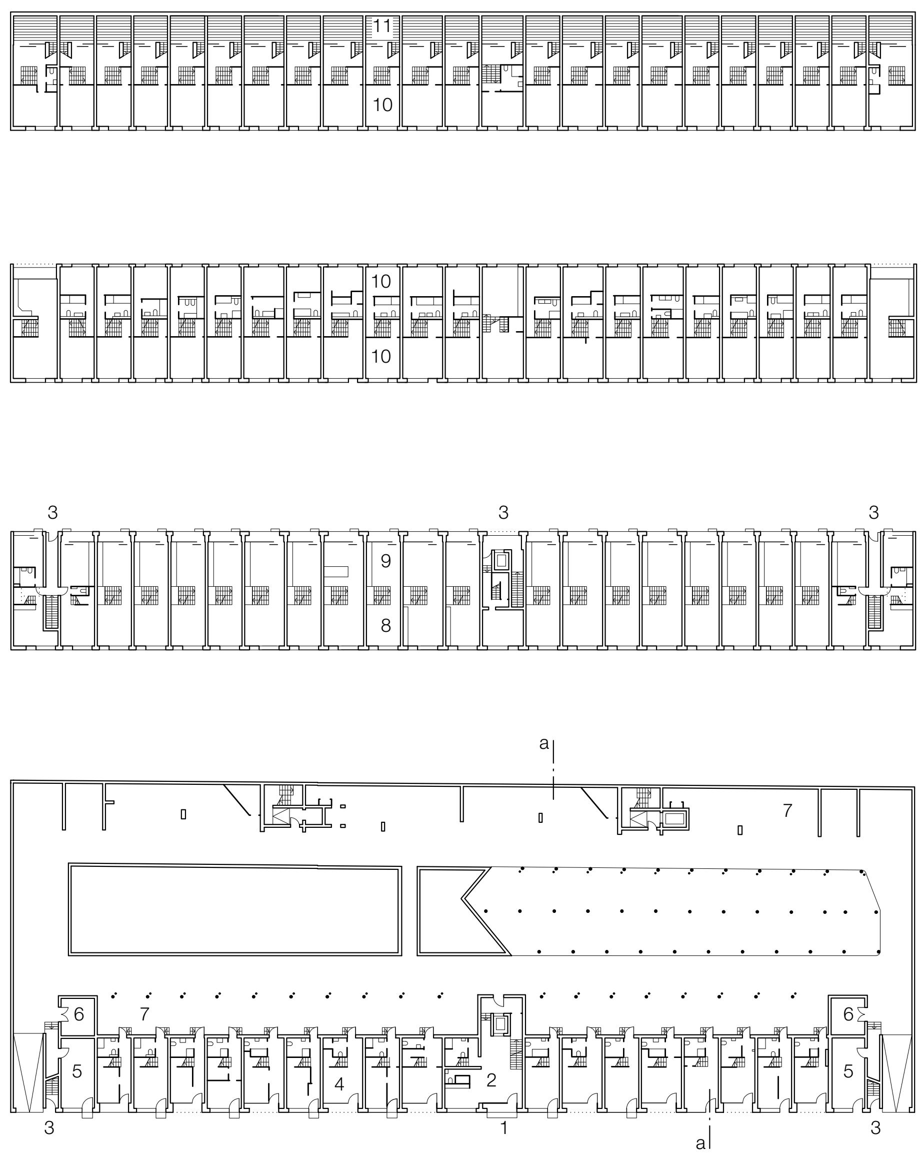
Berlin, D 2010

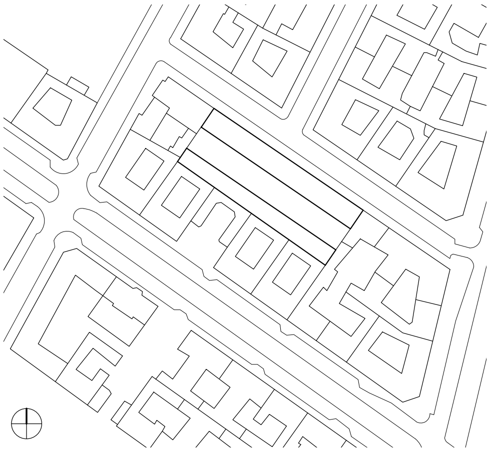
Architects:
zanderroth architekten, Berlin
Sascha Zander, Christian Roth
Assistants:
Kirka Fietzek, Diana Gunkel, Guido Neubeck, Konrad Scholz, Lutz Tinius
Structural planning:
Andreas Leipold, Berlin

Joint venture building groups are an increasingly popular way of creating affordable and individual housing in cities. This project's site, 100 × 34 metres in size with a 22 metre high firewall to the south-west and set in the midst of the closed perimeter block structure typical of Prenzlauer Berg in Berlin, posed planners with a challenge. Zanderroth Architekten responded to this inauspicious starting situation with two oblong blocks of different heights parallel to the street, separated by a 13 metre deep courtyard extending over the entire length of the site. Depending on their position in the building, the individual apartments are divided into three different types. 23 "townhouses" with commercial space at the entrance level are accessed directly from the street. The four storeys are planned as an open split-level with small private roof gardens on top. On the street side, the building presents a severe urban facade of grey sandblasted precast concrete elements, large areas of glass and larch wood openings.
The two plaster and aluminium shingle facades facing the shared inner courtyard are more austere and heterogeneous. The courtyard is set a storey higher than the front street level to let more sun in and to mitigate what might otherwise be a canyon-like space. The parking spaces are below it. There are three entrances from the street to courtyard, through which the entrances to the rear building are accessed. The rear building's lower three storeys house 10 "garden apartments", also split-level, with very high-ceilinged interiors to compensate for any lack of light. Above them, 12 three-storey "penthouses" are accessed through an internal corridor on the fifth floor. In front of the private spaces on the fourth floor, a walkway, open to the courtyard, serves as an emergency exit. Small gardens along the firewall and a roof terrace offer residents private outdoor areas here. Its complicated vertical organisation enables the complex to achieve a floor space density ratio of 2.74. Here, density is not only a characteristic of urban life, but also the result of planning focussed on cost effectiveness and efficiency.

Floor plan ground floor – 3rd floor
Front house
Scale 1:800

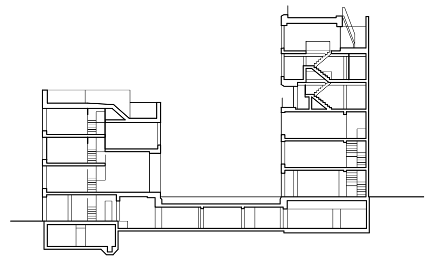
1 Entry, front house
2 Lobby
3 Stairs to the courtyard
4 Commercial space / entry to the apartments
5 Bike room
6 Garbage room
7 Garage
8 Living area
9 Dining / kitchen space, with outdoor seating area
10 Room
11 Patio with stairs to the terrace

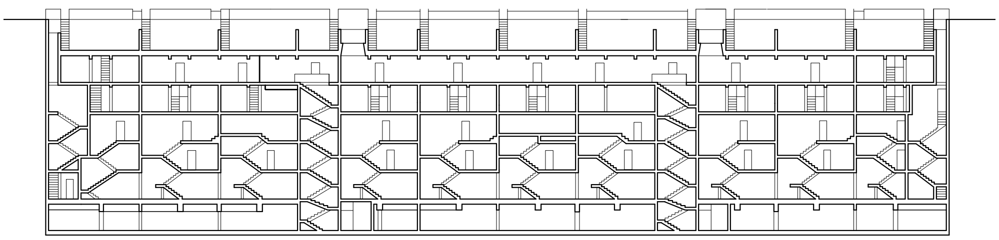




Site plan
Scale 1:4,000

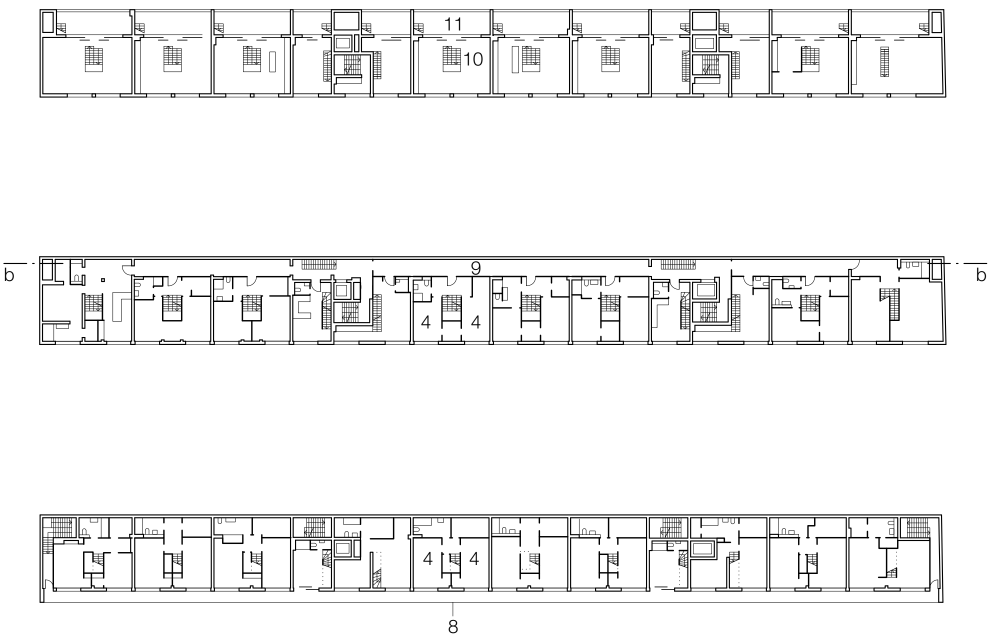
Cross section
Floor plan, rear building
Scale 1:800





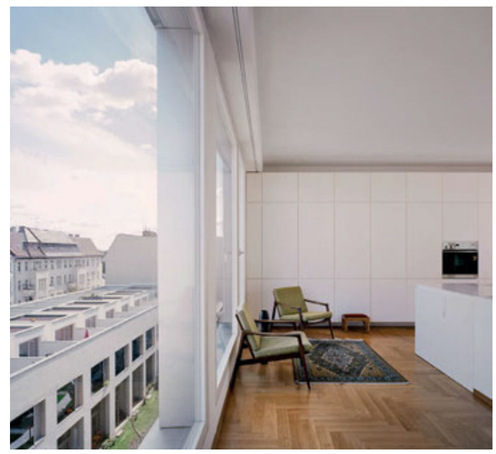
bb

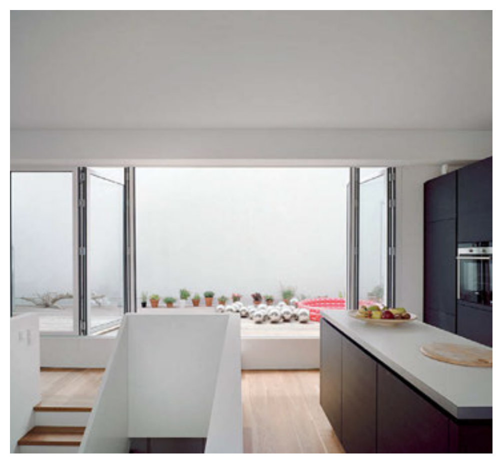
1 Entry to the “penthouses”
2 Lobby
3 Dining/kitchen area
4 Room
5 Air space
6 Living area
7 Guest apartment
8 Corridor (emergency exit)
9 Access corridor
10 Living/dining area
11 Patio with stairs to the terrace



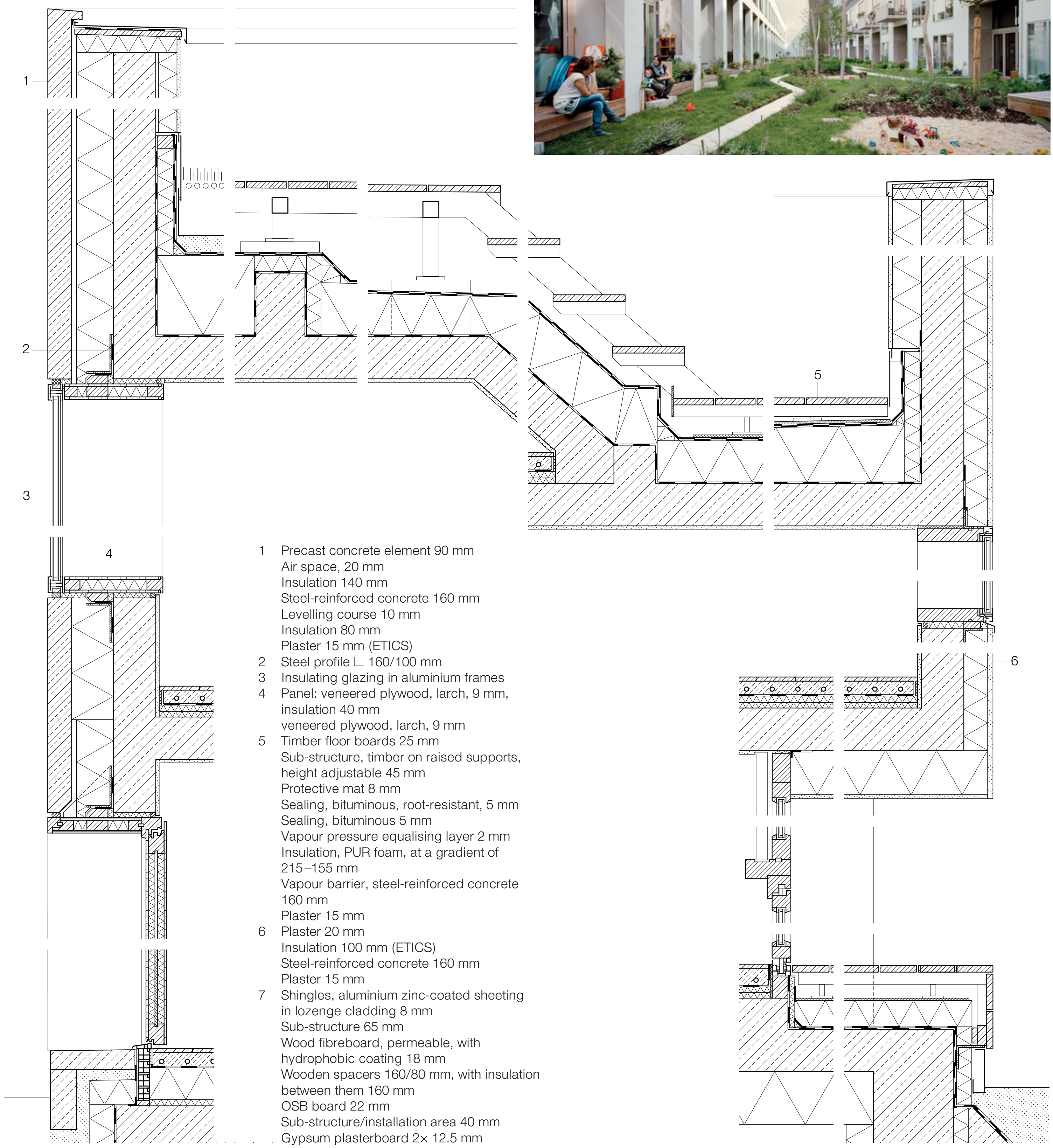
4th – 6th floor “penthouses”

1st – 3rd floor “garden apartments”

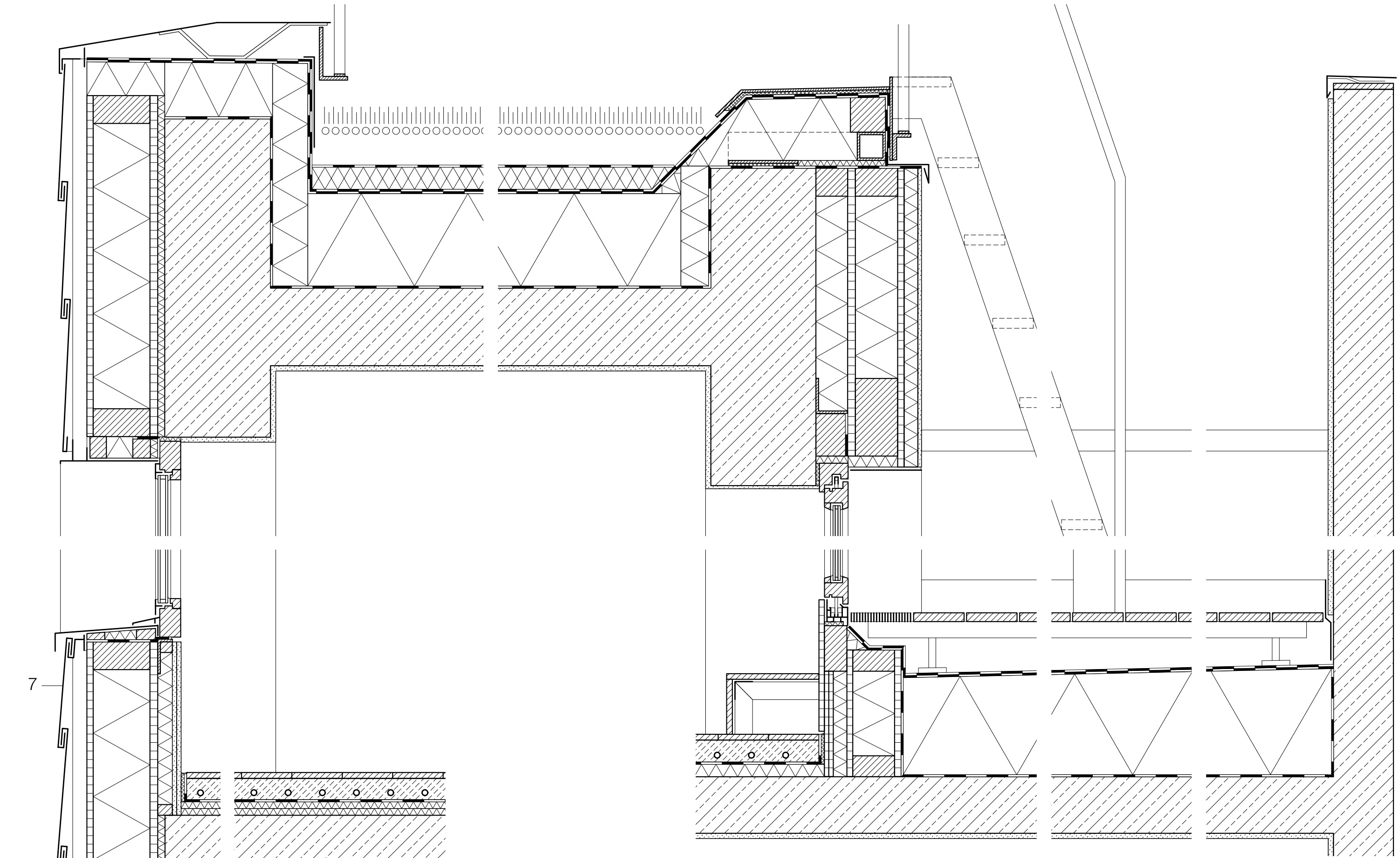


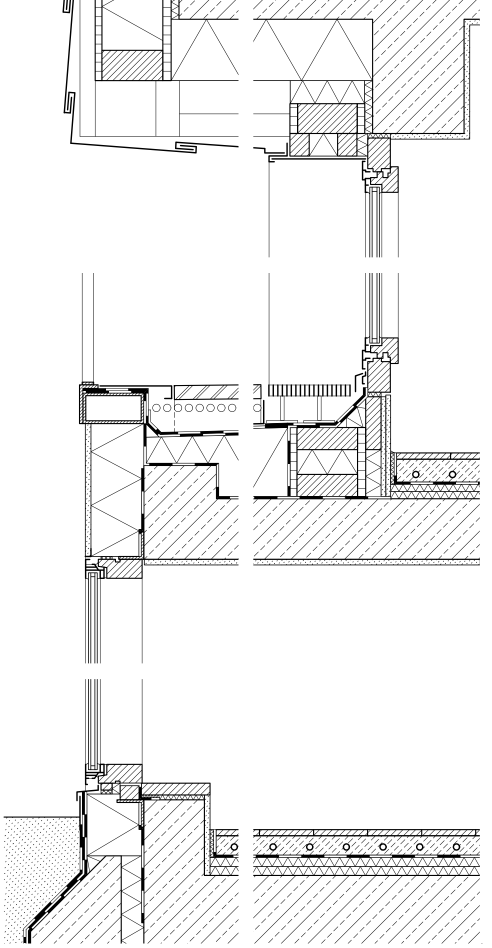


Vertical cross section
Front building • rear building
Scale 1:20



1 Precast concrete element 90 mm
Air space, 20 mm
Insulation 140 mm
Steel-reinforced concrete 160 mm
Levelling course 10 mm
Insulation 80 mm
Plaster 15 mm (ETICS)
2 Steel profile ∟ 160/100 mm
3 Insulating glazing in aluminium frames
4 Panel: veneered plywood, larch, 9 mm,
insulation 40 mm
veneered plywood, larch, 9 mm
5 Timber floor boards 25 mm
Sub-structure, timber on raised supports, height adjustable 45 mm
Protective mat 8 mm
Sealing, bituminous, root-resistant, 5 mm
Sealing, bituminous 5 mm
Vapour pressure equalising layer 2 mm
Insulation, PUR foam, at a gradient of 215–155 mm
Vapour barrier, steel-reinforced concrete 160 mm
Plaster 15 mm
6 Plaster 20 mm
Insulation 100 mm (ETICS)
Steel-reinforced concrete 160 mm
Plaster 15 mm
7 Shingles, aluminium zinc-coated sheeting in lozenge cladding 8 mm
Sub-structure 65 mm
Wood fibreboard, permeable, with hydrophobic coating 18 mm
Wooden spacers 160/80 mm, with insulation between them 160 mm
OSB board 22 mm
Sub-structure/installation area 40 mm
Gypsum plasterboard 2× 12.5 mm


7



Villa extension

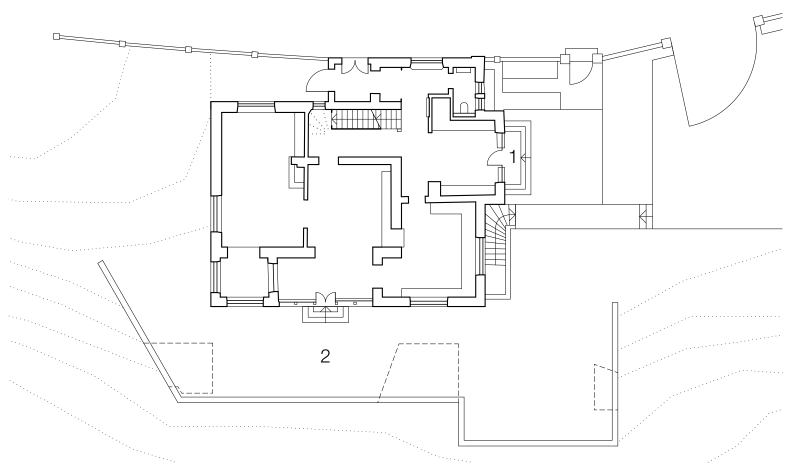
Gauting, D 2010

Architects:
Unterlandstättner Architekten, Munich
Thomas Unterlandstättner
Assistants:
Meike Kübel, Anke Göckelmann
Enrico Schreck, Telemach Rieff, Susanne Forner
Structural planning:
Statoplan, Munich

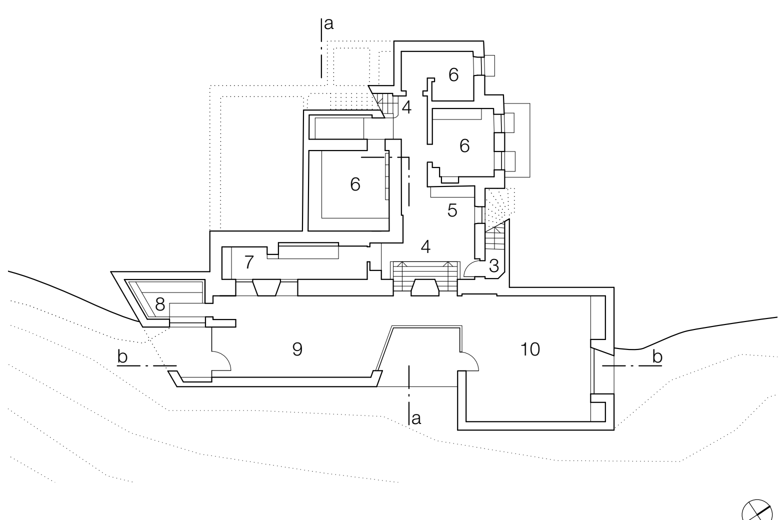
In 1890, a villa was built on a sloping, park-like site near the town centre of Gauting near Munich. Over a century later and despite several alterations, the original basic structure of this listed historic house was largely intact, but in bad condition. During a careful renovation, its original character was renewed, the facade restored in compliance with historic buildings regulations, and its spatial structure was returned to its original condition. An extension was built in place of the dilapidated load-bearing wall supporting the terrace. Soil between the new supporting wall and the existing cellar wall was removed, and the space created was used to build a guest apartment. The new structural elements show a clear and restrained design, inside and out, featuring a simple, light metal porch over the main entrance, a cube-shaped garage clad with panels, and the new extension at garden level, which forms a link between the landscape and the villa's base. The building regulatory authority specified, however, that the extension should not stand out as an additional structural element, so as not to detract from the historic villa's appearance. For this reason, the architects designed the new wall, which is also the extension's facade, to look like a "rock face". The 23 centimetre thick exposed concrete wall, with its coarse-grained bush-hammered surface, was treated manually with jackhammers, obscuring the formwork joints and facade anchors and giving it a monolithic look. Because the surface did not need a protective coating, its natural look and feel blends smoothly into the surrounding landscape.
Three cavernous recesses with floor-to-ceiling glazing let light into the extension's 120 m² of living space, while the interplay between inside and outside lends the elongated apartment's interior its spatial variety. Broad stairs in an aperture in the cellar wall lead into the redesigned entry area of the guest apartment. The homogenous matt white colouring consolidates new and old elements and enables the built-in furniture to merge with the building's overall floor plan.

Floor plan
Cross section
Scale 1:400

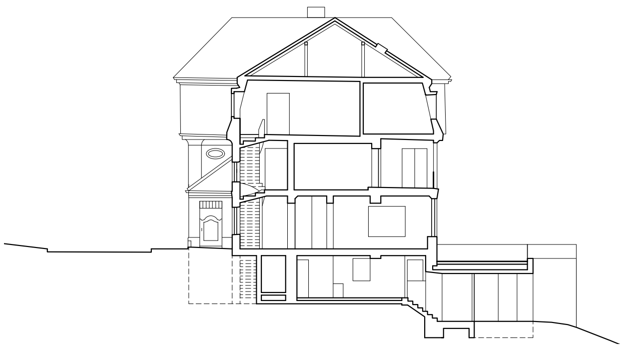
1 Entrance
2 Terrace
3 Entrance to guest apartment
4 Internal access, connecting stairs
5 Kitchen
6 Cellar (existing building)
7 Bathroom
8 Sauna
9 Living area
10 Sleeping area



Ground floor

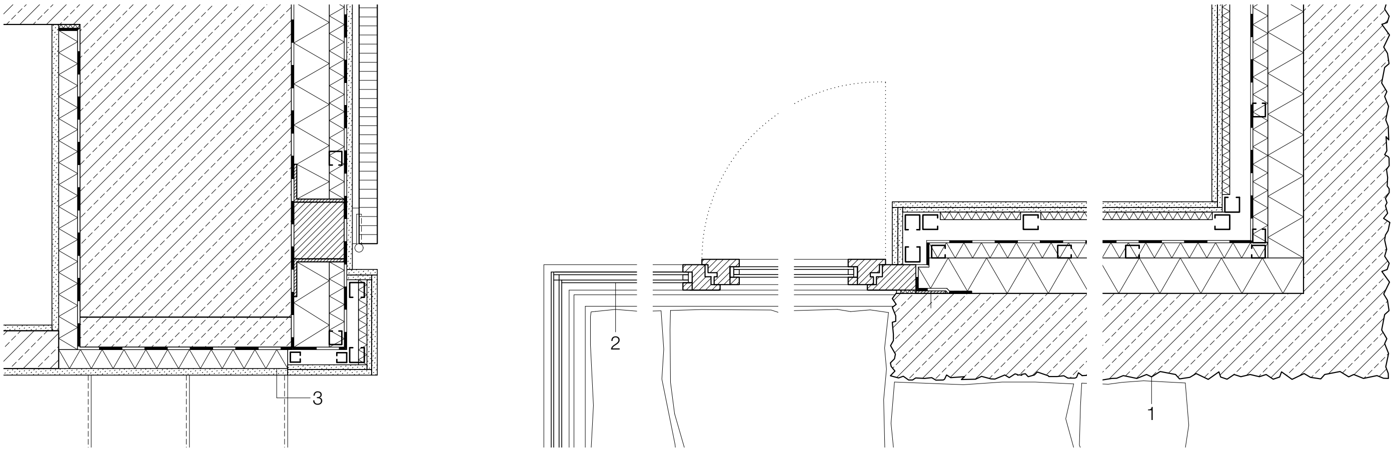


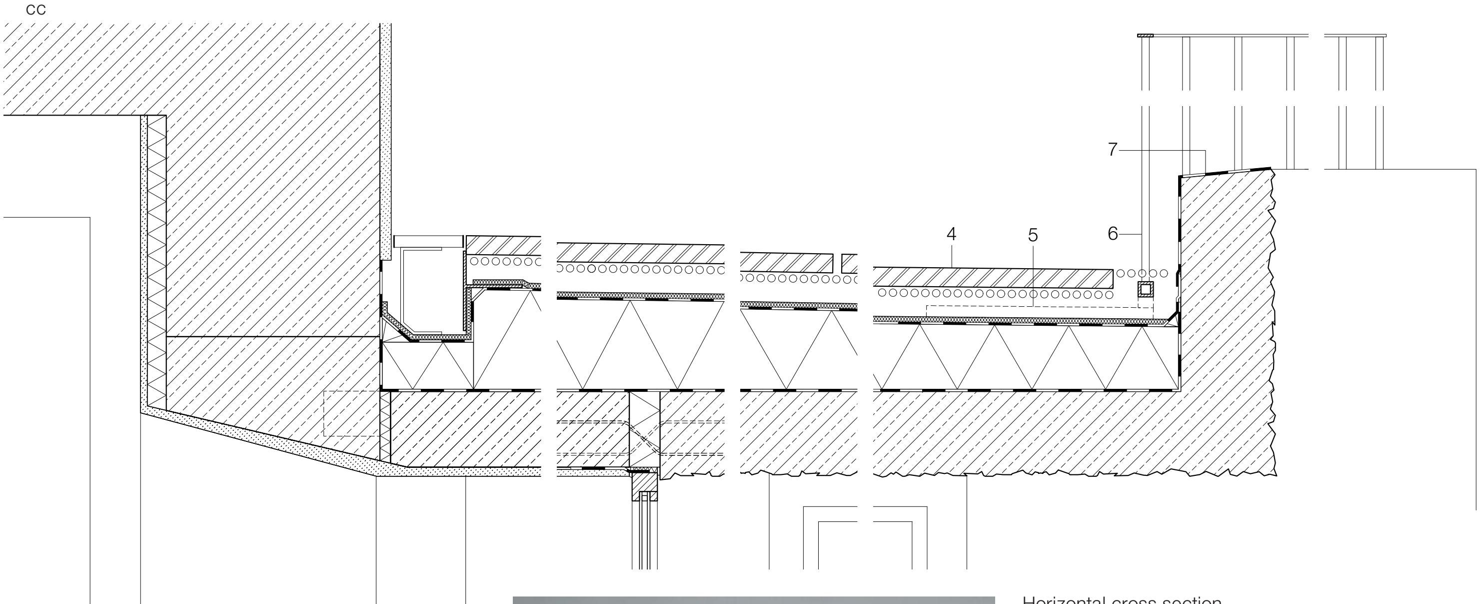
First floor

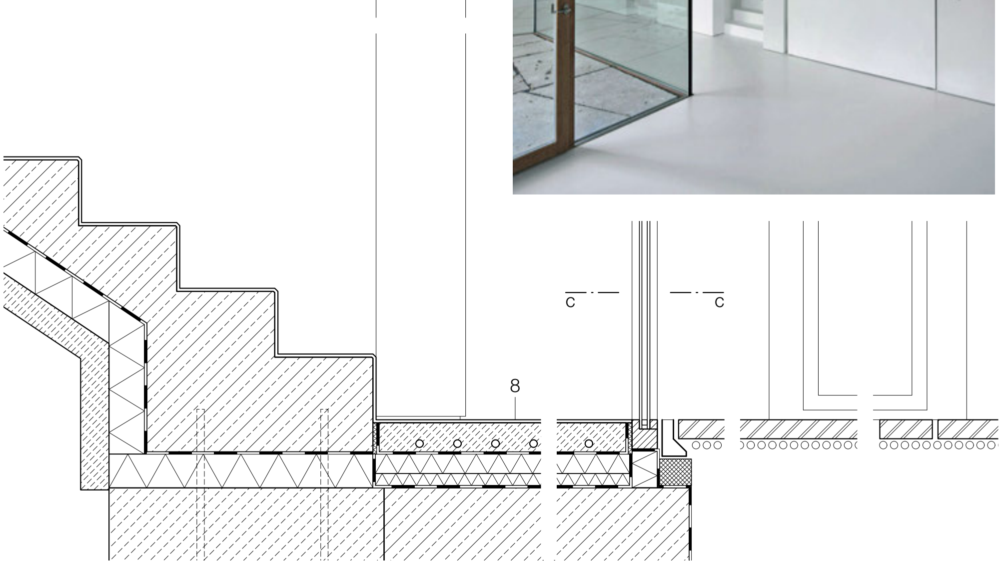


aa

bb







Horizontal cross section
Vertical cross section
Scale 1:20

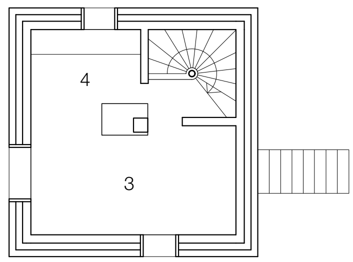
1 Steel-reinforced concrete surface, bush-hammered 230 mm, insulation, mineral wool 140 mm
Vapour barrier
Installation space, 55 mm
Partition wall felt 20 mm
Gypsum plasterboard 12.5 + 15 mm
2 Insulating glazing
safety glass 6 mm + between panes 16 mm + safety glass 6 mm
in oak frames, oiled, natural colour
3 Insulation, foamed glass, plastered 50 mm
4 Wachenzell dolomite 50 mm
Gravel fill 80–140 mm
Stone chip drainage layer,
Bituminous sealing, two-ply
Sloping insulation, bituminous vapour barrier
Steel-reinforced concrete, bush-hammered, 230 mm
5 Anchor plate for the balustrades, steel plate 600/750/30 mm
6 Balustrades, steel tubing Ø 20 mm
7 Sealing, liquid plastic with interspersion, coloured and bush-hammered steel-reinforced concrete surface
8 PU coating, white 5 mm
Heating screed 65 mm
Insulation 50 mm
Polystyrene lightweight concrete fill 30 mm
Sealing, bitumen sheeting
Steel-reinforced concrete 200 mm

Alpine hut in the Laternser Valley

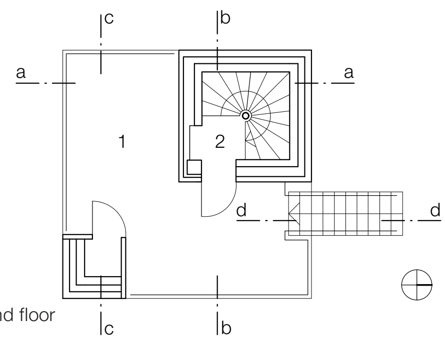
Laterns, A 2011

Architects:
Marte.Marte Architekten, Weiler
Bernhard Marte, Stefan Marte
Assistants:
Clemens Metzler
Structural planning:
Frick Paul, Rankweil

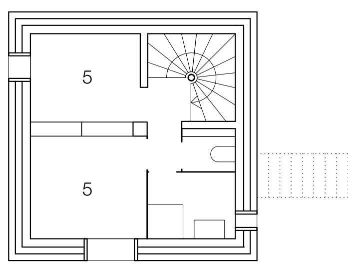
At the edge of a forest in an alpine valley in Austria's Vorarlberg region, a small four-storey tower with a square base rises out of a steeply falling slope. Apart from the access road, the slope was left unchanged and the site kept in its original condition. The building's homogenous material, carefully bush-hammered concrete, marks it out from the surrounding green of the meadows and white of snow. Square windows of various sizes are distributed across the four wall surfaces and sit deep in the double-walled concrete shell, almost as if stamped out of it. On the entry level, which is accessed from outdoor steps, the building's volume is cut back to two load-bearing corner elements, creating an outside area offering views and vistas that is protected from the weather. A spiral staircase connects the upper living area with the two more private levels below. Inside, the window openings with their wide, projecting solid oak frames look like landscape paintings, focusing the gaze on the mountainous massif, gentle slopes and dense forest. The floors, stairs, doors, fixtures and fittings, and furniture made of untreated oak form a warm contrast to the rough exposed concrete surfaces.
The building's inner shell was the first part concreted. Smooth plywood shuttering panels were used, giving the interior's exposed concrete surfaces their velvety look. After the installation of high-strength cavity wall insulation and fibre-reinforced cement spacer sleeves, the outer shell was concreted using the inner shell's existing anchor holes, which were subsequently closed with cement plugs. Profile strips were laid in the formwork to keep the building's edges sharp after bush hammering. Bush hammering with a jackhammer gave the concrete walls their surface structure in patterns up to 3 cm deep. All the connecting surfaces of the embrasures and windows were also ridged with a flat cold chisel. The exterior walls were sprayed with a hydrophobic coating to protect them from damp.



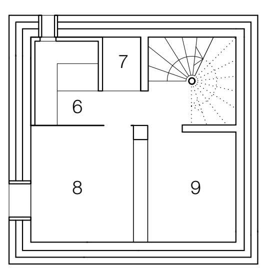
1st floor



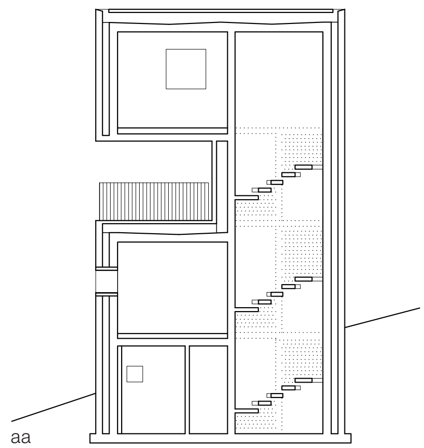
Ground floor



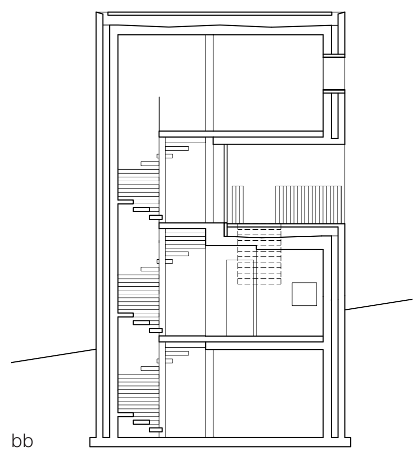
1st basement level



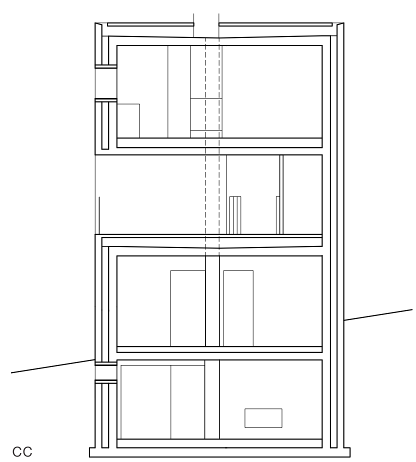
2nd basement level



aa



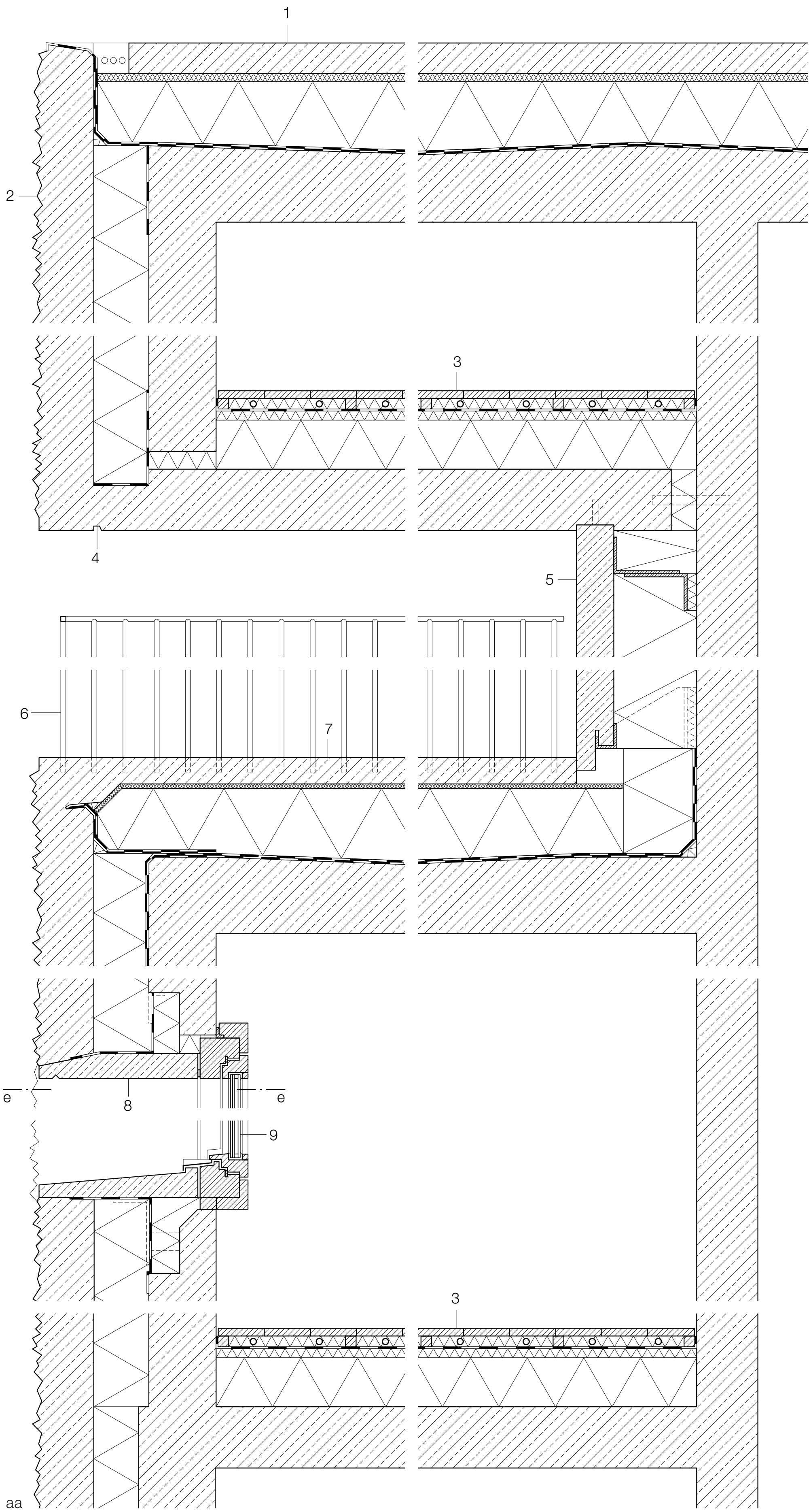
bb



cc

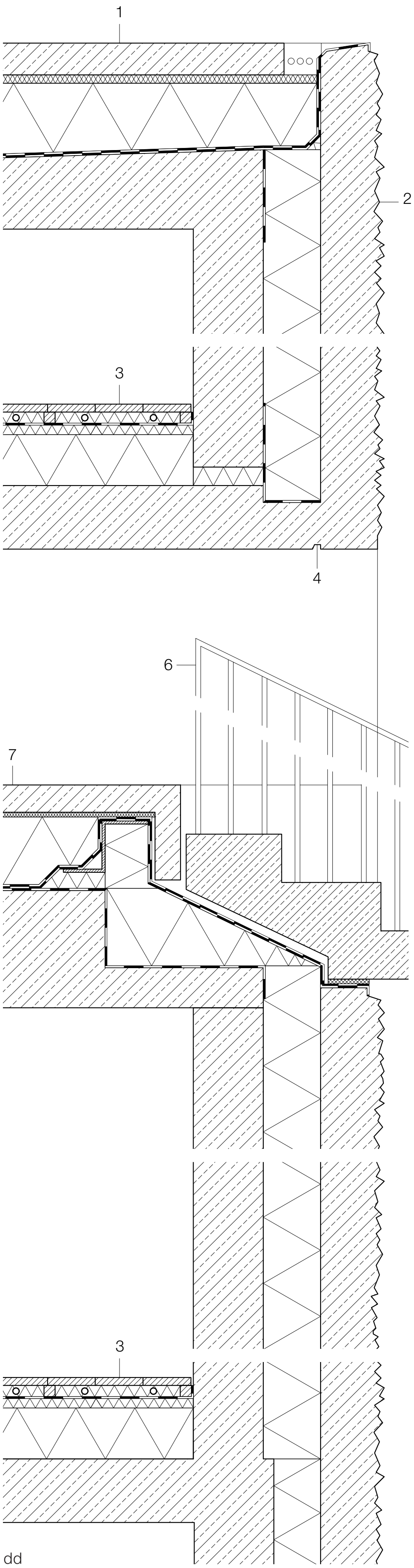
Floor plan
Cross section
Scale 1:200

1 Terrace
2 Entrance
3 Living area
4 Kitchen
5 Bedroom
6 Sauna
7 Shower
8 Cellar
9 Storeroom/technical equipment

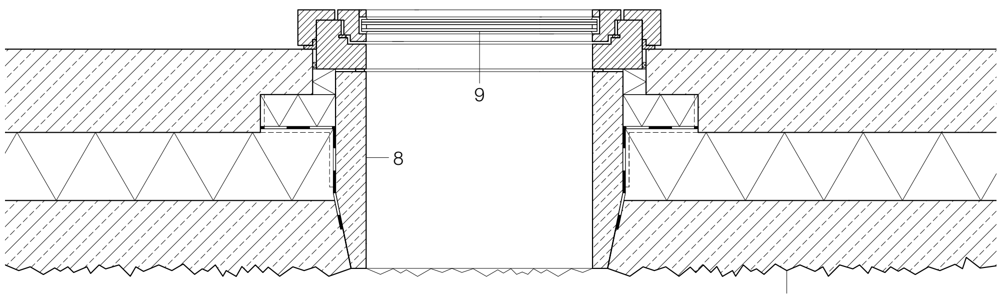


Vertical cross section
Horizontal cross section
Scale 1:20

1 Roof structure:
Reinforced concrete 80–130 mm
Drainage/protection/storage mat, 25 mm
Insulation, XPS, high-strength, 200 mm
Sealing, bitumen, two-ply,
bitumen base coat
Reinforced concrete w/ 200–250 mm gradient
2 Wall structure:
Shell, reinforced concrete, bush-hammered,
w/ hydrophobic coating, 180–200 mm
Core insulation, XPS 180 mm
Reinforced concrete 220 mm
3 Floor structure:
Wooden boards, oak 25 mm
Counter battens, w/ insul. elements between,
EP foam, incl. floor heating 35 mm
Vapour barrier, polyethylene 0.4 mm
Sound insulation, EP foam 30 mm
Insulation, PU foam 160 mm
Reinforced concrete 200 mm
4 Drip nose 25/15 mm
5 Precast reinforced concrete element 120 mm
Insulation 270 mm
Reinforced concrete 220 mm
6 Balustrade, round steel ∅ 16 mm
7 Floor structure, terrace:
Reinforced concrete 80–130 mm
Drainage/protection/storage mat 15 mm
Insulation, XPS high-strength 200 mm
Sealing, bitumen, two ply
Reinforced concrete w/ 250 mm gradient
8 Precast reinforced concrete element 80 mm
9 Triple-glazed insul. glazing, wooden frames



dd



ee

Unauthenticated
Download Date | 3/25/16 9:34 AM

Residential and commercial building

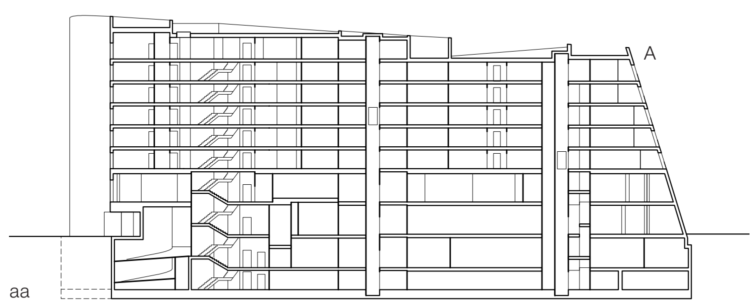
Basel, CH 2010

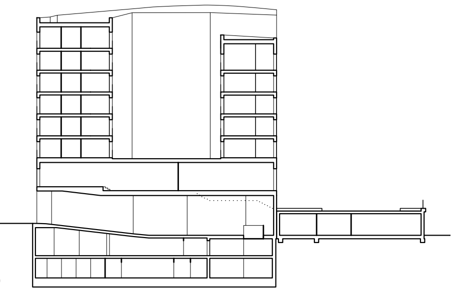
Architects:
Buchner Bründler Architekten, Basel
Daniel Buchner, Andreas Bründler
Project Managers:
Nicole Johann, David Merz, Lukas Baumann
Project Manager, tram stop, kiosks:
Jonas Staehelin
Structural planning:
INGE Beurret + Schmidt, Basel

Site plan Scale 1:5000
Cross section • Floor plans
Scale 1:1000

1 St. Johann station
2 Tram stop
3 Vogesenplatz
4 Voltastrasse
5 Luzernerring
6 Retail space
7 Bank
8 Storeroom
9 Café
10 Access to underground car park
11 Apartment 2.5 rooms
12 Apartment 3.5 rooms
13 Apartment 4.5 rooms
14 Restaurant
15 Office
16 Staffroom

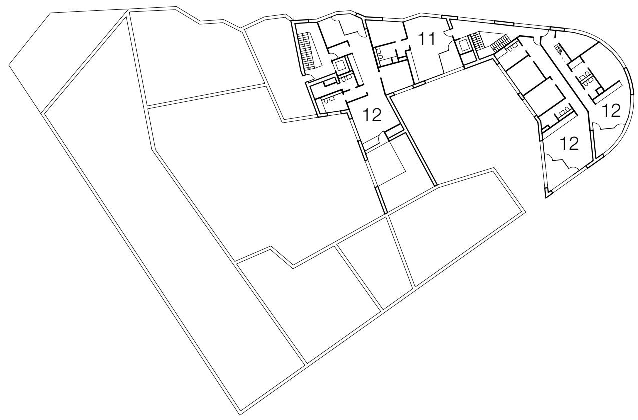
The sculpturally-formed, exposed concrete Volta Centre building is at the heart of the redevelopment of the Äußeres St. Johann district in Basel's north. Its triangular floor plan makes maximum use of the site, while each of its surprisingly different facades reacts to the urban environment it faces, giving the building a very varied appearance.
A striking sharp-edged facade rises to face the railway station and new local railway (S-Bahn) stop. Its undercut ground floor and encircling glass storefront are like an inviting gesture. The sloping gable end on the square's north side lends the building a dynamic look from various perspectives. To the north, a sculptural folded facade signals a transition to the residential area. Here, there are more shops and access to the apartments. The building's rounded tip at the intersection to the northeast corresponds with the form of the adjacent building, although its consistent surface clearly distinguishes it from its neighbour's materiality.
All the exterior walls consist of 40 centimetre thick insulating concrete built with standard formwork and are painted white on the outside, creating an attractive optical effect while minimising their moisture absorption. The structure complies with the heat insulation regulations in force when it was planned, although today's stricter energy consumption standards would require thicker walls or additional insulation. All the anchor points were filled with injection mortar, integrated into anchor bars, or concreted in as inserts.
This building's powerful appearance derives in particular from the use of exposed concrete throughout, with its larger sculptural form subordinate to the overall detailing. The upper edges of the fascia were built without any metal sheeting. All the floor to ceiling windows have dark-coated steel frames and are flush with the facade. Depending on their orientation, the apartment windows and loggias have sound insulating glazing or glass parapets, also flush with the facade.



