ANGUS J. MACDONALD

Structure & Architecture

THIRD EDITION

ROUTLEDGE

Structure and Architecture

This thoroughly updated edition of Angus J. Macdonald's insightful book *Structure and Architecture* offers an in depth analysis of structural design and its relationship with architecture. It draws on clear explanations of the connections between structural form, structural performance and architectural design to explore the interface between the technical and the visual in architecture. Additional chapters in this new edition cover the fields of structural theory, structural philosophy, the contributions of prominent engineers to the evolution of Modern architecture, and the concept and practice of sustainable design. Fully illustrated, this critical appraisal of structures is a core-curriculum text for students of architecture, structural engineering and architectural history, and is also a valuable resource for practitioners of these disciplines.

Angus J. Macdonald is currently Professor Emeritus of Architectural Structures at the Edinburgh School of Architecture and Landscape Architecture, University of Edinburgh. He has served as Head of the Department of Architecture at the University of Edinburgh, as a Commissioner on the Royal Commission on the Ancient and Historical Monuments of Scotland and as a member of the Board of Governors of Edinburgh College of Art. He is the author or co-author of ten books, including: *Structural Design for Architecture*; *Anthony Hunt: The Engineer's Contribution to Contemporary Architecture*; and *John Fowler and Benjamin Baker: The Forth Bridge* (with I. B. Whyte); as well as book chapters, including 'Structure and Architecture: Tectonics of Form', in Kanaani, M. and Kopec, D. (eds), *The Routledge Companion for Architectural Design and Practice*; and numerous articles on the relationship between structure and architecture.

"This new expanded edition is a welcome update of Professor Macdonald's classic book introducing the principles and application of structural engineering to young architects and engineers. Using both historical and recent examples, with drawings and excellent photographs, he brings the subject alive and provides an invaluable resource. Best of all, he offers readers the material to develop a good understanding of the subject which will serve as a source of inspiration to all designers."

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"This well-illustrated, fully revised and extended third edition of Angus Macdonald's book should be obligatory reading for those interested in exploring the often complex relationship between structure and architecture. I was impressed by the new reflective chapters deliberating on the philosophy of structures, the influence of engineers on the development of Modern architecture and, in particular, that drawing attention to the significant contribution that appropriate selection of low embodied energy materials and efficient structural systems can make in minimising a structure's impact on global climate change."

John Chilton, *Emeritus Professor, Architecture & Tectonics, University of Nottingham, UK*

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Third edition

Angus J. Macdonald

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Preface to the third edition

The theme of this book is the relationship between structural engineering and architecture. Its purposes are to provide insights into the role of structural design in architecture, and to offer the reader the key components of the knowledge required to make informed judgements about structure in the critical appraisal of buildings.

The preliminary Chapters (1 to 6) are similar to those in the previous editions and are concerned principally with explaining the properties and behaviour of structures, as a preliminary to the discussion of the types of relationship possible between structural design and architectural design. These chapters have been comprehensively revised and updated, with new illustrations.

Four new chapters have been added in this third edition; these widen the scope of the book to include coverage of the following important topics: structural theory; structural philosophy; the works of prominent engineers of the Modern period; and environmental sustainability.

The intention in these additional chapters is to give an indication of the contribution made by each of these specific topics to the subject as a whole. Each is also intended to demonstrate the breadth and depth of its respective topic, by exploring a limited number of aspects of it in detail. The new chapter on structural theory, for example, closely examines two areas only of this very large field, selected because these allow general conclusions to be drawn about the role and influence of theory on design, and to allow insights into the depth of the subject. Similarly, the chapter on engineers deals with only a very few of the many members of that profession who have made important contributions to the development of architecture in the Modern period, again selected for their particularly significant roles. The final chapter on environmental sustainability is intended to give a general view of this increasingly relevant topic on present and future relationships between structural engineering and architecture.

The book does not attempt to be comprehensive: no single-volume treatment could cover all aspects of this very large field in detail and space limitations have inevitably necessitated many omissions. I hope nevertheless that the book will provide a useful overview of the subject for students and practitioners of both structural engineering and architecture, and also for members of related professions such as urban planning, landscape architecture and architectural history.

Angus J. Macdonald, Edinburgh, July 2018

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I would like to thank all those who have assisted in the making of this book, in its present and previous editions: colleagues and students, past and present, with whom interesting discussions have taken place over many years, in the stimulating and supportive context of the University of Edinburgh, as well as many other academic and practitioner collaborators on various projects; all those who have contributed, or assisted in locating photographs and illustrations, who are either mentioned below or individually credited where the images occur in the book; and also all those involved in various ways in the making of the book itself.

Special thanks are due to the following: Stephen Gibson for his carefully crafted line drawings for the first two editions, the majority of which are included in this third edition; Andrew Siddall for the additional complex line drawings which he generated for this third edition; Pat Hunt, Tony Hunt and the staff of the picture libraries of Ove Arup & Partners and Anthony Hunt Associates; Thérèse Duriez for picture research for the first edition; the staff of Architectural Press (formerly Butterworth-Heinemann) for their hard work and patience