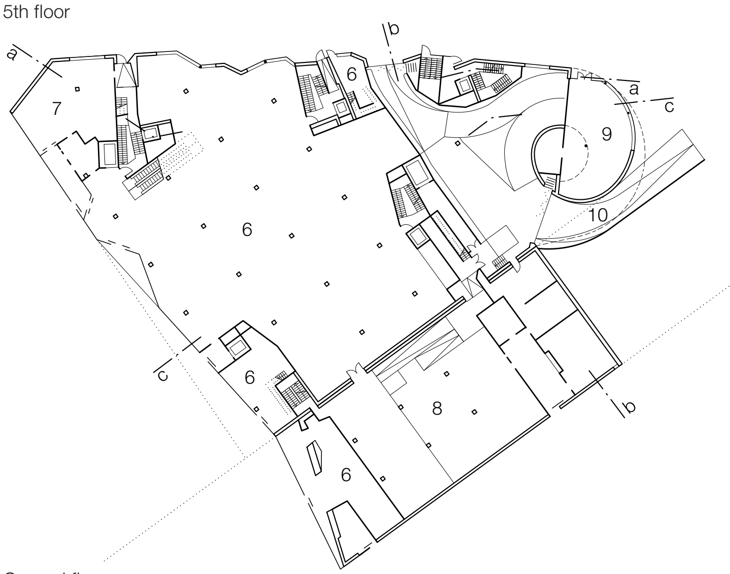


bb

5th floor

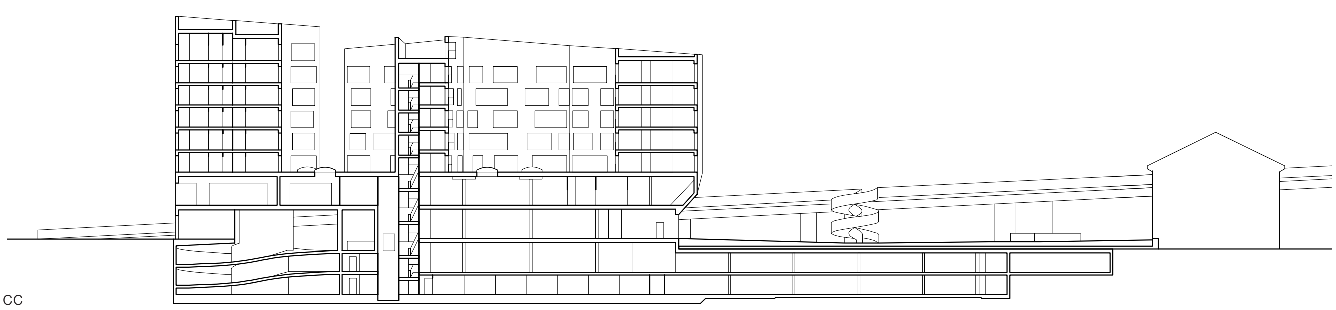


7th floor

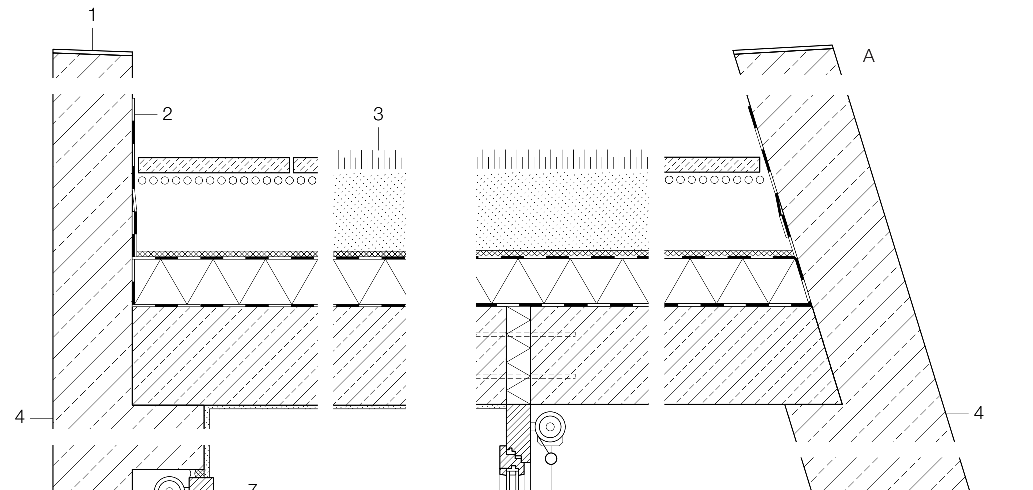


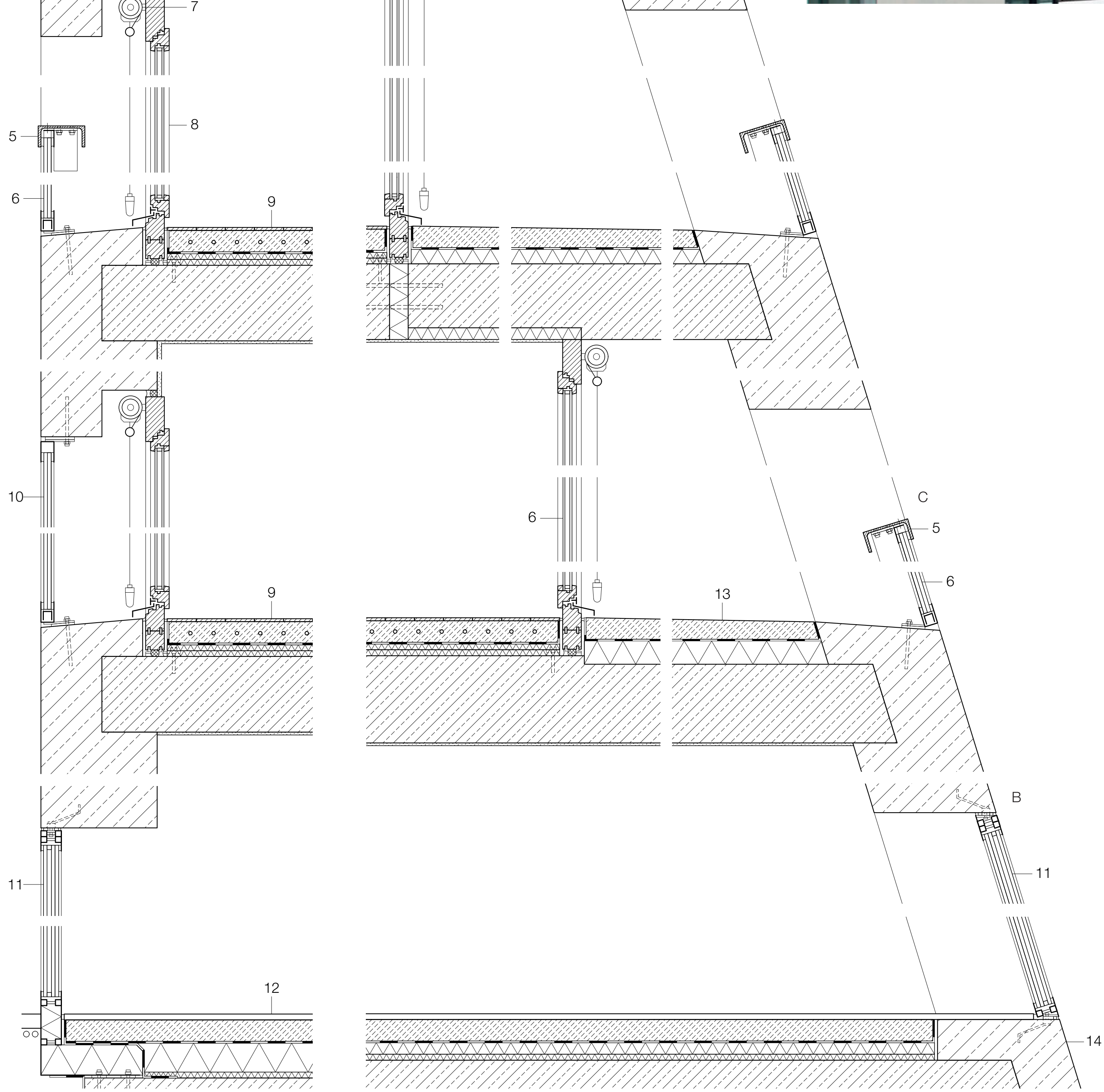
Ground floor

1st floor



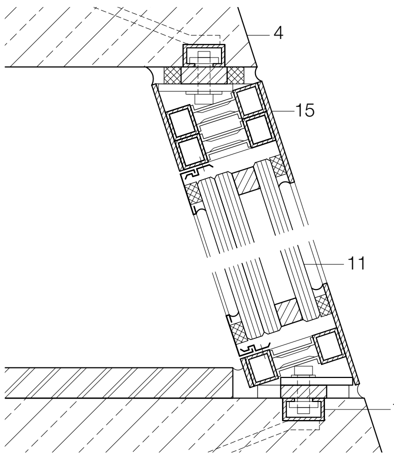
cc



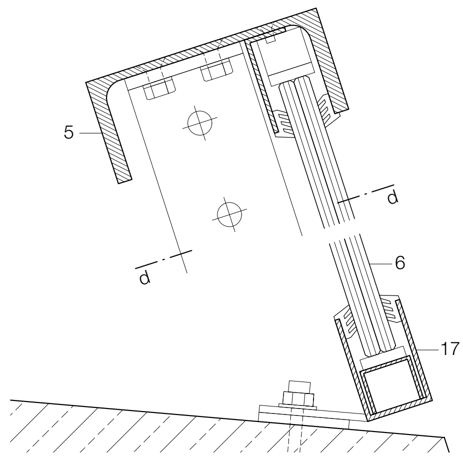

1
2
3
A
4
7
5
8
6
9
10
C
13
B
11
12
14

Vertical cross section Scale 1:20
Detailed cross section Scale 1:5

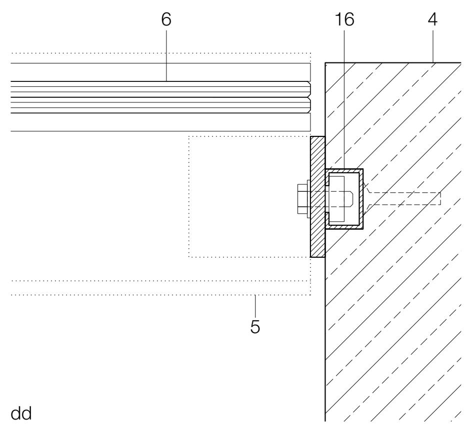
1 Fine mortar, 10 mm, 2 % gradient
2 Upstand, sealed with liquid plastic sealant
3 Substrata layer, green area 230 mm
Filter mat 5 mm, sealing, bitumen sheeting 2× 15 mm
insulation XPS 120 mm, vapour barrier 5 mm
Reinforced concrete 260 mm, plaster inside 12 mm
4 Insulating concrete, 400 mm, gross density approx. 900 kg/m³, thermal conductivity approx. 0.27 W/mK, water-repellent, painted white on the outside
5 Handrail, steel profile UPE 160 zinc powder-coated, black
6 Glass parapet, laminated float glass 2× 0 mm + PVB foil 0.76 mm, polished edges
7 Anti-glare blind/screen, textile roller blind
8 Door, insulating glazing in wooden frame
9 Parquetry, oak, mat, sealed 10 mm
cement heating screed 80 mm, separating layer,
insulation 20 mm, footfall sound insulation 20 mm
reinforced concrete 260 mm, plaster inside 12 mm
10 Sound insulating glazing, laminated float glass 2× 12 mm + PVB foil 1.52 mm
11 Insulating glazing, safety glass 12 + b/w panes 15 + laminated glass 2× 12 mm, black sealing, U = 1.1 W/m²K
12 Floor covering 20 mm, cement screed 80 mm, separating
layer, insulation EP foam 100 mm, footfall
sound insulation 17 mm, steel-reinforced concrete 260 mm
13 Granolithic concrete, dyed 80 mm, 2 % gradient sealing 3 mm, insulation 80 mm, steel-reinforced concrete, 260 mm, plaster inside 12 mm
14 Anti-graffiti coating on the ground floor
15 Steel profile, thermally separate, zinc powder coated, black
16 Anchor bar
17 Steel profile, black 70/45/5 mm



B



C

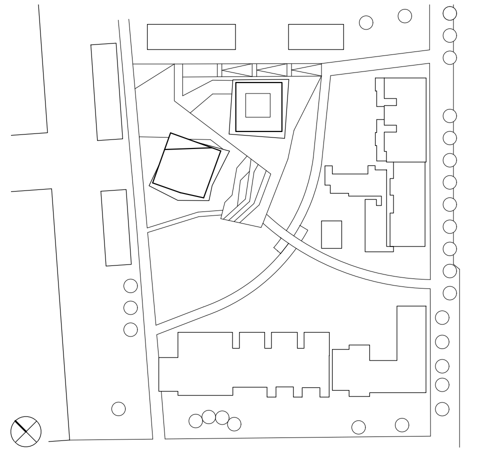


dd

Government-subsidised housing

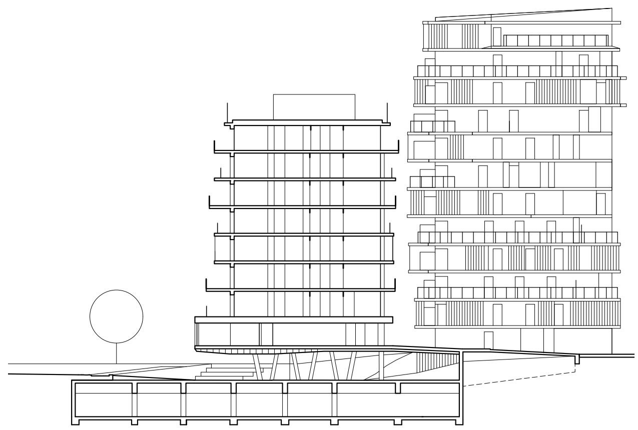
Paris, F 2011

Architects:
Hamonic + Masson, Paris
Gaëlle Hamonic, Jean-Christophe Masson
Project Manager:
Marie-Agnès de Bailliencourt
Structural planning:
SIBAT, Paris

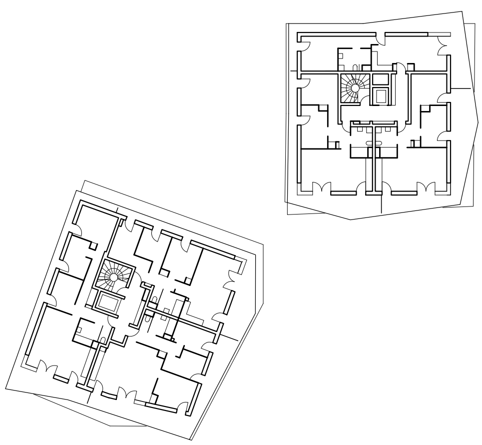


As part of the restructuring of a large residential block between Gare de Lyon station and the River Seine, the complex's inner courtyard was upgraded and new buildings were added, with two tower buildings housing 62 government-subsidised apartments replacing linear 1950s blocks. The perimeter block, up to 16 storeys high, shields the courtyard from the busy road on the bank of the Seine, giving it a surprisingly quiet atmosphere. Bands of balconies circle the nine and twelve-storey high buildings, enlivening the facades with their diverse range of designs. Parapet-high safety barriers and floor-to-ceiling elements alternate on succeeding storeys.
The balconies' layout, which is different on every floor, and layering interrupts the buildings' contours and "plays" with their volume. Although apartments on each succeeding storey have the same floor plan, these differently designed balconies give them an individual look. Depending on the storey, their large private outdoor areas resemble viewing platforms or loggias protected behind glass elements and steel nets. Residents use their extra "outdoor rooms" in very different ways, decorating them with outdoor furniture or plants or using them as storage areas, yet the buildings' filigree shell overcomes this heterogeneity. Reflective surfaces strengthen the impression of the buildings' lightness and translucency and reflect daylight deep into the apartments. Their facades are clad with trapezoidal cross sections, with high-gloss stainless steel and matt aluminium alternating on alternate storeys, subtly reinforcing the structures' overall sculptural impression. The silver-glazed undersides of the prefabricated steel balconies also reflect light.
To minimise the neighbours' ability to see inside and to optimise the buildings' orientation towards the south, the towers are positioned at an oblique angle to each other. They are connected by a wooden terrace with steps for sitting on as a shared outdoor area that fits in harmoniously with the redesigned external structure.

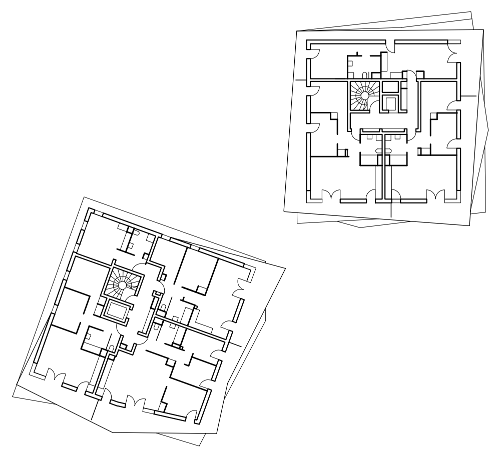
Site plan
Scale 1:2500
Cross section • Floor plan
Scale 1:750



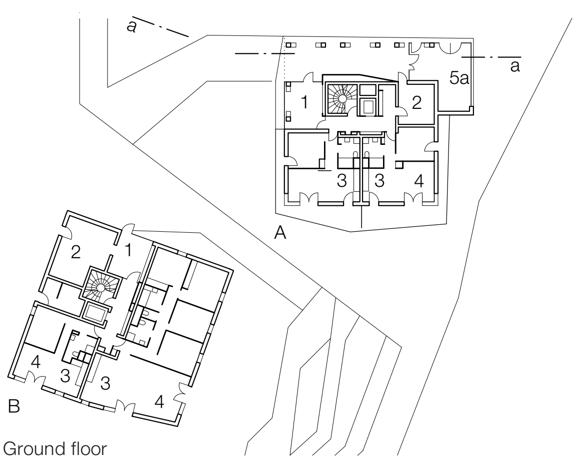
aa



1st–4th floors

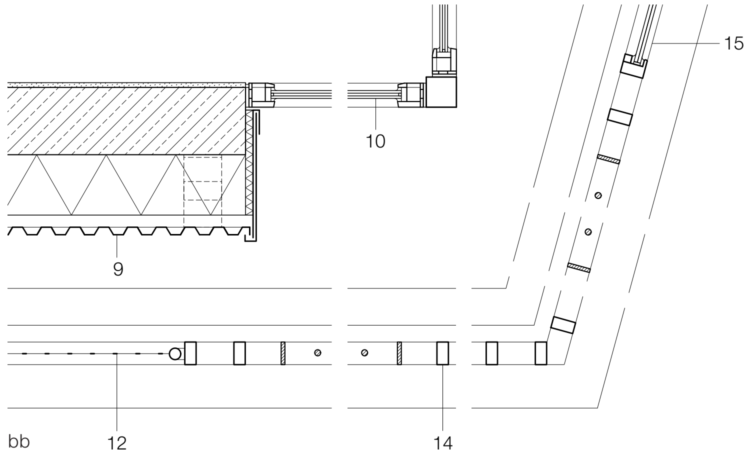


5th–9th floors



Ground floor

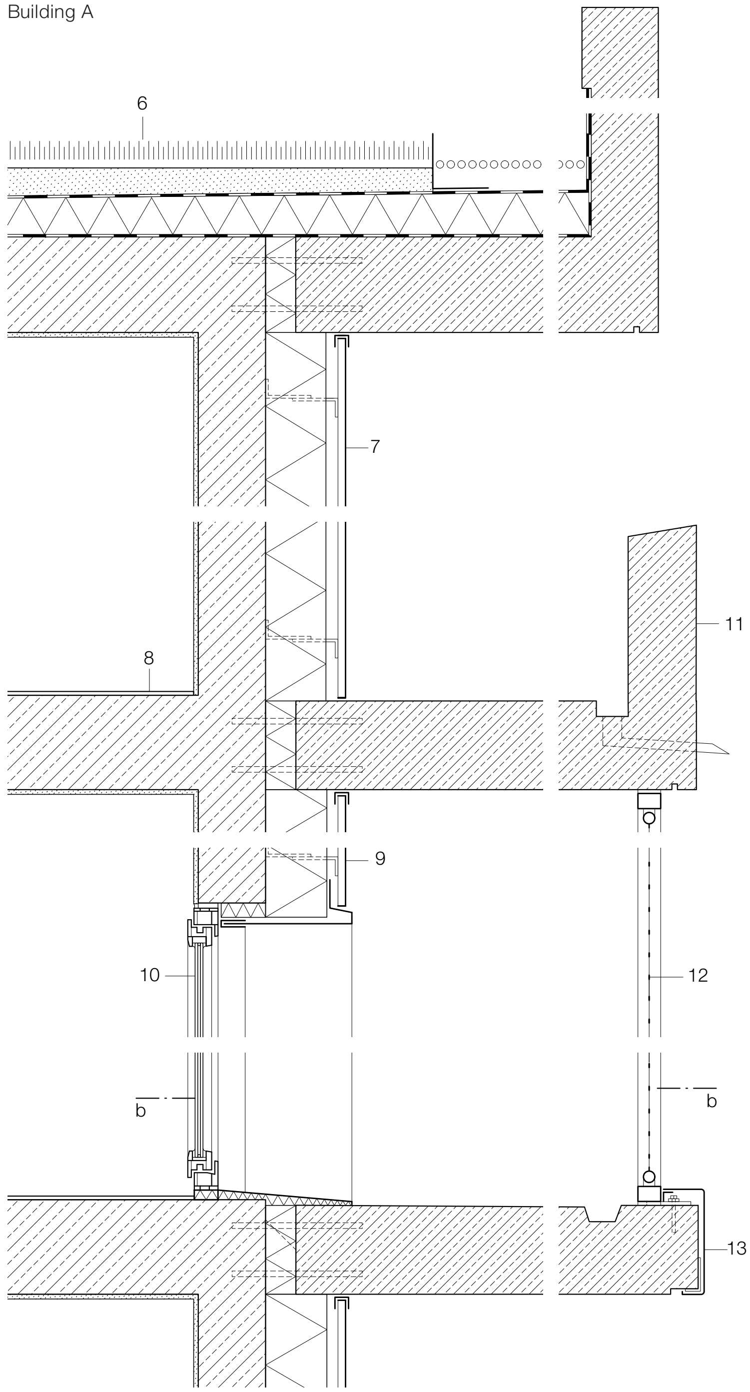
A Nine-storey building
B Twelve-storey building
1 Entry
2 Garbage room
3 Kitchen/dining area
4 Living area
5 Shared space

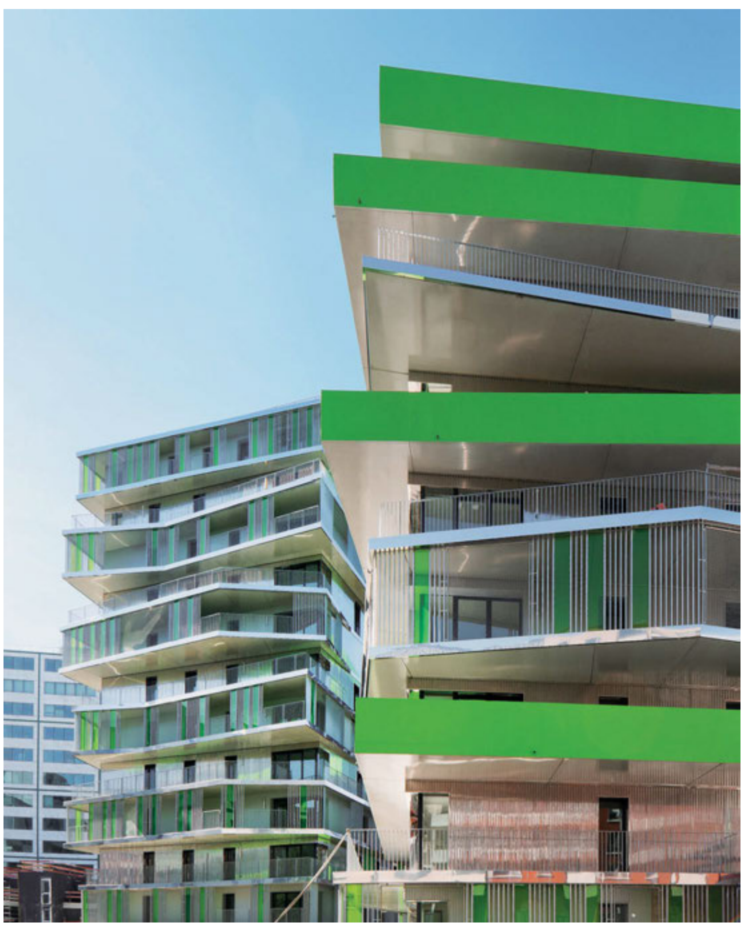


Horizontal cross section
Vertical cross section
Scale 1:20

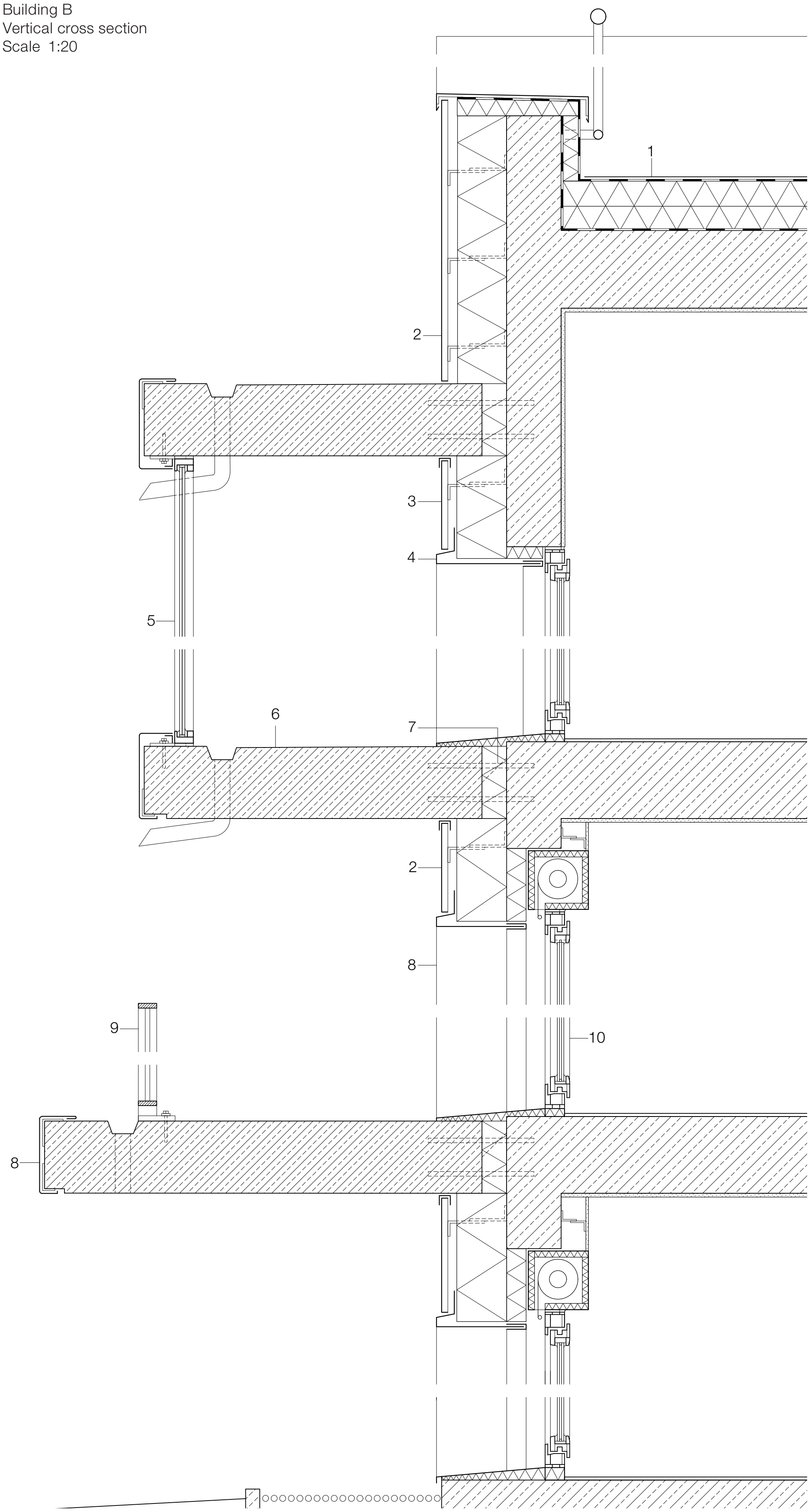
6 Green area, extensive substrata 100 mm
Sealing
Insulation 120 mm,
Vapour barrier 5 mm
Steel-reinforced concrete 200 mm at a gradient of 5%
7 Trapezoidal sheet metal, stainless steel, bright-annealed, high-gloss 20–75 mm
Rear ventilation 20 mm
Insulation, water-resistant 175 mm
Steel-reinforced concrete, 180 mm
8 PVC 10 mm
Steel-reinforced concrete 250 mm
Plaster
9 Trapezoidal sheet metal, aluminium, powder-coated, 20–75 mm
10 Insulating glazing in plastic frames
11 Balcony: parapet, painted green 180 mm
Precast steel-reinforced concrete element 235 mm with a PU synthetic resin coating, silver, water-resistant, silver-glazed underside
12 Safety barrier: net, stainless steel cable ∅ 1.5 mm
Mesh size, 40 mm, in tubular stainless steel frame, ∅ 30 mm
13 Stainless steel sheeting, bright-annealed, high-gloss, 2 mm
14 Safety barrier, floor to ceiling steel tubing, silver-grey enamelled 60/30 mm
15 Safety barrier, fixed laminated glass with 11 mm green PVB foil laminated into the glass, in steel frames, enamelled

Building A





Building B
Vertical cross section
Scale 1:20



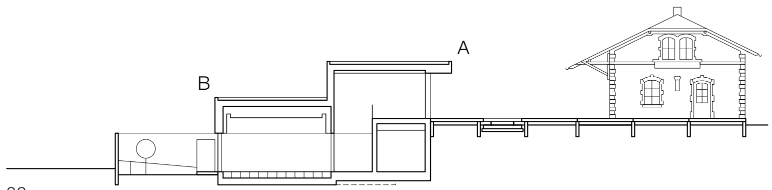
1 Sealing with integrated thin-film solar cells 4.6 mm, insulation 160 mm, vapour barrier 5 mm, steel-reinforced concrete at a gradient of 5 %
2 Trapezoidal stainless steel sheeting, bright-annealed, high-gloss 20–75 mm, rear ventilation 20 mm, water-resistant insulation 175 mm, steel-reinforced concrete 180 mm
3 Trapezoidal aluminium sheeting, powder-coated, 20–75 mm
4 Aluminium sheeting, powder-coated, 3 mm
5 Safety barrier, fixed laminated glass with 11 mm green PVB foil laminated into panes in steel frames
6 PU synthetic resin coating, silver, water-resistant, precast steel reinforced concrete element 235 mm, silver-glazed underside
7 Reinforcement connection, insulated
8 Stainless steel sheet, annealed, high-gloss 2 mm
9 Parapets: steel profile posts, silver-grey enamelled, 60/15 mm, handrail, steel profile 60/10 mm, steel bar, Ø 16 mm
10 Insulating glazing in plastic frames

Seminar building at a historic railway station

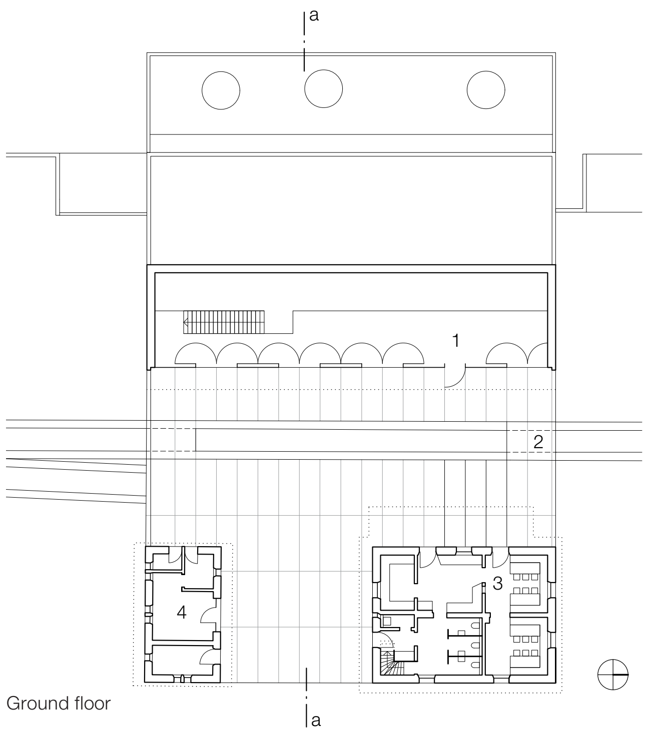
Greisselbach, D 2010

Architects:
Bögl Gierer Architekten, Munich
Assistants:
Kristin Wohlhüter, Katharina Dasch,
Christine Hess, Veronika Gut
Structural planning (new building):
Ingenieurbüro Mederer, Postbauer-Heng

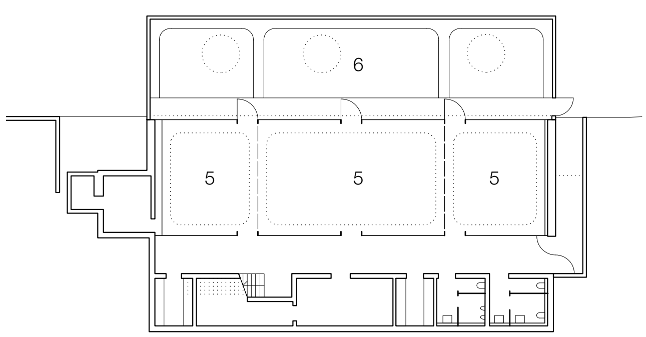
To the south of Neumarkt in the Upper Palatinate district (Oberpfalz), Greisselbach railway station, closed in 1989, sits next to the production facility of a large construction company. The company, which specialises in producing technically sophisticated, precast concrete components such as tower elements for wind power plants or tracks for magnetic levitation trains and high-speed trains, has created a contemporary usage concept here in keeping with the site.
New tracks were laid in front of the carefully renovated, characteristic, listed historic railway station to replace its old tracks, which were removed years ago. In their modern track bed, they serve as both an exhibit and a historic reminiscence.
A concrete slab platform, bush-hammered by machine, corresponds with the height of the limestone base of the existing building. It bridges the railway tracks at two points, merging the old railway station and the new seminar centre opposite it into a single ensemble. Large, inviting double doors open into the foyer of the training centre building along the "platform" and establish the architectural rhythm of its long glazed facade, which reflects the old buildings.
At first sight, the new building looks flat and single-storeyed but it makes use of a fall in the site's ground level towards the rear parking area for construction vehicles to unobtrusively accommodate the training areas in a lower storey. The three flexibly dividable seminar rooms face a gravelled garden courtyard, which box hedges separate into three zones. A precast concrete wall encloses this open space.
Concrete elements with precisely positioned joints structure the facades. Seen from the side, three prefabricated elements, each section interlocking with the next, form the stepped volume.
The old railway station's spatial structure has been largely retained. Seminar participants now meet for lunch here in two canteens. Custom-designed wooden furniture and wall panelling create an interior reminiscent of a traditional country pub, yet are also identifiably contemporary elements.



aa



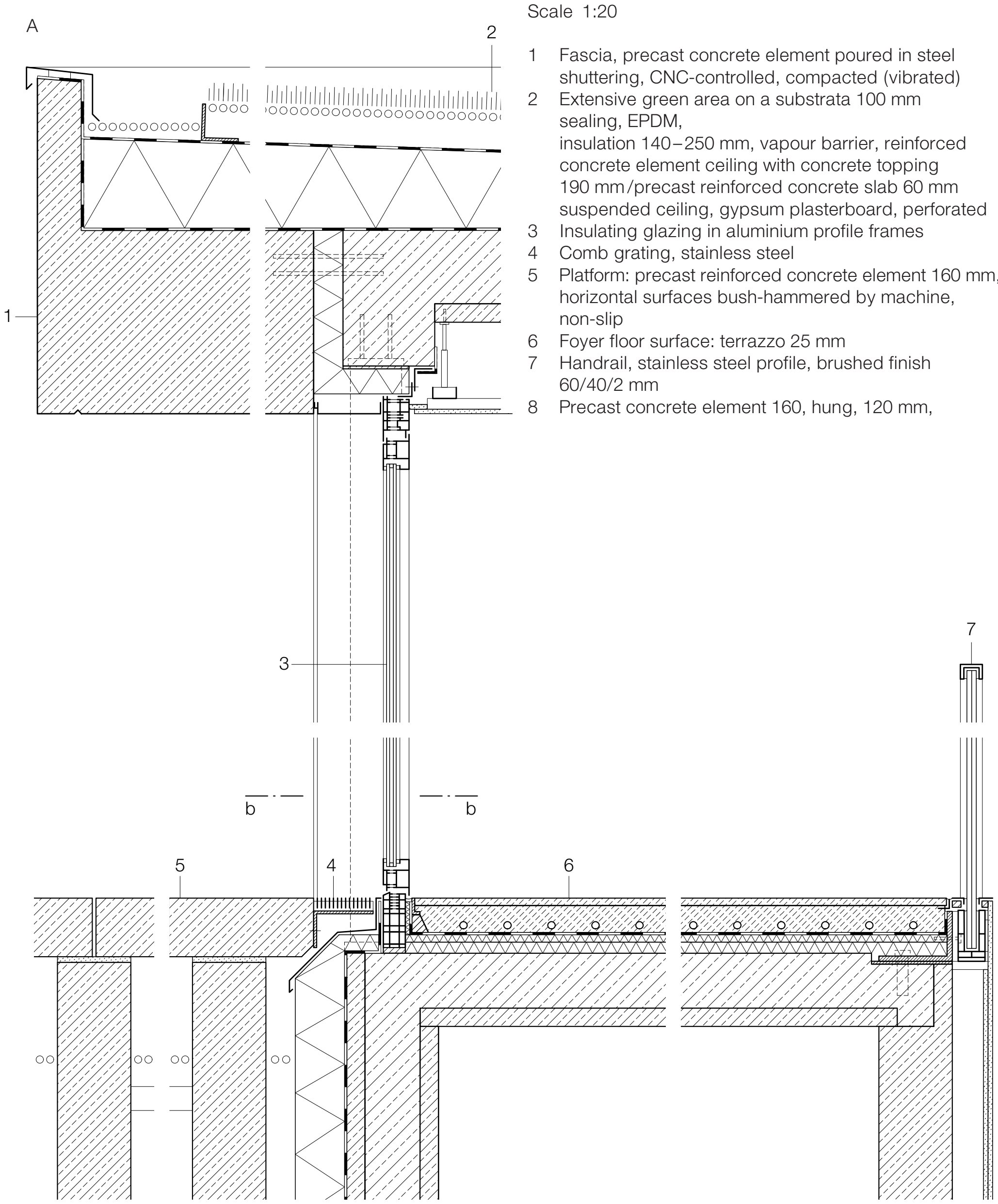
Ground floor



Basement floor

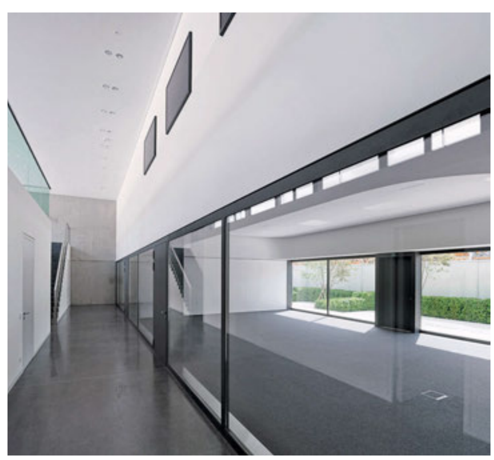
Cross section
Floor plan
Scale 1:500

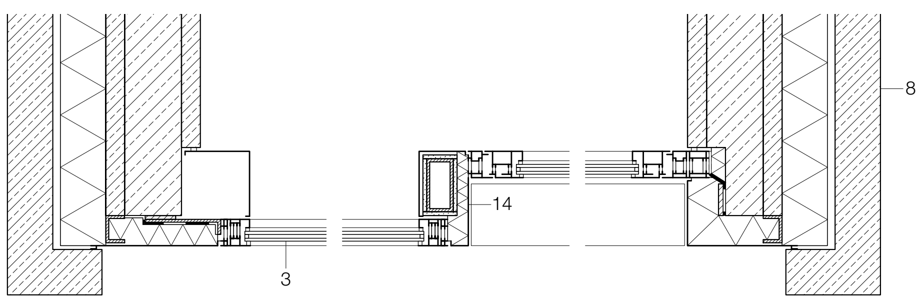
1 Foyer
2 Platform/track bed
3 Canteen (railway station/former reception building)
4 Technical equipment (former washrooms/toilets)
5 Seminar rooms
6 Garden courtyard



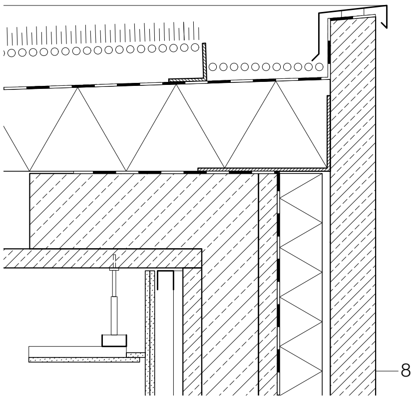
Vertical cross section • Horizontal cross section
Scale 1:20

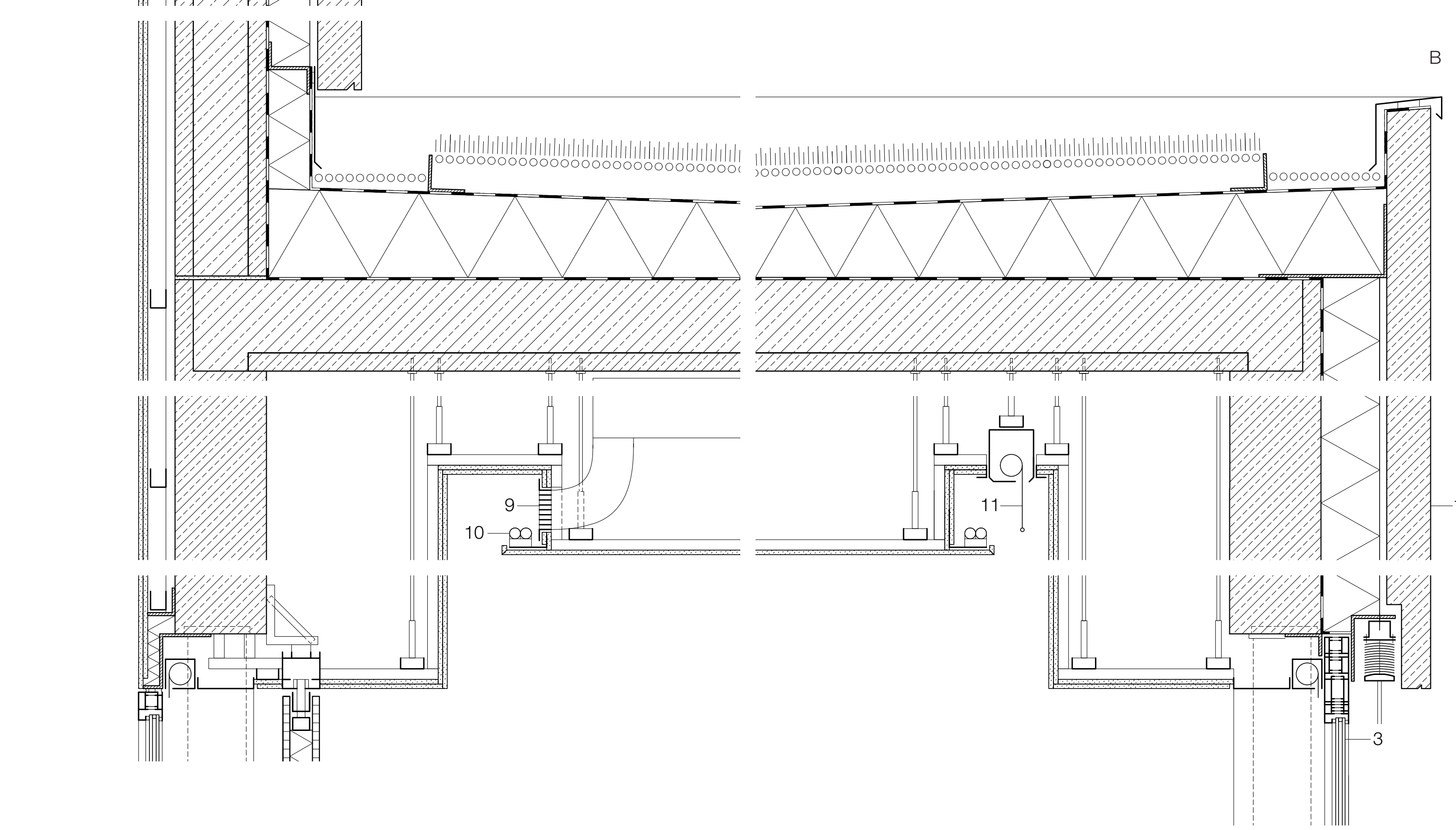
1 Fascia, precast concrete element poured in steel shuttering, CNC-controlled, compacted (vibrated)
2 Extensive green area on a substrata 100 mm sealing, EPDM,
insulation 140–250 mm, vapour barrier, reinforced concrete element ceiling with concrete topping 190 mm/precast reinforced concrete slab 60 mm suspended ceiling, gypsum plasterboard, perforated
3 Insulating glazing in aluminium profile frames
4 Comb grating, stainless steel
5 Platform: precast reinforced concrete element 160 mm, horizontal surfaces bush-hammered by machine, non-slip
6 Foyer floor surface: terrazzo 25 mm
7 Handrail, stainless steel profile, brushed finish 60/40/2 mm
8 Precast concrete element 160, hung, 120 mm, poured in steel shuttering, CNC-controlled, compacted, (vibrated)
Air space 20 mm
Insulation 120 mm, wall element (load-bearing) prefabricated with precast concrete components 50 mm
Pour zone 150 mm, precast concrete element 50 mm
9 Ventilation grille/ventilation duct
10 Fluorescent tubes
11 Projection screen, extendable
12 Precast concrete component, hung 120 mm, poured in steel shuttering, CNC-controlled, compacted (vibrated), air space 20 mm, insulation 160 mm
Lintel, precast concrete component 250 mm
13 Seminar room floor surface: carpet on a double floor
14 Aluminium sheeting 2 mm, aluminium profile frame
15 Mobile partition wall MDF, coated, insulated
16 Steel beams, 140/80 and 70/6.3 mm
fire protection slab, cement bonded 10 mm, insulation, aluminium cladding 3 mm

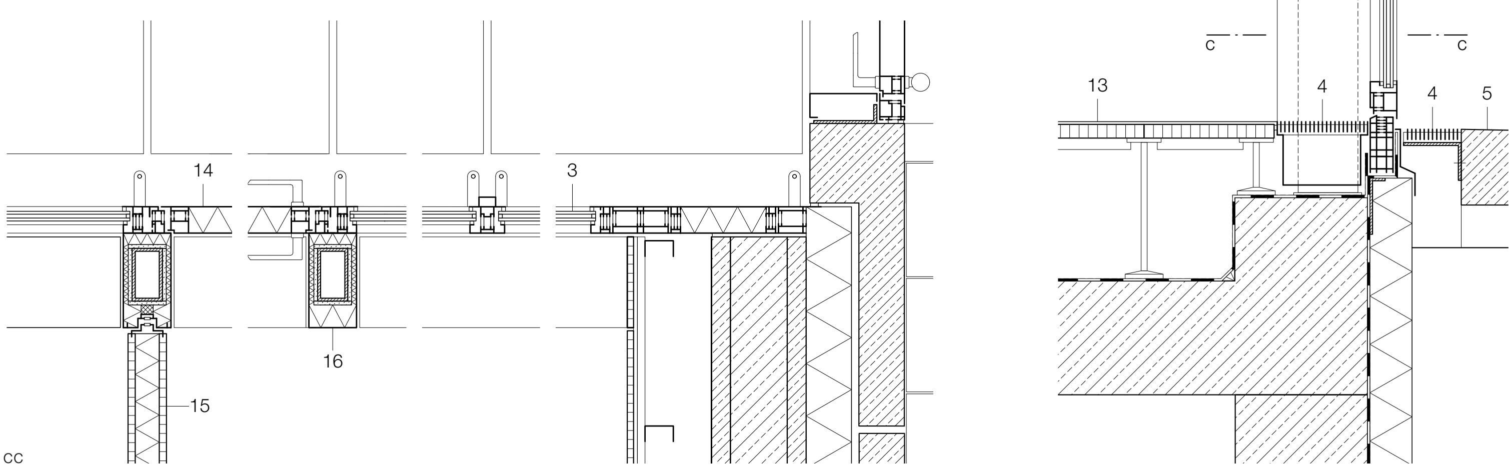




bb





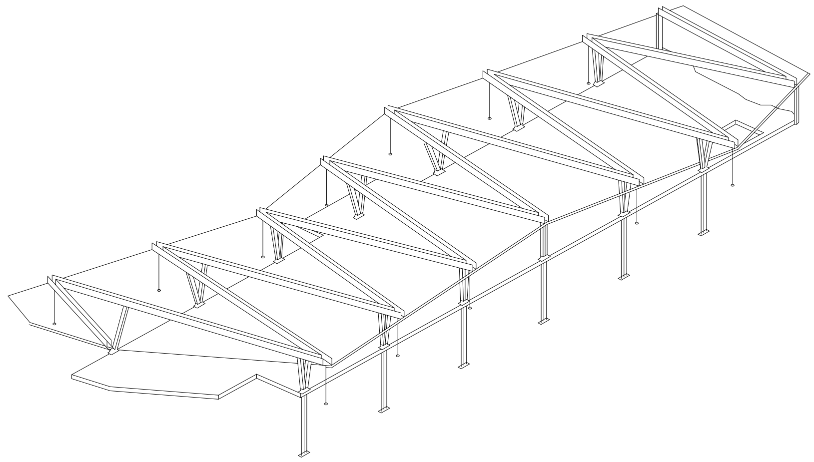


cc

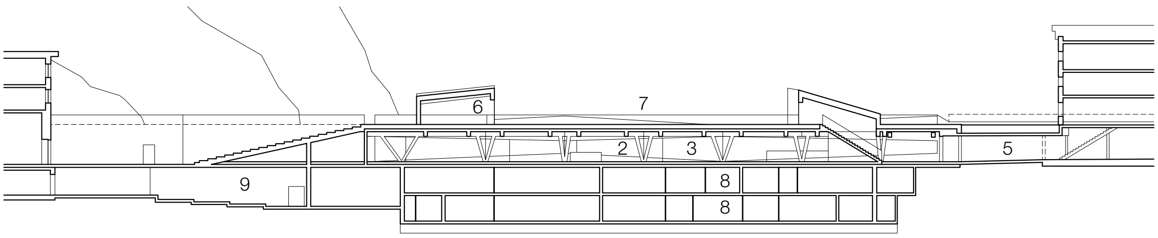
Panorama Gallery, Mt. Pilatus

Kulm, CH 2011

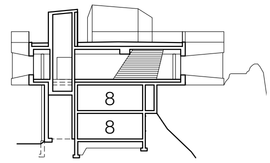
Architects:
Niklaus Graber & Christoph Steiger Architekten, Lucerne
Project Manager:
Philipp Käslin
Construction Manager:
Jürg Gabathuler, Wollerau
Structural planning:
Dr. Schwartz Consulting AG, Zug
Aldo Vital



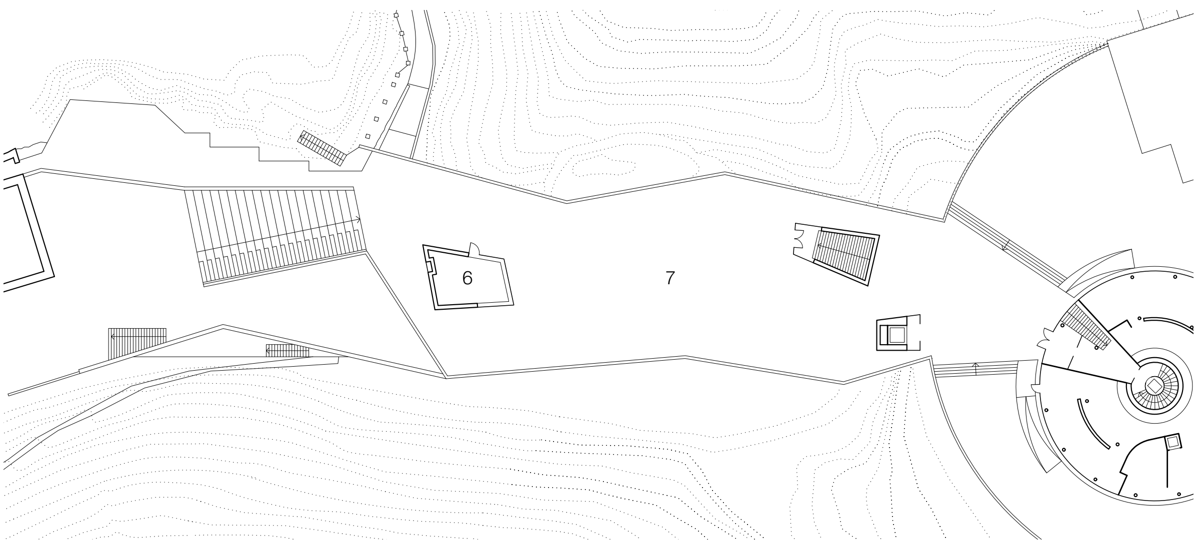
Almost merging into the crags of Mt. Pilatus, the Panorama Gallery is an “architectural mountain path” linking an existing cableway station with two hotels. Instead of the familiar “form follows function” design objective, the “form follows mountain” here. Gentle transitions between the artificial and natural landscape are achieved with a polygonal, meandering floor plan and slight modulations in the cross section. The building almost matter-of-factly joins existing structures at various levels and creates a range of spatial effects, each with its special character and view. The new, single-storey 60 × 20 metre building uses a pre-existing military building as its foundation. The roof of the Gallery serves as a viewing platform and a space for sunbathing. Spaciously laid out cascading stairs link the terrace with the Gallery and hotels.
The structure also reflects the idea of movement. Variously splayed, v-shaped double supports made of steel box beams, with visible joists zigzagging between them, form a spatial grid that supports the ceiling and facade. The concrete ceiling, with its u-shaped steel joists, was poured in situ and functions as a composite structure, allowing spans up to 18 m to be built, even though up to 9 metres of snow can fall on the terrace. Projecting areas of the lower ceiling slab are hung from tension rods on the joists of the upper ceiling slab. Steel profiles penetrate the interior insulation at just a few points, minimising thermal bridges to a negligible level.
The materiality of the building envelope, which is made of precast concrete elements, references the limestone of Mt. Pilatus. Formwork matrices were used to give the surface a fine vertical pattern, a sensual feel and an impression of depth. They also conceal the joints between elements. The concrete parapets were poured in situ onto the elements, which helps distribute ceiling loads in a longitudinal direction. Following the floor plan, the opaque parapets and handrails rise and fall, creating huge picture windows framing dramatic views.

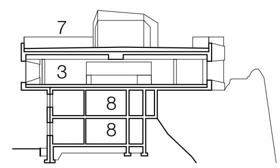


aa



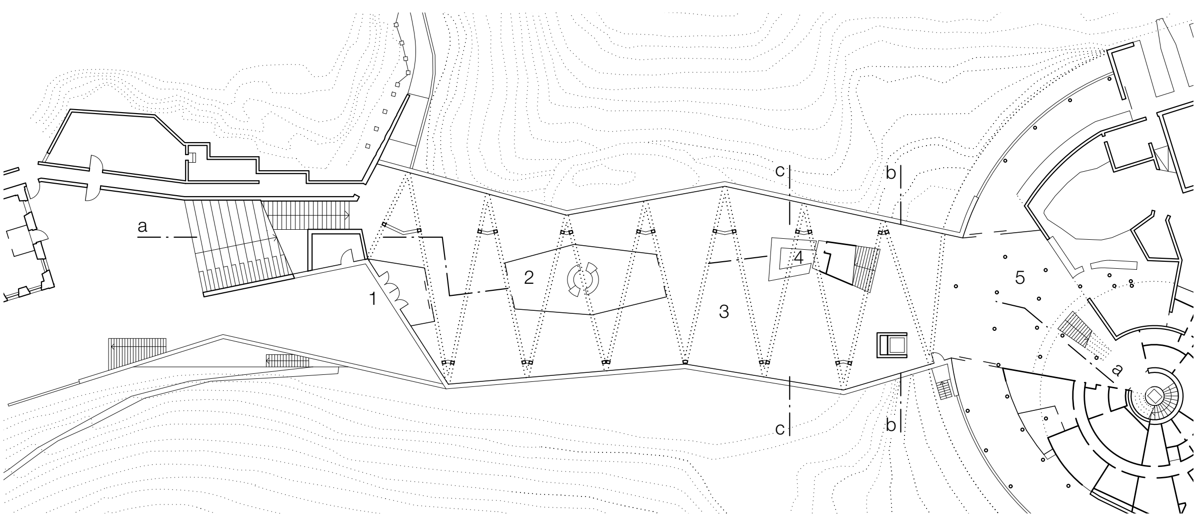
bb





cc

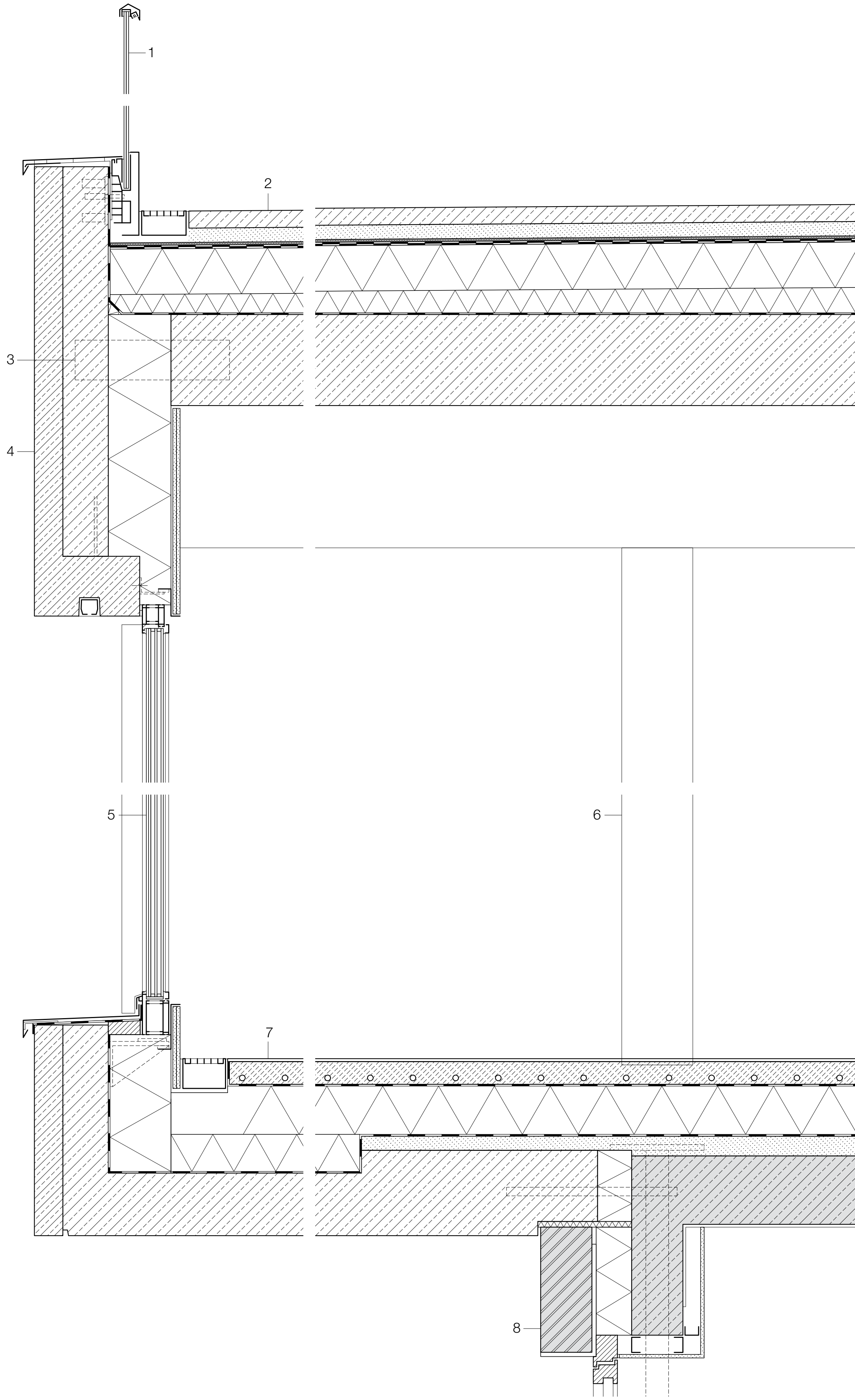
Terrace level



Gallery level

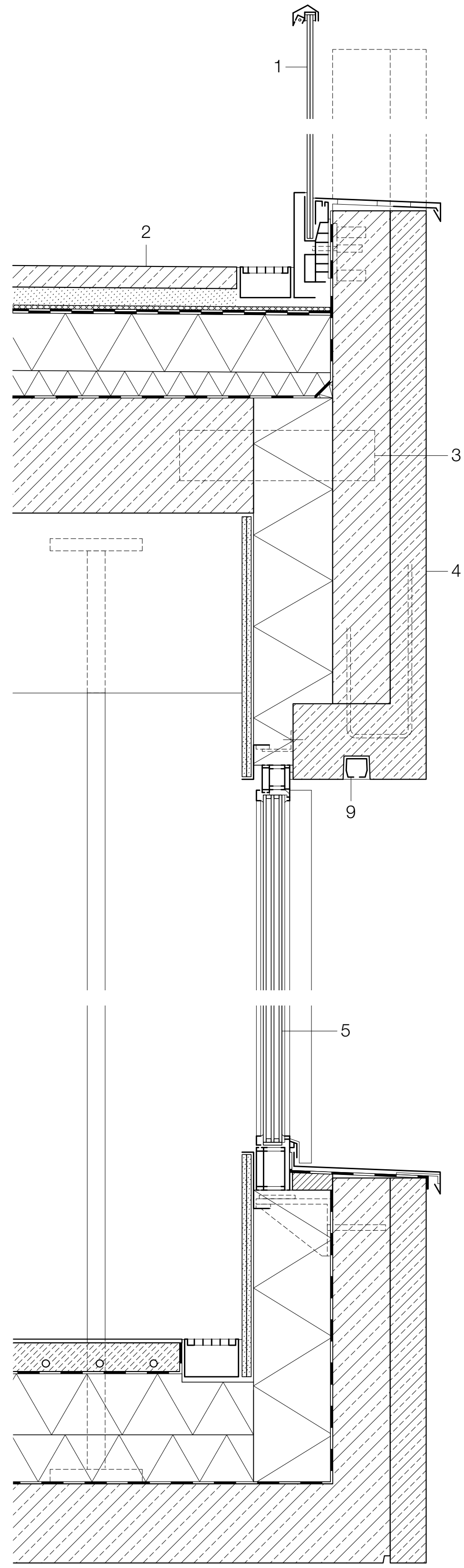
Axonometric projection, frame
Cross section • Floor plan
Scale 1:800

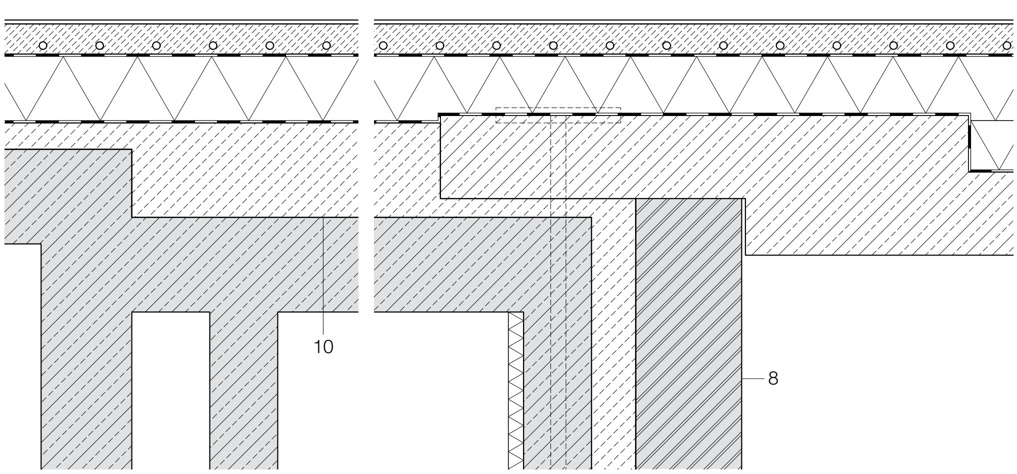
1 Entrance
2 Shop
3 Panorama Gallery
4 Bar
5 Hotel access
6 Kiosk
7 Viewing terrace
8 Army barracks (existing building)
9 Seminar room


1
2
3
4
5
6
7
8

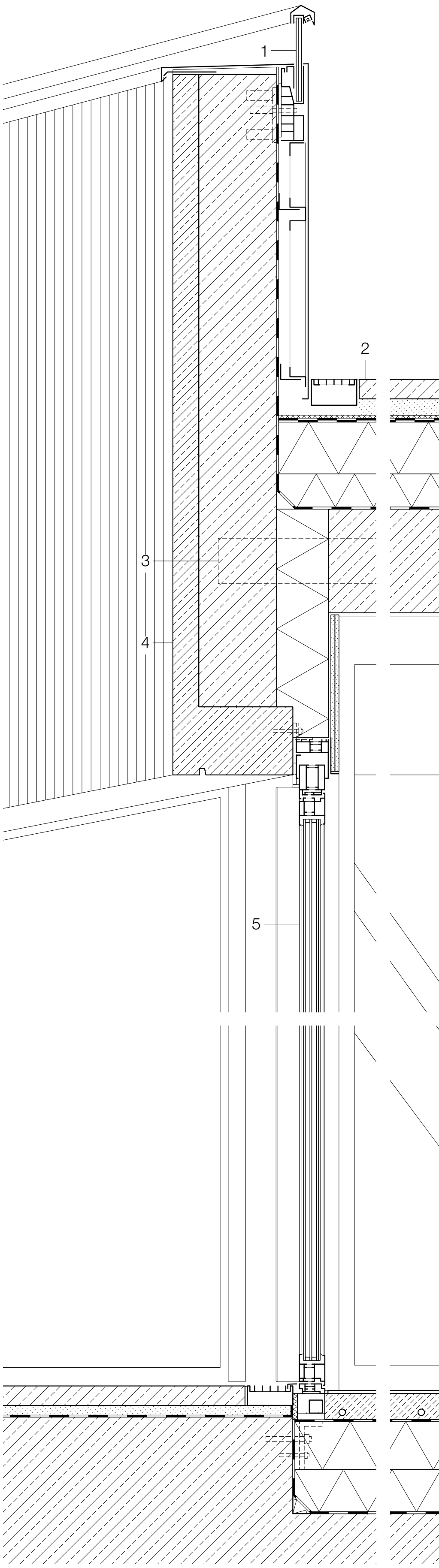
Vertical cross section
Scale 1:20

1 Hand rails, laminated glass (float glass), extra-white 2× 8 mm in an aluminium frame
Handrail, stainless steel, with integrated LED light strip
Fixed part, parapet (variable height):
Precast concrete element with a vertical pattern 100 mm
poured with concrete in situ 160 mm
Parapet cladding, stainless steel sheeting
Interior cladding, stainless steel sheeting
2 Roof structure, U = 0.1/0.15 W/m²K:
Concrete slab 60 mm
Gravel fill 50 mm
Drainage mat, crumb rubber 10 mm
Sealing, bitumen, two ply 20 mm
Insulation, EPS 200–360 mm, gradient 1.5 %
Vapour barrier
Steel-reinforced concrete 320 mm
Steel-reinforced concrete composite beam 500/350 mm
3 Stirrup and cantilever slab connector
4 Exterior wall structure:
Precast concrete element with a vertical pattern 100 mm
poured with concrete in situ 160 mm
Insulation 220 mm
Gypsum board, painted 12.5 mm
5 Triple insulating glazing, safety glass 8 mm + between panes 14 mm + safety glass 8 mm + between panes 14 mm + laminated glass 2× 8 mm, annealed glass with integrated ventilation louvers in aluminium frames, enamelled, U = 0.6 W/m²K
6 V-supports, steel box beams, wall thickness variable depending on loading 10–60 mm
7 Floor structure:
PU coating 3–5 mm
Heating screed, anhydrite 80 mm
Separating layer
Insulation, EPS 300 mm
Separating layer
Steel-reinforced concrete 220 mm
8 Existing wall, office building
9 Anchor point, guide rail, steel, zinc-coated, 65/60 mm
10 Blinding concrete, variable



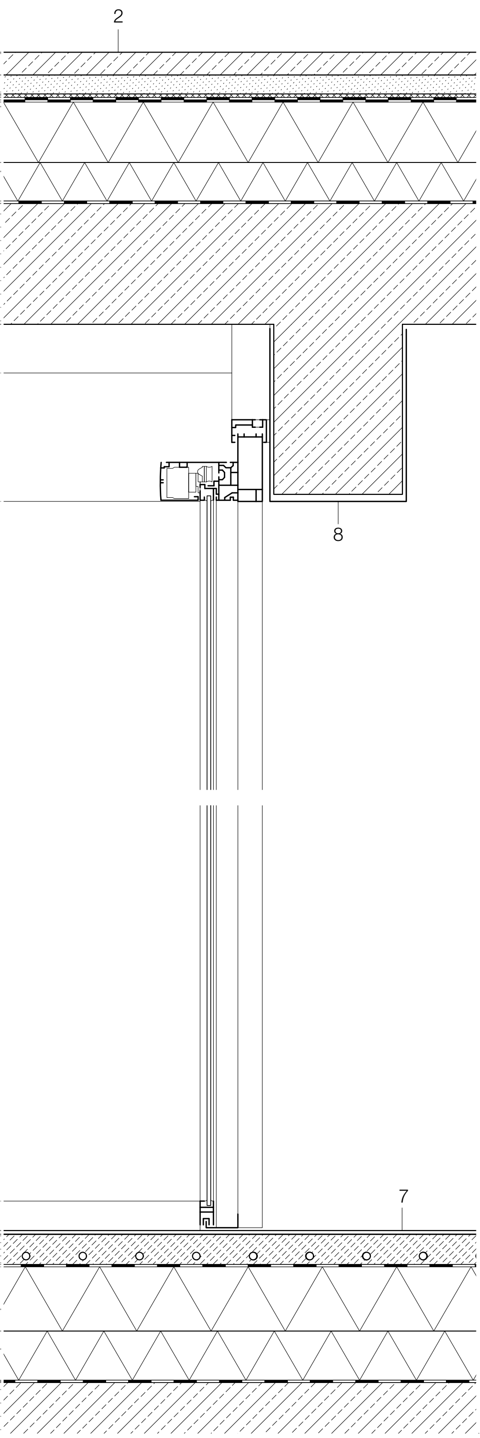


Vertical cross section Scale 1:20



Vertical cross section   Scale 1:20

1 Hand rails, laminated glass (float glass), extra-white 2× 8 mm in an aluminium frame
Handrail, stainless steel, with integrated LED light strip
Fixed part, parapet (variable height):
Precast concrete element with a vertical pattern 100 mm
poured with concrete in situ 160 mm
Parapet cladding, stainless steel sheeting
Interior cladding, stainless steel sheeting
2 Roof structure, U = 0.1/0.15 W/m²K:
Concrete slab 60 mm
Gravel fill 50 mm
Drainage mat, crumb rubber 10 mm
Sealing, bitumen, two ply 20 mm
Insulation, EPS 200–360 mm, gradient 1.5 %
Vapour barrier
Steel-reinforced concrete 320 mm
3 Stirrup and cantilever slab connector
4 Exterior wall structure:
Precast concrete element with a vertical pattern 80 mm
poured with concrete in situ 240 mm
Insulation 160 mm
Gypsum board, painted 12.5 mm
5 Door with triple insulating glazing, safety glass 6 mm + between panes 14 mm + safety glass 6 mm + between panes 14 mm + laminated glass 2× 6 mm, annealed glass in aluminium frames, enamelled, U = 0.6 W/m²K
6 V supports, steel box beams, wall thickness variable depending on the load 10–60 mm
7 Floor structure:
PU coating 3–5 mm
Heating screed, anhydrite 80 mm
Separating layer
Insulation, EPS 300 mm
Separating layer
Steel-reinforced concrete 220 mm
8 Steel-reinforced concrete composite truss 500/350 mm

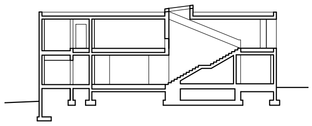


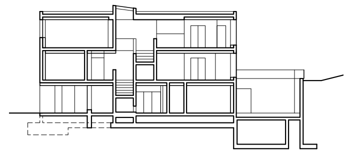
Nature park centre, primary school and kindergarten

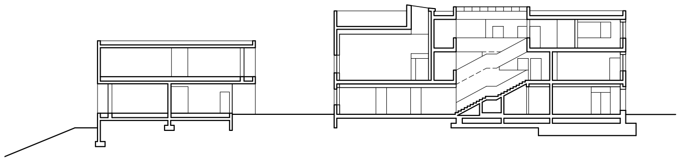
St. Magdalena, I 2009

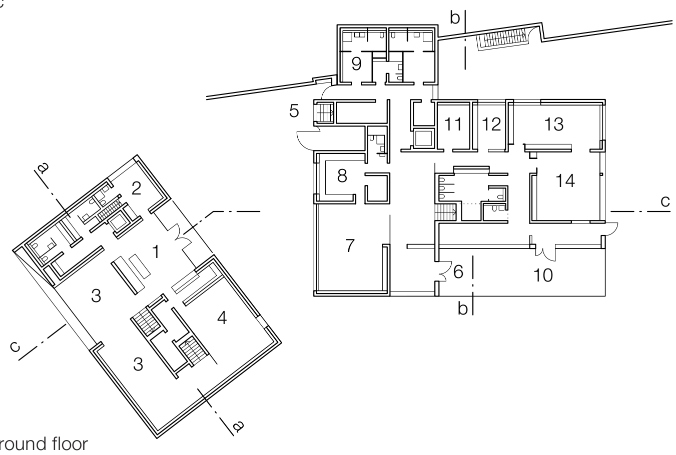
Architects:
Burger Rudacs Architekten, Munich
Stefan Burger, Birgit Rudacs
Assistant:
André Frühoff
Structural planning:
Ingenieurteam Bergmeister, Neustift-Vahrn

At the edge of the Puez-Odle Nature Park in the South Tyrol, with its distinctive serrated mountaintops, the small settlement of St. Magdalena lies at the head of the Villnöß valley. Here, on the site of a 1980s school building, a new primary school and kindergarten, as well as a visitors' centre for the nature park, were built.
In this imposing mountain landscape, the architects created two monolithic buildings, whose warm beige-coloured exposed concrete surfaces correspond well with the surrounding craggy mountains. Their surfaces were roughened using stonemasonry techniques, with the aggregate freed from the surface laitance by hand and exposed. With their precisely positioned openings framed by larch wood, the two buildings look as if they were cut from a single crag.
Standing at an angle to each other, the two buildings follow the contours of the hillside meadows and the course of a nearby stream. Between them is a square, emphasising the ensemble's public character. The nature park's car park was deliberately placed a short distance away so that visitors have to follow a path through the park to reach the museum entrance. In the exhibition area, which extends over two levels, visitors can find information on the nature park. Three large picture windows facing in various directions offer panoramas of the surrounding landscape. The primary school and kindergarten are housed together in the larger, three-storey building, but each institution has its own entrance. The cafeteria, library and the large multi-purpose hall that the children use as a gymnasium are part of the primary school space but shared with the kindergarten. The park's visitor centre also uses this space, with the multi-purpose hall in particular occasionally hosting events or functioning as an extra exhibition space. Inside, the interplay of the facade materials continues, with warm larch wood or cool concrete predominating depending on each room's function.


aa


bb

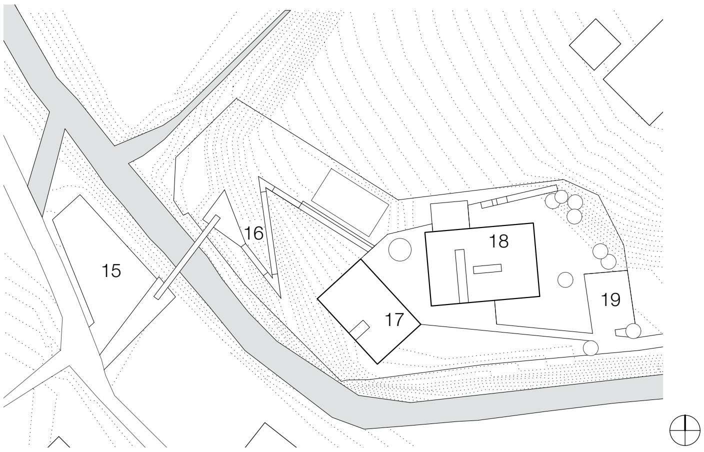

cc

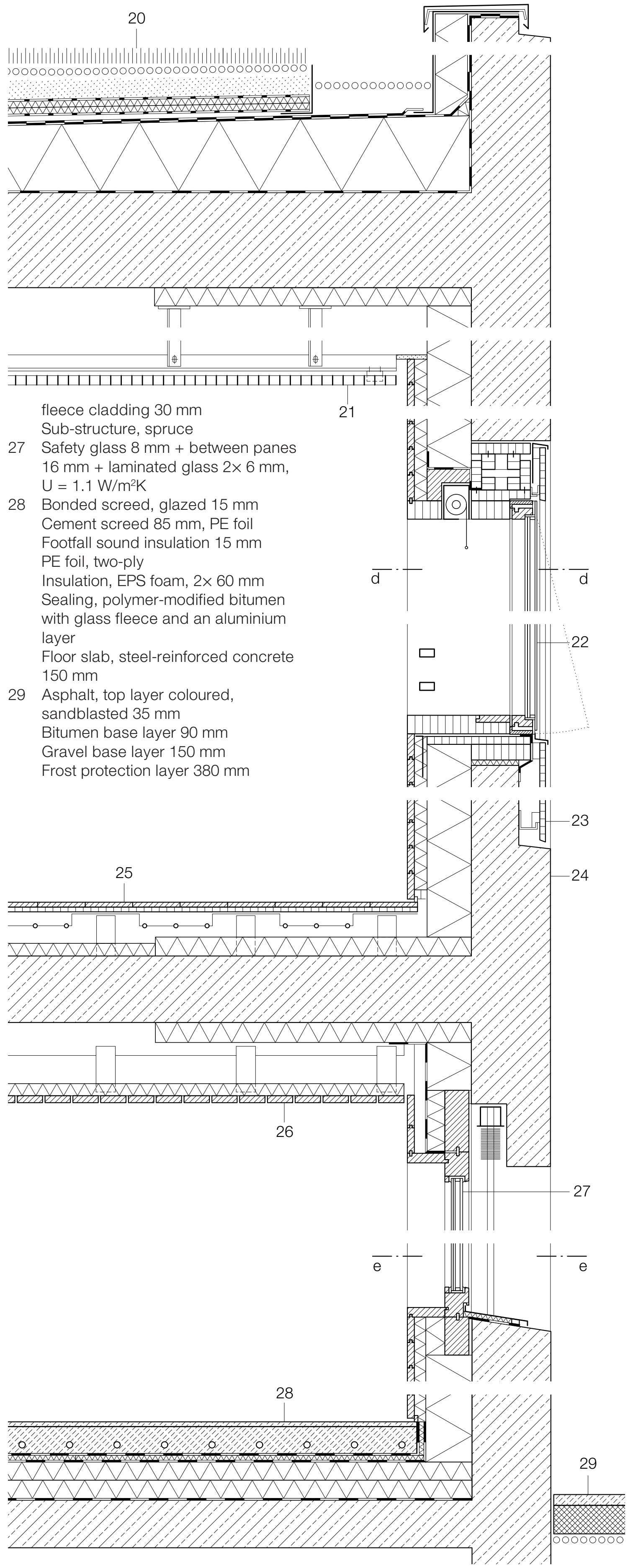


Ground floor

Cross section • Floor plan
Scale 1:750
Site plan
Scale 1:2000

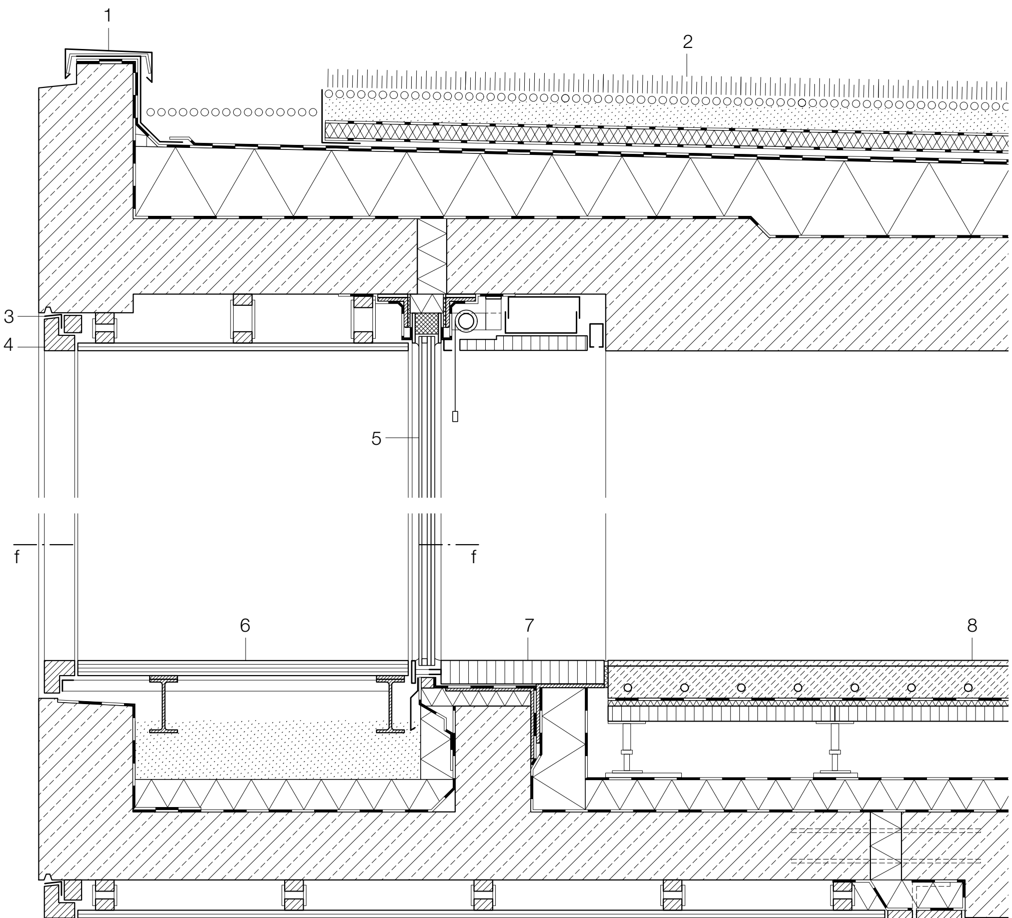
1 Entrance to the nature park centre
2 Office
3 Exhibition
4 Lecture room
5 Entrance to the nature park centre
6 Entrance to the primary school
7 Cafeteria
8 Kitchen
9 Changing room
10 Entrance to the kindergarten
11 Storage/storeroom
12 Staffroom
13 Gymnasium
14 Space for groups
15 Visitor parking
16 Footpath
17 Nature park centre
18 Primary school/kindergarten
19 Teacher parking

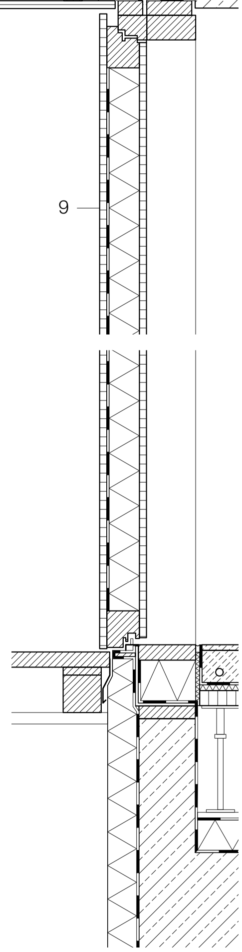


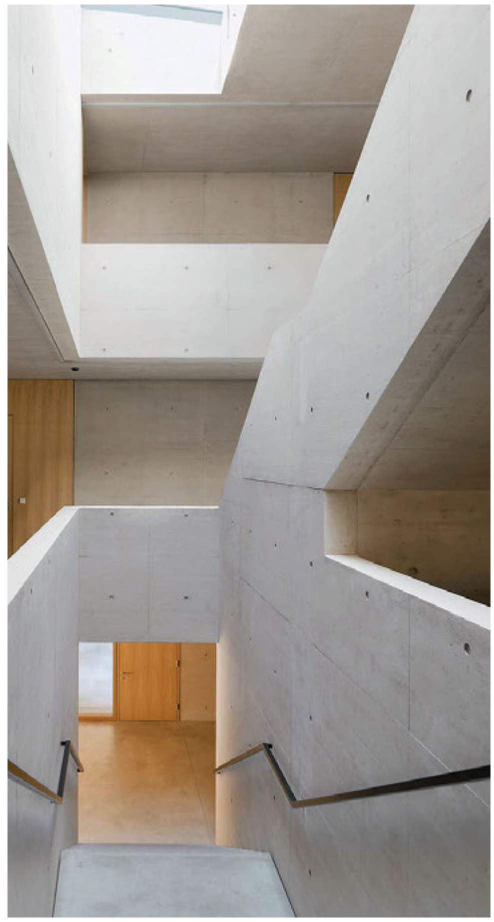


Vertical cross section
Scale 1:20

20 Green area, extensive gravel between it, Substrata 60 mm, woven filter medium Drainage layer, expanded slate 40 mm Protective and storage fleece Structural protection mat Sealing, elastomeric bitumen with fleece layer Insulation, PUR foam 130–210 mm (2 % gradient) Vapour barrier, elastomeric bitumen with aluminium layer Bitumen undercoat Steel-reinforced concrete 300 mm
21 Grating, steel, foldable, 30 mm on a steel sub-structure
22 Safety glass H 6 mm + between panes 16 mm + laminated glass 2× 8 mm, U = 1.1 W/m²K
23 Triple-layer panel, larch, oiled 22 mm
24 Exterior wall, exposed concrete, pigmented 250 mm, bush-hammered surface Insulation, foamed glass 140 mm Sub-structure 60/40 mm, between it mineral wool insulation, 40 mm Cladding, larch, solid wood, 22 mm
25 Triple-layer parquetry, larch 15 mm False floor, 15 mm on double swing beams and point supports Footfall sound insulation, mineral wool, aluminium-clad 30 mm Steel-reinforced concrete 210 mm
26 Cladding, larch, solid wood 22 mm, acoustic insulation with black fleece cladding 30 mm Sub-structure, spruce
27 Safety glass 8 mm + between panes 16 mm + laminated glass 2× 6 mm, U = 1.1 W/m²K
28 Bonded screed, glazed 15 mm Cement screed 85 mm, PE foil Footfall sound insulation 15 mm PE foil, two-ply Insulation, EPS foam, 2× 60 mm Sealing, polymer-modified bitumen with glass fleece and an aluminium layer Floor slab, steel-reinforced concrete 150 mm
29 Asphalt, top layer coloured, sandblasted 35 mm Bitumen base layer 90 mm Gravel base layer 150 mm Frost protection layer 380 mm

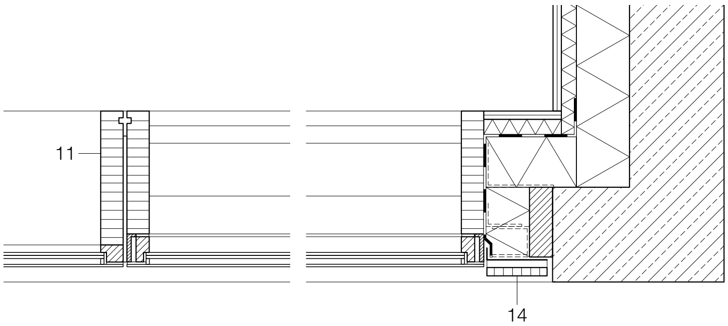




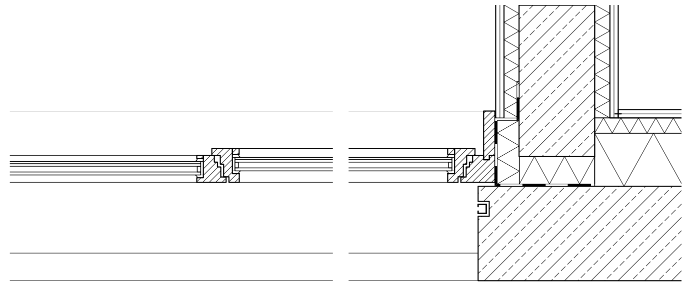


1 Aluminium sheeting, anodised 2.5 mm
2 Green area, extensive gravel between it
Substrata 60 mm, woven filter medium
Drainage layer, expanded slate 40 mm
Protective and storage fleece
Structural protection mat
ealing, elastomeric bitumen
with a fleece layer
Insulation PUR foam,
130–210 mm (2 % gradient)
Vapour barrier, elastomeric bitumen with an
aluminium layer, bitumen undercoat
Steel-reinforced concrete 300 mm
3 Metal bracket, anodised 30/40/1 mm
4 Edge profile, larch 90/85 mm
5 Safety glass H 8 mm + between panes 16 mm +
laminated glass 2× 10 mm, U = 1.1 W/m²K
6 Planks, larch 40 mm
Steel sheeting, zinc-coated 70/6 mm, IPE 140
Gravel bed 52–125 mm
Insulation XPS 80 mm
Sealing, bitumen, two-ply
Steel reinforced concrete 180 mm (1 % gradient)
Sub-structure, spruce
Cladding, larch, solid wood 22 mm
7 Veneered plywood, larch,
veneered 60 mm
8 Bonded screed, glazed 15 mm
Cement screed 85 mm, PE foil
Footfall sound insulation 15 mm
Calcium sulphate panelling 40 mm
Stanchion floor system
9 Entrance door: triple-layer panelling,
larch 19 mm (both sides)
10 Cladding, larch 20 mm
11 Facade mullions, veneered plywood,
larch veneer 60/385
12 Pressure bar, anodised aluminium 60/10 mm
13 Sealing, silicon, black, UV-resistant
14 Triple-layer panel, larch 19 mm

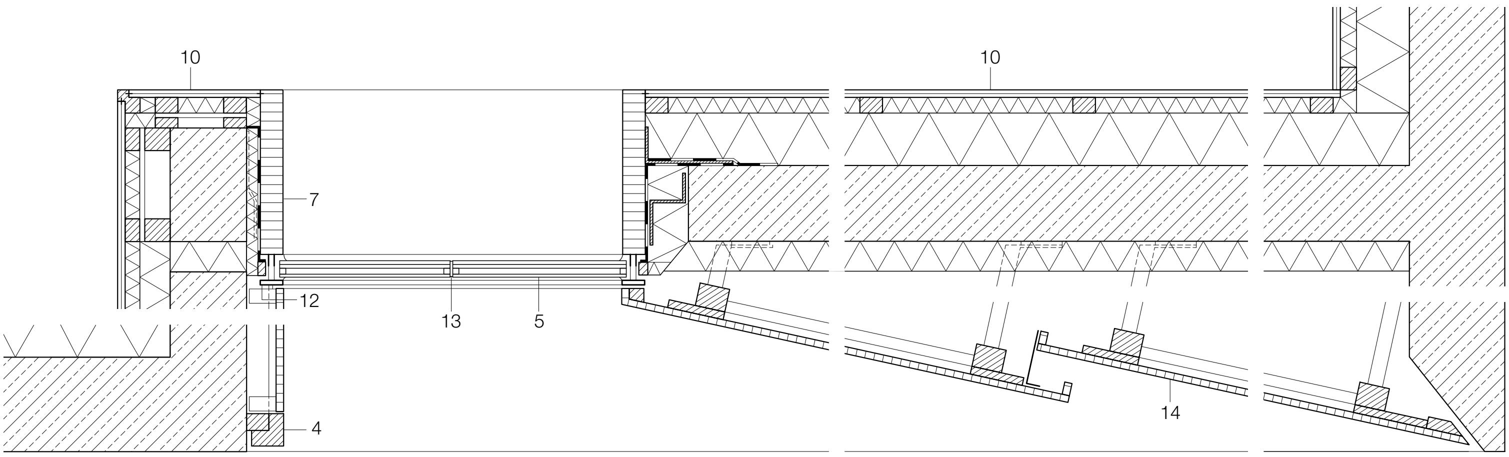
Vertical cross section
Horizontal cross section
Scale 1:20



dd



ee



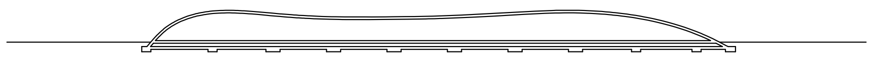
ff

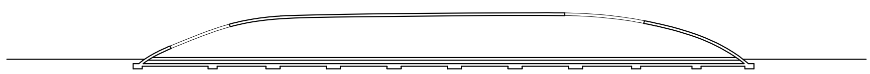
Museum

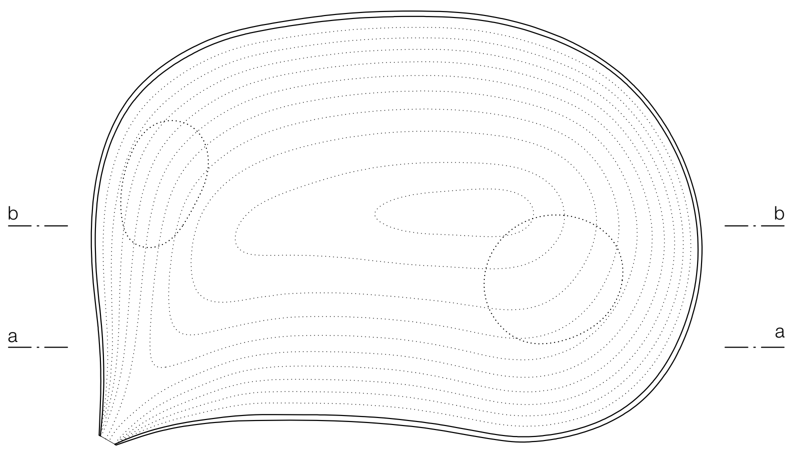
Teshima, J, 2010

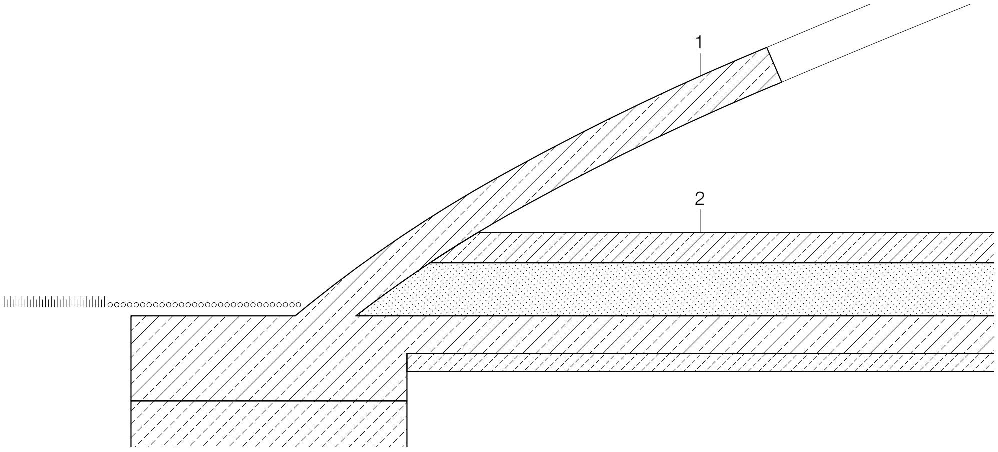
Architects:
Office of Ryue Nishizawa, Tokyo
Ryue Nishizawa, Yusuke Ohi
Artist:
Rei Naito, Tokyo
Structural planning:
Sasaki Structural Consultants, Tokyo

Like a white drop of concrete, the Teshima Art Museum lies on a steeply rising coastline in the hilly landscape of the Japanese island of the same name. Magnificent views across the Seto Inland Sea, with its craggy islands, compete here with the intense green of the surrounding forests and rice fields.
Patron of the arts Soichiro Fukutake wanted to commission architecture that would be inseparably rooted in its location and found a like-minded collaborator in the architect Ryue Nishizawa. Working in close cooperation with the artist Rei Naito, he created a white concrete shell composed of free curves. Approaching the museum along winding white concrete paths, the visitor barely notices the structure's volume. The very low building fits perfectly into its surroundings. A sluice-like entrance leads into the art gallery. Neither pictures nor sculptures are shown in this apparently unsupported space, just nature, presented using economical means. Two oval openings connect the outside with the inside. The sun provides a rich play of light and shadow over the smooth surfaces, wind moves the threads arranged by Naito, and raindrops persist on the ground as completed forms or form small watercourses on sloping ground. The comprehensive structural calculations and material analyses required to create this building, which blurs the boundary between art and architecture, made it possible to reduce the height of the arches to 4.50 m and the ceiling's thickness to 25 cm. The concrete formwork was created by exactly modelling a mound of earth as a negative form of the museum, the contours of which were based on 3,500 previously identified measuring points. Maximum discrepancies of just 5 mm were permitted in creating the form by computer. The reinforcement was first laid on a layer of mortar, then a special concrete made of white cement and limestone aggregate was added to that within one day, after which it was carefully smoothed and the surface coated with plastic. After a five-week drying phase, the earth was removed and the interior surface coated with a water-resistant finish.





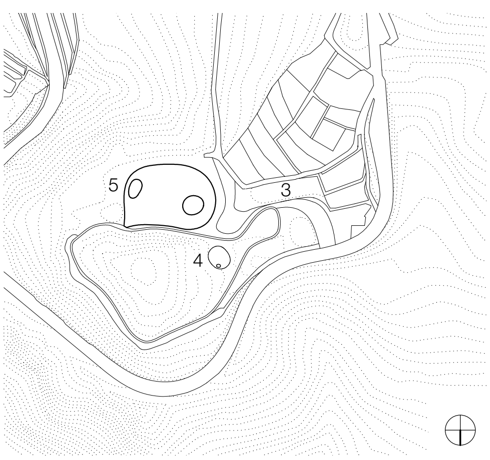




Cross section Scale 1:50

1 Coating, polyvinyl fluoride, transparent
Exposed concrete 250 mm,
Surface, smoothed
2 Water-resistant coating, transparent
Steel-reinforced concrete 200 mm,
Surface, smoothed
Layer of sand 350 mm
Floor slab, steel-reinforced concrete 250 mm
Blinding concrete sub-base, unreinforced
concrete120 mm

a Aerial photo of the building site: The excavated soil was heaped up, compacted and precisely modelled to create the negative form for the Museum.



Cross section • Floor plan
Scale 1:750 site plan
Scale 1:5,000

3 Entry area, dug into the site
4 Café
5 Museum

a

Showroom

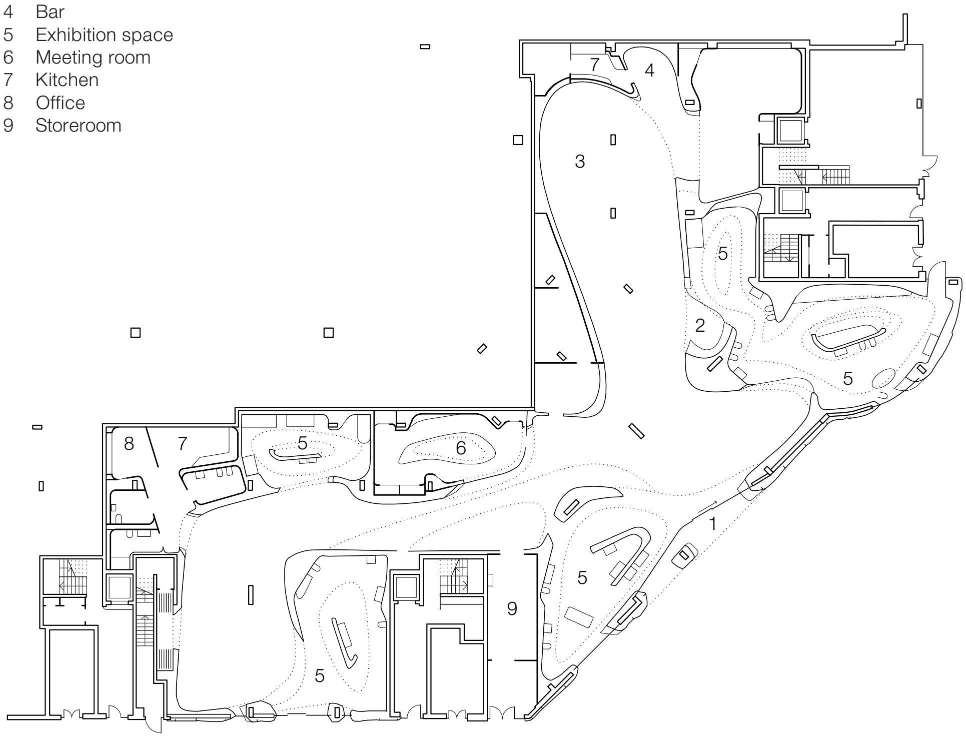
London, GB 2011

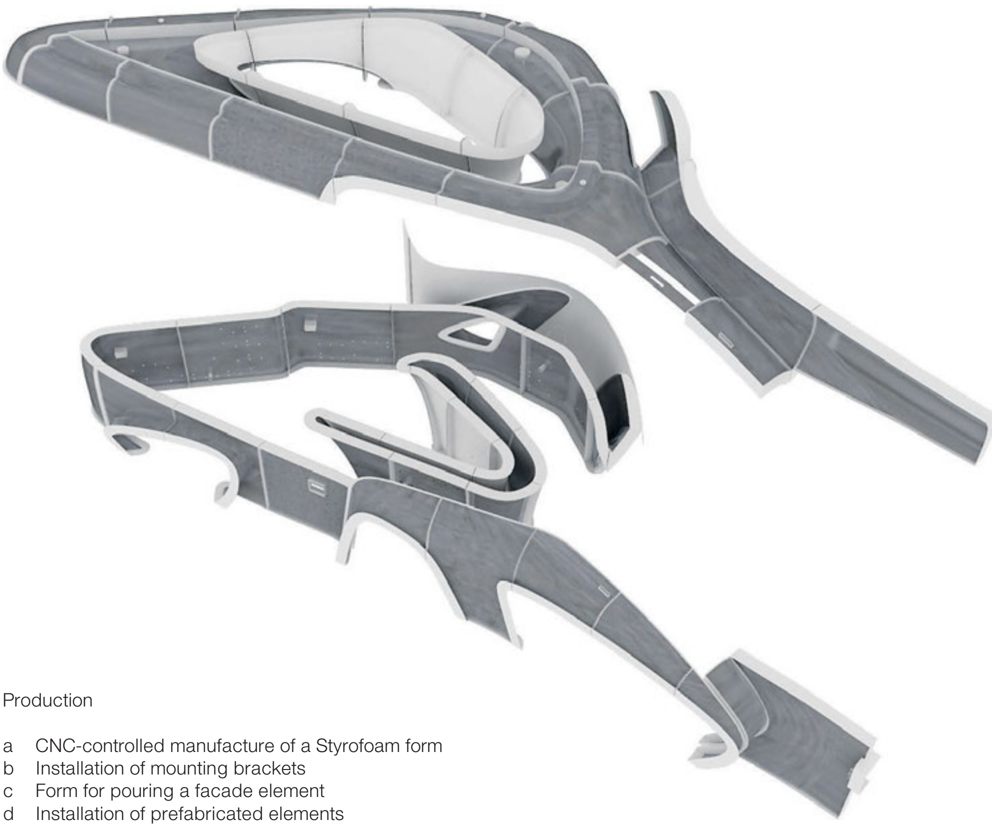
Architects:
Zaha Hadid Architects, London
Zaha Hadid and Patrik Schumacher
Project Managers:
Woody Yao, Maha Kutay
Assistant:
Margarita Yordanova Valova
Structural planning and facade planner:
Buro Happold, London
Concrete construction:
B & T Bau & Technologie, Raubling

The element of water was the source of the architects' inspiration in designing the Roca Gallery in London. Roca, a bathroom fittings and furniture manufacturer, found a suitable location for presenting its products and for training on the ground floor of an existing building. Organic forms extend from the building's outer shell through facade openings and into its 1,100 m^2 interior, where there are almost no corners; all the walls and ceilings merge fluidly into one another.
The architects first designed the cavernous area in three dimensions on a computer, and then divided the curving interior into individual production elements. A Bavarian company took on the challenge of developing and producing the structural elements, which curve through several axes, in detail. One of the most important specifications, apart from a completely even and flawless surface, was to impose as little weight as possible on the existing building. At the same time, structural elements had to be stable enough to support sometimes heavy ceramic products, some of which would be fixed to them. It took more than two years to find the optimum composition of materials and structure. Tests revealed that textile-reinforced, composite fibre components based on concrete, with an aluminium honeycomb core and a total thickness of just 60 mm and a weight of 50 kg/m^2, would be best suited to this context. The concrete mix developed specially for this project bonds well with the aluminium and results in high levels of compressive and bending strength. Polymers added to the mix increased the concrete's plasticity while preventing cracks from forming in the thin-walled concrete elements, especially during transport and installation. For the light-coloured structural elements, white cement was used, the colour of which was determined with the help of numerous samples. Indirect lighting integrated into the curving ceilings emphasises their free forms. All the joints were precisely planned and have completely straight edges. The dark floor, consisting of individually computer-controlled customised ceramic tiles, is precisely adapted to the structure. After a construction period of twelve months, the showroom was opened.

Floor plan
Scale 1:500

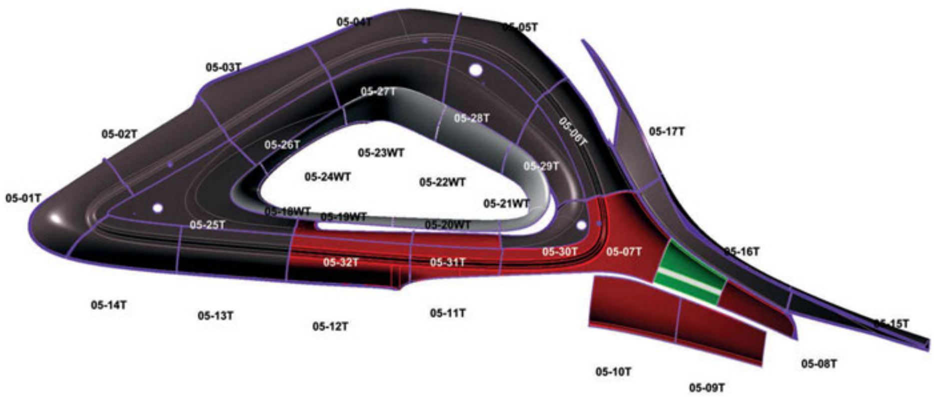
1 Entrance
2 Reception
3 Lounge
4 Bar
5 Exhibition space
6 Meeting room
7 Kitchen
8 Office
9 Storeroom

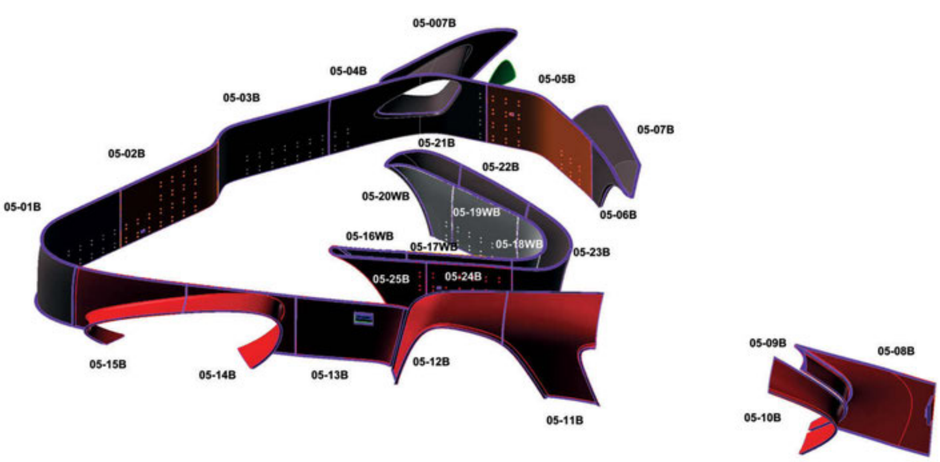




Production

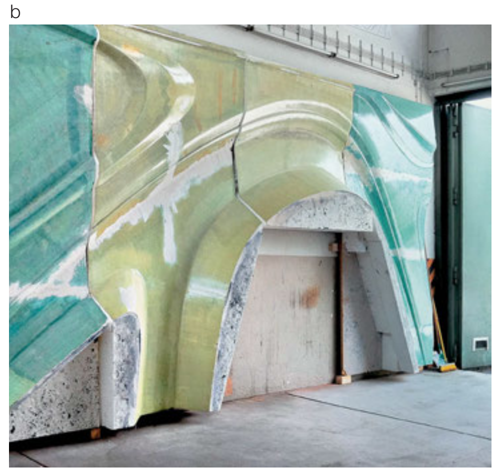
a CNC-controlled manufacture of a Styrofoam form
b Installation of mounting brackets
c Form for pouring a facade element
d Installation of prefabricated elements



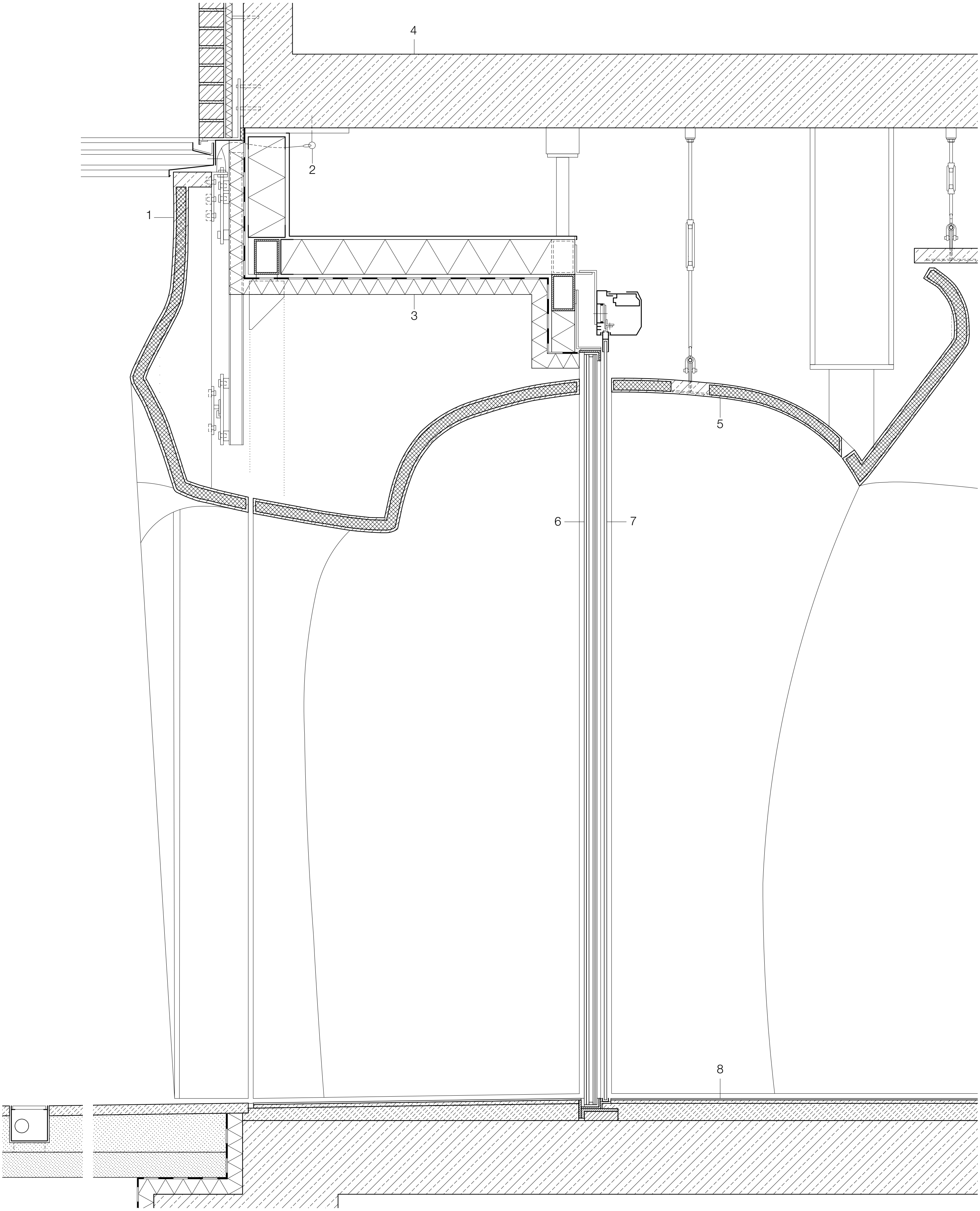



a


b

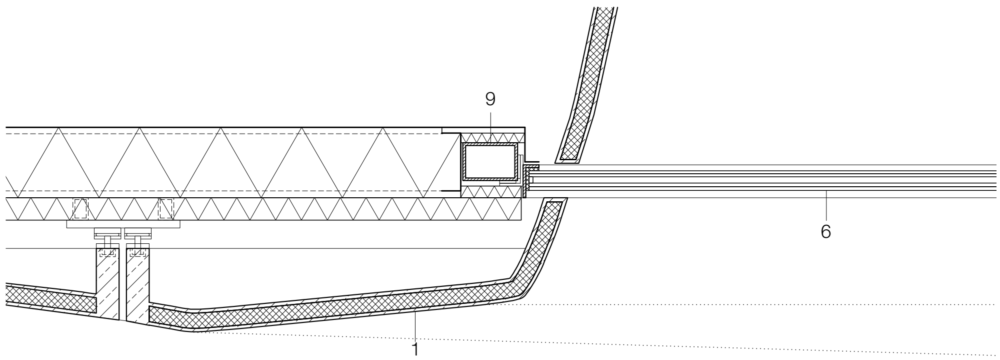

c


d

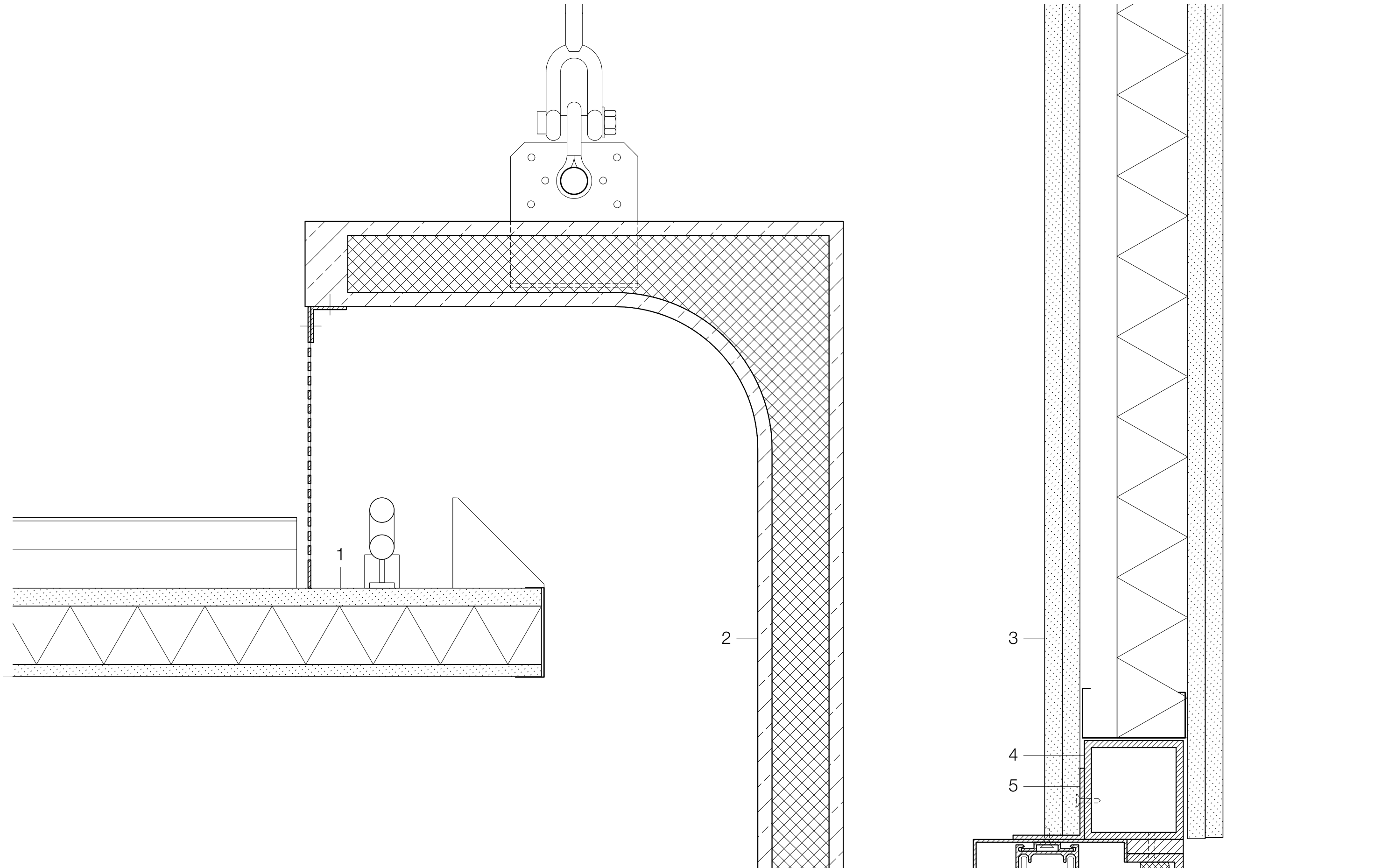

4
2
1
3
5
6
7
8

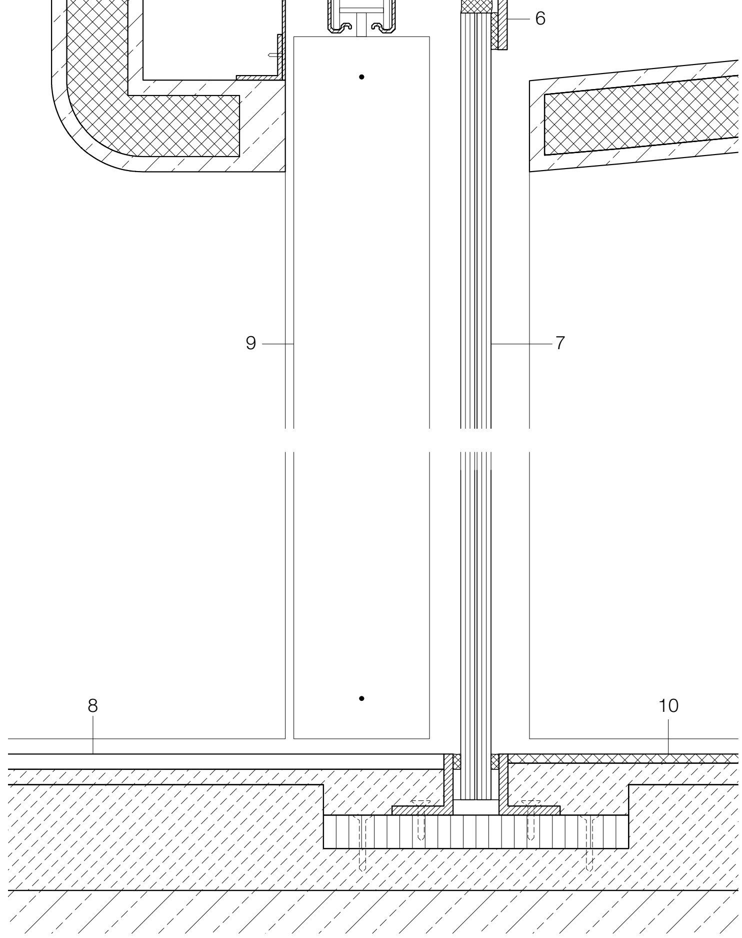
Vertical cross section
Horizontal cross section
Scale 1:20

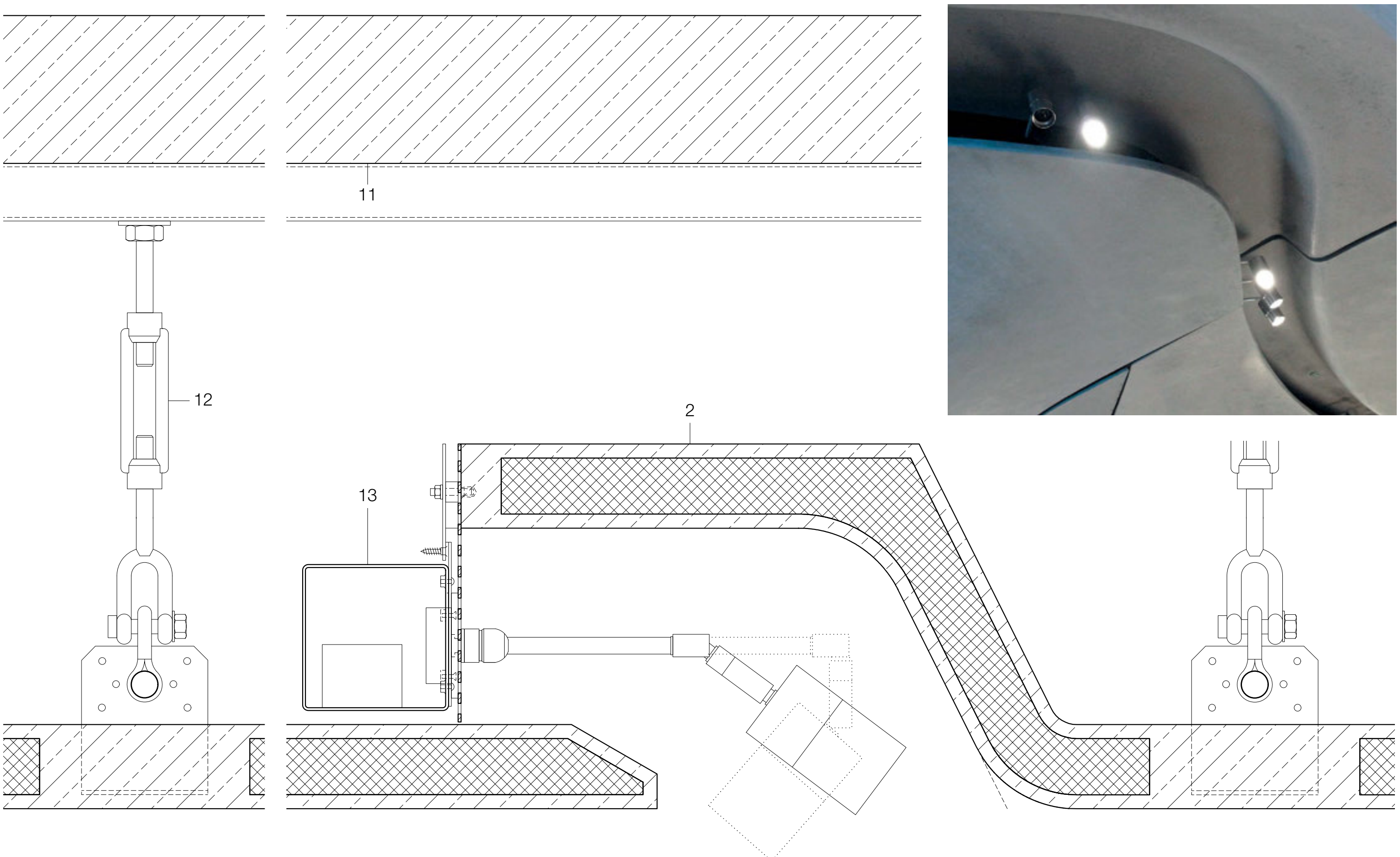
1 Concrete element, textile-reinforced 60 mm
with aluminium honeycomb core: Weight 50 kg/m²
Compressive strength > 45 N/mm²
Bending strength 10 N/mm²
2 Cable securing a concrete element, steel cable ∅ 4 mm
3 Insulation, expanded polystyrene foam, 60 mm
Sealing
Insulation 155 mm
4 Steel-reinforced concrete (existing structure)
5 Inspection hatch, concrete element,
textile-reinforced 60 mm
6 Fixed glazing
Laminated glass 2× 10 mm + space between panes
16 mm + laminated glass 2× 8 mm
7 Sliding door, safety glass 10 mm
8 Epoxy resin 6 mm
Screed, self-levelling 14 mm
Screed 70 mm
Steel-reinforced concrete (existing structure) 300 mm
9 Steel pipe ▱ 100/150/10 mm



aa


1
2
3
4
5
6
7
8
9
10





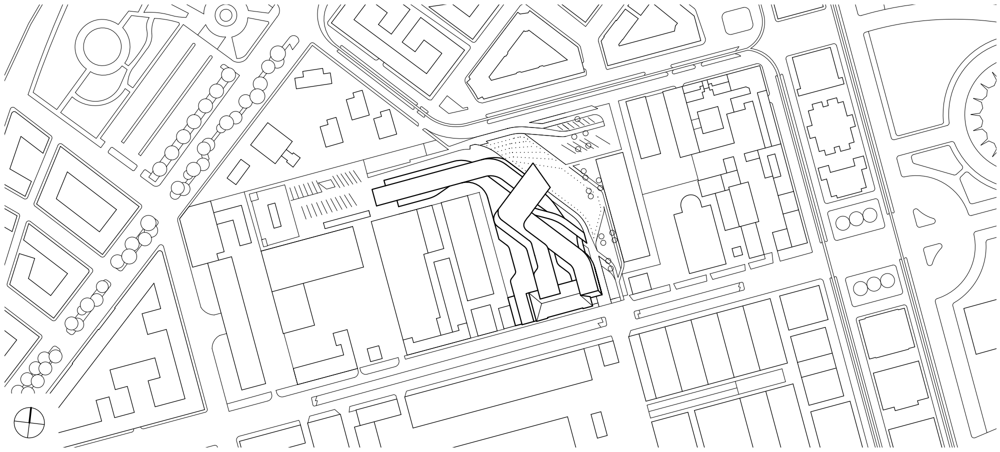
Cross section, detail
Scale 1:5

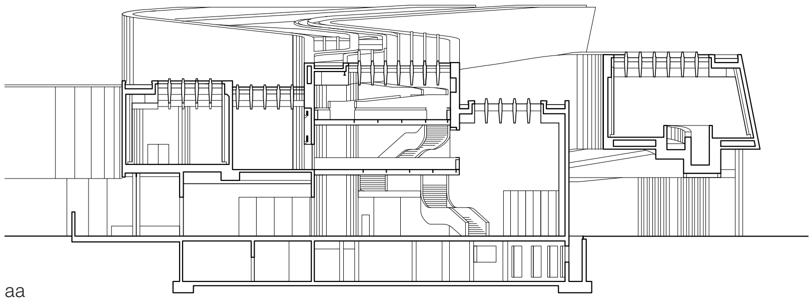
1 Gypsum plasterboard 12.5 mm
Acoustic panelling 50 mm
2 Concrete element, textile-reinforced 60 mm
with aluminium honeycomb core
Weight 50 kg/m^2
Compressive strength > 45 N/mm^2
Bending strength 10 N/mm^2
3 Gypsum plasterboard 2× 12.5 mm
Insulation, mineral fibre 50 mm
Gypsum plasterboard 2× 12.5 mm
4 Steel pipe ⌀ 70/70/5 mm
5 Steel profile ∟ 50/50/3 mm
6 Aluminium profile ∟ 40/40/6 mm
7 Laminated glass 2× 10 mm
with an acoustic foil layer,
PVB (Polyvinylbutyral)
8 Floor structure, meeting room:
Carpet 10 mm
Screed, self-levelling 14 mm
Screed 70 mm
Steel-reinforced concrete (existing structure)
9 Cladding system vertical blinds, motor-operated
10 Floor structure:
Epoxy resin 6 mm
Screed, self-levelling, 14 mm
Screed 70 mm
Steel-reinforced concrete (existing structure)
300 mm
11 Steel-reinforced concrete (existing structure)
12 Suspension brackets
13 Steel pipe ⌀ 104 mm

MAXXI Museum

Rome, I 2009

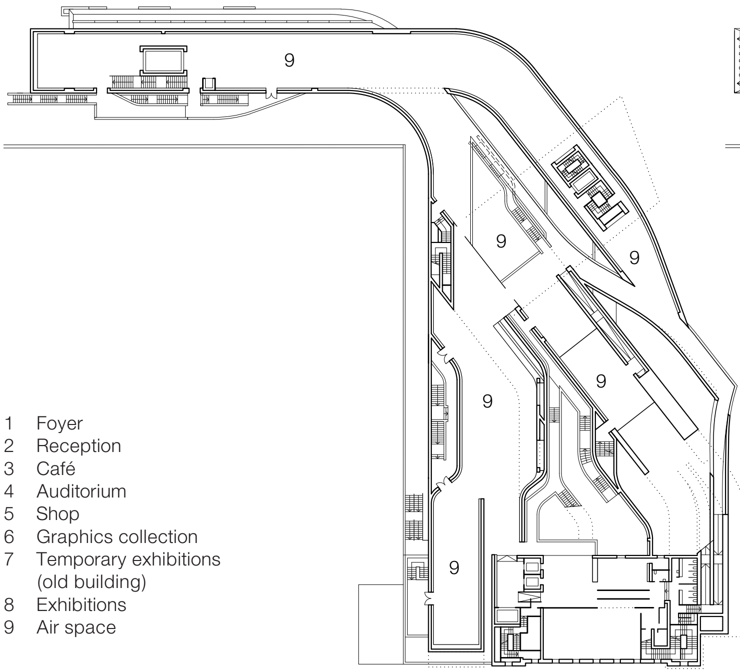
Architects:
Zaha Hadid Architects, London
Zaha Hadid and Patrik Schumacher
ABT, Rome
Assistants:
Gianluca Racana (Project Manager)
Paolo Matteuzzi, Anja Simons, Mario Mattia (Site Manager)
Structural planning:
Anthony Hunt Associates, London
OK Design Group, Rome





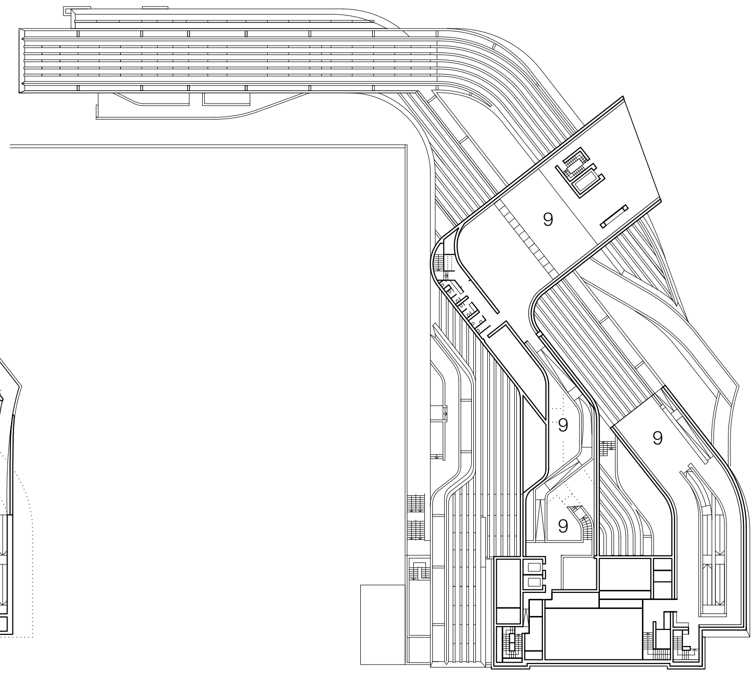
Site plan
Scale 1:6,000
Cross section
Scale 1:750
Floor plan
Scale 1:1,500

Built on a former military site in northern Rome, the Italian National Museum of 21st Century Arts opened in 2010. Variously networked wings emanating from an existing main building lie in an L-shape around an old barracks, smoothly continuing the main orientation of the surrounding urban grid and allowing this “concrete sculpture” to fit into its neighbourhood surprisingly well.
The concrete walls of the gallery section inside serve as free-spanning longitudinal supports up to 30 metres long and define the network of the design. A facing shell provides a neutral background for works of art, conceals the technical equipment required for the museum’s operations, and leaves the ceilings free for carefully formed skylights, from which artwork or partition walls can be hung. Since the building rests solely on its walls, the museum was built entirely without columns. A graphic on the ceiling reminiscent of rails and “blades” made of glass fibre reinforced concrete elements emphasises the flow of the elongated galleries. In contrast to these calm spaces, intersections, ramps and stairs lend the spaces dynamism. Movement is also impressively showcased in the multi-storey foyer and the black stairs and walkways, with their translucent luminous undersides criss-crossing the space throughout the entire height of the building.
A specially developed steel-reinforced concrete with specific additives and components was used to build the Museum. Because of the high levels of reinforcement in the exterior walls and risk of cracks forming in the self-compacting concrete, a very free-flowing concrete was chosen and vibrated by vibrators attached to the outside of the formwork. To prevent cracks from forming during hardening, no concrete was poured from June to September, and the formwork was stripped only after 96 hours during the cooler months. Steel elements were integrated into the intersections of the concrete walls to transfer point loads. Where structurally and statically necessary, concrete pilasters in front of the walls, yet concealed behind cladding, strengthen the walls at various points.

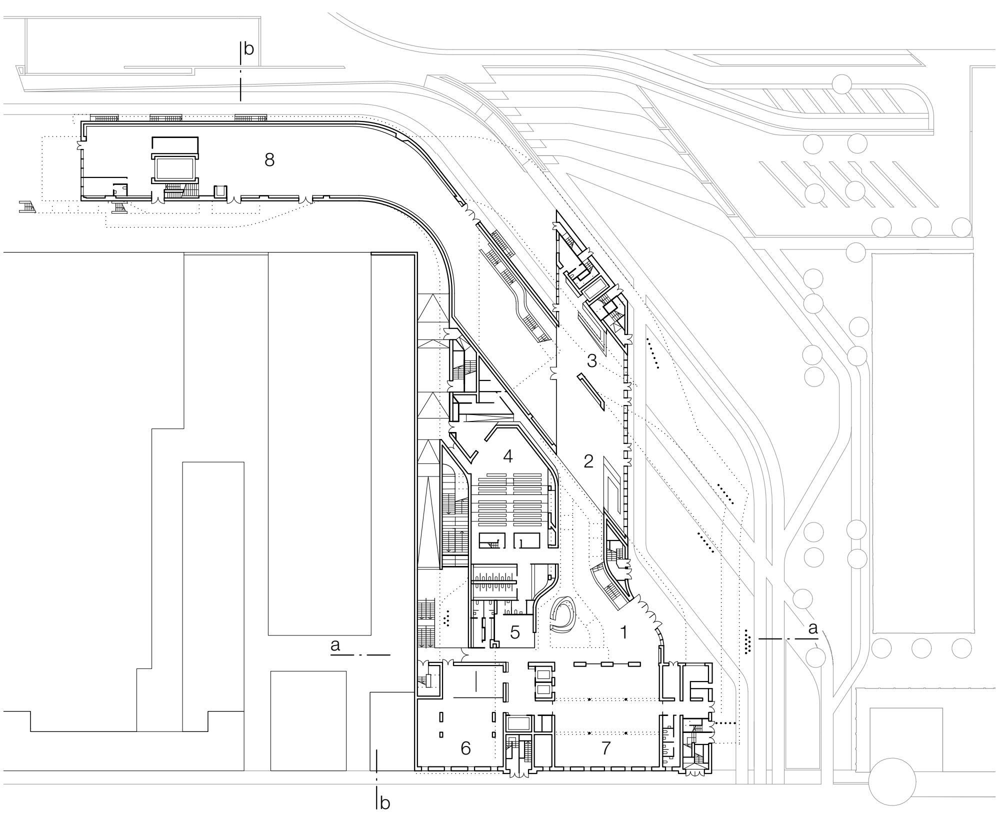


1 Foyer
2 Reception
3 Café
4 Auditorium
5 Shop
6 Graphics collection
7 Temporary exhibitions (old building)
8 Exhibitions
9 Air space

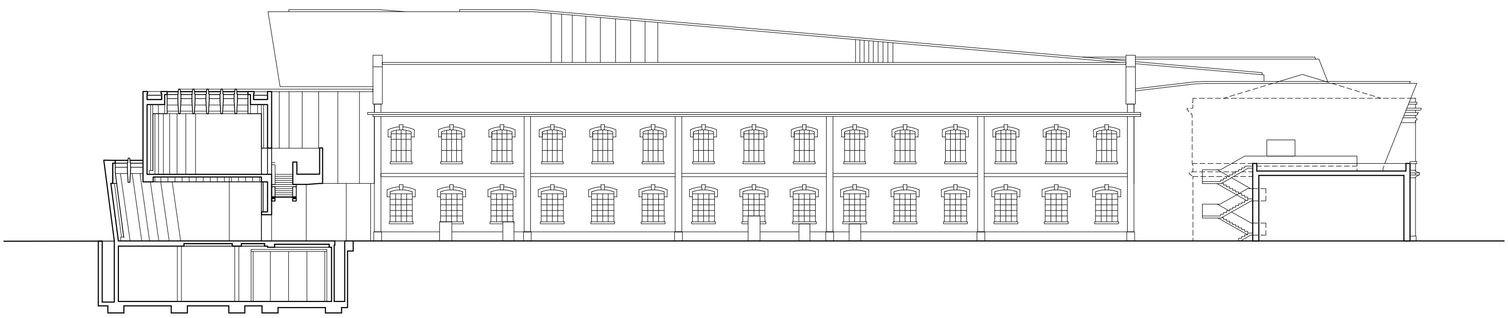
1st floor



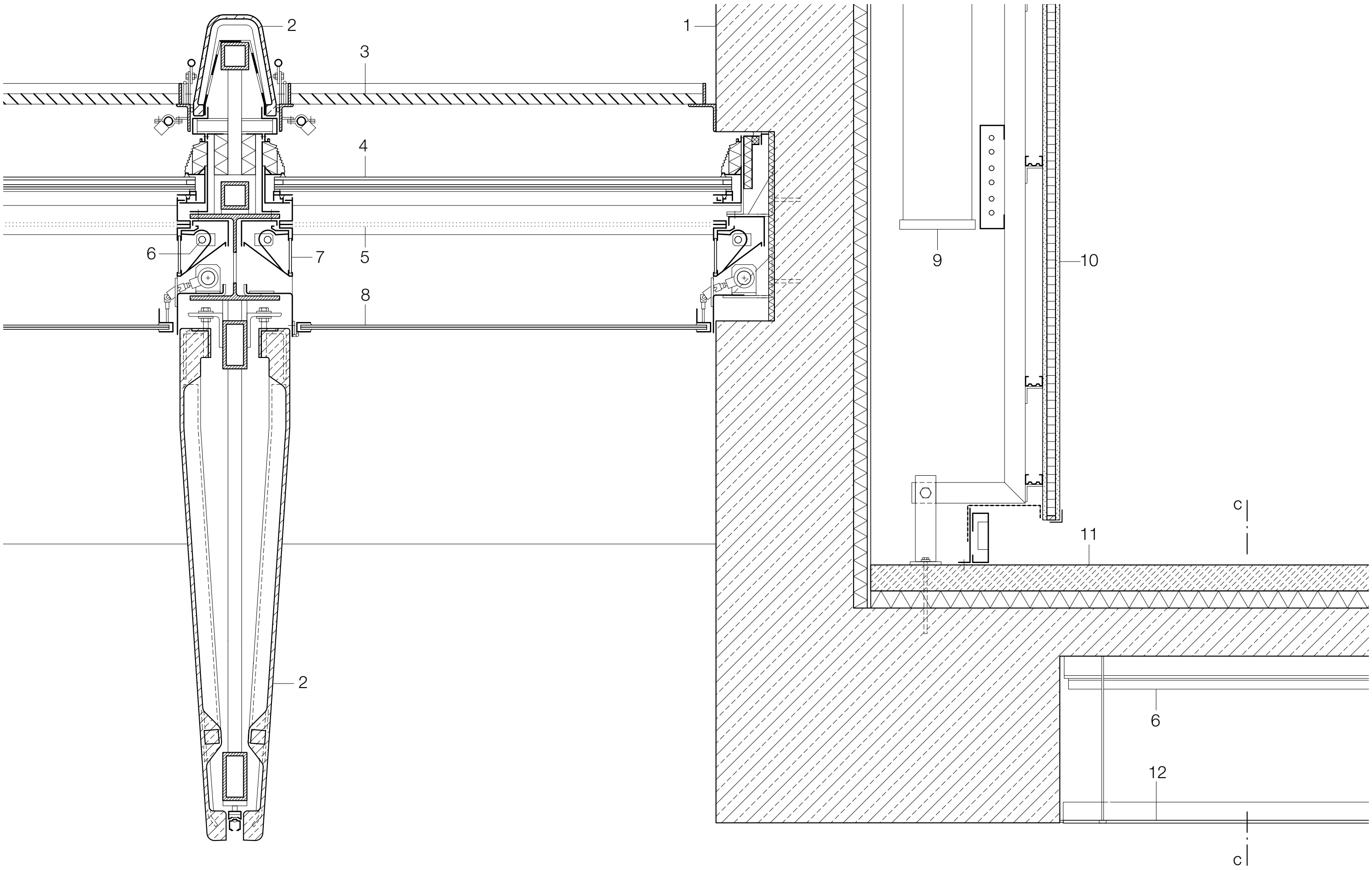
2nd floor



Ground floor

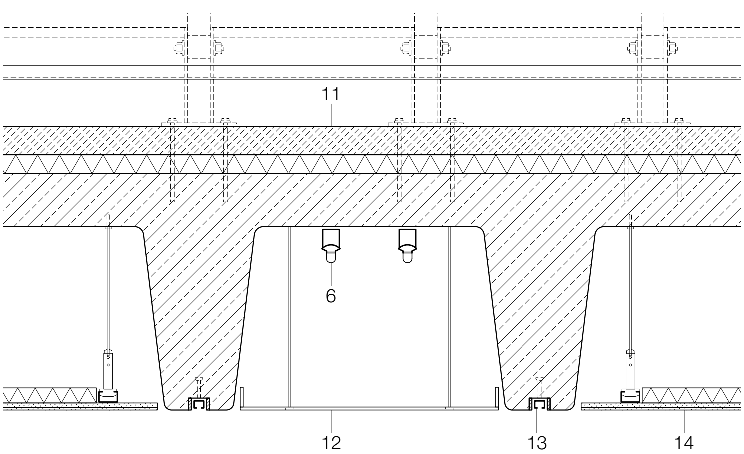


bb

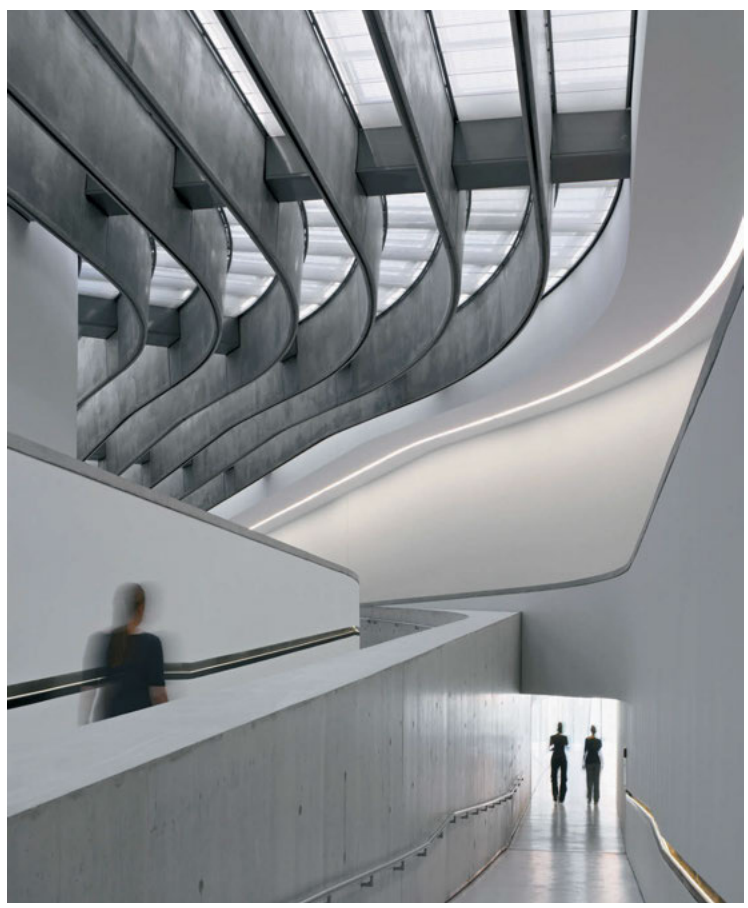


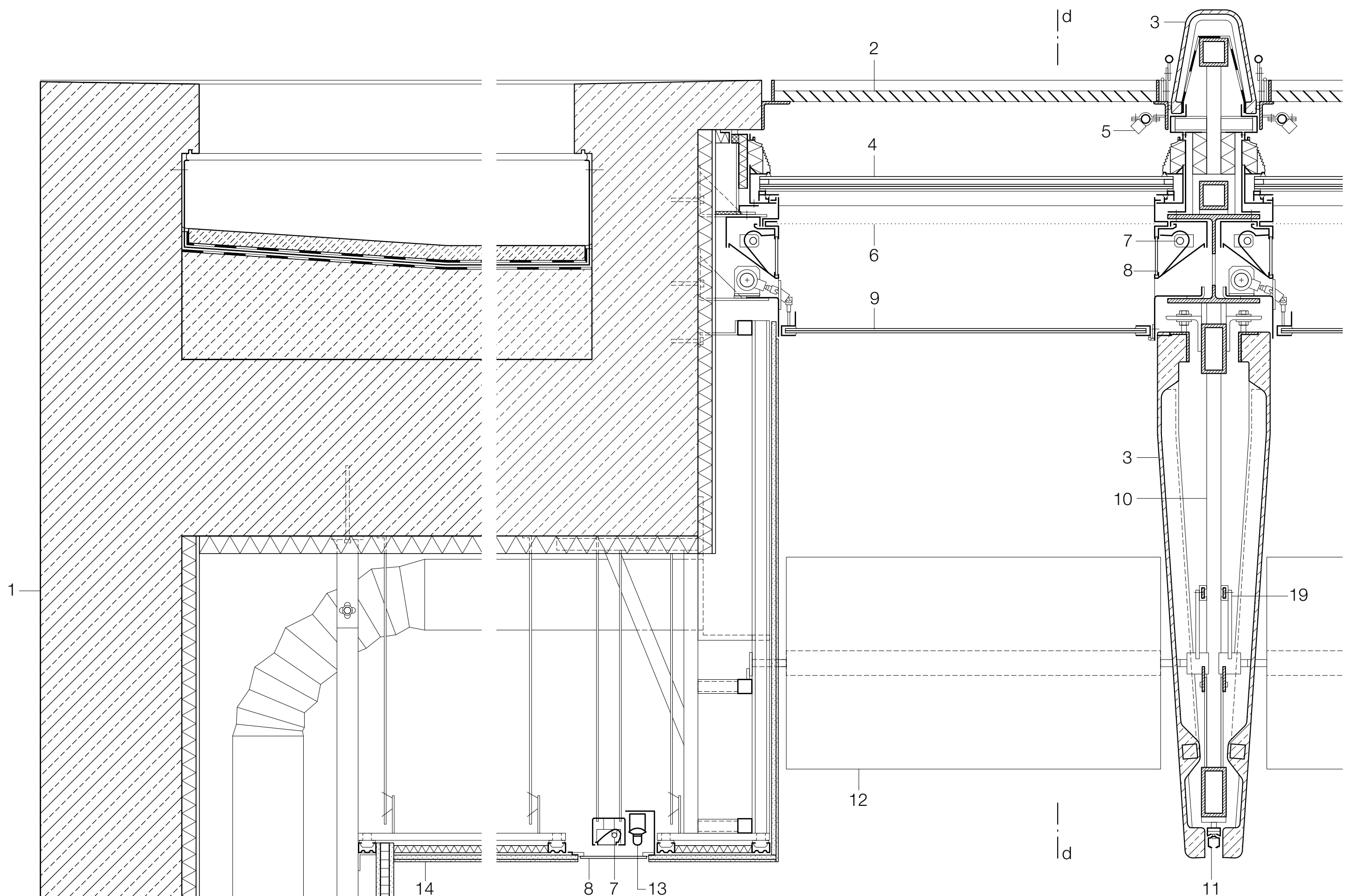
Cross section
Scale 1:750
Vertical cross section, gallery
Scale 1:20

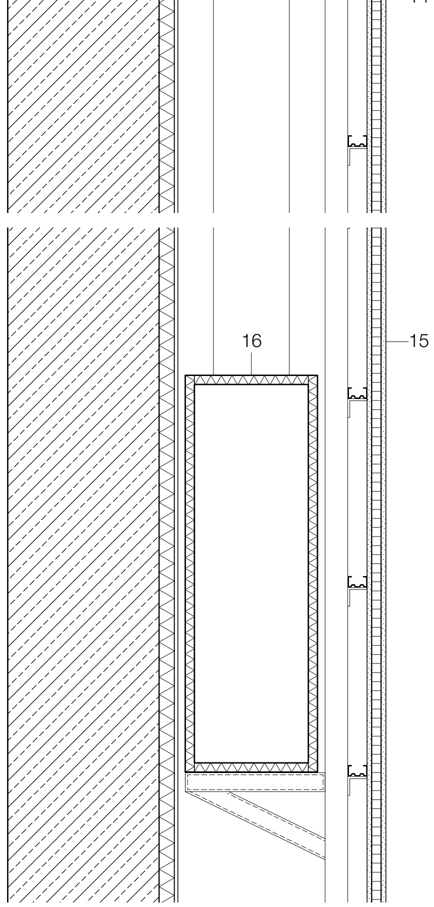
1 Exterior wall, exposed concrete 400 mm
2 Concrete element, glass fibre reinforced
3 Steel grate for diffusing light
4 Solar protection glazing: safety glass 8 + between panes 15 + laminated glass 11 mm
5 Roller blind, completely blocking and filtering light (double)
6 Fluorescent tubes
7 Acrylic glass, translucent 6 mm
8 Laminated glass, extra clear 12 mm
9 Fresh air duct
10 Gypsum plasterboard, glass fibre reinforced, 12.5 mm, MDF 25 mm Gypsum plasterboard, glass fibre reinforced 12.5 mm
11 Floor, epoxy resin
12 Polycarbonate, translucent 8 mm
13 Rail for hanging objects anchored in the ribbed concrete ceiling
14 Acoustic plaster, sprayed on 5 mm Gypsum plasterboard, perforated 12.5 mm Acoustic insulation matting 20 mm

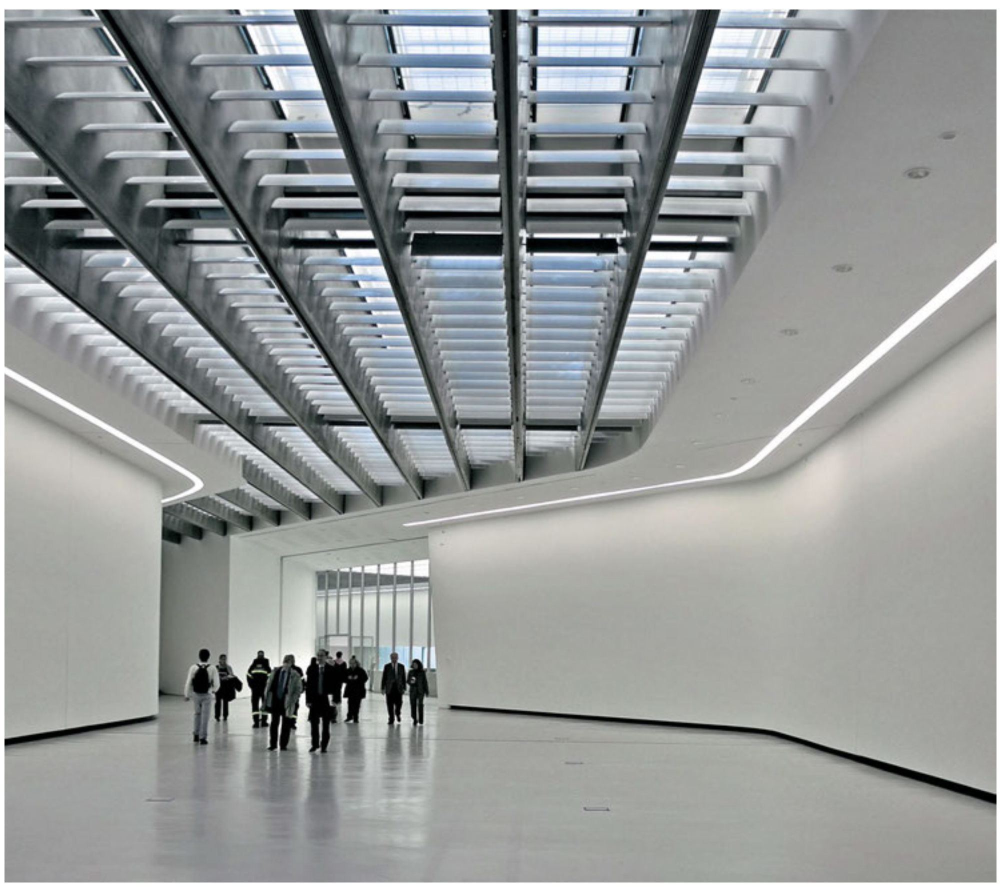


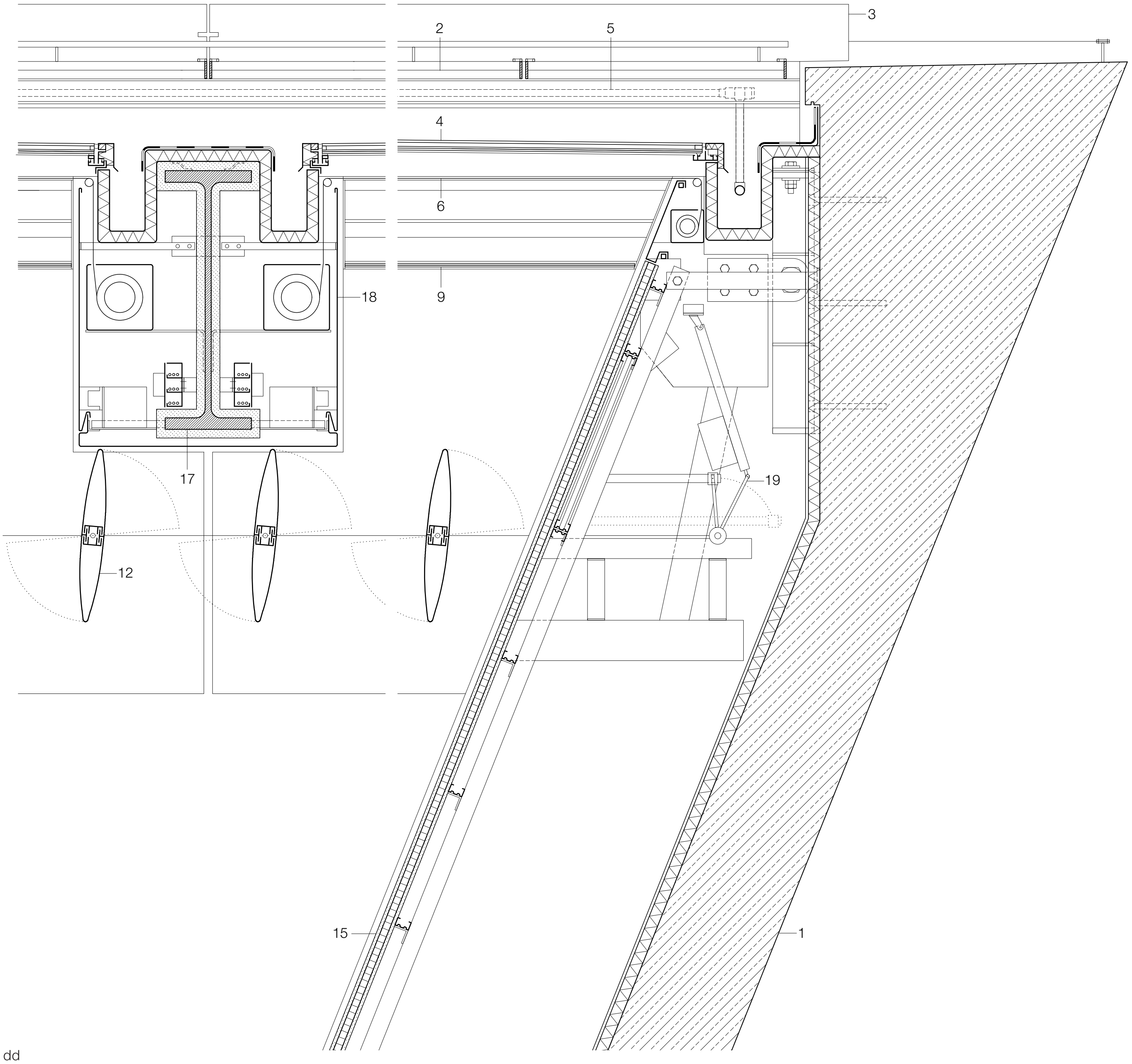
cc




d
3
2
5
4
6
7
8
9
3
10
1
19
12
d
14
8
7
13
11


16
15





dd

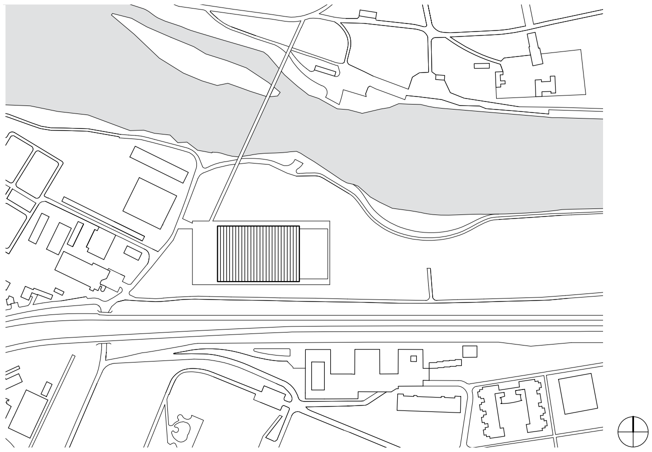
Vertical cross section, gallery 1st floor Scale 1:20

1 Exterior wall, exposed concrete 400 mm
Insulation panel 50 mm
2 Steel grate for diffusing light, zinc-coated, painted
3 Concrete element, glass fibre reinforced 12 mm
4 Solar protection glazing
Safety glass 8 mm + between panes 15 mm + laminated glass 11 mm
5 Window cleaning system, automatic
6 Roller blind for completely blocking light
7 Fluorescent tubes
8 Acrylic glass pane, translucent, light diffusing 6 mm
9 Laminated glass, extra clear 12 mm, mechanically foldable for maintenance and cleaning, three panes, each 600 mm long, mounted in aluminium frames (open joints for ventilation)
10 Sub-structure, steel truss beam
11 Rail for hanging objects from
12 Light-deflecting louvers, aluminium, rotating
13 Emergency lighting, fluorescent tubes
14 Acoustic plaster, sprayed on 5 mm
Gypsum plasterboard, perforated 12.5 mm
Acoustic insulation matting 20 mm
15 Gypsum plasterboard, glass fibre reinforced 12.5 mm
MDF board 25 mm
Gypsum plasterboard, glass fibre reinforced 12.5 mm
Steel sub-structure, zinc-coated
16 Ventilation duct
17 Cross beam, steel profile HEM 900, with fire protective coating
18 Cladding, aluminium sheeting, coated
19 Linear, spindle-drive light-deflecting louvers, electronic

Mülimatt sports education and training centre

Brugg / Windisch, CH 2010

Architects:
Studio Vacchini Architetti, Locarno
Assistants:
Jerôme Wolfensberger, Luciana Bruno, Eloisa Vacchini, Mauro Vanetti
Structual planning:
Fürst Laffranchi Bauingenieure, Wolfwil
Massimo Laffranchi, Armand Fürst

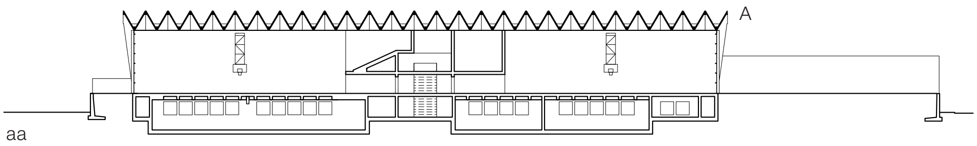


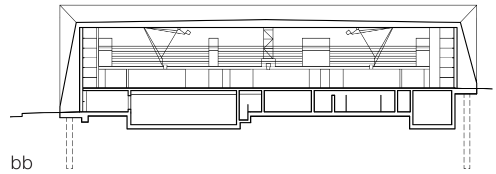
Site plan
Scale 1:7,500

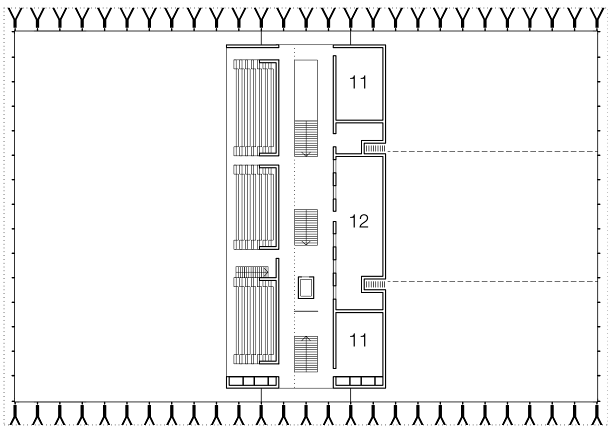
Cross section • Floor plan
Scale 1:1,000

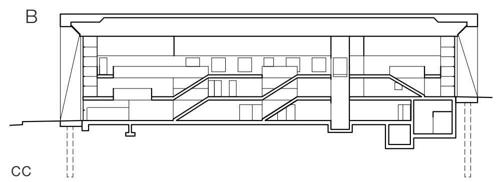
1 Entrance
2 Foyer
3 Multi-purpose space
4 Meeting / theory
5 Gymnasium
6 Teachers
7 Cloakrooms
8 Materials storage
9 Plant room
10 Triple-field sports hall
11 Equipment room
12 Training room

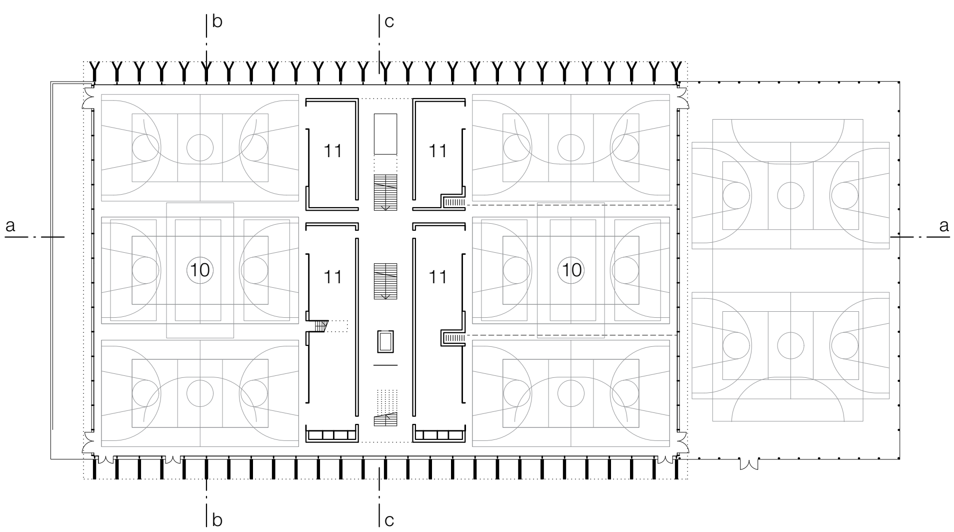
On the banks of the Aare, an overarching folded plate structure made of precast concrete elements consolidates two sports halls, one each for the university of applied sciences and the local vocational education and training centre, into a single complex. Its compact construction and resulting minimised building envelope enable the structure to achieve the "minergy" standard. The roof, the "fifth facade", has the same structure, with the roof and support structure forming a single entity. The roof is entirely coated with a sealant that was poured on in liquid form. Rainwater collects in between the folds and is channelled through grooves in the frame stanchions to the ground.
With its powerful sculptural appearance, the exterior support structure houses a 55 metre wide space without any columns and transparent facades. Precisely developed down to the last detail, the interior's exposed concrete surfaces are of the highest quality.
Although the striking folded structure appears monolithic, it is made of prefabricated elements. This construction method allows for much better control of the cement mixture and production conditions than concrete cast in situ. The formwork used could be opened and closed hydraulically. To ensure better filling of the elements with their v-shaped cross sections, they were concreted with the haunches downwards. It was necessary to optimally deaerate the concrete to create a pore and void-free surface. A self-compacting concrete (SCC) with an aggregate particle size of 0–8 mm was used because of the thin walls and high reinforcement ratio, including sheaths for prestressing cables. To enable the elements to be filled in a single concreting operation and stripped after just 14 hours, a combination of two high-performance super-plasticisers and a viscosity regulator commonly used for SCC was added. After positioning, the installation openings, which were provided with steel cores for connections, were poured with self-compacting, fine-grained concrete, the frames prestressed, and the prestressing points closed with infill concrete. A total of 27 frame units with a section height of 2.59 m and a span of 52.60 m were installed.

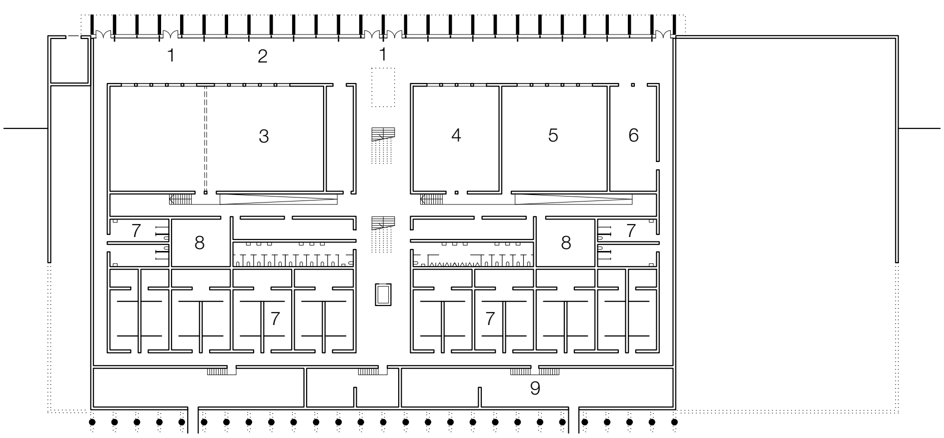

A
aa

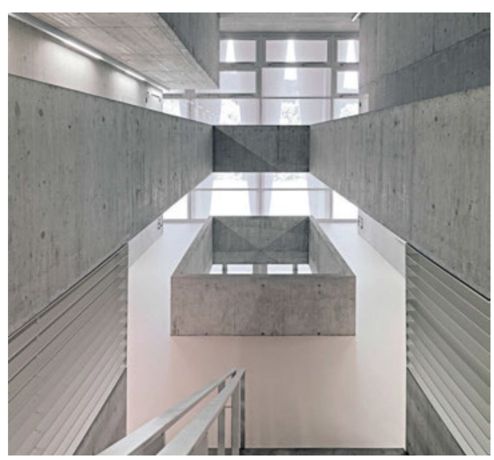

bb

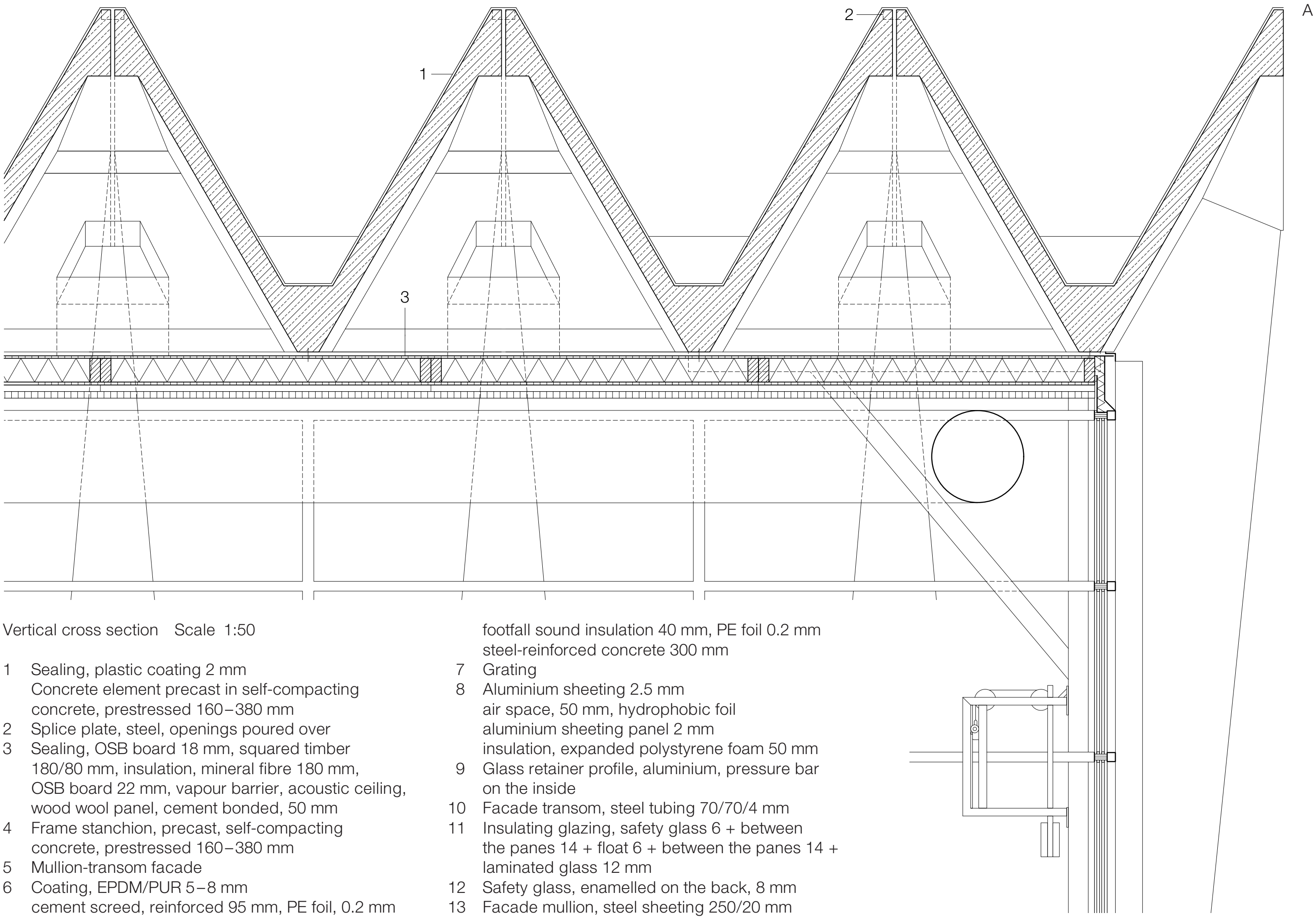

11
12
11


B
cc


b
c
a
11
11
10
11
11
10
a
b
c

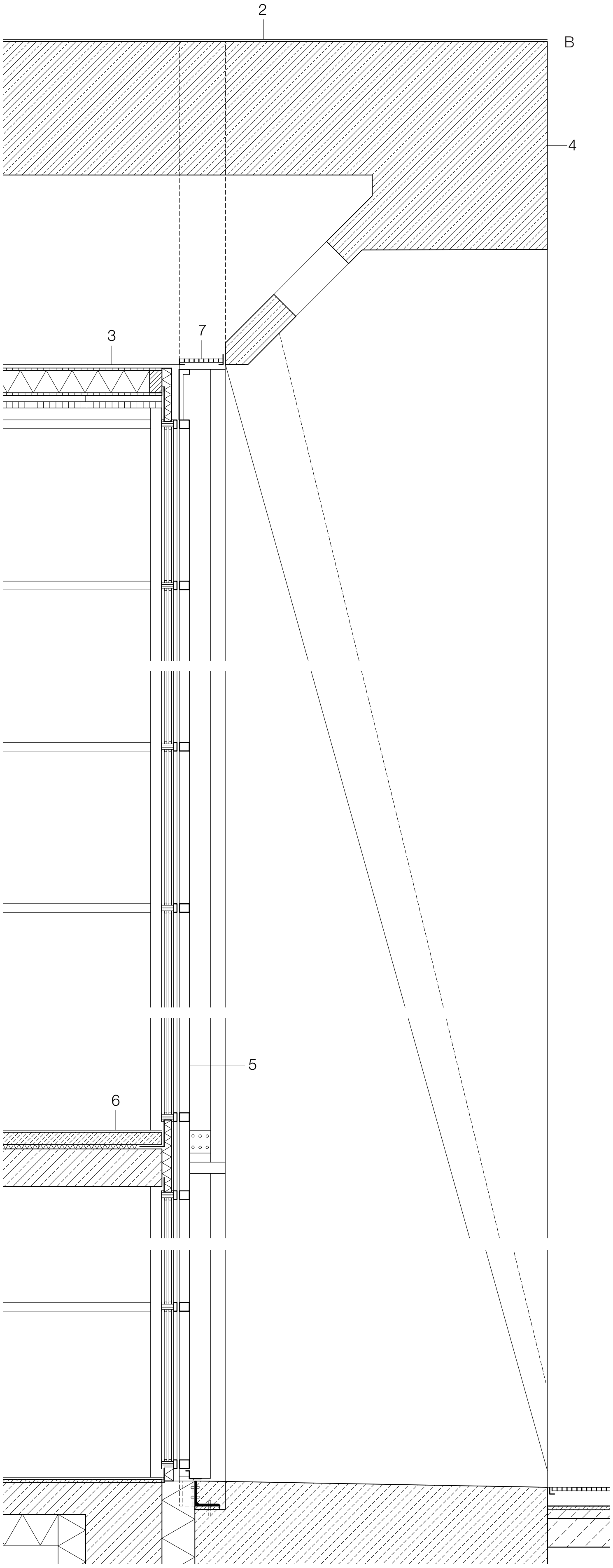

1
2
1
3
4
5
6
7
8
8
7
7
7
9



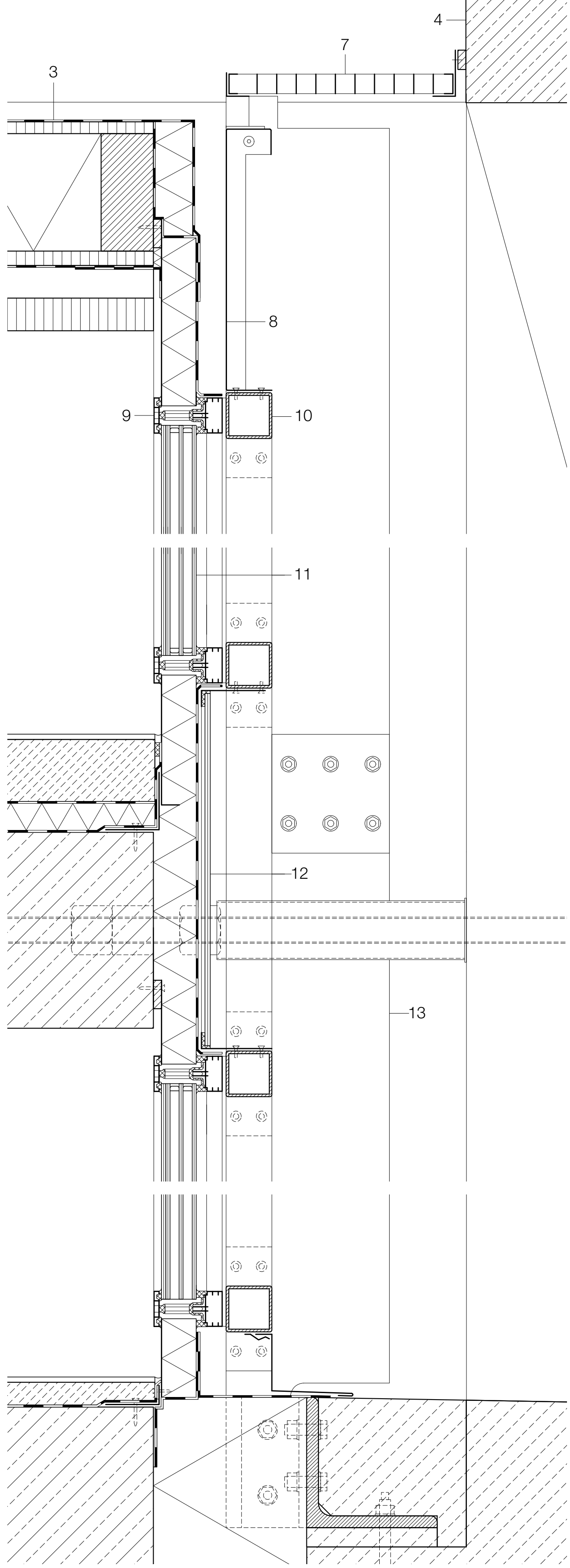


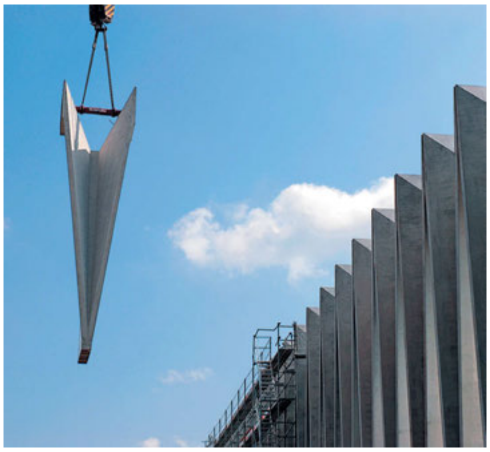
Vertical cross section Scale 1:50

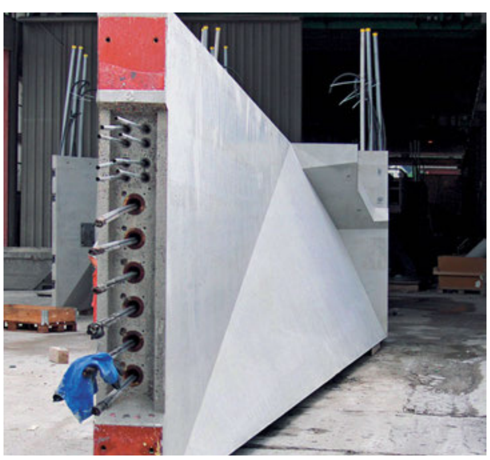
1 Sealing, plastic coating 2 mm
Concrete element precast in self-compacting concrete, prestressed 160–380 mm
2 Splice plate, steel, openings poured over
3 Sealing, OSB board 18 mm, squared timber 180/80 mm, insulation, mineral fibre 180 mm, OSB board 22 mm, vapour barrier, acoustic ceiling, wood wool panel, cement bonded, 50 mm
4 Frame stanchion, self-compacting concrete, prestressed 160–380 mm
5 Mullion-transom facade
6 Coating, EPDM/PUR 5–8 mm
cement screed, reinforced 95 mm, PE foil, 0.2 mm
footfall sound insulation 40 mm, PE foil 0.2 mm
steel-reinforced concrete 300 mm
7 Grating
8 Aluminium sheeting 2.5 mm
air space, 50 mm, hydrophobic foil
aluminium sheeting panel 2 mm
insulation, expanded polystyrene foam 50 mm
9 Glass retainer profile, aluminium, pressure bar on the inside
10 Facade transom, steel tubing 70/70/4 mm
11 Insulating glazing, safety glass 6 + between the panes 14 + float 6 + between the panes 14 + laminated glass 12 mm
12 Safety glass, enamelled on the back, 8 mm
13 Facade mullion, steel sheeting 250/20 mm



Detailed cross section
Scale 1:10



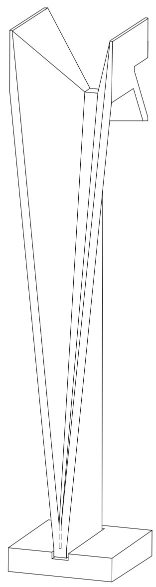




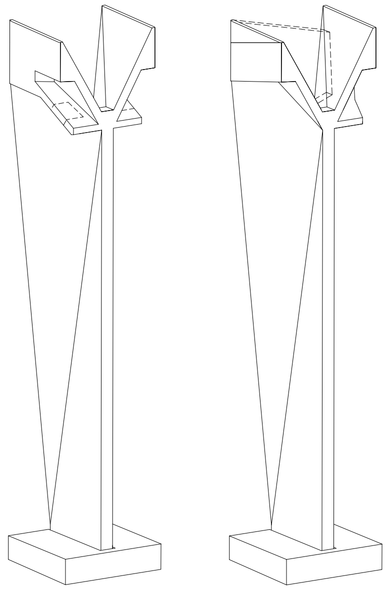
Overview of the folded plate structure modules
Scale 1:500

Vertical cross section
Horizontal cross section
Precast steel-reinforced concrete element
Scale 1:100

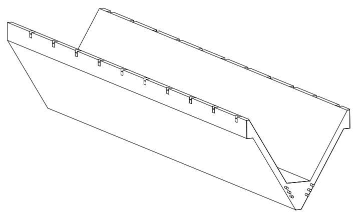
a Frame stanchion, standard
b Frame stanchion, ends of the hall
c Central element, frame beam
d Course of the prestressing cables



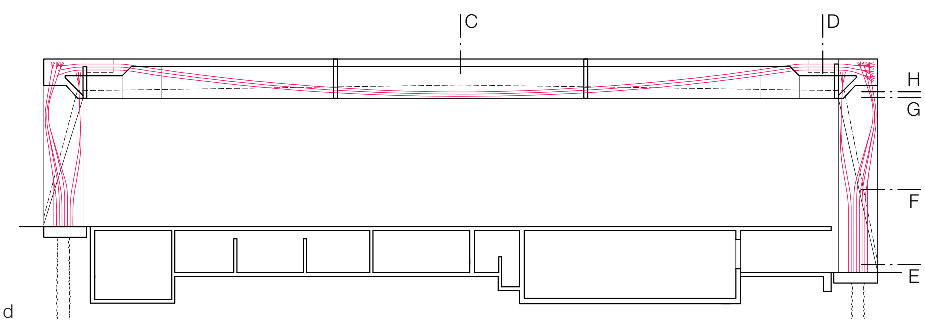
a



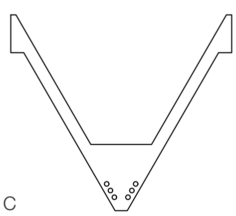
b



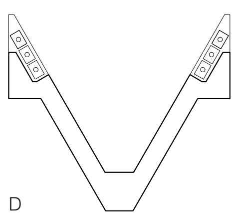
c



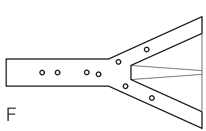
d



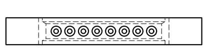
C



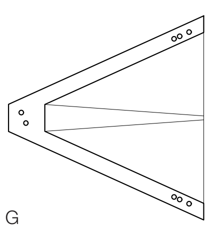
D



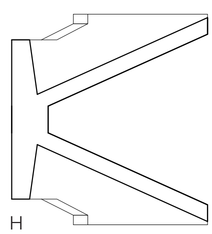
F



E



G



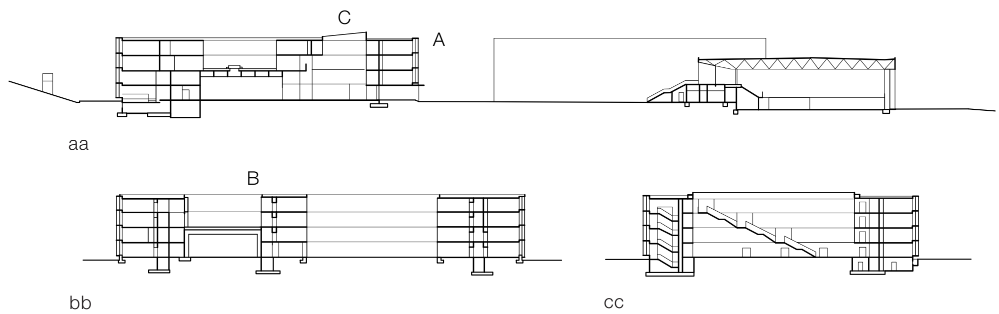
H

Vocational colleges

Recklinghausen, D 2008

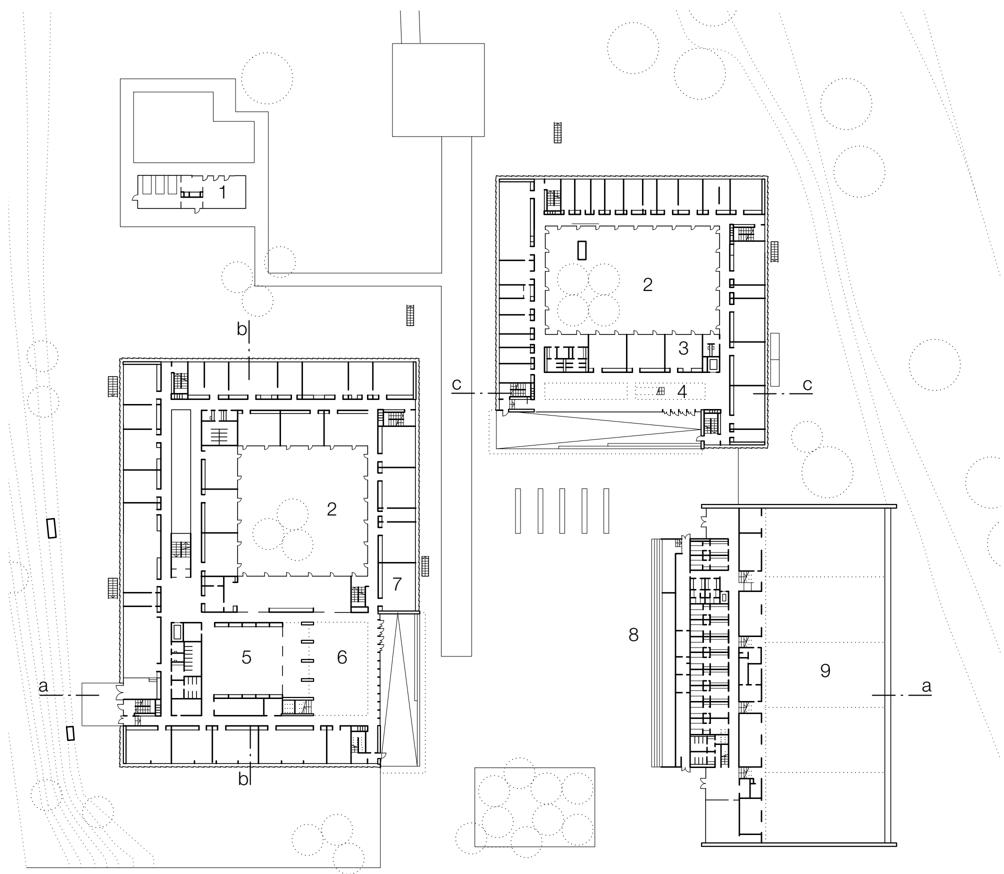
Architects:
scholl architekten partnerschaft
scholl.balbach.walker, Stuttgart
Rainer Scholl, Wolfgang Balbach,
Michael Walker
Assistants:
W. Elflein, R. Fetzer, M. Hügle, S. Lindenau,
D. Olschewski, J. Schust, C. Schwerdfeger,
J. Seiffert, H. Wiest
Structural planner:
Bollinger + Grohmann Ingenieure, Frankfurt/M.

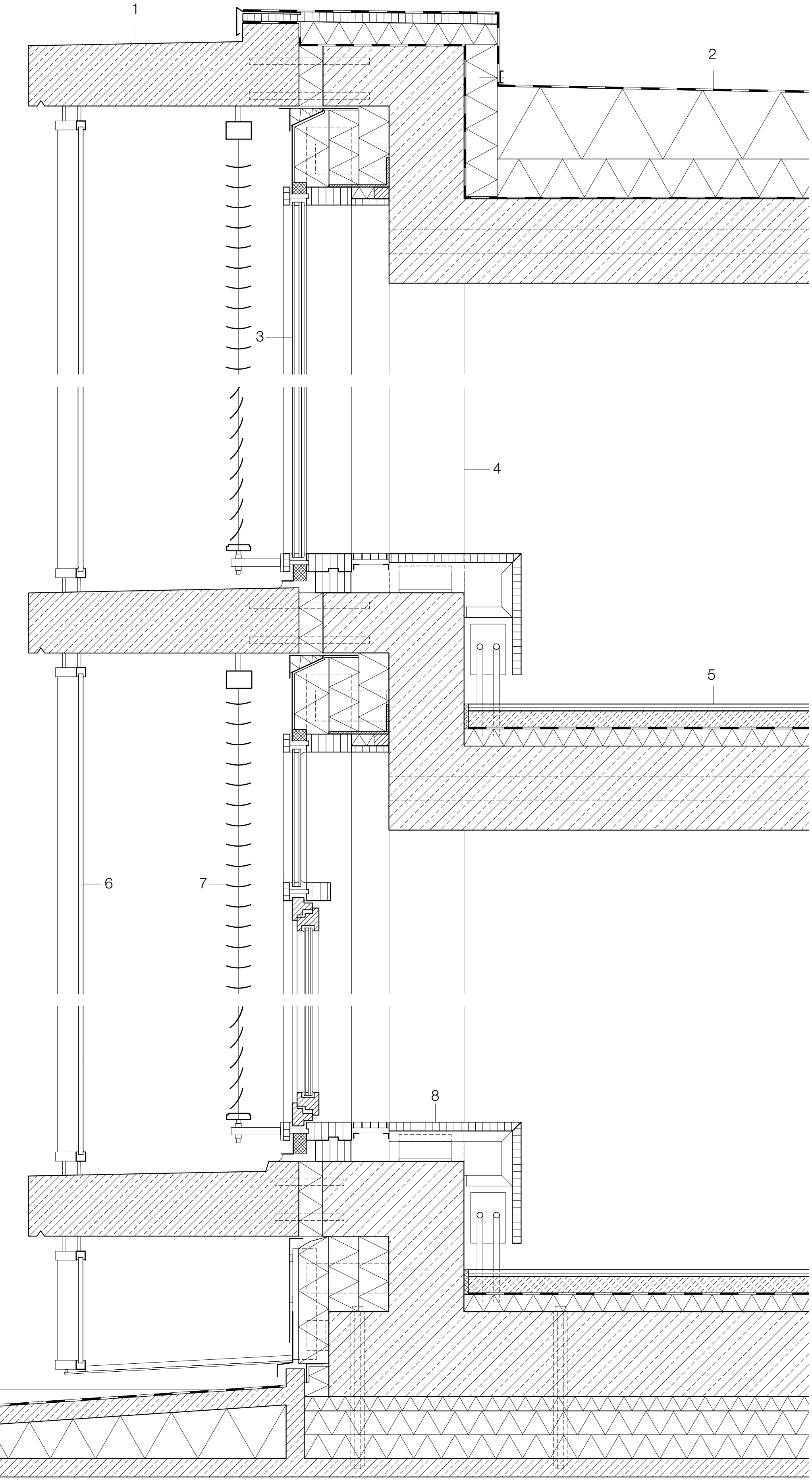
When the Recklinghausen district government decided in 2001 to build a new building complex on a disused coal mine site instead of renovating two independent vocational colleges, it also wanted to send a positive signal to a region affected by changes to established economic structures. A five-field sports hall for public events and a coal mine gas power plant complete the ensemble of the two schools for about 4,500 students and 200 teachers.
The solid structures, made of steel-reinforced concrete flat roofs and longitudinal walls and columns, largely dispense with cladding to improve energy efficiency. Surfaces were built using high-quality exposed concrete in exposed concrete class SB4. Formwork seams and clamping holes were regularly positioned without visible joints between sections of construction work in continuous wall surfaces, comprising both a main design element of the access areas and a stone-like facade. A built-in cupboard zone along corridor walls houses washbasins and cloakrooms as well as ventilation and heating distribution systems, so the focus stays on the architectural space and its high-quality surfaces.
A double-shelled glass facade with floor-to-ceiling slanting panes of glass in front of an external buffer zone that also lets air in is characteristic of both school buildings. It protects the interior mullion-and-transom structure, as well as the sun protection with fixed glazing, from vandalism and the effects of the weather. The slender openings were designed only to allow smoke to escape and for maintenance purposes since the rooms are equipped with a controlled ventilation and heat recovery system that is integrated into the concrete ceiling to regulate the temperature in elements of the building. Lightweight metal ventilation ducts concreted into the ceiling slab are ribbed on the inside, providing the largest possible heat exchange surface. This enabled the structures' storage mass to be integrated into systems regulating its comfort and energy use with a modest investment outlay. The pleasant air quality and comfortable temperatures of the rooms are proof of how well the innovative ventilation concept works.



Cross section
Floor plan
Scale 1:1500

1 Greenhouse
2 Inner courtyard
3 Break snacks counter
4 Entry hall Herwig-Blankerz Vocational College
5 Assembly hall Max-Born Vocational College
6 Entry hall
7 Library
8 Outdoor stairs
9 Sports hall

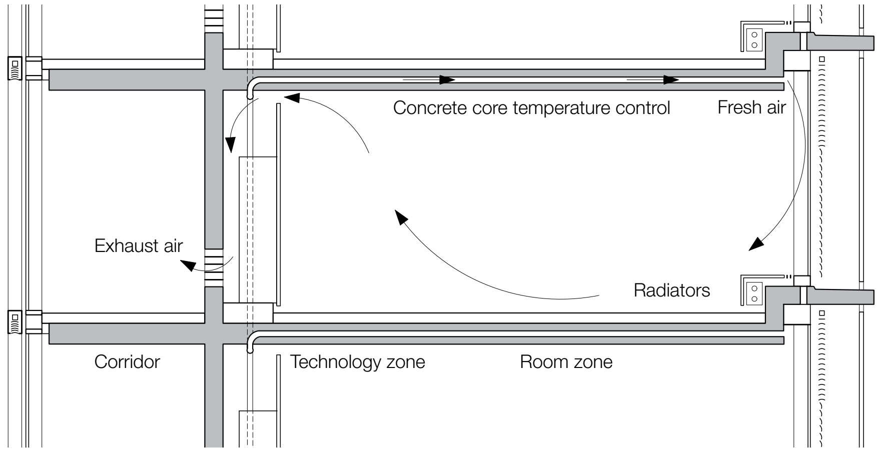




A

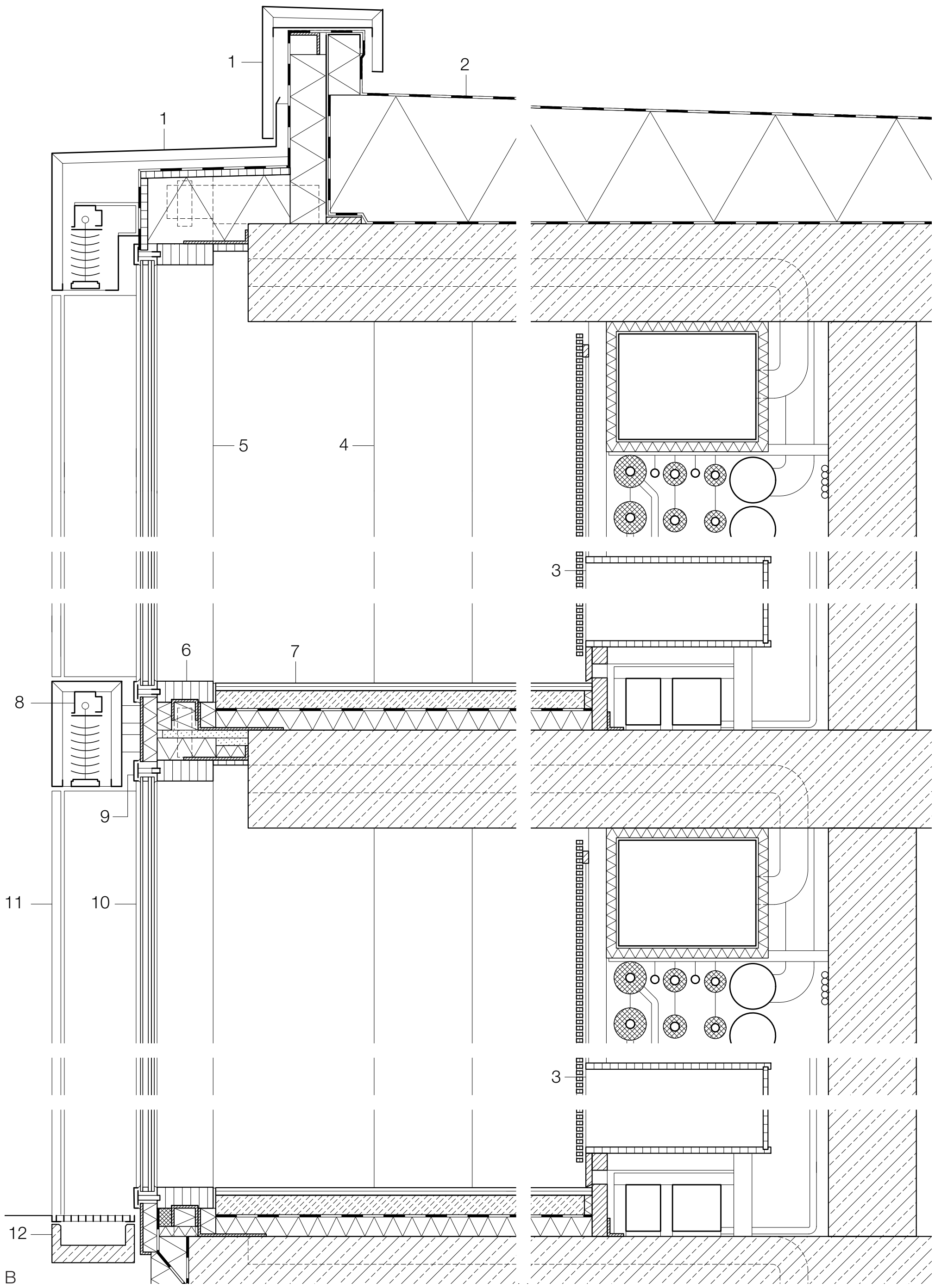
Vertical cross section
Scale 1:20

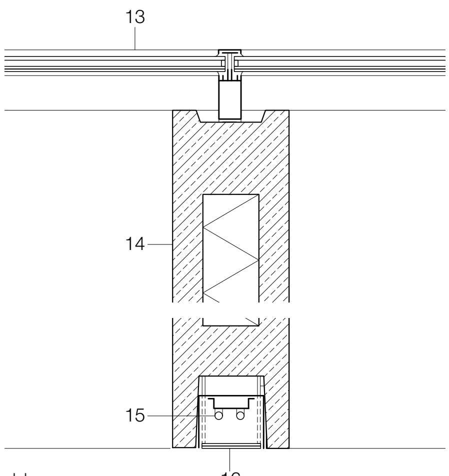
1 Precast exposed concrete element 200 mm
2 Roof structure:
Sealing, plastic foil
Insulation (sloping) EPS 200–320 mm
Insulation EPS 125 mm
Vapour barrier
Steel-reinforced concrete flat roof 280 mm
3 Solar protection glazing U = 1.1 W/m²K comprising safety glass 8 mm + 16 mm between panes + laminated glass 12 mm
4 Steel-reinforced concrete columns 250/250 mm
5 Floor structure:
Parquetry panels, oak 23 mm
Screed 55 mm, separating layer
Footfall sound insulation 5 mm
Insulation 55 mm
Steel-reinforced concrete flat roof 280 mm with ventilation pipes, lightweight metal ∅ 80 mm for regulating the concrete core temperature
6 ESG 15 mm
7 Blinds with daylight control
8 Plywood boards, birch 30 mm on a steel profile sub-structure
9 Sealing, plastic, poured on in liquid form
Cantilever slab, precast steel-reinforced concrete with core insulation 300 mm



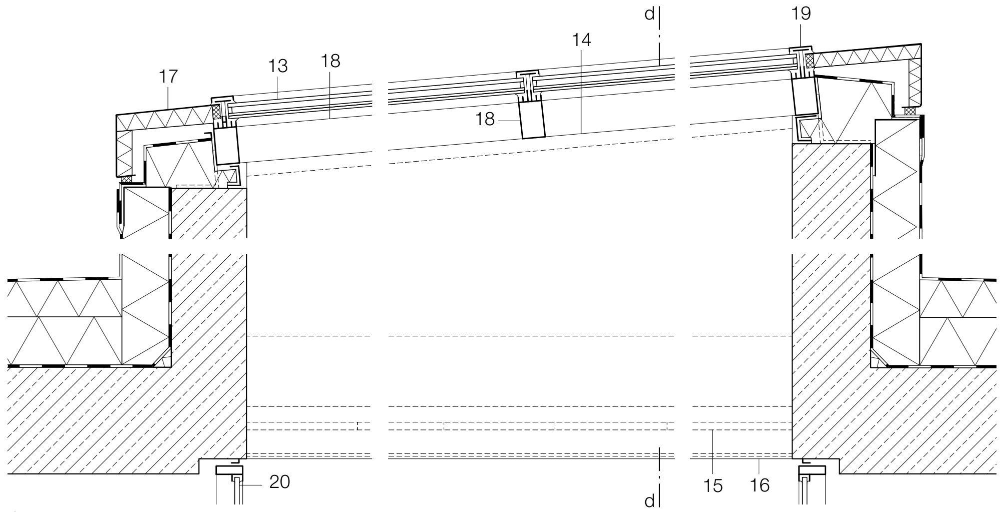
Plan cross section
Scale 1:100

Vertical cross section
Scale 1:20





dd



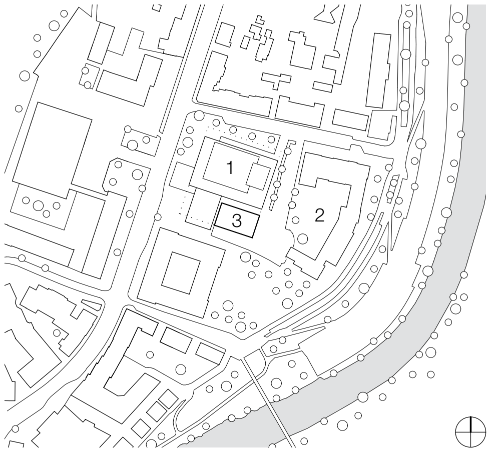
C

1 Aluminium sheeting, chamfered, 3 mm
2 Roof structure:
Sealing, plastic foil
Insulation (sloping) EPS 200–320 mm
Vapour barrier
Steel-reinforced concrete flat roof 280 mm with ventilation pipes, lightweight metal ∅ 80 mm for regulating the concrete core temperature
3 Built-in cupboards:
Birch veneer plywood 19 mm
with integrated technology zone and ventilation transfer flow
4 Steel-reinforced concrete column ∅ 280 mm
5 Mullion, glulam, oak 150/60 mm
6 Transom, glulam, oak 150/60 mm
7 Floor structure:
Parquetry panels, oak 23 mm
Screed 55 mm
Separating layer
Footfall sound insulation 5 mm
Insulation 55 mm
Flat steel-reinforced concrete roof 280 mm with ventilation pipes, lightweight metal ∅ 80 mm for regulating the concrete core temperature
8 Blinds with daylight control
9 Cover strip, aluminium 30/60 mm
10 Solar protection glazing
U = 1.1 W/m²K comprising
safety glass 8 mm + 16 mm between panes + 2× laminated glass 12 mm
11 Aluminium panel, hung
12 Facade drainage gutter, precast concrete element
13 Solar protection glazing,
can be walked on, U = 1.1 W/m²K comprising safety glass 10 mm + 16 mm between panes + laminated glass 14 mm
14 Beam, precast steel-reinforced concrete element 310/925–1800 mm, with hollow core insulation
15 Strip lighting, staggered
16 Laminated glass made of 2× safety glass 4/175 mm and translucent foil
17 Aluminium sheeting, chamfered 3 mm
on an insulation panel
18 Aluminium profile 115/60 mm
19 Clamping profile with
aluminium cover strip 60/12 mm
20 Smoke protection glazing G 30 laminated glass made of safety glass 5 mm + PVB 0.8 mm + safety glass 5 mm

School extension

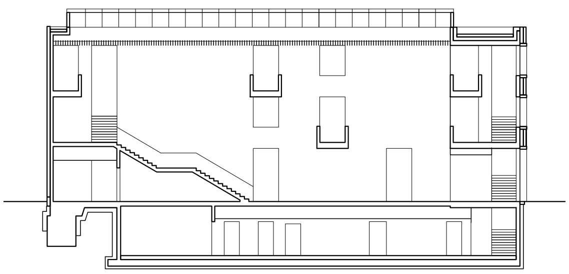
Marburg, D 2010

Architects:
Hess / Talhof / Kusmierz
Architekten und Stadtplaner, Munich
Assistants:
Werner Schürer, Veronika Seitz, Sarah Michels, Bettina Schneck, Heike Unger, Nicola Schick, Alexandra Häsler
Structural planning:
A. Hagl Ingenieurgesellschaft, Munich

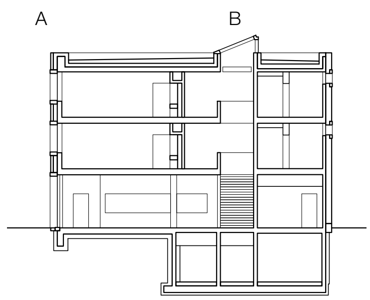


Site plan
Scale 1:6,000

In 2005, the City of Marburg held a competition to redesign the Stadthalle (city hall), built in 1969, and extend the adjoining Martin Luther School.
All the main utility rooms of this compact passive house face south, the ancillary rooms north. A central access area between them, lit from above, links all the storeys along the building's entire length.
The interiors feature robust surfaces reduced to just a few materials: exposed concrete with a fine wood-grain structure, slit and painted acoustic cladding and rubber floors. The exposed concrete surfaces in C30/37 steel-reinforced concrete were built in SB2 quality, which entails certain specifications of texture (T2), porosity (P2), a consistent colour (FT2) and evenness (E1). Cracks were not permitted to be more than 0.15 mm wide. Formwork pattern plans determined the dimensions of the formwork panels, the sequence of concreting and the number and position of anchor holes, which were closed with protruding, bonded fibre cement anchor hole plugs. Trial surfaces in the basement served as reference surfaces for the quality of the completed surfaces.
The school's southern and eastern facades were the first part of the new Stadthalle's shell, with its extension following immediately afterwards in a second phase of construction (due for completion in 2015). Non-bearing, precast concrete elements evoke the existing structure: Their relief-like surfaces show a negative impression of the old washed concrete cladding, which was made using synthetic matrices. To achieve the desired granulated surface, the forms were made using an idealised piece of washed concrete enlarged to 120 %. This 6 × 3 m template was made larger than the individual completed pieces to make it possible to take impressions for various areas, creating variety in the relief. Each matrix had to be cleaned after two pieces had been concreted and could be reused about 20 times. The completed parts were rendered hydrophobic after stripping and drying and given a graffiti protection coating on the schoolyard side. Deeper precast elements with smooth surfaces frame the windows and doors, lending the building envelope plasticity.



aa



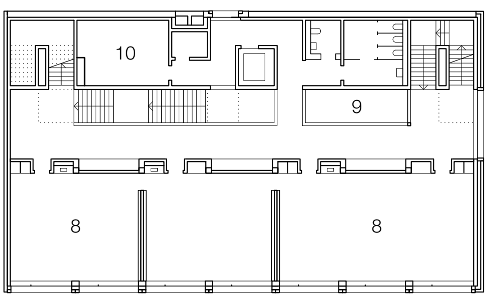
bb

Cross section • Floor plan, scale 1:500

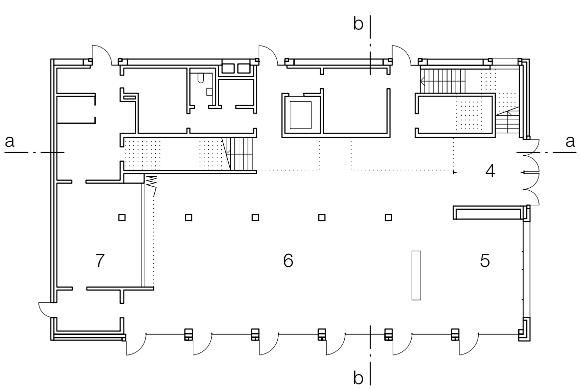
1 Existing Stadthalle
2 Existing school
3 School extension
4 Porch
5 Lounge
6 Break hall / cafeteria
7 Food counter
8 Classroom
9 Air space
10 Teaching materials

Pictograms, construction phases

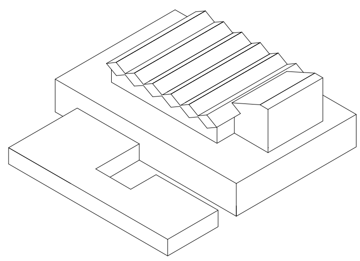
a Existing Stadthalle
b School extension, completion 2010
c Conversion, extension to the Stadthalle, completion 2015



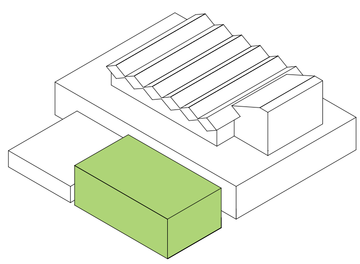
1st floor



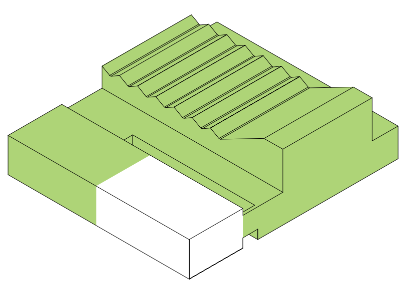
Ground floor



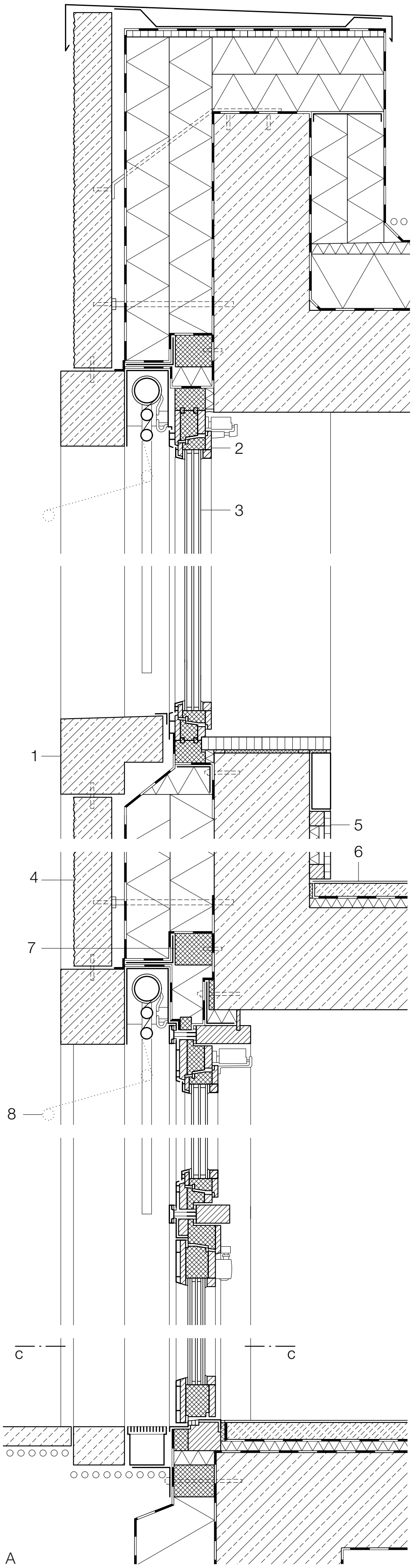
a



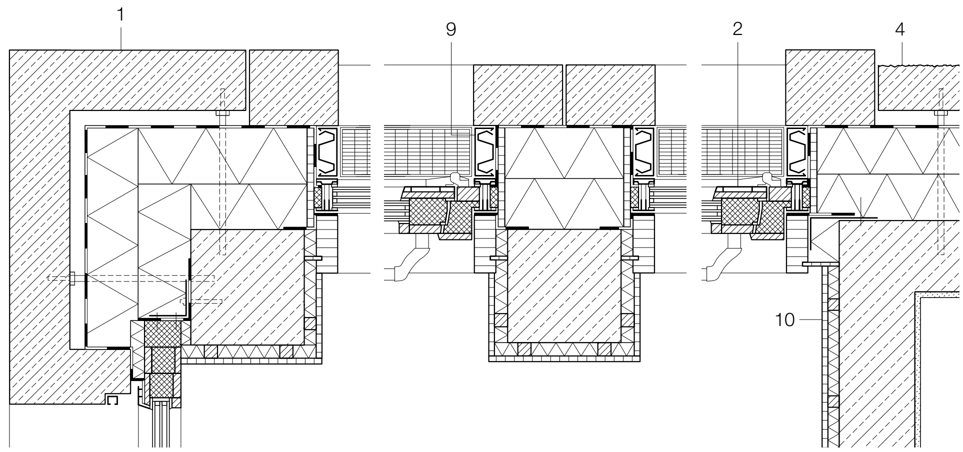
b



c

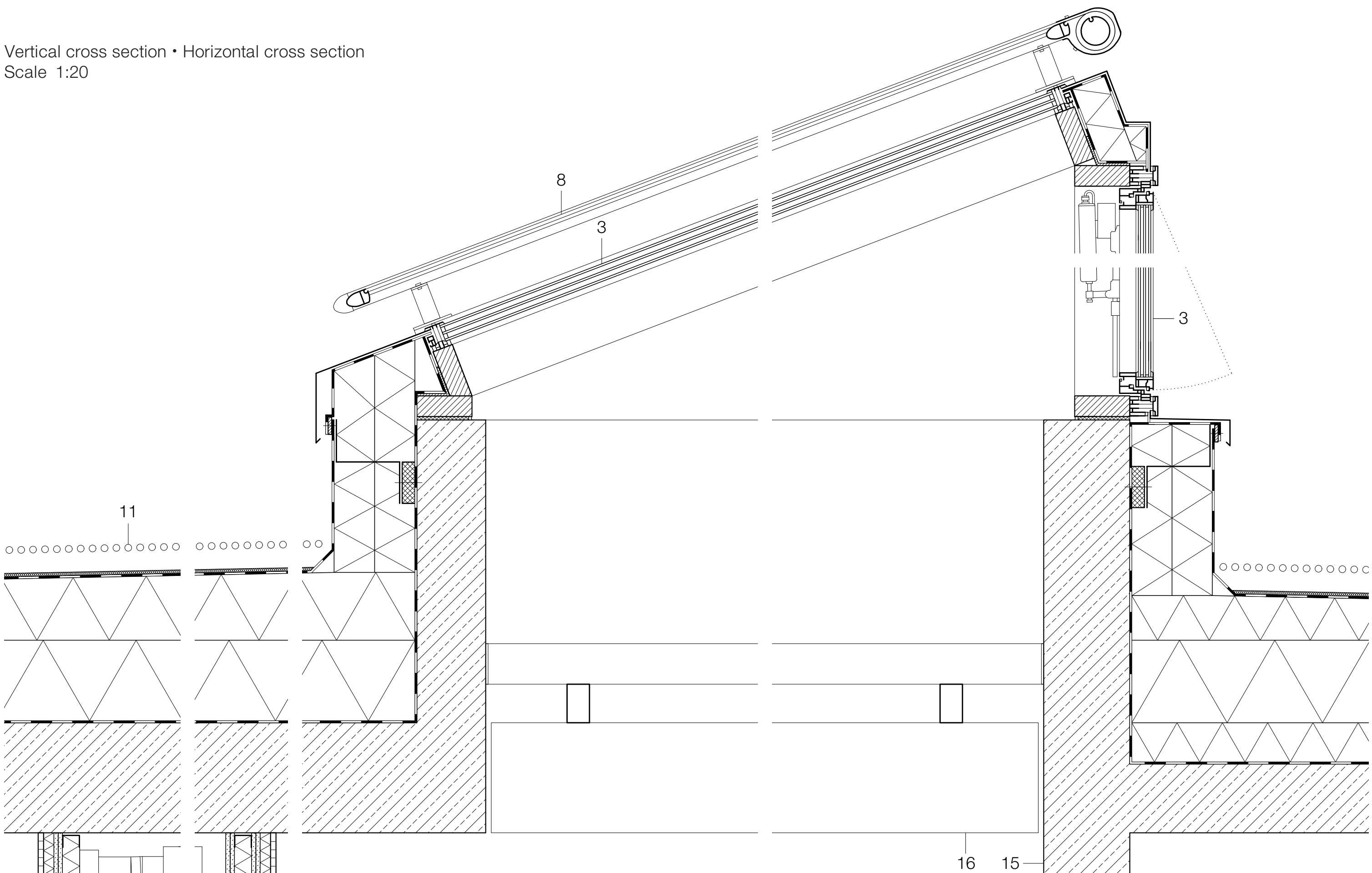


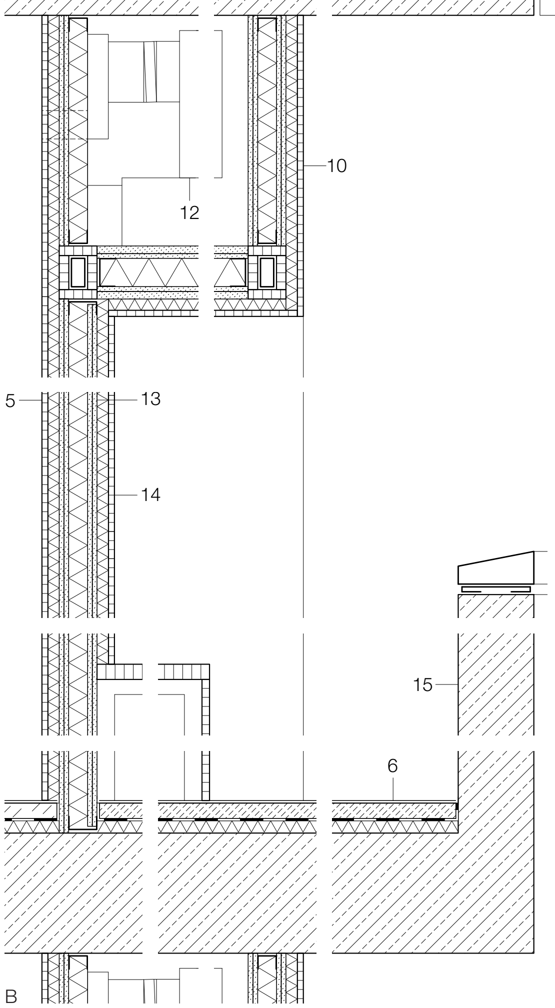
A



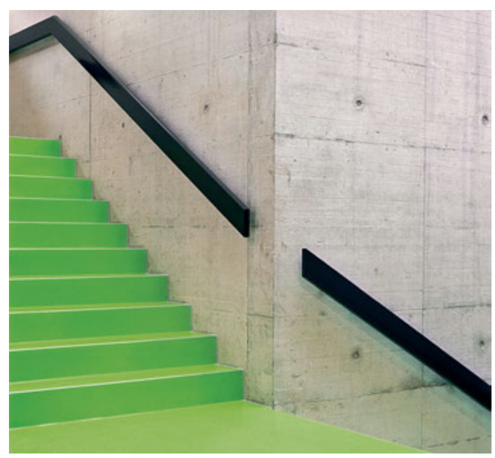
cc

Vertical cross section • Horizontal cross section
Scale 1:20





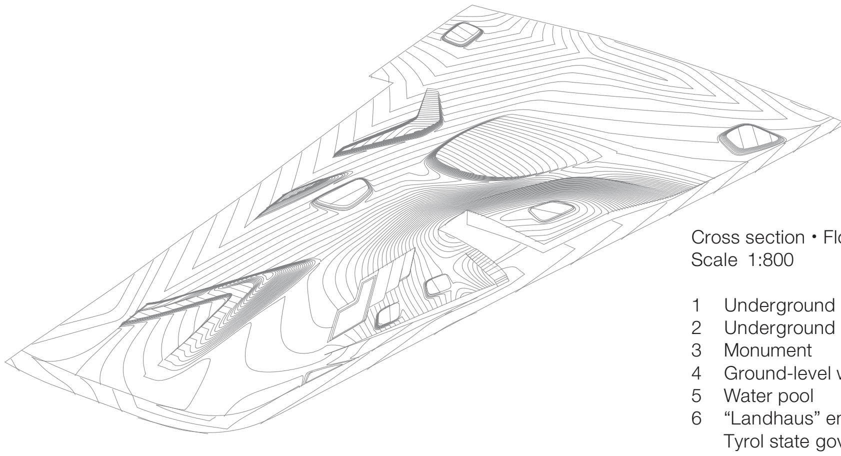
1 Prefabricated reinforced concrete element, smooth surface
2 Timber-aluminium passive house window w/ airtight joints: frame, spruce wood, insulated & painted, ceiling shell, alum., exterior powder-coating
3 Insulating triple glazing
Float 6 + between panes Argon 16 + Float 6 + between panes Argon 16 + Float 6 mm
4 Prefabricated reinforced concrete surface, textured (negative impression of washed concrete) 120 mm spacers, thermally separated, rear ventilation 40 mm, sealing, insulation 2× 140 mm, reinforced concrete 300 mm
5 Wall cladding (invisibly installed): acoustic panel MDF slit, painted w/ transp. lacquer 16 mm, acoustic insulation 30 mm
6 Floor covering, rubber, stuck down 7 mm
Cement screed 55 mm, separating layer, sound insulation 20 mm
Reinforced concrete C30/37 underside exposed concrete quality SB2, texture T2, porosity P2 320 mm
7 Spacer, foamed glass, thermal separation of sun protection structure
8 Sun protection, textile
9 Embrasure cladding, alum., powder coated 3 mm
10 Acoustic-insulating fibre panel (non-flammable), slit, painted green 16 mm, insulation 30 mm
11 Gravel, sealing, sloping insulation 200–500 mm vapour barrier, reinforced concrete 320 mm
12 Ventilation system / fresh air duct
13 Metal stud wall 100 mm:
Insulation 40 mm, clad w/ fire protection panels, both sides, gypsum panels 2 × 12.5 mm
14 Fibre panel (non-flammable), painted green 16 mm, insulation 30 mm
15 Exposed concrete w/ light timber-grain structure 200 mm
16 Aluminium anodised panels



Redesign of Landhausplatz

Innsbruck, A 2012

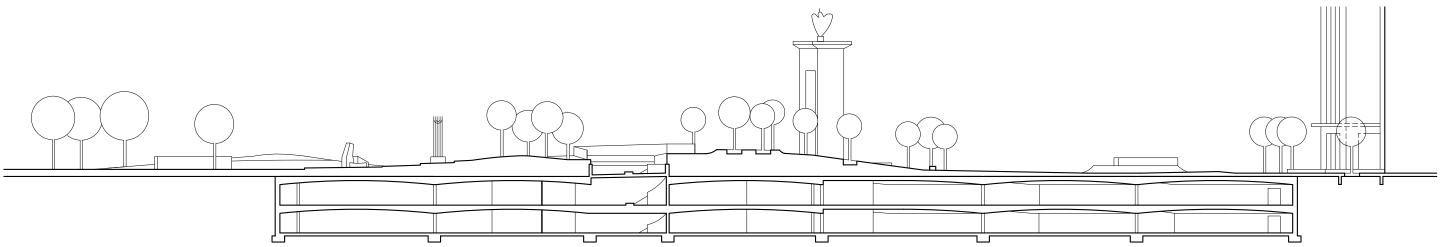
Architects:
LAAC Architekten, Innsbruck
Stiefel Kramer Architecture, Vienna
grüner.grüner, Innsbruck
Assistants:
Peter Griebel, Thomas Feuerstein,
Structural planning:
Alfred Brunnsteiner, Innsbruck



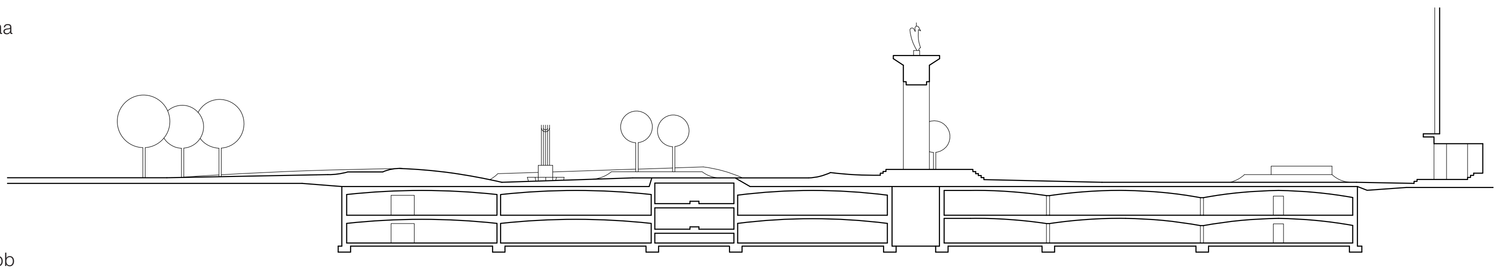
Cross section • Floor plan
Scale 1:800

1 Underground car park entrance
2 Underground car park stairs
3 Monument
4 Ground-level water fountain
5 Water pool
6 “Landhaus” entry (Offices of the Tyrol state government)

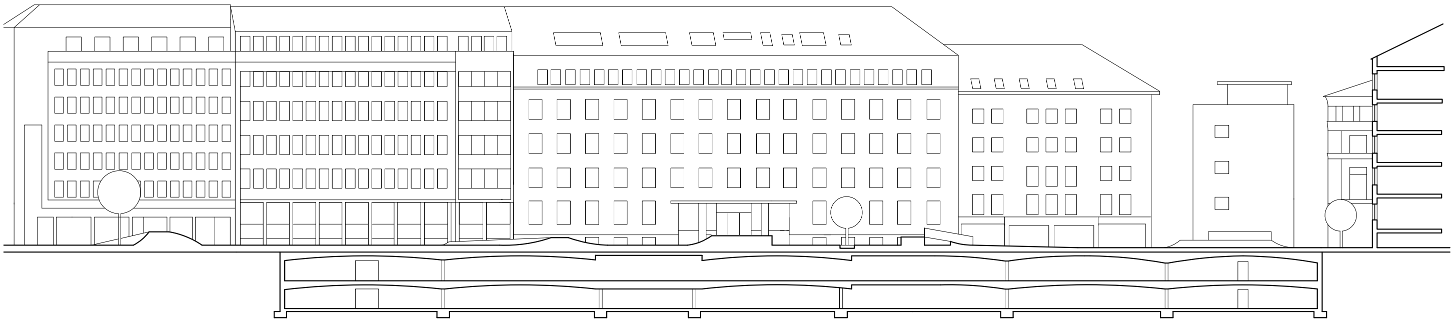
Before it was redesigned, Landhausplatz square, situated between Innsbruck’s railway station and the Old Town, with an underground car park under almost its entire length, was hardly more than a 9,000 m² “leftover” site, which, despite the many monuments “erected” there, was fairly neglected. After implementation of an award-winning architectural design from 2008, the square now looks decidedly urban, almost like a horizontal sculpture that can be walked on, with fluid geometric shapes in light-coloured concrete rising out of the square’s surface. Seen from above, the curving artificial landscape may seem somewhat alien and flat in this town of right angles. Seen from a pedestrian’s perspective, however, it becomes clear that the geometry structures the space and fulfils several tasks: creating secluded or exposed areas, resulting in clearly arranged open-air service areas for two gastronomic businesses, integrating an entrance and stairs to the underground car park, and not least providing an exciting space for physical activity for children on bicycles and young skaters. The peaceful coexistence between groups of users of various ages is regulated not by prohibitions but by a “code of behaviour” developed jointly by youth groups and the Tyrol state government (Landesregierung). Although the first-class quality of the concrete surface and grid-shaped appearance of the joints do not immediately suggest it, the square's entire topography is made up of concrete panels made on site from a very robust B7 concrete. The concrete specialists formed the entirely digitally planned concave and convex geometries with a layer of foam glass gravel and around the trees with a substrata fill, which they then covered with a 15–20 cm layer of semi-fluid, fast-setting concrete. Sloping concrete surfaces were roughened by milling and their top layers polished. The square is drained entirely through the joints between the steel-reinforced concrete panels, which were a maximum of 100 m² in size. Prefabricated parts were not suitable here due to the square’s high geometric complexity and lack of repeating forms.



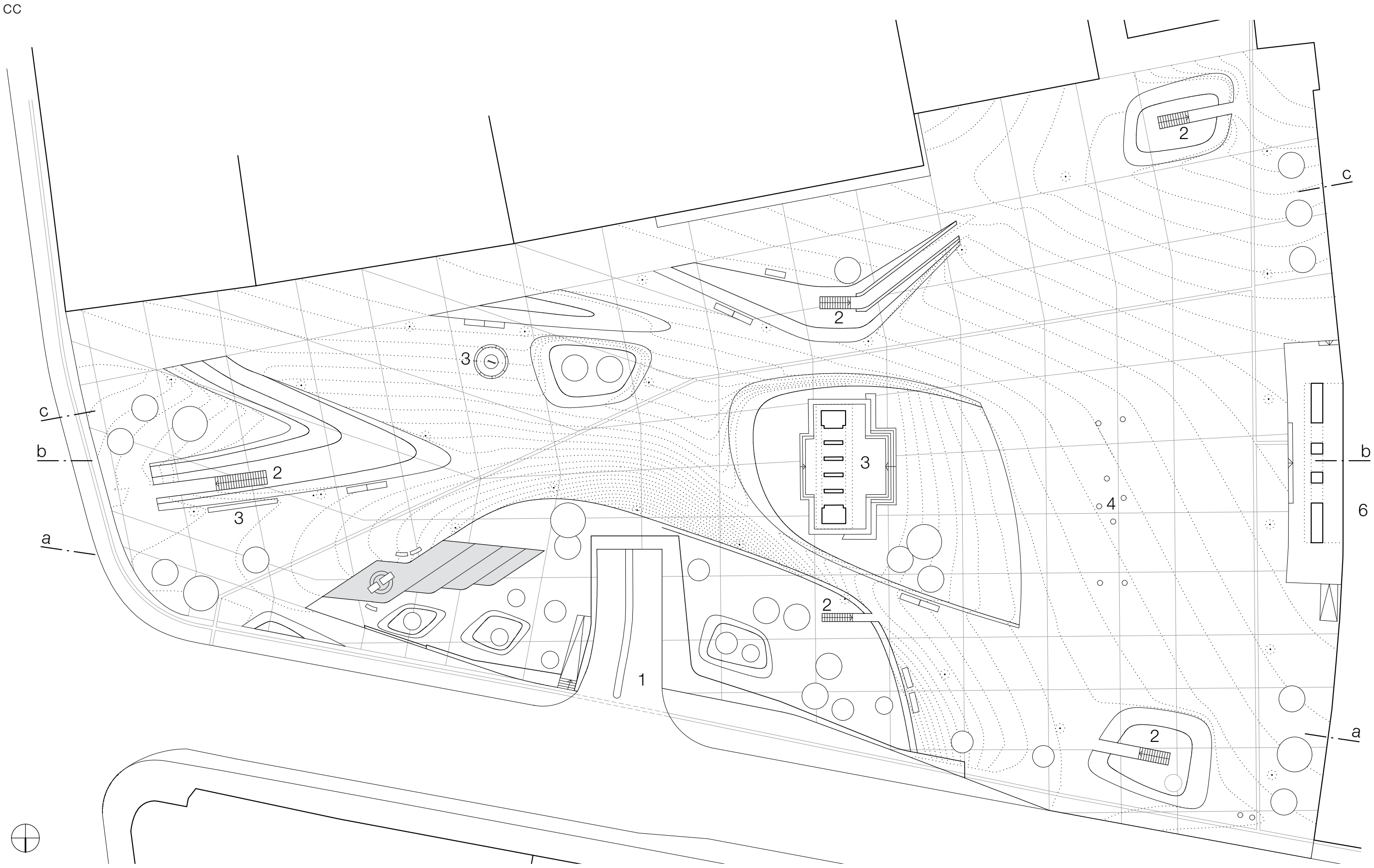
aa

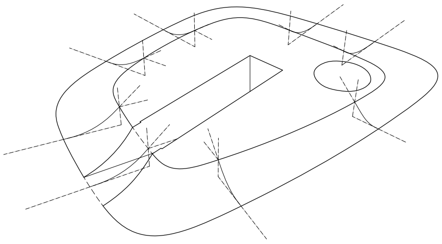


bb

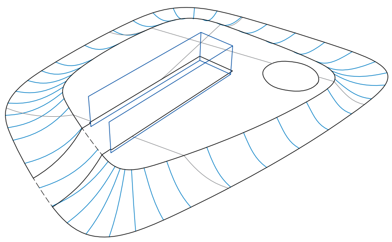


cc



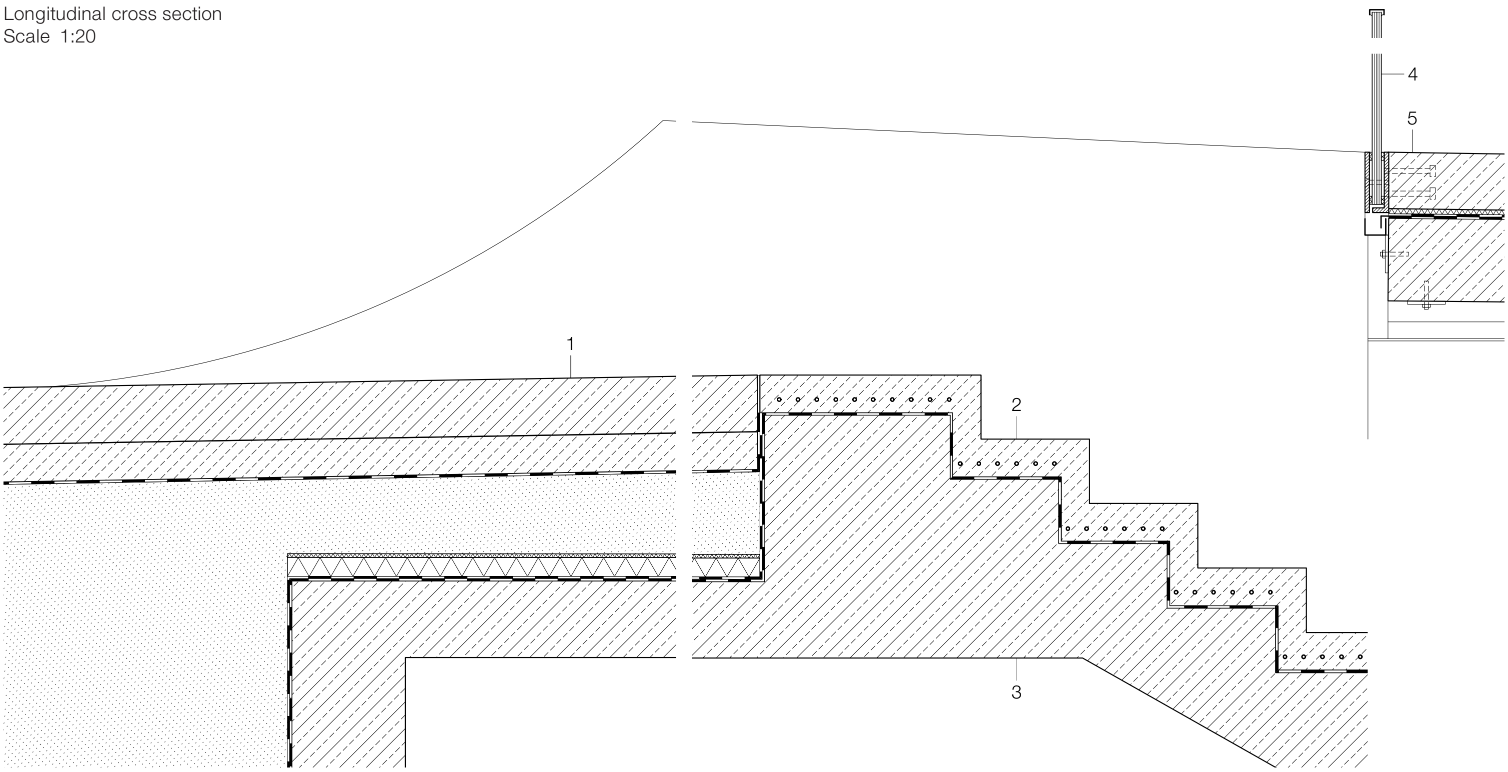


a

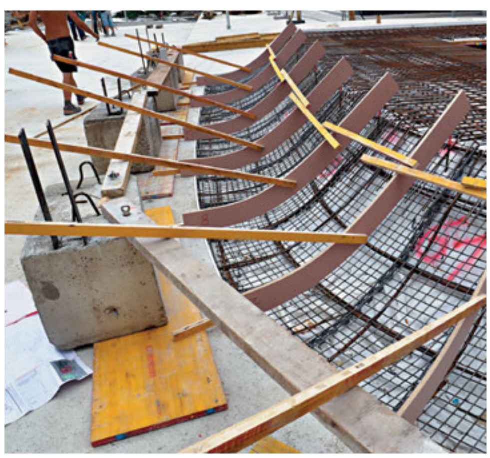


b

Longitudinal cross section
Scale 1:20

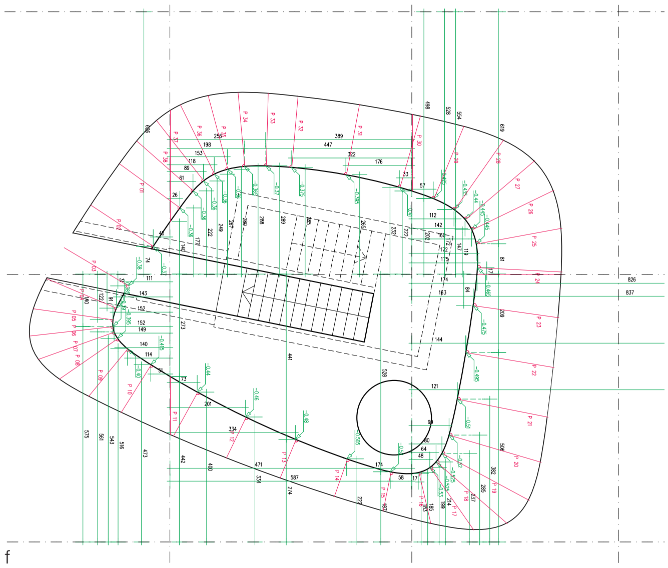


c

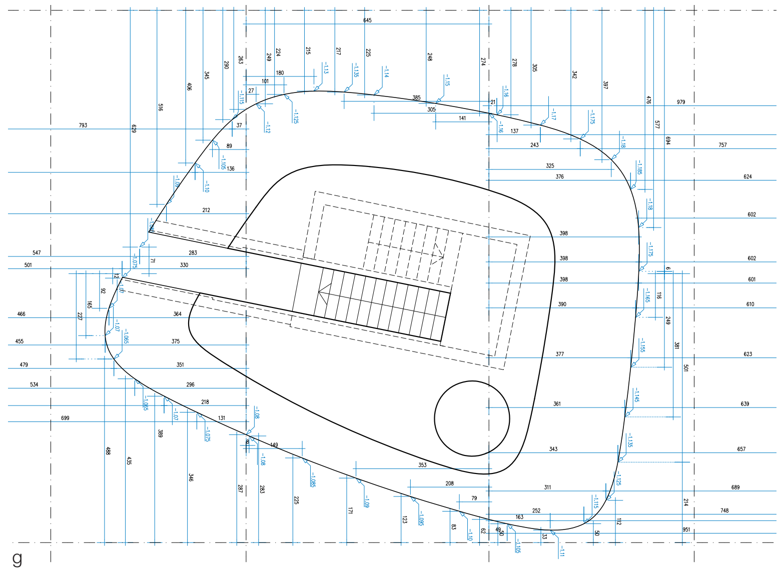


d

e

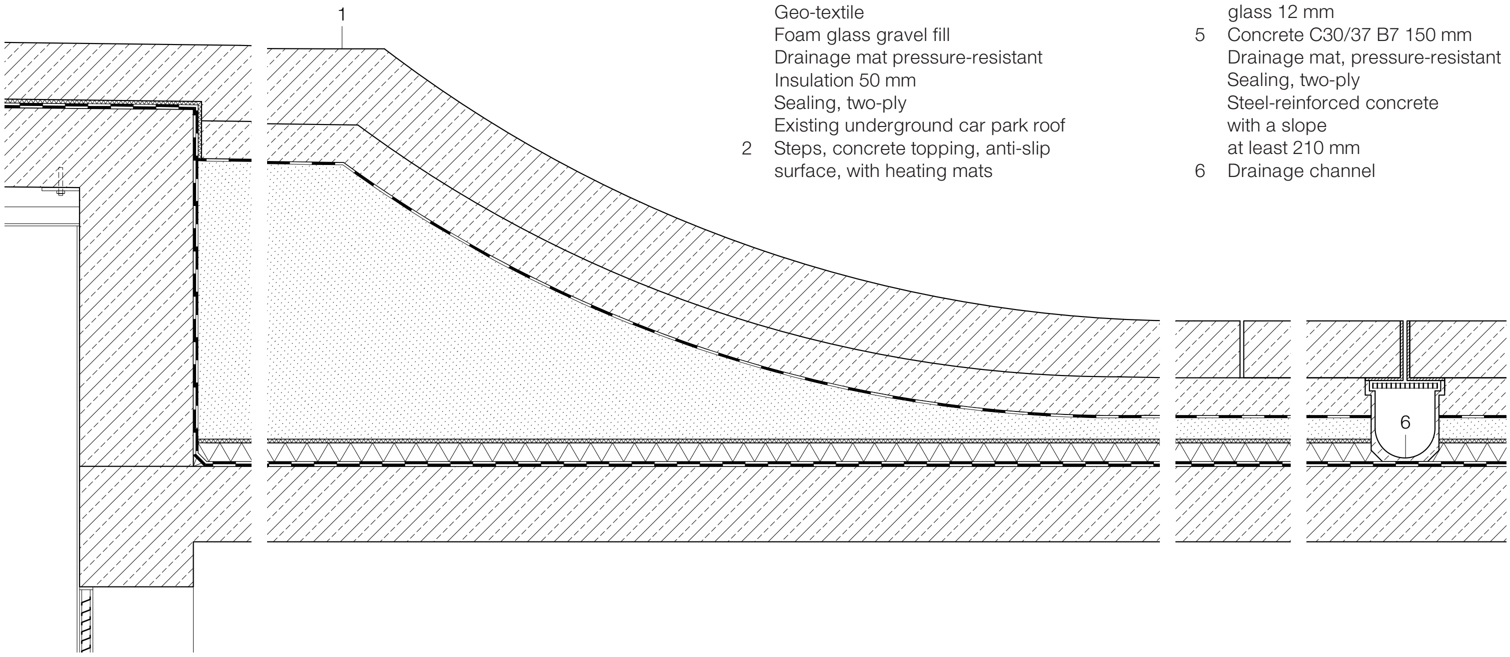


f



g

1 Concrete C30/37 B7
150–200 mm,
with a slope of 1.25 %
(diagonal 1.75 %)
Concrete sub-base at least 100 mm
Geo-textile
Foam glass gravel fill
Drainage mat pressure-resistant
Insulation 50 mm
Sealing, two-ply
Existing underground car park roof
2 Steps, concrete topping, anti-slip surface, with heating mats
3 Existing steel-reinforced concrete stairs
4 Glass railing
laminated glass made of heat-strengthened glass 12 + safety glass 12 mm
5 Concrete C30/37 B7 150 mm
Drainage mat, pressure-resistant
Sealing, two-ply
Steel-reinforced concrete
with a slope
at least 210 mm
6 Drainage channel



a To precisely create the geometrical topography, the whole square was divided into individual objects and surfaces. These were mapped with mathematical curves to ensure exact control over the curve continuities and surface continuity. This means that slightly curved surfaces could be flattened and connections to them optimally adjusted to the surface continuity, which made a major contribution to the economic optimisation of the surfaces.
b The geometry of the hill was mapped for the subsequent construction using lower and upper guiding lines and vertical cutting profiles.
c Finished concreted horizontal floor panels with reinforcing bars to join to the hill
d The lower edges of wooden CNC cutting profiles precisely calibrated on site defined the subsequent concrete surface of the sloping hill.
e Subsequent treatment of the set concrete
f Construction plan with reference dimensions between the axes and the upper guiding line (green) and for the positioning of the cutting mould (red), scale 1:200
g Construction plan with reference dimensions between axes and the lower guiding line, scale 1:200
h Black, white and yellow granite chippings give the completed concrete surface a lively appearance.

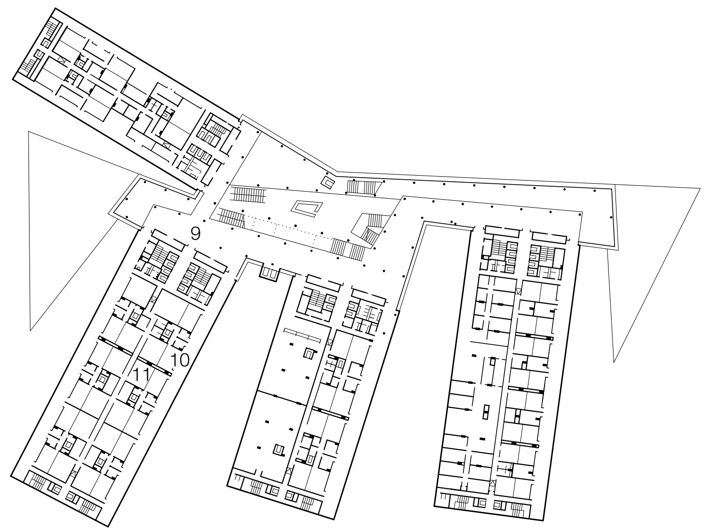
h

City of Justice

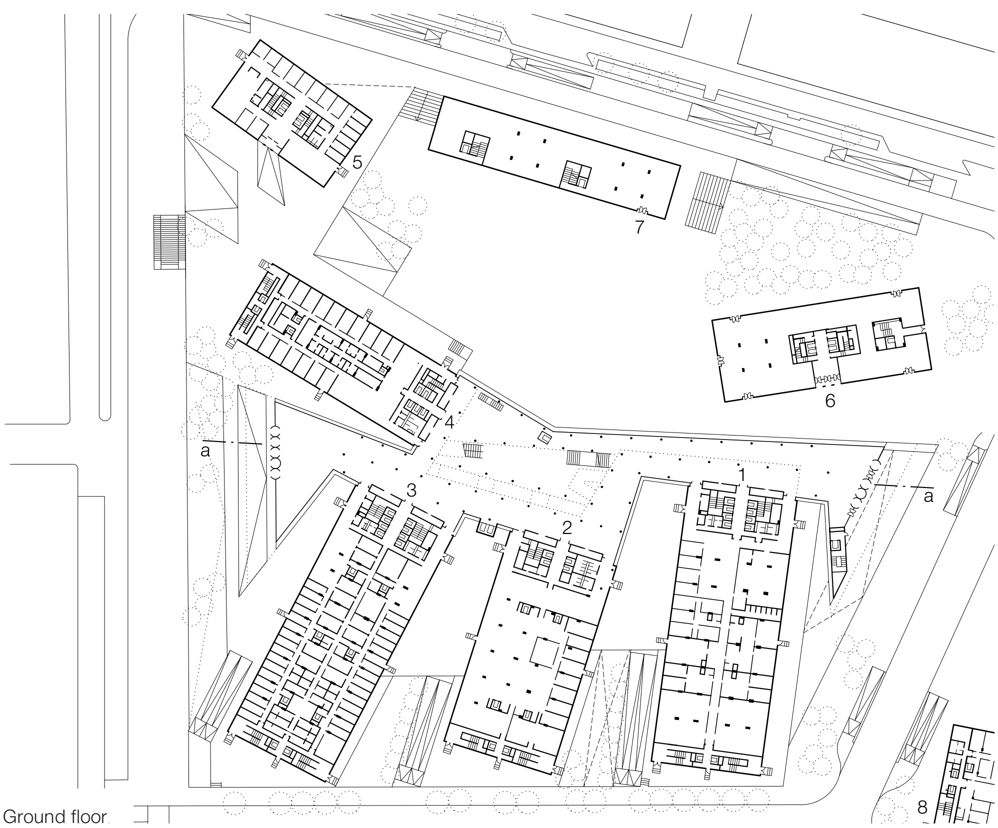
Barcelona, E 2009

Architects:
David Chipperfield Architects, London
b720 Fermín Vázquez Arquitectos, Barcelona
Structural planning:
BOMA, Barcelona
Jane Wernick Associates, London

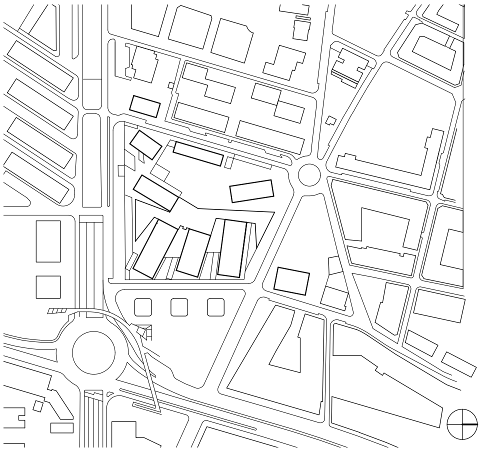
Barcelona's new law courts district, a "city within a city", is presented in the form of colourful, cubic high-rise blocks, whose seemingly playful arrangement and proportions create a structural reference to their broader environment. Its external appearance is made up of a single module repeated almost 12,000 times. The buildings' price of 900 Euros per square metre was achieved only by consistently simplifying and optimising this facade detail throughout the entire planning process. The facade, with its staccato sequence of narrow slit windows, was poured on site in concrete pigmented with different colours, building by building, storey by storey during construction. In contrast to ordinary ventilated curtain wall facades, the building's shell here partly takes on the bracing and vertical loads, which allowed for a reduction in the number of supports required in the building. Structural forces, increasing in a downwards direction, are absorbed by an appropriately adjusted reinforcement. The walls are 25 cm thick over the entire height of the building. The glass surfaces and glass safety railings mounted in front of them are set well back and barely visible from the outside, giving the concrete structure the appearance of a latticed relief. The consistent 60 cm width of the windows, columns and rails creates a regularity that the individual grid strips, with wider windows for fire brigade ladders and a maximum of two expansion joints on each longitudinal side, only minimally disrupt. The windows' deep embrasures and slender format mean that their glass is largely shaded, which enhances energy efficiency by providing passive sun protection. Anti-glare roller blinds inside also prevent the building from overheating.
The interior insulation, just 70 mm thick, is unproblematic for the physics of buildings in the Spanish climate.
Technical and economic aspects apart, the project's main focus was on the architectural goal of lending the entire ensemble a presence and physicality, which could not have been achieved with a complex comprised of different individual parts.

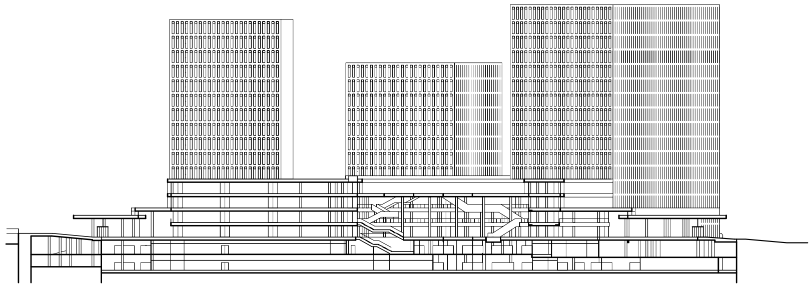


1st floor

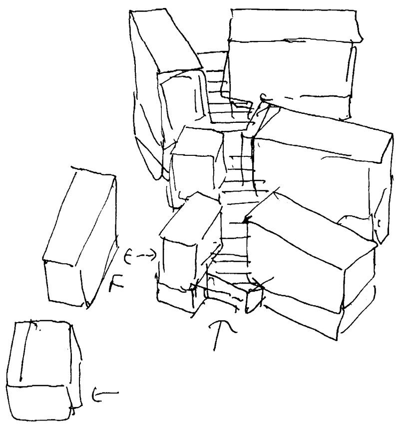


Ground floor





aa

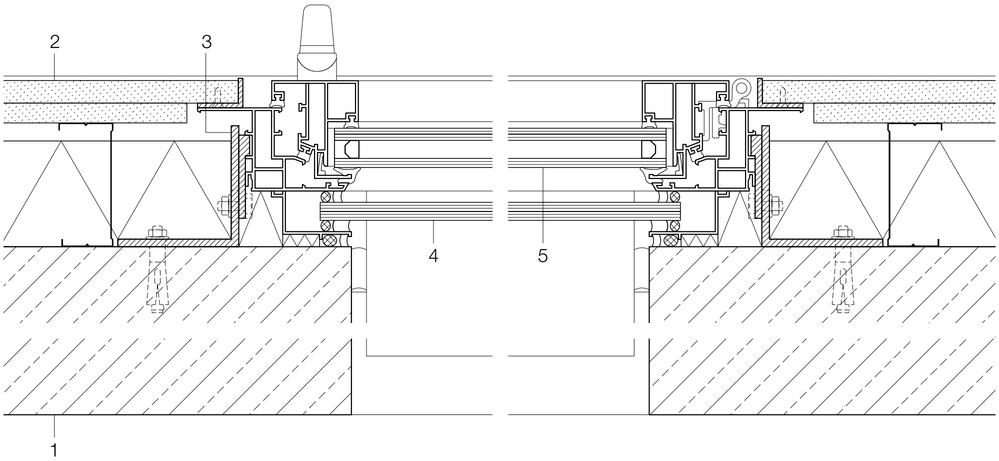


Floor plan • Cross section
Scale 1:2,000
Site plan
Scale 1:10,000

Design sketches
David Chipperfield

Arrangement of buildings – legal areas

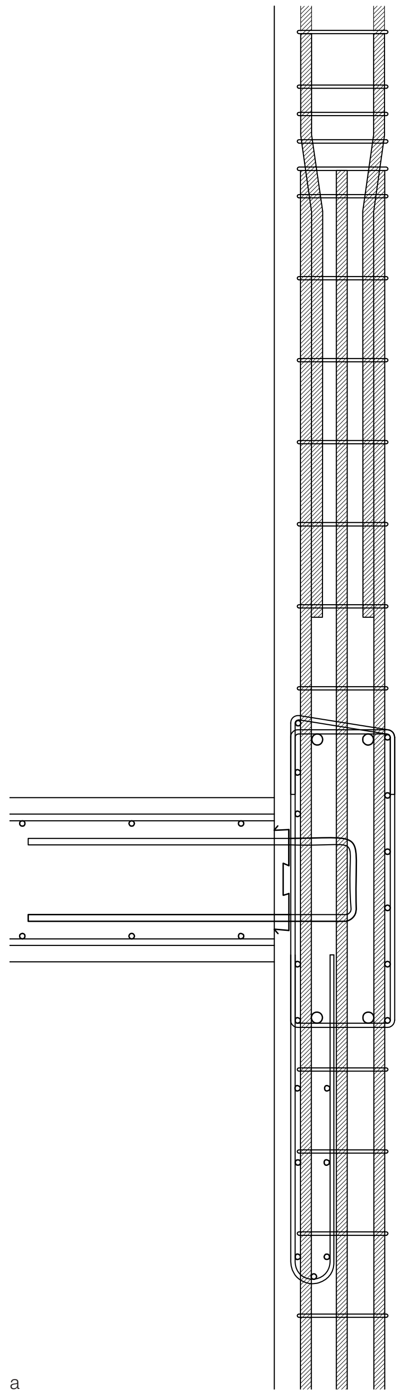
1 Civil law
2 Criminal law
3 Family law
4 Juvenile law
5 Forensic medicine
6 Offices
7 Right of abode law
8 Courts of the L'Hospitalet district
9 Access to the family law building
10 Public waiting area
11 Court room

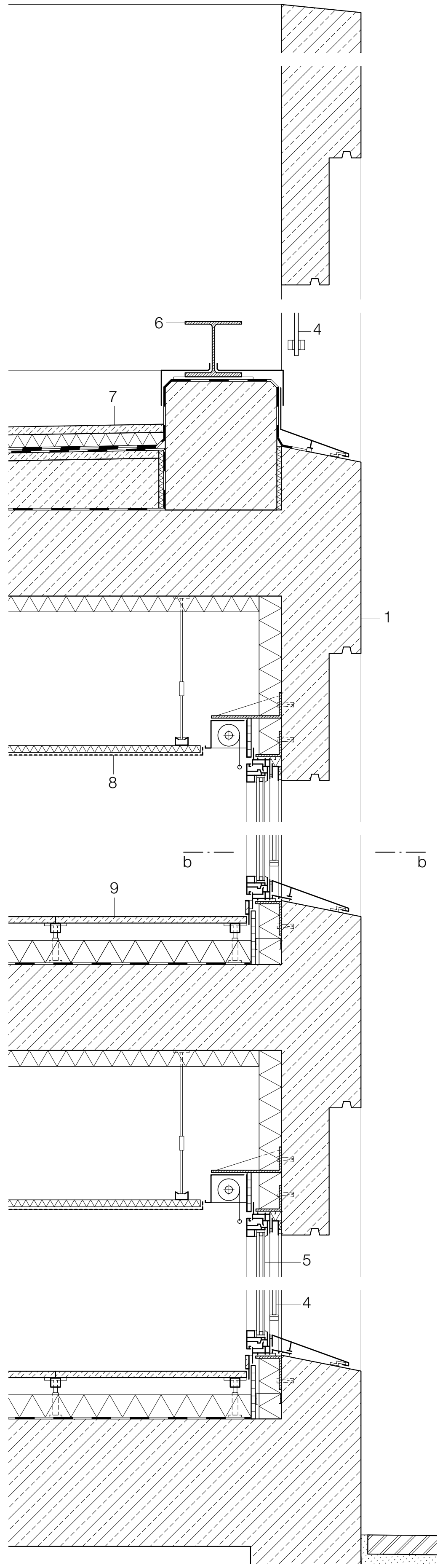


bb

Horizontal cross section
Scale 1:5
Vertical cross section
Scale 1:20

a Tying of the ceiling reinforcement in the facade


a

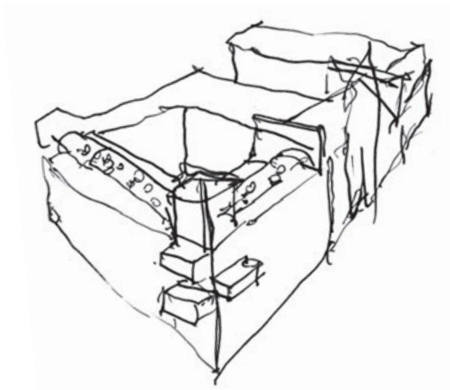


1 Steel reinforced concrete, dyed 150–250 mm
with a protective coating to prevent carbonisation
Insulation, mineral wool 70 mm
2 Gypsum plasterboard, two-ply
13 + 15 mm
3 Aluminium profile ∟ 80/80/5 mm
4 Safety railing laminated glass 2x 6 mm
5 Insulating glazing
safety glass 6 mm + space
between panes 12 mm +
laminated glass 2× 4 mm,
with a low-E-coating in aluminium frames
6 Rail cleaning system, steel profile HEA 180
7 Composite tiles 600/600 mm, can be walked on,
made of 40 mm polystyrene insulation, with a 35 mm
cement covering layer
Separating layer geotextile
Sealing
Separating layer, geotextile
Mortar 25 mm
Lean concrete with a gradient
40–150 mm
Vapour barrier
Steel-reinforced concrete 270 mm
8 Suspended modular ceiling, metal,
micro-perforated acoustic insulation 20 mm
9 Terrazzo tiles 600/600/20 mm,
in steel frames, floor mounted
Insulation strips b = 1.5 m
Mineral wool 70 mm
Separating layer
Steel-reinforced concrete 270 mm

BTV Stadtforum

Innsbruck, A 2006

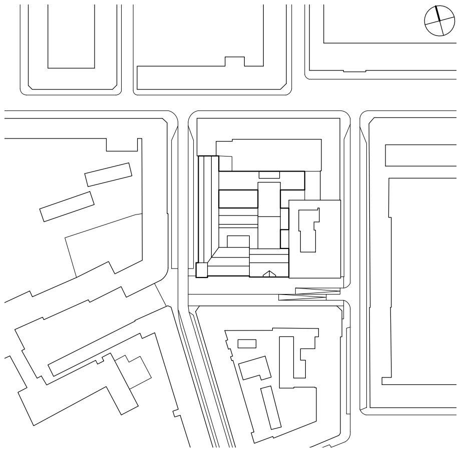
Architects (design):
Heinz Tesar, Vienna
Architects (construction):
Obermoser arch-omo, Innsbruck
Structural planning:
ZSZ Ingenieure, Innsbruck

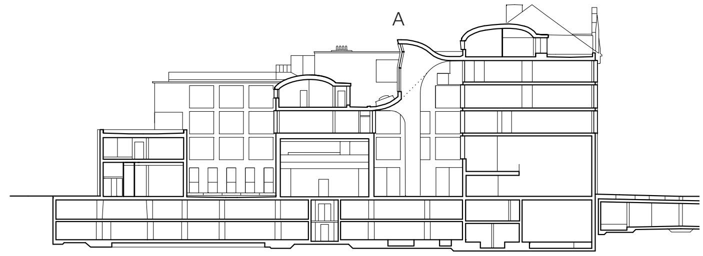


Site plan
Scale 1:5,000
Cross section
Floor plan
Scale 1:1,000

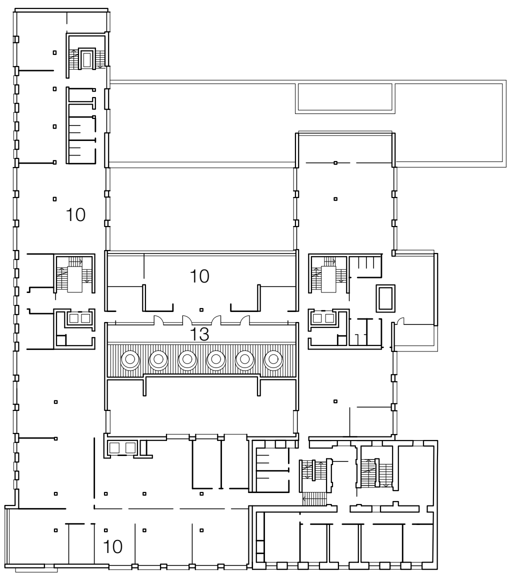
1 Entrance
2 Service hall
3 Night desk
4 Reception
5 Hall
6 Gallery
7 Concert hall
8 Water garden
9 Training centre
10 Office
11 Director's office
12 Board meeting room
13 Roof terrace

Just a few steps from Innsbruck's lively Maria-Theresien-Strasse sits the headquarters of the Bank für Tirol und Vorarlberg (BTV), a complex element of the city's urban planning with various public functions. From its pedestrian-only forecourt, visitors pass a service hall and enter its central hall, with ceilings extending to the height of the building. Housing an adjoining gallery and concert hall, an atrium and the bank's own training centre, the hall is distinguished by curving ceilings and load-bearing exposed concrete wall panels. Here, the joints between the formwork panels were exactly planned to create a linear joint in the area of curved surfaces, which echoes the lines of the round skylights. A large window extending along the hall's entire length illuminates the impressive space; this "strip of light" also offers views of the Nordkette mountain peaks from offices on the inside of the upper floors. Outside, three large window frames project sculpturally out of the white plaster surface and are staggered, emphasising the building's tower-like corners and main entrance.
A total of 152 large, almost square steel-reinforced concrete window frames with a facing width of just 8 cm lend the exterior and interior facades their sober character. The highly reinforced frames project 34 to 47 cm out of the facade surface. Their thin walls and the high demands made on the finished surface's quality, the sharpness of its edges and the precision of its measurements made it necessary to use a self-levelling and self-compacting dry concrete (SCC, self-compacting concrete), which spreads through the formwork without having to be vibrated. The concrete's flow path was kept as short as possible during pouring to create an even and void and pore-free surface with minimal shrinkage.
To ensure that elements would retain their even, consistent concrete colour and look "all of a piece", no formwork joints were allowed to remain visible. It was also designed to be stripped after just 18 hours, be completely crack-free and have high compressive strength. The window frames were installed by crane on site and attached to the exterior steel-reinforced concrete wall with stainless steel angle brackets.

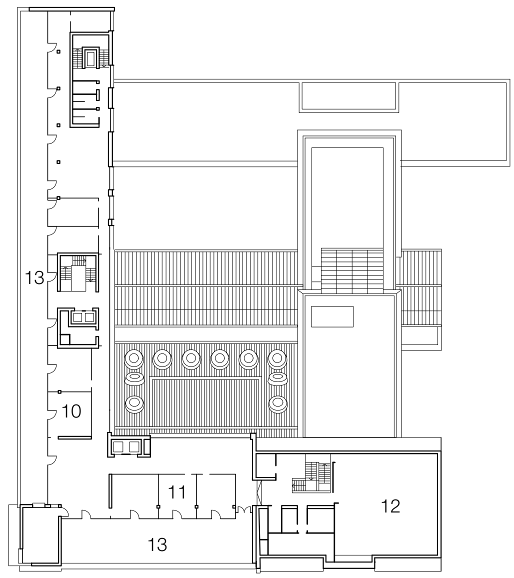




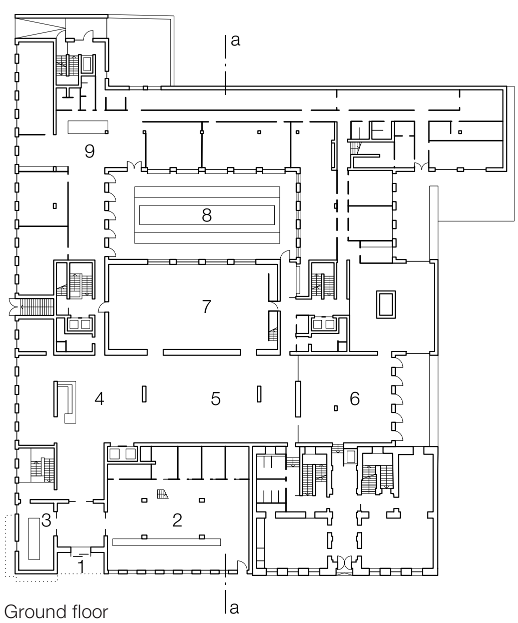
aa



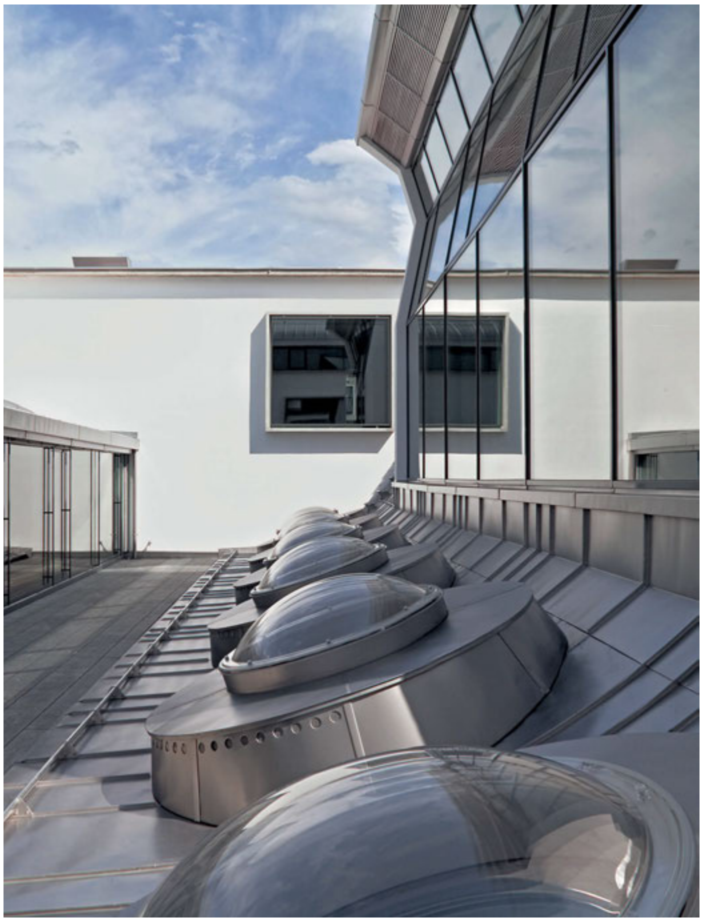
3rd floor

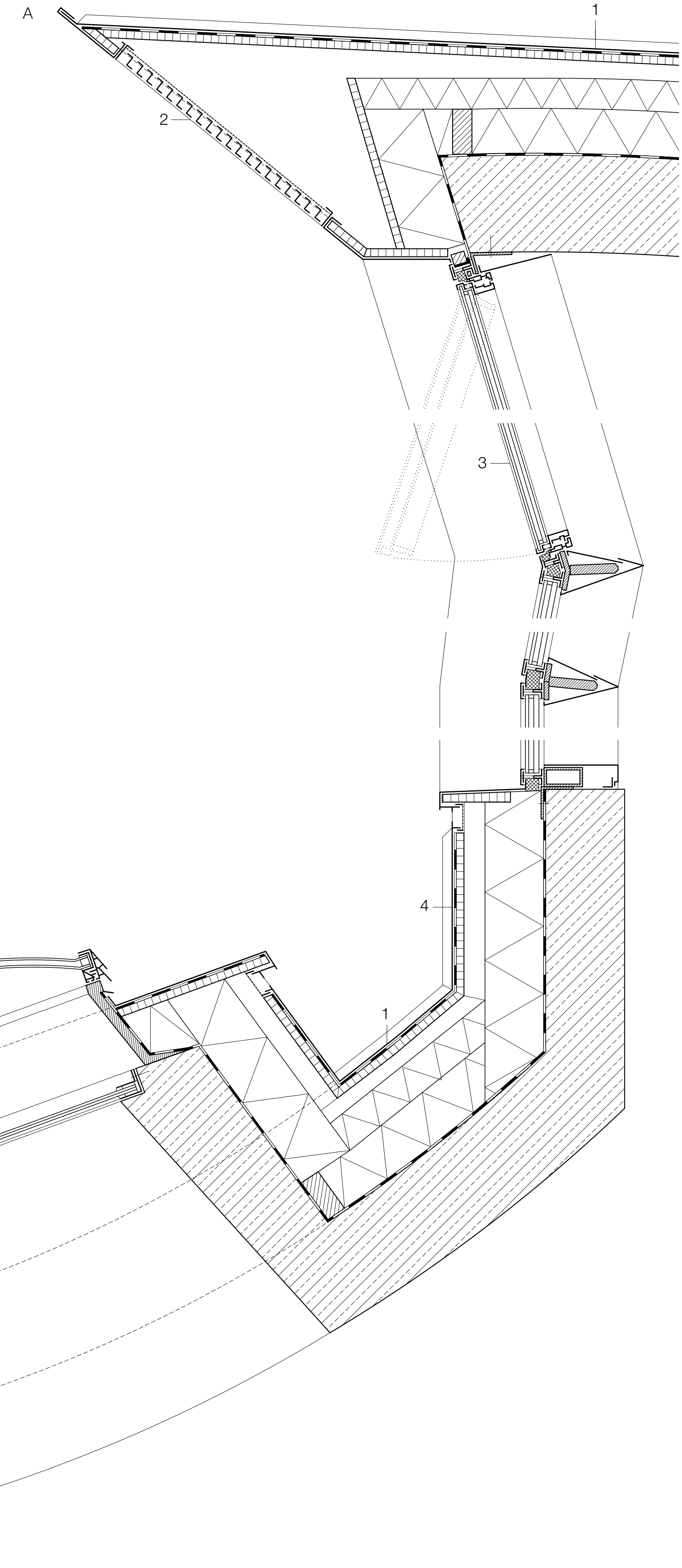


5th floor

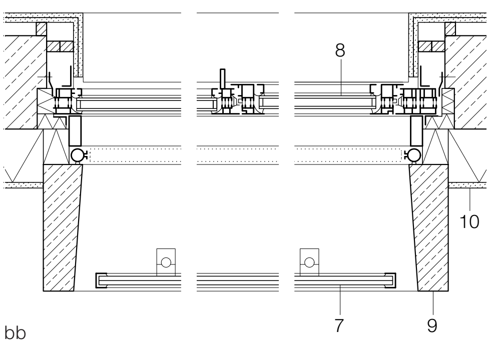


Ground floor

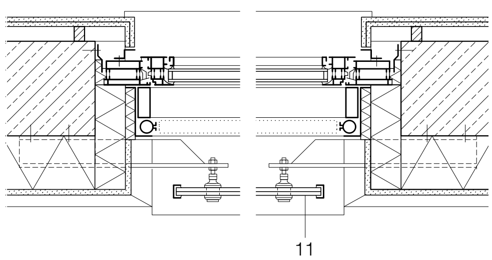




Vertical cross section
Horizontal cross section
Scale 1:20

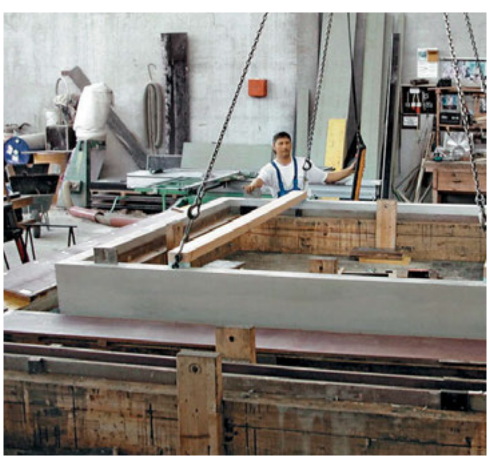


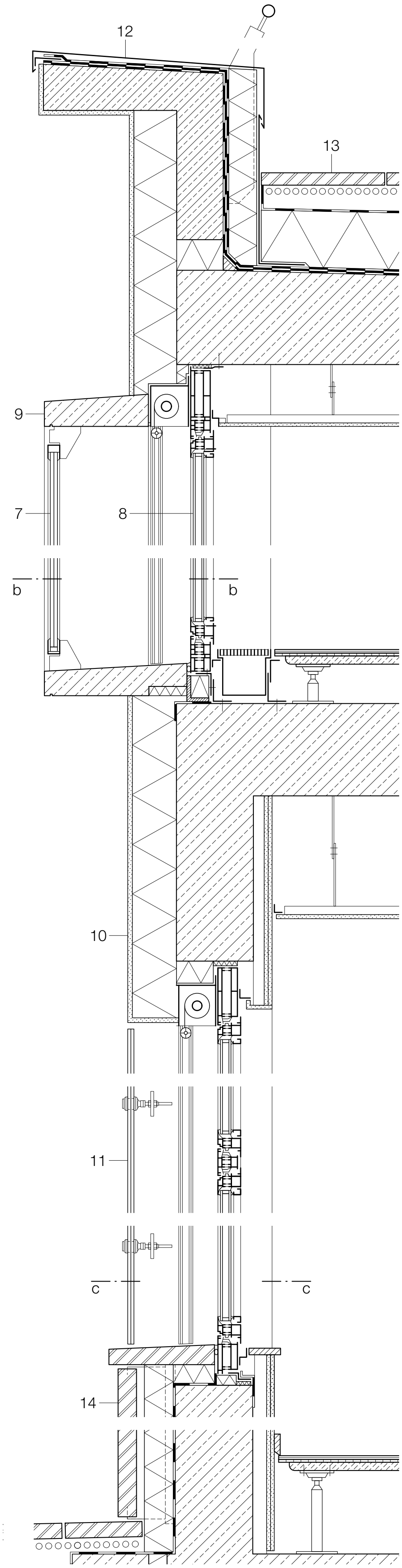
bb



cc

1 Stainless steel standing seam cover, milled matt surface
Plastic sealing sheeting, PP 8 mm w/ mono-filament core
OSB panels 25 mm on wooden substructure, rear ventilation between ≥ 60 mm & mineral wool insulation 100 mm + 140 mm
Bitumen prime coating
Curved reinforced concrete 300 mm
2 Ventilation panels, stainless steel frames
Insect screens
3 Insulating glazing float 10 mm + between panes 16 mm + laminated glass 16 mm in a mullion-transom facade, steel, welded, w/ steel sheet cladding 2 mm
4 Stainless steel standing seam cover, milled matt surface
Plastic sealing sheeting, PP 8 mm w/ mono-filament core
OSB panels 25 mm, wooden substructure, rear ventilation between, 60 mm & mineral wool insulation 180 mm
Bitumen prime coating, reinforced concrete 250 mm
5 Dome light, acrylic glass
6 Fire-protective glazing (G 30) 2× laminated glass 8 mm w/ intermediate foam layer
7 Laminated glass 2× 12 mm, alum. frames
8 Insulating glazing safety glass 6 mm + between panes 22 mm + safety glass 6 mm in alum. frames
9 Prefabricated reinforced concrete element
10 Plaster 15 mm, polystyrene insulation 140 mm
Reinforced concrete 250 mm, gypsum panel 2× 12.5 mm
11 Laminated glass 2× 12 mm point-fixed
12 Aluminium fascia covering
Sealing two-ply, emergency sealing sheeting
Prefab reinforced concrete element
13 Panel cladding, natural stone 40 mm
Gravel fill 50 mm, protective fleece, polystyrene insulation 180 mm, sealing two-ply, emergency sealing sheeting, reinforced concrete w/ 250–300 mm gradient
14 Valser quartzite cladding, 60 mm
Rear ventilation 25 mm, polystyrene insulation 100 mm, sealing, reinforced concrete 250 mm
Gypsum plasterboard cladding 2× 12.5 mm

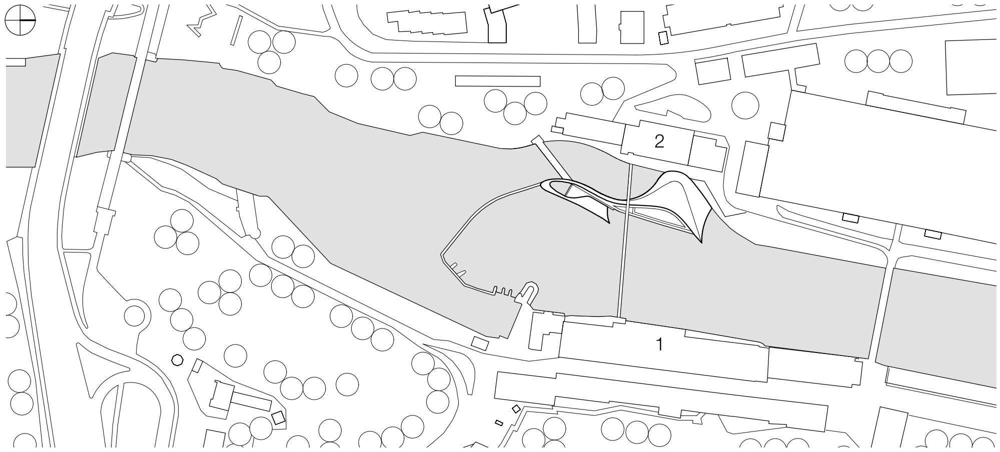




Hydro-electric power station

Kempten, D 2010

Architects:
becker architekten, Kempten
Michael Becker, Bernhard Kast,
Franz G. Schröck
Structural planning (underground):
RMD Consult, Munich
Structural planning (above ground):
Konstruktionsgruppe Bauen, Kempten



An elegantly curved continuous shell encompasses the necessary technical plant and engineering structures of the hydro-electric power station on the banks of the Iller. The image of water-worn rock formations in the river and the transfer of the dynamism of the water inside the power station into the architecture define the formal language of this softly modelled, amorphous building-sculpture. Numerous models were used to develop the design before the building's envelope was translated into a 3D data model.

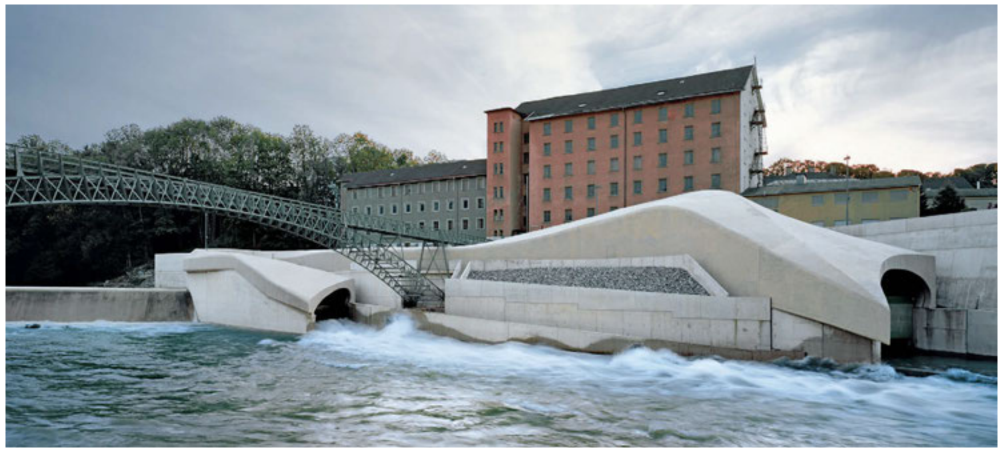
The new building replaces the hydro-electric power plant of a nearby historic listed spinning and weaving mill. With an output of 10.5 million kWh a year, the new power plant now produces electricity for around 3,000 households. A harmonious reinforced concrete shell links the turbine house with the generators and the plank weir at the other end of the plant. The building "dives" under and through the historic steel truss arches of a cable footbridge, saving it from demolition.

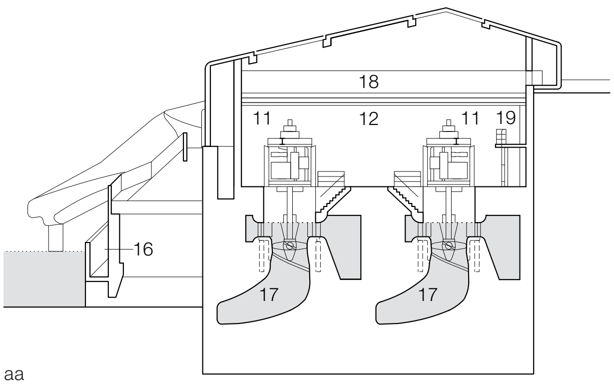
Directly continuing the underground structure, the shell is set on sliding bearings at various points and has a circumferential horizontal joint so that it can autonomously balance longitudinal deformations. Ribbed arches every 5 metres stabilise the structure laterally. These were made together with the curved walls and ceilings in six concreting sections. A conventional commercial concrete in strength class C30/37 with no chemical additives or special aggregate and reinforcement tied by hand was used for the exterior. Concrete's potential is shown in the formation of the building's curved forms and sophisticated design of the surfaces, which, built using rough-sawn plank formwork, look coarse and rough inside and smooth on the outside. A subsequent application of cost-effective, sprayed-on PU coating blended with pebbles from the Iller creates a homogenous skin that strengthens the overall sculptural impression. Technically necessary openings are integrated into the homogenous shell as completely removable concrete plates.

The result is a structure enclosing the "world of hydro-electric power", whose opening was celebrated by 10,000 guests.

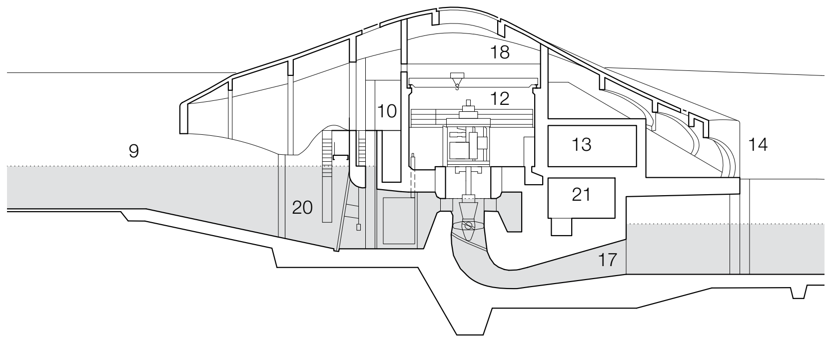
Site plan
Scale 1:4,000
Cross section • Layout
Scale 1:500

1 Former spinning mill
2 Former weaving mill
3 Plank weir
4 Hatch protection
5 Weir crown
6 Rack cleaner
7 Historic cable footbridge
8 Bank wall
9 Inflow
10 Stoplog, upstream
11 Generators
12 Machine room
13 Transformer room
14 Stoplog, downstream
15 Outflow
16 Fish ladder
17 Suction hose
18 Crane runway
19 Gallery
20 Intake racks
21 Cable cellar

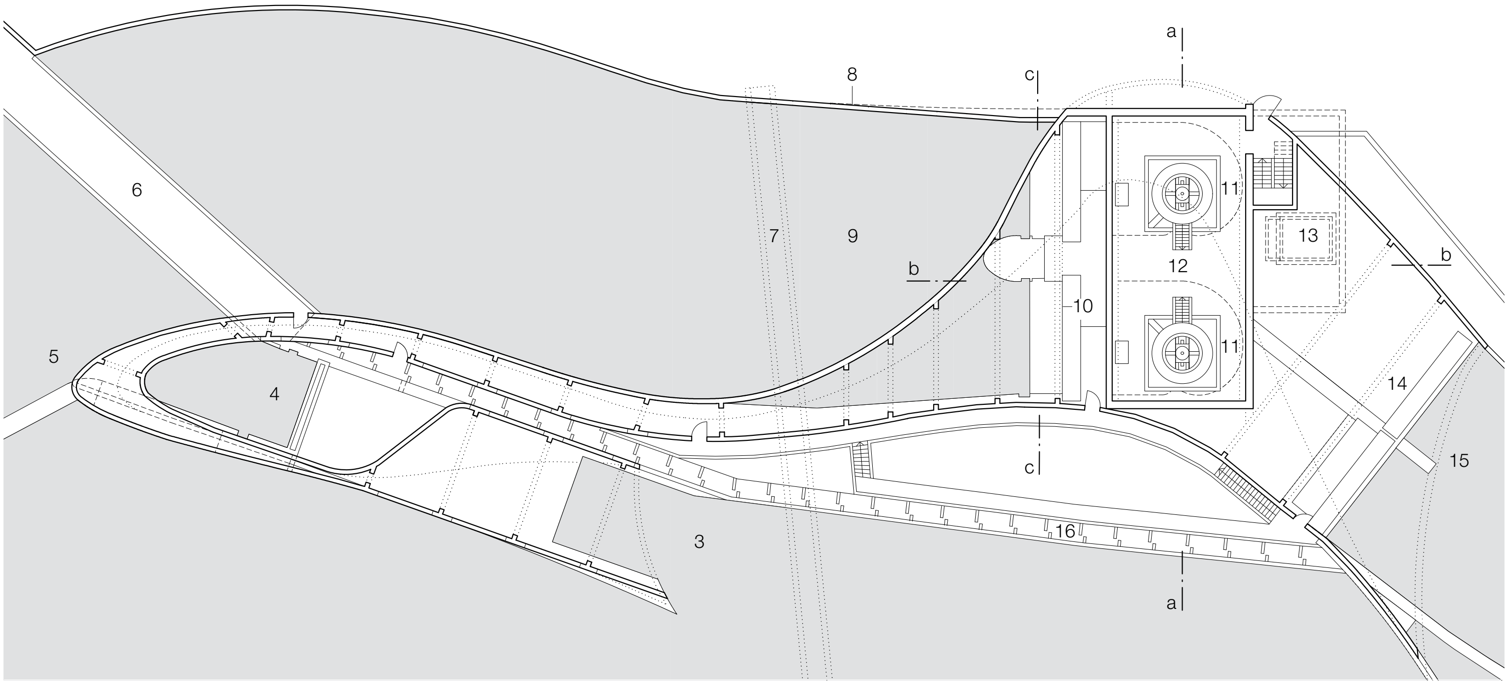




aa



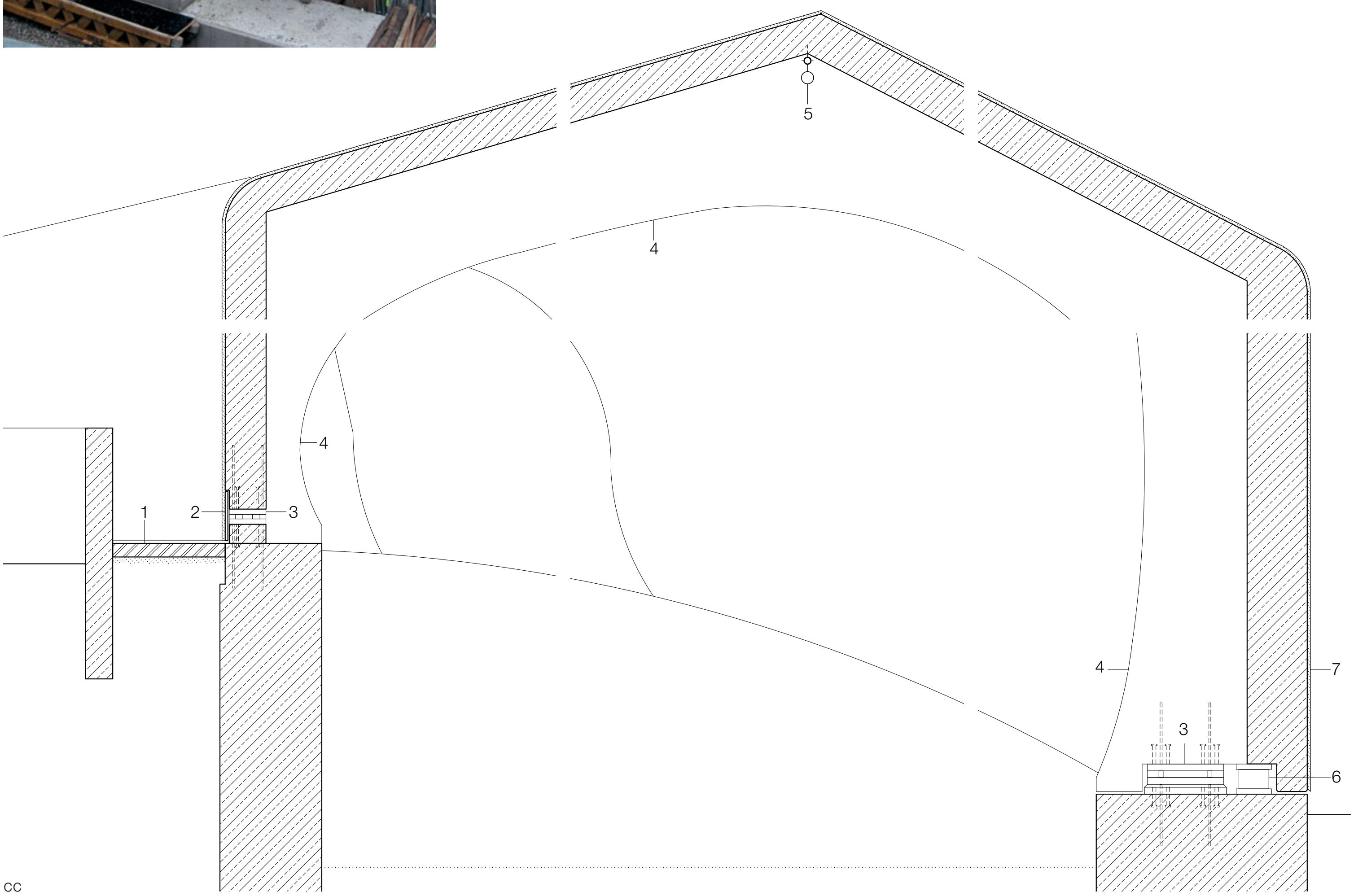
bb



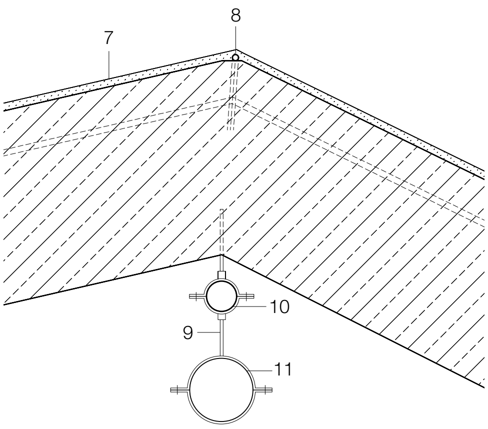
Vertical cross section
Scale 1:50

Detailed cross section
Scale 1:10

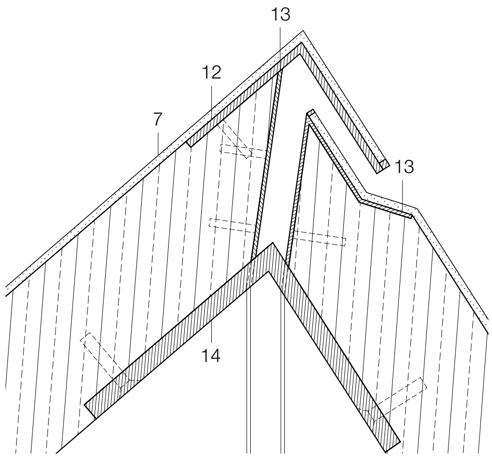
a Roof ridge with lightning protection and lighting
b The apex – a removable structural element
c Stoplog tops
d Lower edge of the facade :
Cantilever over the bike path



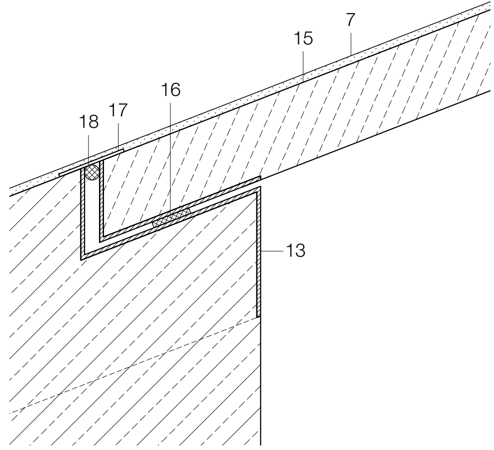
cc



a

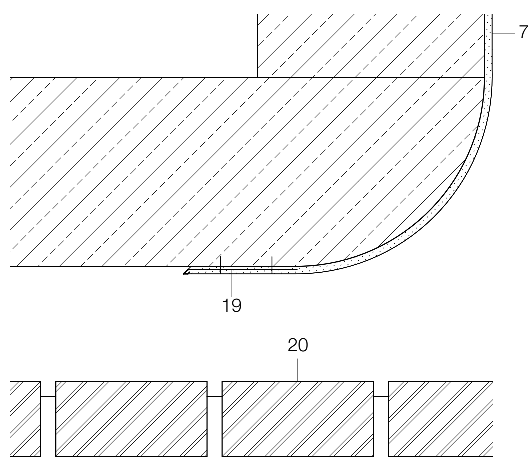


b



c

1 Maintenance access
2 Covering of sliding bearings
3 Sliding bearings
4 Ribbed arches
5 Roof ridge lighting
6 Hydraulic press
7 Spray-on PU coating, triple-layered, waterproof, mixed with Iller pebble chipping 10 mm, reinforced concrete, on the inside built with rough-sawn plank formwork 250 mm
8 Lightning protection ∅ 8 mm
9 Threaded bar ∅ 5 mm
10 Steel pipe, zinc-coated ∅ 40/3 mm in steel, zinc-coated pipe clamps
11 Tubular light with pipe clamp, steel, zinc-coated ∅ 90 mm, hung on a threaded bar
12 Stainless steel sheeting, chamfered10 mm
13 Stainless steel sheeting, chamfered 5 mm
14 Stainless steel sheeting 4 × 300 + 300/150/25 mm, attached with socket dowel, M16 100 mm, as a detachable connection
15 Removable stoplog tops, lightweight concrete 100 mm
16 Neoprene bearing 8 mm
17 Separators
18 Sealing strip
19 Stainless steel sheeting 150/2 mm
20 Concrete stone paving for the pedestrian and bike path



d

Authors

Martin Peck (editor)
Born in 1954
from 1973 Concrete technologist (managing building site inspection centres and in precast part and ready-mix concrete plants), worked abroad for 7 years
1990–1999 Freelancer, then Technical Director of an engineering firm working on concrete technology, techniques and building renovation
until 1999 Studied civil engineering at the RWTH Aachen while working in the field
from 2000 Director of the concrete technology division of Cement Construction Consultancy at the German Cement Works Association (BDZ)
from 2003 Head of the technical division of Beton Marketing Süd GmbH in Munich
Member of standards committees and concrete construction technical boards and bodies, involved in producing the BDZ/DBV "Exposed concrete" data sheet (Merkblatt)
Author and co-author of technical brochures in the German Cement Works Association (DBZ) series and editor of other books on concrete

Christoph Dauberschmidt
Born in 1969
Studied civil engineering at the TUM (Technische Universität München)
1995–1998 Structural and project planning, IBTB Berlin
1999–2005 Research Assistant at the Institute of Building Materials' Research at the RWTH Aachen University while gaining a doctorate
2005–2009 Team manager and expert assessor with the Schießl engineering firm
from 2009 Professor of Building Materials and Restoration at Munich University of Applied Sciences (Hochschule für angewandte Wissenschaften)
from 2010 Partner in the engineering firm of Professors Dauberschmidt and Vestner
Trainer on many training courses ("Building inspection in accordance with DIN 1076", "Expert planning", "Non-destructive testing procedures" etc.)

Stephan Engelsmann
Born in 1964
Trained as a bricklayer in Augsburg
Studied civil engineering at the TUM (Technische Universität München)
1991–1993 Project engineer in the Dr. Kupfer engineering firm, Munich
1993–1998 Research Assistant at the Institute of Structural Design at the University of Stuttgart
1998 Awarded a doctorate at the University of Stuttgart with a dissertation on "Solid concrete bridges – planning and designing bridges without joints and bearings"
1998–1999 Masters in Architecture at the University of Bath
1999–2007 Project Manager and authorised representative manager (Prokurist) at the engineering firm of Werner Sobek Ingenieure, Stuttgart
from 2002 Professor of Structural Design and Engineering at Stuttgart State Academy of Arts and Design
2005–2008 Director of the Weissenhof Interdisciplnary Forum for Architecture, Interior Space and Design at Stuttgart State Academy of Arts and Design
from 2006 Engelsmann Peters, consultant engineer
2007–2010 Prorector of Stuttgart State Academy of Arts and Design
from 2007 Vice-President of Baden-Württemberg Chamber of Engineers
from 2012 Board Member of the Federal Chamber of Engineers

Ulrike Förschler
Born in 1960
Studied interior architecture at Stuttgart State Academy of Arts and Design
1991–1993 Studied architecture at Stuttgart State Academy of Arts and Design
1995–1998 Post-graduate studies on timber at the Federal Institute of Technology (ETH) Zurich
1987–1990 Research Assistant at Stuttgart State Academy of Arts and Design
1994–1996 Artistic Assistant at Stuttgart State Academy of Arts and Design
until 1992 Freelance and employed architect and interior architect
from 1993 Freelance interior architect
from 1996 Freelance architect and interior architect
from 2001 Professor of Building Structures and Technology in the Faculty of Interior Architecture at Rosenheim University of Applied Sciences
Member of national boards and bodies, of competition juries, and has provided international expert consulting for the GTZ

Torsten Förster
Born in 1971
Studied architecture at the Bauhaus Universität Weimar and Ecole National Supérieure d'Architecture de Paris Belleville
Studied industrial engineering at Berlin University of Applied Sciences
1998–2006 Worked for various architects' firms in Berlin, including as project manager
from 2006 Architecture and construction policy consultant, initially at the Federal German Cement Works Association (BDZ), then at the German Cement Works Association (VDZ)
from 2012 Managing Director of the InformationsZentrum Beton (Concrete Information Centre)

Franz Forstlechner
Born in 1980
Studied civil engineering at Graz Technical University
2006–2008 Worked in engineering firms in Salzburg and Graz
from 2012 Research Assistant at the Institute of Structural Design in the Architecture Faculty at Graz Technical University

Peter Lieblang
Born in 1969
Studied civil engineering at the RWTH University Aachen
2000 Awarded a doctorate in the field of materials' mechanics
2000–2006 Expert consultant to the Federal German Cement Works Association (BDZ)
2006–2010 Professor of Building Materials at Bochum University of Applied Sciences
from 2009 Executive Director of the Institute of Concrete and Prefabricated Construction (a partner institute at Bochum University of Applied Sciences)
from 2010 Professor of Building Physics and Materials and head of the building physics laboratory at Cologne University of Applied Sciences
from 2011 Partner in the "KL – Architektur, Bauphysik und Baustoffe" firm
Has sat on national and international boards and panels

Stefan Peters
Born in 1972
Studied civil engineering at the University of Stuttgart
1998–2000 Project engineer in the engineering firm of Dietmar Kirsch, Stuttgart
2001–2002 Project engineer in the engineering firm of Werner Sobek Ingenieure, Stuttgart
2000–2006 Research Assistant at the Institute of Building Structures and Structural Design, University of Stuttgart
2006 Awarded a doctorate from the University of Stuttgart with a dissertation on "Adhesion of GFC and glass in construction applications"
2005–2006 Co-founder of the Transfer and Entrepreneurial Centre (ITKE) Product development and construction technology at the University of Stuttgart
from 2006 Engelsmann Peters consultant engineers, Stuttgart
2006 Lecturer on Structural Design and Construction at Biberach University of Applied Sciences
2006–2008 Lecturer on Structural Design at Berlin's University of the Arts
2007–2010 Lecturer on Structural Design at Stuttgart State Academy of Arts and Design
from 2010 Professor of Structural Design in the Architecture Faculty at Graz Technical University
since 2013 Dean of the Faculty of Architecture at Graz Technical University
since 2013 Engelsmann Peters, consultant engineers, Graz

Valerie Spalding
Born in 1974
Studied architecture at the RWTH Aachen
2000–2001 James Carpenter Design Associates, New York
2002 – 2005 Carpenter/Lowings Architecture & Design, London
from 2005 Member of the Baden-Württemberg Chamber of Architects
2005–2011 Research Assistant to the "Building Structures and Structural Design" course at Stuttgart State Academy of Arts and Design
from 2011 Worked for Engelsmann Peters consultant engineers, Stuttgart
2013 Awarded a doctorate from Stuttgart State Academy of Arts and Design. Dissertation on "The art of folding: folded plate structures composed of plastic panels"

Tobias Wallisser
Born in 1970
Studied architecture at Berlin Technical University and the University of Stuttgart
1997 Postgraduate Masters at Columbia University, New York
1997 Architect at Asymptote Architecture
1997 Architect in the UNStudio, van Berkel & Bos Amsterdam
2001–2007 Creative Director UNStudio, van Berkel & Bos Amsterdam, contributing architect in the Mercedes-Benz Museum and Arnheim Centraal
2006 Professor of Innovative Construction and Spatial Concepts at Stuttgart State Academy of Arts and Design
from 2007 Partner in LAVA – Laboratory for Visionary Architecture
Member of the Association of German Architects (BDA) and ADC (Art Directors Club Deutschland)

Arthur Wolfrum
Born in 1969
Studied architecture at the TUM (Technische Universität München) and Graz Technical University
1997–2004 Worked in various architects' firms in Munich
2004–2011 Research Assistant to the Chair for Timber Structures and Building Construction in the Civil Engineering Faculty at the TUM
since 2005 Co-founder of the Girnghuber Wolfrum Architekten firm
since 2012 Professor of Building Technology and Design at Munich University of Applied Sciences (Hochschule für angewandte Wissenschaften)

Fig. E Spacer on the inside of a double concrete wall

Regulations, directives, standards

The EU has issued directives on a number of products to ensure the health and safety of users. These directives must be implemented in binding laws and regulations in member states.
The directives themselves do not contain technical details, but rather mandatory basic requirements. Technical details are specified in the relevant technical rules and in harmonised European standards (EN standards).
Technical rules are generally designed to be operational guidelines and aids in everyday work. They are not statutory regulations but can be helpful in decision making, providing guidelines for correct technical operations and/or in substantiating and specifying the content of regulations. Anyone can use technical rules but they only become legally binding when they are incorporated into statutes, regulations or specifications (e.g. in building law) or when specific standards are stipulated as contractually binding on partners in a contract.
Technical rules include DIN standards, Association of German Engineers (VDI) standards and similar works referred to as technical rules (e.g. technical rules on hazardous materials).
Standards are divided into product, application and testing standards and often deal with a specific group of materials or products, setting out appropriate testing and research methods for individual materials. A standard's newest version is usually the valid one and should reflect the latest technological developments. A new or revised standard is published for discussion in the form of a draft standard before being adopted as a standard.
A standard's title reflects its origins and scope. DIN plus a number (e.g. DIN 4108) is of mainly national significance in Germany (where draft standards are prefixed with an "E" and "prestandards" with a "V"). DIN EN plus a number (e.g. DIN EN 335) denotes a German version of a European standard from CEN, the European Committee for Standardisation, that Germany has adopted without change. Euro norms listed in the chapters are shown in their German versions (DIN EN). The British standards versions (BS EN) are listed after these for English-speaking readers. Standards prefixed with EN usually designate standards applying to the respective national application and publication areas, although the standards' content and all their requirements are identical. DIN EN ISO (e.g. DIN EN ISO 13786) is standard with national, European and global scope. A European standard based on an International Organisation for Standardization (ISO) standard that has been reviewed and adopted as a DIN standard in Germany is prefixed with DIN ISO (e.g. DIN ISO 2424), indicating unchanged adoption of the ISO standard as a German national standard.
The following list is a selection of regulations, directives and standards incorporating the latest technological developments (as of July 2013).

DAfStb Technical Rule – Load tests on concrete buildings. 2000-09
DAfStB Technical Rule – Concrete in accordance with DIN EN 206-1 and DIN 1045-2 with recycled aggregates in accordance with DIN EN 12620. 2010-09
DAfStb Technical Rule – Manufacture and use of cement-bonded infill concrete and liquid mortar. 2011-11
DAfStb Technical Rule – Quality of reinforcement – Supplementary specifications on handling and laying steel reinforcement. 2010-10
DAfStb Technical Rule – Protecting and restoring concrete building components. Berlin 2001-10
DAfStb Technical Rule – Steel fibre reinforced concrete – Additions and supplements to DIN EN 1992-1-1 and DIN EN 1992-1-1/NA, DIN EN 206-1 and DIN 1045-2 and DIN EN 13670 and DIN 1045-3 – Part 1: Design and construction – Part 2: Specifications, properties, production and conformity – Part 3: Execution of construction. 2012-11
DAfStB Technical Rule – Water-impermeable concrete structures. 2003-11

Energy Saving Act as amended of 01/09/2005 (BGBl. I p. 2684)
Real estate valuation ordinance of 20/05/2010, BGBl. I p. 639
Closed Cycle and Waste Management Law of 24/02/2012 (BGBl. I p. 212)
Data sheet on polished cement-bonded floor systems (not including screed). Published by the Federal Working Group on Artificial Stone, PreCast Concrete Elements, Terrazzo and Natural Stone, in the Central Association of the German Construction Industry (Zentralverband des Deutschen Baugewerbes), Quality Assurance working group work on "Beautiful concrete floors (Schöne Betonböden)" 2008-09
Data sheet on exposed concrete. Published by the German Society for Concrete and Construction Technology and the Association of German Cement Manufacturers, 1st corrected reprint of the version of 2004-08
Model guidelines for the construction and operation of high-rise buildings (Muster-Hochhaus-Richtlinie – MHHR) in the version of April 2008, last amended by resolution of the Expert Commission on Building Inspection on 02/2012
Austrian Society for Construction Technology's Exposed Concrete Guideline– Formed concrete surfaces
Directive 2012/27/EU of the European Parliament and of the Council of 25/10/2012 on energy efficiency, amending Directives 2009/125/EG and 2010/30/EU and repealing Directive 2004/8/EG and 2006/32/EG. Official Journal of the European Union L 315/1 of 14/11/2012
Directive 2010/31/EU of the European Parliament and of the Council of 19/05/2010 on the energy performance of buildings (recast)
Directive on Inspecting the Safety of Federal Government Buildings (RÜV)
Directive on Inspecting the Safety of Federal Government Buildings (RÜV published by the Federal Ministry of Transport, Building and Urban Development (BMVBS). Valid as of 2008
Directive on Planning Competitions (RPW 2008) Published by the Federal Ministry of Justice and Consumer Protection
Property Value Directive of 05/09/2012, Austrian Federal Gazette AT, 18/10/2012 B1
Ordinance on energy saving thermal insulation and energy saving systems engineering in buildings (Energy Saving Ordinance – EnEV) of 24/07/2007. Bgbl. I No 34, 26/07/2007
Ordinance amending the Energy Saving Ordinance of 29/04/2009, Bgbl. I No. 23, 30/04/2009

VDI standard 2067 Economic efficiency of building installations – Fundamentals and economic calculation. 2012-09
VDI standard 4100 Sound insulation between rooms in buildings – Dwellings – Assessment and proposals for enhanced sound insulation between rooms. 2012-10
VDI standard 6200 Structural safety of buildings – Regular inspections. 2010-02

DIN 276-1 Building costs – Part 1: Building construction. 2008-12
DIN 1045-2 Concrete, reinforced and pre-stressed concrete structures, Part 2: Concrete, Specifications, properties, production and conformity. Application rules for DIN EN 206-1. 2008-08
DIN 1045-3 Concrete, reinforced and pre-stressed concrete structures, Part 3: Execution of structures, Application rules for DIN EN 13670. 2013-07
DIN 1504-5 Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 5: Concrete injection 2013-06
DIN 1946-6 Ventilation and air conditioning – Part 6: Ventilation for residential buildings; general requirements, requirements for measuring, performance and labelling, delivery/acceptance (certification) and maintenance. 2009-05
DIN 4102-2 Fire behaviour of building materials and building components, Part 2: Building components, definitions, requirements and tests. 1977-09
DIN 4102-4 Fire behaviour of building materials and building components, Part 4: Synopsis and application of classified building materials, components and special components. 1994-03
DIN 4108 Thermal protection and energy economy in buildings – Thermal bridges – Examples for planning and performance. 2006-03
DIN 4108-2 Thermal protection and energy economy in buildings, Part 2: Minimum requirements to thermal insulation. 2013-02
DIN 4108-3 Thermal protection and energy economy in buildings, Part 3: Protection against moisture subject to climate conditions; Requirements, and directions for design and construction. 2001-07
DIN 4108-4 Thermal protection and energy economy in buildings – Part 4: Protection against moisture subject to climate conditions. 2013-02
DIN 4109 Sound insulation in buildings; requirements and testing. 1989-11
DIN 4160 Bricks for floors, statically inactive. 2000-04
DIN 18195-5 Waterproofing of buildings – Part 5: Waterproofing against non-pressing water on floors and in wet areas, design and execution. 2011-05
DIN 18195-2 Waterproofing of buildings – Part 2: Materials. 2009-04
DIN 18217 Concrete surfaces and formwork surface. 1981-12
DIN 18218 Pressure of fresh concrete on vertical formwork. 2010-01
DIN 18331 German construction contract procedures (VOB), Part C: General technical specifications in construction contracts (ATV), Concrete works. 2012-09
DIN 18353 German construction contract procedures (VOB), Part C: General technical specifications in construction contracts (ATV) – Laying of floor screed. 2012-09
DIN 18365 German construction contract procedures (VOB), Part C: General technical specifications in construction contracts (ATV) – Flooring work. 2012-09
DIN 18 551 (draft standard) Shotcrete – National rules for series DIN EN 14487 and rules for design of sprayed concrete constructions. 2013-06
DIN 18560-2 Floor screeds in building construction – Part 2: Floor screeds and heating floor screeds on insulation layers (floating screeds). 2009-09
DIN 18960 User costs of buildings. 2008-02
DIN 45631 Calculation of loudness level and loudness from the sound spectrum; Zwicker method. 1991-03
DIN 52115-2 (draft standard) Test methods for aggregates, Part 2: Impact test on crushed and broken aggregates larger than 32 mm. 2013-06

BS EN 206-1 Concrete – Part 1: Specification, performance, production and conformity
BS EN 442 Radiators and Convectors
BS EN 450-1 Fly ash for concrete – Part 1: Definition, specifications and conformity criteria
BS EN 480-15 Admixtures for concrete, mortar and grout – Test methods – Part 15: Reference concrete and method for testing viscosity modifying admixtures, 2013-11-27
BS EN 933-9 Tests for geometrical properties of aggregates – Part 9: Assessment of fines – Methylene blue test
BS EN 934-2 Admixtures for concrete, mortar and grout – Part 2: Concrete admixtures – Definitions, requirements, conformity, marking and labelling
BS EN 1008 Mixing water for concrete – Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete
BS EN 1504-9 Products and systems for the protection and repair of concrete structures – Definitions, require-

ments, quality control and evaluation of conformity – Part 9: General principles for the use of products and systems
BS EN 1520 Prefabricated reinforced components of lightweight aggregate concrete with open structure with structural or non-structural reinforcement
BS EN 1990 Basis of Structural Design – Guidelines for implementation and application
BS EN 1992-1-1 Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings
BS EN 1991-1-3 Eurocode 1: Actions on structures – Part 1-3: General actions – Snow loads
BS EN 1991-1-4 Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions
BS EN 1992-1-1 Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings
BS EN 1994-1-2 Eurocode 4: Design of composite steel and concrete structures – Part 1-2: General rules – Structural fire design
BS EN 1998 Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings
BS EN 12354-1 Building acoustics. Estimation of acoustic performance of buildings from the performance of elements. Part 1. Airborne sound insulation between rooms
BS EN 12620 Aggregates for concrete
BS EN 12812 Falsework – Performance requirements and general design
BS EN 12878 Pigments for the colouring of building materials based on cement and/or lime – Specifications and methods of test
BS EN 13055 Lightweight aggregates – Part 1: Lightweight aggregates for concrete, mortar and grout
BS EN 13225 Precast concrete products – Linear structural elements
BS EN 13263 Silica fume for concrete – Part 1: Definitions, requirements and conformity criteria
BS EN 13318 Screed material and floor screeds – Definitions
BS EN 13501-1 Fire classification of construction products and building elements – Part 1: Classification using data from reaction to fire tests
BS EN 13670 Execution of concrete structures
BS EN 13813 Screed material and floor screeds – Screed material – Properties and requirements
BS EN 13829 Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurisation method (ISO 9972:1996, modified)
BS EN 13877-1 Concrete pavements – Part 1: Materials
BS EN 13877-2 Concrete pavements – Part 2: Functional requirements for concrete pavement
BS EN 13892-2 Methods of test for screed materials – Part 2: Determination of flexural and compressive strength
BS EN 14199 Execution of special geotechnical works – Micropiles
BS EN 14843 Precast concrete products – Stairs
BS EN 14889 Fibres for concrete – Part 1: Steel fibres – Definitions, specifications and conformity
BS EN 15037 Precast concrete products – Beam-and-block floor systems – Part 5: Lightweight blocks for simple formwork
BS EN 15643 Sustainability of construction works – Sustainability assessment of buildings – Part 1: General framework
BS EN 15804 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products

BS EN ISO 717-1 Acoustics – Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation
BS EN ISO 717-2 Acoustics – Rating of sound insulation in buildings and of building elements – Part 2: Impact sound insulation
BS EN ISO 6946 Building components and building elements – Thermal resistance and thermal transmittance – Calculation method
BS EN ISO 7730 Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
BS EN ISO 10211 Thermal bridges in building construction – Heat flows and surface temperatures – Detailed calculations
BS EN ISO 10456 Building materials and products – Hygrothermal properties – Tabulated design values and procedures for determining declared and design thermal values
BS EN ISO 12569 Thermal performance of buildings and materials – Determination of specific airflow rate in buildings – Tracer gas dilution method
BS EN ISO 14025 Environmental labels and declarations – Type III environmental declarations – Principles and procedures
BS EN ISO 14040 Environmental management – Life cycle assessment – Principles and framework
BS EN ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines
BS EN ISO/IEC 17065 Conformity assessment – Requirements for bodies certifying products, processes and services

DIN ISO 226 Acoustics – Normal equal-loudness level contours. 2006-04

DIN V 4108-6 Thermal protection and energy economy in buildings – Part 6: Calculation of annual heat and energy use. 2003-06
DIN V 4701-10 Energy efficiency of heating and ventilation systems in buildings – Part 10: Heating, domestic hot water supply, ventilation. 2003-08
DIN V 18500 Cast stone – Terminology, requirements, testing, inspection. 2006-12
DIN V 18599 Energy efficiency of buildings – Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting. 2010-01

Bibliography

Part B

Building material and product

Beddoe, Robin; Springenschmid, Rupert: Feuchtetransport durch Bauteile aus Beton. In: Beton- und Stahlbetonbau, 94/1999, pp. 158–166
Deutscher Beton- und Bautechnikverein e. V. (pub.): Betonschalungen und Ausschalfristen. DBV-Merkblatt. Berlin 2006
Deutscher Beton- und Bautechnikverein e. V. (pub.): Parkhäuser und Tiefgaragen. DBV-Merkblatt. Berlin 2010
Ebeling, Karsten; Lohmeyer, Gottfried: Weiße Wannen einfach und sicher. Konstruktion und Ausführung wasserundurchlässiger Bauwerke aus Beton. Dusseldorf 2009
Kampen, Rolf; Peck, Martin; Pickhardt, Roland; Richter, Thomas: Bauteilkatalog. Planungshilfe für dauerhafte Betonbauteile. Erkrath/Dusseldorf 2011
Pickhardt, Roland; Bose, Thomas; Schäfer, Wolfgang: Beton – Herstellung nach Norm. Erkrath/Dusseldorf 2012
Röhling, Stefan; Eifert, Helmut; Jablinski, Manfred: Betonbau. Vol. 1. Stuttgart 2012
Röhling, Stefan: Betonbau. Vol. 2. Stuttgart 2012
Röhling, Stefan; Eifert, Helmut; Jablinski, Manfred: Betonbau. Vol. 3. Stuttgart 2013
Verein Deutscher Zementwerke e. V. – VDZ (pub.):
Hersel, Otmar: Zemente und ihre Herstellung. Zement-Merkblatt B 1. Dusseldorf 01/2006
Biscoping, Michaela: Gesteinskörnungen für Normalbeton. Zement-Merkblatt Betontechnik B 2. Dusseldorf 08/2011
Kampen, Rolf: Betonzusätze, Zusatzmittel, Zusatzstoffe. Zement-Merkblatt B 3. Dusseldorf 09/2005
Pott, Jens Uwe; Oesterheld, René: Expositionsklassen von Beton. Zement-Merkblatt B 9. Dusseldorf 01/2010
Bosold, Diethelm: Leichtbeton. Zement-Merkblatt B 13. Dusseldorf 04/2008
Dickamp, Michael J.; Eppers, Sören: Selbstverdichtender Beton – Eigenschaften und Prüfung. Zement-Merkblatt B 29. Dusseldorf 07/2006
Bose, Thomas; Kampen, Rolf: Wasserundurchlässige Betonbauwerk. Zement-Merkblatt H 10. Dusseldorf 01/2010
Weber, Robert: Guter Beton. Erkrath/Dusseldorf 2010

Concrete construction operations

Deutscher Beton- und Bautechnikverein e. V. (pub.): Betondeckung und Bewehrung. DBV-Merkblatt. Berlin 07/2002
Deutscher Beton- und Bautechnikverein e. V. (pub.): Betonschalungen und Ausschalfristen. DBV-Merkblatt. Berlin 09/2006
Verein Deutscher Zementwerke e. V. – VDZ (pub.):
Biscoping, Michaela, Richter, Thomas: Frischbeton Eigenschaften und Prüfung. Zement-Merkblatt B 4. Dusseldorf 03/2013
Peck, Martin; Pickhardt, Roland: Überwachen von Beton auf Baustellen. Zement-Merkblatt B 5. Dusseldorf 01/2011
Kampen, Rolf: Transportbeton – Festlegung, Bestellung, Lieferung, Abnahme. Zement-Merkblatt B 6. Dusseldorf 01/2013
Kampen, Rolf: Bereiten und Verarbeiten von Beton. Zement-Merkblatt B 7. Dusseldorf 03/2011
Pickhardt, Roland; Schäfer, Wolfgang: Nachbehandeln von Beton. Zement-Merkblatt B 8. Dusseldorf 03/2011

Materiality and surface

Bundesverband der Deutschen Zementindustrie (BDZ); Deutscher Beton- und Bautechnik-Verein (DBV): Merkblatt Sichtbeton. Berlin 2008
Deutscher Beton- und Bautechnikverein e. V. (pub.): Sichtbeton. DBV-Merkblatt. Berlin 08/2004

Fiala, Hannes et al.: Wegweiser Sichtbeton. Gütersloh 2007
IGF-Vorhaben Nr. 15873: Neue Sichtbetontechnik – Integration der Erkenntnisse zu Wechselwirkungen zwischen Schalhaut, Trennmittel und Betonoberfläche in die Prozesskette beim Sichtbeton
Peck, Martin; Bosold, Diethelm; Bose, Thomas: Technik des Sichtbetons. Erkrath/Dusseldorf 2007
Verein Deutscher Zementwerke e.V. – VDZ (pub.): Peck, Martin; Bosold, Diethelm: Techniken der Flächengestaltung. Zement-Merkblatt H 8. Dusseldorf 01/2009

Designing structures with structural concrete

Angerer, Fred: Bauen mit tragenden Flächen. Konstruktion und Gestaltung. Munich 1960
Bachmann, Hubert; Hahn, Volker; Steinle, Alfred: Bauen mit Betonfertigteilen im Hochbau. In: Beton-Kalender 2009. Vol. 1. Berlin 2009, p. 151f.
Baker, William F.: Beton im Hochhausbau: Burj Dubai, Trump Tower und Infinity Tower. In: Detail 1-2/2010, p. 72f.
Bauermeister, Ulrich; Furche, Johannes: Elementbauweise mit Gitterträgern. In: Beton-Kalender 2009. Vol. 1. Berlin 2009, p. 151f.
Bergmeister, Konrad; Keuser, Manfred; Taferner, Josef: Integrale Konstruktionen aus Beton. In: Beton-Kalender 2009. Vol. 2. Berlin 2009, p. 231f.
Bergmeister, Konrad: Konstruieren mit Fertigteilen. In: Beton-Kalender 2005. Vol. 2. Berlin 2005, p. 163f.
Beton- und Stahlbetonbau. Fachzeitschrift. Berlin
Bindseil, Peter: Stahlbetonfertigteile: Konstruktion, Berechnung, Ausführung. Cologne 2007
Bobran, Hans; Bobran-Wittfoht, Ingrid; Schlauch, Dirk: Flachdachaufbauten mit Dichtungsbahnen – Die Suche nach dem sicheren Dach. In: Detail 7-8/2002, p. 954f.
Born, Joachim: Schalen, Faltwerke, Rippenkuppeln und Hängedächer in Stahlbeton und Spannbeton. Vol. 3: Rippenkuppeln, Faltwerke, Hängedächer. Dusseldorf 1964
Bose, Thomas; Kampen, Rolf: Wasserundurchlässige Betonbauwerke. In: Zement-Merkblatt Hochbau H 10. Dusseldorf 01/2010
Brauer, Norbert: Betonbauten als Dichtkonstruktionen. In: Institut für Stahlbetonbewehrung e.V. 03/2004
Busenkell, Michaela; Cachola Schmal, Peter (pub.): Best High-Rises 2010/11 – Internationaler Hochhauspreis 2010. Munich 2010
Council on Tall Buildings and Urban Habitat (CTBUH): Publikationen und Proceedings
Curbach, M; Jesse, F: High-Performance Textile-Reinforced Concrete. *Structural Engineering International 9* (1999) 9, pp. 289–91
Deutscher Ausschuss für Stahlbeton (pub.): Sachstandsbericht Ultrahochfester Beton. Berlin 2008
Deutscher Beton- und Bautechnik-Verein (DBV) und Bundesverband der Deutschen Zementindustrie (BDZ): Merkblatt Sichtbeton
Ebeling, Karsten; Lohmeyer, Gottfried: Weiße Wannen einfach und sicher. Konstruktion und Ausführung wasserundurchlässiger Bauwerke aus Beton. Dusseldorf 2009
Ebeling, Karsten; Lohmeyer, Gottfried: Weiße Wannen im Hochbau. In: Beton-Kalender 2010. Vol. 2. Berlin 2010, p. 137f.
Ehlig, Daniel et al.: Textilbeton – Ausgeführte Projekte im Überblick, In: Beton- und Stahlbeton 11/2012
Eisele, Johann; Kloft, Ellen (pub.): Hochhaus Atlas. Munich 2002
Eligehausen, Rolf, Rehm, Gallus, Mallée, Rainer: Befestigungstechnik, In: Beton-Kalender 1997. Vol. 2. Berlin 2012, pp. 609–754
Engelsmann, Stephan; Schlaich, Jörg; Schäfer, Kurt: Entwerfen und Bemessen von Betonbrücken ohne Fugen und Lager. Berlin 2000
Engelsmann, Stephan: Integrale Betonbrücken – Entwerfen und Bemessen von Brücken ohne Lager und Fugen. Dissertation Universität Stuttgart, 1998
Fachvereinigung Deutscher Betonfertigteilbau e.V. (pub.): Ausbaudetails im Fertigteilbau – Entwurfshilfen für den Fertigteilbau. Dusseldorf 2002
FDB Fachvereinigung Deutscher Betonfertigteilbau e.V. (pub.): Betonfertigteile im Geschoss- und Hallenbau. Grundlagen für die Planung. Bonn 2009
Fingerloos, Frank: Normen und Regelwerke. In: Beton-Kalender 2009. Vol. 1. Berlin 2009, p. 555f.
Franz, Gotthard; Hampe, Erhard; Schäfer, Kurt: Konstruktionslehre des Stahlbetons. Vol. 2: Tragwerke, Part B. Berlin/Heidelberg 1991
Franz, Gotthard; Schäfer, Kurt: Konstruktionslehre des Stahlbetons. Vol. 2: Tragwerke, Part A. Berlin/Heidelberg 1988
Franz, Gotthard: Konstruktionslehre des Stahlbetons. Vol. 1: Grundlagen und Bauelemente, Part A. Berlin/Heidelberg 1980
Franz, Gotthard: Konstruktionslehre des Stahlbetons, Vol. 1: Grundlagen und Bauelemente, Part B. Berlin/Heidelberg 1983
Freytag, Bernhard: Die Glas-Beton Verbundbauweise, Dissertation Technische Universität Graz, 2002
Goldberger, Paul: Wolkenkratzer. Das Hochhaus in Geschichte und Gegenwart. In: Baumeister 01/2006
Goris, Alfons; Hegger, Josef: Stahlbetonbau aktuell 2013: Praxishandbuch. Berlin 2013
Grasser, Emil et al.: Bemessung für Biegung, Längskraft, Querkraft und Torsion nach EC 2. In: Beton-Kalender 1993. Vol. 1. Berlin 1993, p. 313f.
Graubner, Carl-Alexander; Hausmann, Guido; Karasek, Jiri: Bemessung von Betonfertigteilen nach DIN 1045-1. In: Beton-Kalender 2005. Vol. 2. Berlin 2005, p. 287f.
Grünberg, Jürgen; Vogt, Norbert: Teilsicherheitskonzept für Gründungen im Hochbau. In: Beton-Kalender 2009. Vol. 1. Berlin 2009, p. 555f.
Hegger, Josef; Kerkeni, Naceur; Roggendorf, Thomas: Zum Tragverhalten von Slim-Floor-Konstruktionen. In: Beton- und Stahlbetonbau 01/2008, p. 5f.
Heinle, Erwin; Schlaich, Jörg: Kuppeln aller Zeiten – aller Kulturen. Stuttgart 1996
Hock, Bernd; Schäfer, Kurt; Schlaich, Jörg: Fugen und Aussteifungen in Stahlbetonskelettbauten. Berlin 1986
Hosser, Dietmar; Richter, Ekkehard: Konstruktiver Brandschutz im Übergang von DIN 4102 zu den Eurocodes. In: Beton-Kalender 2009. Vol. 1. Berlin 2009, p. 499f.
in puncto Transportbeton GmbH (pub.): TB-Info: Mitgliederzeitschrift des Bundesverbandes der Deutschen Transportbetonindustrie e.V.
Joedicke, Jürgen: Schalenbau. Konstruktion und Gestaltung. Stuttgart 1962
Kohlmeyer, Christian et al.: Verbundträger und Deckensysteme. In: Stahlbau-Kalender 2010. Berlin 2010, p. 483f.
König, Gert; Liphardt, Siegfried: Hochhäuser aus Stahlbeton. In: Beton-Kalender 2003. Vol. 1. Berlin 2003
König, Gert; Tue, Nguyen Viet; Schenk, Gunter: Grundlagen des Stahlbetonbaus: Einführung in die Bemessung nach DIN 1045-1. Wiesbaden 2008
Kretz, Joachim; Sauerborn, Norbert: Verbundstützen. In: Stahlbau-Kalender 2010. Berlin 2010, p. 423f.
Leonhardt, Fritz; Mönnig, Eduard: Vorlesungen über Massivbau, Part 1: Grundlagen zur Bemessung von Stahlbetonbau. Berlin/Heidelberg 1984
Leonhardt, Fritz; Mönnig, Eduard: Vorlesungen über Massivbau, Part 2: Sonderfälle der Bemessung im Stahlbetonbau. Berlin/Heidelberg 1986
Leonhardt, Fritz; Mönnig, Eduard: Vorlesungen über Massivbau, Part 3: Grundlagen zum Bewehren im Stahlbetonbau. Berlin/Heidelberg 1977
Leonhardt, Fritz: Vorlesungen über Massivbau, Part 4: Nachweis der Gebrauchstauglichkeit. Berlin/Heidelberg 1978
Leonhardt, Fritz: Vorlesungen über Massivbau, Part 5: Spannbeton. Berlin/Heidelberg 1980
Mallée, Rainer; Fuchs, Werner; Eligehausen, Rolf: Bemessung von Verankerungen in Beton nach CEN/TS 1992-4. In: Beton-Kalender 2012. Vol. 2. Berlin 2012, pp. 93–173
Meichsner, Heinz; Rohr-Suchalla, Katrin: Risse in Beton und Mauerwerk. Stuttgart 2011
Meyer, Julian; Rohr, Martin; Theile, Volker: Geschossbauten – Verwaltungsgebäude. In: Beton-Kalender 2003. Vol. 1. Berlin 2003, p. 71f.
Mihala, Ronald; Bergmeister, Konrad: Befestigungstechnik – einbetonierte und eingemörtelte Bewehrungsstäbe sowie Gewindestangen. In: Beton-Kalender 2012, Vol. 2. Berlin 2012, pp. 175–208
Nervi, Pier Luigi; Herzog, Thomas; Schneider, Martina: Arcus 7. Gestalten in Beton. Zum Werk von Pier Luigi Nervi. Cologne 1989
Peck, Martin (pub.): Baustoff Beton. Munich 2005
Phocas, Marios: Hochhäuser. Tragwerk und Konstruktion. Stuttgart/Leipzig/Wiesbaden 2005
Phocas, Marios: Tragwerke für den Hochhausbau. System, Verformungskontrolle, Konstruktion. Berlin 2001
Polonyi, Stefan; Austermann, Claudia: Stahlbetonkonstruktionen im Hochbau. In: Beton Atlas. Munich 2009, p. 106f.
Pötzl, Michael: Robuste Tragwerke – Vorschläge zu Entwurf und Konstruktion In: Bauingenieur 71, 1996, p. 481f.
van Rooden, Clementine: Faltwerk aus Spannbeton. Sportausbildungszentrum Mülimatt. In: tec21 40/2010, pp. 23–26
Schäfer, Kurt; Steidle, Peter: Trag- und Verformungsfähigkeit von Stützen bei großen Zwangsverschiebungen der Decken. In: Schriftenreihe des Deutschen Ausschusses für Stahlbeton 376, 1986
Schlaich, Jörg; Schäfer, Kurt: Konstruieren im Stahlbetonbau. In: Beton-Kalender 1998. Vol. 2. Berlin 1998, p. 721f.
Schmid, Michael et al.: Ultra-High Performance Concrete and Nanotechnology in Construction. Kassel 2012
Schöck Bauteile GmbH (pub.): Schöck Tronsole: Technische Informationen. Baden-Baden 05/2013
Schöck Bauteile GmbH (pub.): Schöck-Isokorb: Technische Informationen nach EC2. Baden-Baden 03/2013
Slim Floor. Das innovative Konzept für Flachdecken. Produktinformationen von Arcelor Mittal
Schunck, Eberhard et al.: Dach Atlas. Munich/Basel 2002
Sedlbauer, Klaus et al.: Flachdach Atlas. Munich/Basel 2010
Sippel, Thomas M.: Verankerungs- und Bewehrungstechnik, In: Beton-Kalender 2012. Vol. 2. Berlin 2012, pp. 209–256
Spalding, Valerie: Die Kunst der Falte. Faltwerke aus plattenförmigen Kunststoff-Halbzeugen, Dissertation Staatlichen Akademie der Bildenden Künste Stuttgart, 2013
Thomsing, Martin: Spannbeton: Grundlagen, Berechnungsverfahren, Beispiele. Stuttgart/Leipzig/Wiesbaden 2002
Tillmann, Mathias: Knotenverbindungen für Betonfertigteile – Hinweise für Bemessung und Konstruktion. Published by the Fachvereinigung Deutscher Betonfertigteilbau e.V. Dusseldorf 2011
Witt, Karl Josef (pub.): Grundbau-Taschenbuch. Vols. 1–3. Berlin 2008
Zehetmaier, Gerhard; Zilch, Konrad: Bemessung im konstruktiven Betonbau. Berlin/Heidelberg 2010
Zement + Beton Handels- und Werbeges.m.b.H. (pub.): Vorgespannte Flachdecken mit Vorspannung ohne Verbund – freie Spanngliedlage, Tagungsband Expertenforum Beton 2005. Vienna 2005
Zentralverband des Deutschen Dachdeckerhandwerks (pub.): Deutsches Dachdeckerhandwerk – Regeln für Abdichtungen. Cologne 2012

Digital design and fabrication methods

Burry, Jane; Burry, Mark: The New Mathematics of Architecture. London 2012
Gramazio, Fabio; Kohler, Matthias: Digital Materiality in Architecture. Zurich 2008
Kolarevic, Branko; Klinger, Kevin: A Manufacturing Material Effects: Rethinking Design and Making in Architecture. London 2008
Rivka Oxman, Robert Oxman, The New Structuralism: Design, Engineering and Architectural Technologies, Hoboken 2010
Steele, Brett (ed.): O-14: Projection and Reception, Reiser + Umemoto. London 2012

Part C

Sustainable construction with concrete

Bauhaus Universität Weimar (pub.): Einsatz von Betonbrechsand in der Portlandzementklinkerherstellung, 17. Internationale Baustofftagung. Weimar 2009

Bundesministerium für Verkehr, Bau und Stadtentwicklung: Leitfaden Nachhaltiges Bauen bei Bundesbauten. Berlin 2011

Bundesverband Baustoffe Steine und Erden e.V. (pub.): Mineralische Bauabfälle, Monitoring 2010. Berlin 2013

Deutscher Ausschuss für Stahlbeton (pub.): Beton nach DIN EN 206-1 und DIN 1045-2 mit rezyklierter Gesteinskörnung nach DIN EN 12620. Berlin 2010

Deutscher Ausschuss für Stahlbeton (pub.): Schlussberichte zur ersten Phase des DAfStb/BMBF-Verbundforschungsvorhabens "Nachhaltig Bauen mit Beton", publication series issue 572, 2007

Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (pub.): Kurzstudie Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 2011. Hanover 2011

DIN Fachbericht 100: Beton – Zusammenstellung von DIN EN 206-1 Beton – Part 1: Festlegung, Eigenschaften, Herstellung und Konformität und DIN 1045-2 Tragwerke aus Beton, Stahlbeton und Spannbeton – Part 2: Beton – Festlegung, Eigenschaften, Herstellung und Konformität – Anwendungsregeln zu DIN EN 206-1. Berlin 2010

Enquete-Kommission des Deutscher Bundestags: Mehr Zukunft für die Erde – Nachhaltige Energiepolitik für dauerhaften Klimaschutz – Schlußbericht. Bundestagsdrucksache 12/8600, 1994

Enquete-Kommission des Deutscher Bundestags: Konzept Nachhaltigkeit – Vom Leitbild zur Umsetzung – Schlussbericht. Bundestagsdrucksache 13/11200, 1998

Eyerer, Peter; Reinhardt, Hans-Wolf: Ökologische Bilanzierung von Baustoffen und Gebäuden: Wege zu einer ganzheitlichen Bilanzierung. Basel 2000

Food and Agriculture Organization of the United Nations (pub.): State of the World's Forests. Rome 2011

Frondel, Manuel et al.: Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen. Rheinisch-Westfälisches Institut für Wirtschaftsforschung, Fraunhofer-Institut für System- und Innovationsforschung, Bundesanstalt für Geowissenschaften und Rohstoffe. Essen 2006

Hauer, Bruno et al.: Verbundforschungsvorhaben: Nachhaltig Bauen mit Beton – Potenziale des Sekundärstoffeinsatzes im Betonbau – Teilprojekt B. In: DAfStb Issue 584. Berlin 2011

Jacobs, Jean-Pierre (pub.): Sustainable benefits of concrete structures. European Concrete Platform 2009

Löckener, Ralf: Nachhaltige Transport- und Logistikketten – Ist-Analyse der deutschen Zementindustrie. www.initiative-nachhaltigkeit.de/downloads/SUSTAIN-CONSULT_Logistik_Zementindustrie_2008.pdf. Accessed on 08/07/2013

Polley, Heino; Hennig, Petra; Schwitzgebel, Frank: Holzvorrat, Holzzuwachs, Holznutzung in Deutschland. In: AFZ – Der Wald 20/2009, pp. 1076–1078

Trendelenburg, Reinhard; Mayer-Wegelin, Hans: Das Holz als Rohstoff. Munich 1955

Verein Deutscher Zementwerke e.V. (pub.): Zement-Taschenbuch. Dusseldorf 2008

Verein Deutscher Zementwerke e.V. (pub.): Umweltdaten der deutschen Zementindustrie. Published annually World Commission on Environment and Development (pub.): Our common future. Oxford 1987

Costs and economics

Bundesministerium für Verkehr, Bau und Stadtentwicklung (pub.): Leitfaden Nachhaltiges Bauen bei Bundesbauten. Berlin 2011

Gondring, Hanspeter (pub.): Immobilienwirtschaft. Immobilienwirtschaft. Handbuch für Studium und Praxis. Munich 2004

Thermal building physics and energy efficiency

Brüel & Kjær (pub.): Thermal Comfort. Technical Review 2/1982

Buderus Heiztechnik (pub.): Handbuch für Heizungstechnik. Berlin 2002

Eichler, Friedrich; Fasold, Wolfgang; Sonntag, Ernst (pub.): Bauphysikalische Entwurfslehre. Vols. 1–4. Gütersloh

Fanger, Poul Ole: Thermal Comfort. Analysis and Applications in Environmental Engineering. New York 1973

Goulding, John R.; Lewis, J. Owen; Steemers, Theo C. (pub.): Energy conscious Design. Publication No. EUR 13445 of the Commission of the European Communities. London 1992

Grigull, Ulrich: Die Grundgesetze der Wärmeübertragung. Berlin/Heidelberg 1955

Hill, Rodney: Elastic Properties of Reinforced Solids: Some Theoretical Principles. In the Journal of the Mechanics and Physics of Solids 05/1963, pp. 357–372

Innova AirTech Instruments (pub.): Ventilation Measurements.

Palz, Wolfgang (pub.): European Solar Radiation Atlas. Berlin/Heidelberg 1996

Tipler, Paul A.: Physik. Berlin/Heidelberg 2009

Building acoustics

Beranek, Leo L.: Noise Reduction. New York 1960

Berger, Richard: Über die Schalldurchlässigkeit. Dissertation TH München, 1911

Bundesgerichtshof: Judgement from 14/05/1998, VII ZR 184/97

Bundesgerichtshof: Judgement from 14/06/2007, VII ZR 45/06

Deutsche Gesellschaft für Akustik: BR 0101 Memorandum Die DIN 4109 und die allgemein anerkannten Regeln der Technik in der Bauakustik (http://www.dega-akustik.de/fachausschuesse/bra/dokumente/DEGA_BR_0101.pdf)

Deutsche Gesellschaft für Akustik: Empfehlung 103 Schallschutzausweis (http://www.dega-akustik.de/publikationen/DEGA_Empfehlung_103.pdf)

Deutscher Beton- und Bautechnikverein e.V. (pub.): Betonierbarkeit von Bauteilen aus Beton und Stahlbeton – Planungs- und Ausführungsempfehlungen für den Beton-einbau. DBV-Merkblatt. Berlin 2004

Gesetz zum Schutz gegen Fluglärm vom 31. Oktober 2007 (Bundesgesetzblatt Jahrgang 2007 Teil I Nr. 56, ausgegeben zu Bonn am 9. November 2007)

Gösele, Karl: Schalldämmung von Doppelwänden mit steifen Wandschalen. In: Betonwerk + Fertigteiltechnik 05/1978, pp. 248–253

Henning Alphei, Thomas Hils: Welche Abstufung der Schalldämm-Maße sind bei Anforderungen an die Luftschalldämmung sinnvoll? In: wksb 59/2007, pp. 26–31

Lieblang, Peter: Wirtschaftlicher Schallschutz bei nicht unterkellerten Häusern. In: beton 05/2006, pp. 202–205

Lieblang, Peter: Schallschutz von Lochsteinmauerwerk aus Leichtbeton. In: Tagungsband Ulmer Betontage 2011. Gütersloh 2011

Lieblang, Peter; Hilz, Gerhard: Schallschutz von Haustrennwänden. In: Das Deutsche Architektenblatt 06/2005, pp. 60–65

Lieblang, Peter; Höfker, Gerrit: Schallschutz mit Leichtbeton. In: Das Mauerwerk 01/2009, pp. 21–26

Möser, Michael: Technische Akustik. Berlin/Heidelberg 2012

Möser, Michael (pub.): Messtechnik der Akustik. Berlin/Heidelberg 2010

Müller, Gerhard; Möser, Michael (pub.): Taschenbuch der technischen Akustik. Berlin/Heidelberg 2004

Northwood, Thomas D. (pub.): Architectural Acoustics. Stroudsburg 1977

Oberlandesgericht Stuttgart: Judgement from 17/10/2011, 5 U 43/11

Reichsgericht: Judgement from 11/10/1910, IV 644/10, RGSt. 44,76 (79)

Sechste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz (Technische Anleitung zum Schutz gegen Lärm – TA Lärm) of 26/08/1998 (GMBl Nr. 26/1998 p. 503)

Weisse, Karlhans: Leitfaden der Raumakustik für Architekten. Berlin 1949

Zwicker, Eberhard; Fastl, Hugo: Psychocoustics. Berlin/Heidelberg 1999

Renovation and restoration

Curbach, M; Jesse, F: High-Performance Textile-Reinforced Concrete. *Structural Engineering International 9* (1999) 9, pp. 289–91

DAfStb Issue 467: Verstärken von Betonbauteilen, Sachstandbericht. Berlin 1996

DAfStb Issue 591: Verstärken von Betonbauteilen mit geklebter Bewehrung, Sachstandbericht. Berlin 2011

Ehlig, D.; Jesse, F.; Curbach, M.: Textile Reinforced Concrete (TRC) Strain Specimens under High Temperatures. In: Aldea, C.-,M. (ed.) Proceedings of the ACI 2010 Spring Convention, Chicago, 21-25/03/2010, 2010.

Raupach, Michael; Orlowsky, Jeanette: Schutz und Instandsetzung von Betontragwerken. Dusseldorf 2008

Seim, Werner: Bewertung und Verstärkung von Stahlbetontragwerken. Berlin 2007

Interiors, design, vision

Cascade – Das Magazin der erfreulichen Dinge. Hrsg. von InformationsZentrum Beton GmbH

Fehlhaber, Jörg M.; Drees, Holger; Knopp, Wolfgang: Beton und Kunst. Dusseldorf/Erkrath 1997

Fuhrimann, Andreas; Hächler, Gabrielle: Was ein Haus in sich selbst verankert – sieben Bauten. Zurich 2010

Kind-Barkauskas, Friedbert et al.: Beton Atlas. Basel/Munich 2001

Meyhöfer, Dirk: Concrete Creations. Contemporary Buildings and Interiors. Salenstein 2007

Peck, Martin (pub.): Baustoff Beton. Munich 2005

Picture credits

The authors and publisher would like to sincerely thank everyone who helped create this book by providing us with their images, granting reproduction rights and by contributing information. All the drawings in this work were made especially for it. Photos that are not credited were taken by the authors and architects, are technical photos, or come from the Detail magazine archive. Despite intensive efforts, we were not able to identify some of the copyright holders of the photos and images used, although the rights of the copyright holders to them remain reserved. Please contact us if you have any information on this issue. The numbers shown refer to figure numbers.

Part A

A 1 Stefan Bauer, http://www.ferras.at
A 2 Lambrecht, Heinz-Otto: Opus Caementitium – Bautechnik der Römer. 4th edition. Dusseldorf 1993
A 3 Dyckerhoff & Widmann, Munich
A 4a Foto Marburg, Marburg
A 4b Christian Schittich, Munich
A 5 Image from: Cembureau, Brussels
A 6 Thomas Dix/Architekturphoto, Dusseldorf
A 7a Lutz Artmann, Berlin
A 7b Liapor GmbH & Co. KG, Hallerndorf-Pautzfeld
A 8 Sven Paustian, Pirmasens
A 9 Hisao Suzuki, Barcelona
A 10a Frank Kaltenbach, Munich
A 10b Bollinger + Grohmann Ingenieure, Frankfurt am Main
A 11 Luise Rellensmann
A 12 Klemens Ortmeyer, Hanover
A 13 Archiv Olgiati, Chur
A 14 Pietro Savorelli, Florence
A 15b, c Hans-Christian Schink, Stuttgart
A 16 Roland Halbe, Stuttgart

Part B

B Christian Schittich, Munich

Building material and products
B 1.1 BetonBild/Christian Pfitzer
B 1.2 Verlag Bau + Technik, Erkrath/Dusseldorf
B 1.7 Heidelberger Zement, Heidelberg
B 1.10 Christian Richters, Berlin
B 1.14 Studio Ernst/Kieswerke Rheinbach
B 1.15 Gerhard Neff, Darmstadt
B 1.17 Institut für Werkstoffe des Bauwesens, Universität der Bundeswehr, Munich
B 1.21 Bundesverband der Deutschen Zementindustrie, Berlin
B 1.22 Verein Deutscher Zementwerke e.V. (VDZ), Dusseldorf
B 1.25–27 thomas gruppe, Geschäftsfeld Betonbauteile
B 1.28 Jens Masmann, Munich
B 1.29 Uponor GmbH, Haßfurt
B 1.30 Gaston Bergereut/AMC, Paris
B 1.31 Jörg Steck, Berlin
B 1.34–36 Gaston Bergereut/AMC, Paris
B 1.37 Institut für Textiltechnik/RWTH Aachen
B 1.38 Juergen Glaesle, Hürth
B 1.39 IBB Fehling + Jungmann GmbH
B 1.40 Bouygues SA, Paris
B 1.44 Lukas Schaller, Vienna
B 1.45 Roland Krippner, Nuremberg
B 1.46 Thomas Freimann, Nuremberg
B 1.47, 49 LUCCON Lichtbeton GmbH, Dornbirn
B 1.48 LUCEM Lichtbeton, Stolberg
B 1.50 Bürkle Kellerbau GmbH + Co. KG, Sasbach

Concrete construction operations
B 2.1 Eva Schönbrunner, Munich
B 2.2–4 Doka GmbH, Amstetten
B 2.10 Hermann Rudolph Baustoffwerk GmbH, Weiler-Simmerberg
B 2.13, 14 Hermann Rudolph Baustoffwerk GmbH, Weiler-Simmerberg
B 2.16, 17 Hermann Rudolph Baustoffwerk GmbH, Weiler-Simmerberg

Materiality and surface
B 3.1, 2 Guido Erbring, Cologne
B 3.3 Daniel Roos, Reil
B 3.4 Reckli GmbH, Herne
B 3.5 Benoît Fougeirol, Paris
B 3.6 Eva Schönbrunner, Munich
B 3.7 Dagmar Flex, Munich
B 3.8a, b Ralph Feiner, Malans
B 3.9a, b BetonBild
B 3.9c Eva Schönbrunner, Munich
B 3.10 a–c Dyckerhoff Weiss AG, Wiesbaden
B 3.11 Michael Heinrich, Munich
B 3.12a Guido Erbring, Cologne
B 3.12b Christian Schittich, Munich
B 3.13 Gunter Bieringer, Munich
B 3.14 Eva Schönbrunner, Munich
B 3.15 Michael Heinrich, Munich
B 3.16 Merkblatt Sichtbeton, Deutscher Beton- und Bautechnikverein, 2004
B 3.19, 20 betonretousche.eu

Designing structures with structural concrete
B 4.4 Image from: Zehetmaier, Gerhard; Zilch, Konrad: Bemessung im konstruktiven Betonbau. Berlin/Heidelberg 2010, p. 38
B 4.7 as for B 4.4, p. 381
B 4.8 as for B 4.4, p. 5
B 4.10 http://www.splietker.de/typo3temp/pics/1a9110c04a.jpg
B 4.11a Image from: Schlaich, Jörg; Schäfer, Kurt: Konstruieren im Stahlbetonbau. In: Beton-Kalender 1998, Vol. 2. Berlin 1998, p. 805
B 4.11b Image from: Zehetmaier, Gerhard; Zilch, Konrad: Bemessung im konstruktiven Betonbau. Berlin/Heidelberg 2010
B 4.13 Image from: Schlaich, Jörg; Schäfer, Kurt: Konstruieren im Stahlbetonbau. In: Beton-Kalender 1998, Vol. 2. Berlin 1998, p. 752
B 4.14 as for B 4.13, p. 757
B 4.15 as for B 4.13, p. 828
B 4.16, 17 Image from: Fachvereinigung Deutscher Betonfertigteilbau e.V.: Merkblatt Nr. 7 über Brandschutzanforderungen von Betonfertigteilen (11/2012)
B 4.18 Ivan Baan, Amsterdam
B 4.21, 22 Image from: Zehetmaier, Gerhard; Zilch, Konrad: Bemessung im konstruktiven Betonbau. Berlin/Heidelberg 2010, p. 9
B 4.23 Hans-Peter Fuchs/rodgau-bahn.de
B 4.28 Filippo Simonetti, Brunate
B 4.35–38 Image from: DAfStb-Richtlinie Wasserundurchlässige Bauwerke aus Beton. 2003-11 und Berichtigung zur WU-Richtlinie 2006-03
B 4.39 Image from: DIN EN 14199 Ausführung von besonderen geotechnischen Arbeiten (Spezialtiefbau) – Pfähle mit kleinen Durchmessern (Mikropfähle). 2005
B 4.41 FRANKI Grundbau GmbH & Co. KG, Seevetal
B 4.42 www.nba-hannover.wsv.de
B 4.43 DYWIDAG-Systems International (DSI)
B 4.45 Image from: Schlaich, Mike; El Zareef, Mohamed: Infraleichtbeton. In: Beton und Stahlbeton, Issue 04/2008
B 4.46 Berding Beton GmbH, Steinfeld
B 4.49 Taiheiyo Cement Corporation, Tokyo
B 4.50 Image from: FDB Fachvereinigung Deutscher Betonfertigteilbau e.V. (pub.): Betonfertigteile im Geschoss- und Hallenbau. Grundlagen für die Planung. Bonn 2009, p. 60
B 4.52 Image from Schlaich, Jörg; Schäfer, Kurt: Konstruieren im Stahlbetonbau. In: Beton-Kalender 1998, Vol. 2. Berlin 1998, p. 757
B 4.54a Schöck-Isokorb. Technische Informationen nach EC2, published by Schöck Bauteile GmbH, Baden-Baden. Valid as of March 2013
B 4.55c www.halfen.de
B 4.56 Cobiax Technologies GmbH, Wiesbaden
B 4.57 Martín Lejarraga, Cartagena
B 4.63 Image from: DIN EN 1520 Vorgefertigte Bauteile aus haufwerksporigem Leichtbeton und mit statisch anrechenbarer oder nicht anrechenbarer Bewehrung. 2011-06, p. 35
B 4.64 Image from: Theile, Volker; Rohr, Martin; Meyer, Julian: Geschossbauten – Verwaltungsgebäude. In: Beton-Kalender 2003. Berlin 2003, p. 93
B 4.66a Image from: Arcelor Mittal: Slim Floor Produktinformationen, p. 16
B 4.66b ArcelorMittal Construction Solutions, Luxembourg
B 4.67–70 BetonMarketing Deutschland: www.planungsatlas-hochbau.de
B 4.71 Klaus Mellenthin, Berlin
B 4.72a Cemex Beton-Bauteile GmbH, Bad Dürkheim
B 4.72b Image from: Schöck Bauteile GmbH, Baden-Baden
B 4.73 Image from: Schöck Bauteile GmbH, Baden-Baden
B 4.78–82 Image from: Fachvereinigung Deutscher Betonfertigteilbau e.V.
B 4.86 René Rötheli, Baden
B 4.88 Shinkenchiku-sha, Tokyo
B 4.92a Udo Meinel, Berlin
B 4.93 Klaus Bang/Arkitema Architects
B 4.94 Claudia Fuchs, Munich
B 4.95 Lafarge Ciments, Saint-Cloud

Digital design and fabrication methods
B 5.1 MOKA/UNStudio
B 5.2 From Weston, Richard: Utzon. Kiel 2001, p. 126: Bent Ryberg/Planet Foto
B 5.3 Werner Huthmacher/arturimages
B 5.4 Eva Schönbrunner, Munich
B 5.5 Fresh Media FZZ LLC – Alexander
B 5.6 Chalabi architects & partner, Vienna
B 5.7 Bollinger + Grohmann Ingenieure, Frankfurt am Main
B 5.8 From the documentary film *Pedra líquida. Descobrint els secrets de Gaudí,* 02/11/2010, Kanal 33, Catalonia
B 5.9 UN Studio Amsterdam
B 5.11 Roland Halbe, Stuttgart
B 5.12 Design to Production
B 5.13 Dr. A. Kanellopoulos/cubus hellas
B 5.14, 15 Thomas Mayer Archive
B 5.16, 19 Reiser + Umemoto, New York
B 5.20 Florian Hafele, Innsbruck
B 5.21 soma, Vienna
B 5.22 Martin Schroth, Staatliche Akademie der Bildenden Künste Stuttgart
B 5.23 Peter Ignaz Kirsten, architect, developer and patent holder
B 5.24 D-shape, London

Part C

C Frank Kaltenbach, Munich

Sustainable construction with concrete
C 1.1 Stefanie Grebe, Dusseldorf
C 1.3 Image from: Bundesanstalt für Geowissenschaften und Rohstoffe – BGR
C 1.4 Deutsche Rohstoffagentur (DERA) in the Bundesanstalt für Geowissenschaften und Rohstoffe (pub.): Reserven, Ressourcen und

Verfügbarkeit von Energierohstoffen 2011 – Kurzstudie. Hanover 2011
C 1.5 Image from: Bild 1 from DIN EN ISO 14040
C 1.6 Image from: Food and Agriculture Association of the United Nations: State of the World's Forests. Rome 2011
C 1.7 Institut Bauen und Umwelt e. V. (IBU), Berlin
C 1.9 Bundesverband der Deutschen Transportbetonindustrie e. V. (pub.): Ökobilanzielle Baustoffprofile für Transportbeton, Technischer Bericht (TB-BTe2135/2007). Duisburg 2007 and Hauer, Bruno et al.: Verbundforschungsvorhaben "Nachhaltig Bauen mit Beton" – Potenziale des Sekundärstoffseinsatzes im Betonbau – Teilprojekt B. DAfStb booklet 584. Berlin 2011
C 1.11 Verlag Bau+Technik GmbH, Erkrath / Dusseldorf
C 1.12 Image from: Verein Deutscher Zementwerke e. V.
C 1.13 Image from: Wolfgang Czernin
C 1.14 Image from: Verein Deutscher Zementwerke e. V.
C 1.15 Image from Verein Deutscher Zementwerke e. V.: Umweltdaten der deutschen Zementindustrie
C 1.16 Image from Hauer, Bruno et al.: Verbundforschungsvorhaben "Nachhaltig Bauen mit Beton" – Potenziale des Sekundärstoffseinsatzes im Betonbau – Teilprojekt B. DAfStb booklet 584. Berlin 2011
C 1.18 Image from: Verein Deutscher Zementwerke e. V.
C 1.19 Kleemann GmbH, Goeppingen
C 1.20 Stetter GmbH, Memmingen

Costs and economics
C 2.1 Isabel Simon, Berlin
C 2.5 BMVBS (pub.): Bewertungssystem Nachhaltiges Bauen, Steckbrief: Gebäudebezogene Kosten im Lebenszyklus
C 2.13 noshe / Collection Boros, Berlin
C 2.14 Hans Blossey, Hamm

Thermal building physics and energy efficiency
C 3.1 AFC Air Flow Consulting, Zurich
C 3.15 Image from: DIN 4701-10 Energetische Bewertung heiz- und raumlufttechnischer Anlagen – Teil 10: Heizung, Trinkwassererwärmung, Lüftung. 2003-08
C 3.18 BetonMarketing Deutschland: www.planungsatlas-hochbau.de
C 3.19 Pfeifer Seil- und Hebetechnik GmbH, Memmingen
C 3.23 Bundesverband der Deutschen Zementindustrie, Berlin
C 3.24 Bundesverband Wärmepumpe (BWP) e. V., Berlin
C 3.26 ISOCAL HeizKühlsysteme GmbH, Friedrichshafen
C 3.27 HeidelbergCement AG, Heidelberg
C 3.28 Max Kant, Berlin
C 3.29 Innogration GmbH, Bernkastel-Kues
C 3.32 CleanVerTec GmbH, Vienna

Renovation and restoration
C 5.2 Image from: DIN EN 1504-9 Produkte und Systeme für den Schutz und die Instandsetzung von Betontragwerken – Definitionen, Anforderungen, Qualitätsüberwachung und Beurteilung der Konformität. Teil 9: Allgemeine Grundsätze für die Anwendung von Produkten und Systemen. 2008-11
C 5.4 a Raupach, Michael: Grundlagen der Korrosion von Stahl in Beton. Zertifizierung zum sachkundigen Planer für Betoninstandsetzung. Munich 2012
C 5.7 Image from: Raupach, Michael; Orlowsk, Jeanette: Schutz und Instandsetzung von Betontragwerken. Dusseldorf 2008
C 5.9 Image from: Seim, Werner: Bewertung und Verstärkung von Stahlbetontragwerken. Berlin 2007
C 5.11 b Image from Deutscher Ausschuss für Stahlbeton (DAfStb) (pub.): booklet 467. Verstärken von Betonbauteilen. 1996-10
C 5.12 a www.textil-beton.de
C 5.12 b Silvio Weiland / TUDALIT e. V
C 5.21 b Image from: Raupach, Michael; Dauberschmidt, Christoph: Kathodischer Korrosionsschutz mit Zink-Opferanoden. In: Technische Forschung und Beratung für Zement und Beton (TFB). Fachveranstaltung 824761/62, Betoninstandsetzung – aus Fehlern lernen. Wildegg 2003, Chapter 1

Interiors, design, vision
C 6.1 Dominique Marc Wehrli, Regensdorf
C 6.2 Archiv Olgiati, Chur
C 6.3 www.guentheregger.at
C 6.4 Arbeitsgemeinschaft Betonlasur, Oliver Jungheim / Jürgen Steines GbR, Berlin
C 6.5 betonWare / Alexis Oehler
C 6.6 Cappellini
C 6.7 werkform®
C 6.9 Klemens Ortmeyer, Hanover
C 6.10 a, 14 Valentin Jeck, Uerikon
C 6.11 Eternit (Switzerland) AG, Niederurnen
C 6.12 Cristobal Palma, London
C 6.13 Melanie Weber, Munich
C 6.16 steininger.designers gmbh / Catherine Roider, Linz
C 6.17 Bertille Gentil
C 6.18 Ivanka Design, Budapest
C 6.19 http://www.steinmanufaktur-jaensch.de/wp-content/gallery/materialien/mischungfein.jpg
C 6.21 Dagmar Schmidt, Langenhagen / ©VG -Bild-Kunst
C 6.22 memux, Vienna
C 6.23 Lukas Roth, Cologne
C 6.24–27 Archiv Hochschule Rosenheim / Prof. Ulrike Förschler

Part D

D Roland Halbe, Stuttgart

p. 182–184 Walter Mair, Zurich
p. 185–189 Simon Menges
p. 190–192 Michael Heinrich, Munich
p. 193–195 Marc Lins, New York
p. 196, 197, 199 bottom Ruedi Walti, Basel
p. 198, 199 top Andreas Gabriel, Munich
p. 200 Claudia Fuchs, Munich
p. 201, 202 Sergio Grazia, Paris
p. 203–205 Michael Heinrich, Munich
p. 206, 207, 209–211 Dominique Marc Wehrli, Regensdorf
p. 212–215 Paul Ott, Graz
p. 216, 217 Ivan Baan, Amsterdam
p. 218, 221, 222, 223 bottom Hufton + Crow Photographers
p. 223 top Eva Schönbrunner, Munich
p. 224 Ivan Baan, Amsterdam
p. 225, 226 Roland Halbe, Stuttgart
p. 227 Richard Bryant/arcaid /archenova
p. 228 Thomas Madlener, Munich
p. 229 Christian Schittich, Munich
p. 230 Alexandre Kapellos, Zurich
p. 231, 232 René Rötheli, Baden (CH)
p. 234 3rd from the top, 4th from the top BASF, Zurich
p. 235–237, 238 top, 239 Hans Jürgen Landes, Dortmund
p. 240, 241, 242 top left, 242 bottom, 243 top, Florian Holzherr, Munich
p. 244, 246 top, 247 Günter Richard Wett, Innsbruck
p. 248, 249 Christian Richters, Berlin
p. 250 Duccio Malagamba, Barcelona
p. 251 Rafael Vargas Fotografía, Barcelona
p. 252–254, 255 top Nikolaus Schletterer, Innsbruck
p. 256, 257, 258 bottom, 259 Brigida Gonzáles, Stuttgart

E Christian Schittich, Munich

Index

Institut für internationale Architektur-Dokumentation · Munich

Modern Concrete Construction MANUAL

Once an innovative, modern building material, which later fell into disrepute due to some very stereotypical applications in recent times, concrete, with its many different facets, is now more popular than ever among designers and clients. As well as its wide range of static and structural properties, the great diversity of the material's qualities and surface finishes offers enormous potential. In addition to the technical possibilities classically ascribed to concrete construction, the current debate around energy efficiency and sustainability is making it increasingly attractive because it seems ideal for meeting certain requirements. This publication focuses not only on the design and structural planning of concrete structures, but also on its materiality and haptic and sensual side. Exposed concrete with a "flawless smooth grey" finish is not the only quality that concrete has to show for itself. Designers and interior designers are now using concrete to create innovative furniture and spaces of hitherto unimaginable sensuality.
The "Modern Concrete Construction Manual" gives planners sound expert information on concrete, from its manufacture and materiality through to designing concrete structures and including the current possibilities of digital design and manufacturing processes. Covering issues such as economic efficiency, energy and sustainability, repairing and restoring concrete structures, and continuing through to design and interior design, this standard reference work offers readers comprehensive knowledge, down to the last detail.
An extensive selection of built examples is designed to provide inspiration and encourage designers and planners to put this classic building material to modern use.

The authors:
Martin Peck, Dipl.-Ing. (editor)
Christoph Dauberschmidt, Prof. Dr.-Ing.
Stephan Engelsmann, Prof. Dr.-Ing.
Ulrike Förschler, Prof. Dipl.-Ing.
Torsten Förster, Dipl.-Ing.
Franz Forstlechner, Dipl.-Ing.
Peter Lieblang, Prof. Dr.-Ing.
Stefan Peters, Prof. Dr.-Ing.
Valerie Spalding, Dr.-Ing.
Tobias Wallisser, Prof. Dipl.-Ing.
Arthur Wolfrum, Prof. Dipl.-Ing.

Institut für internationale
Architektur-Dokumentation
GmbH & Co. KG, Munich
www.detail.de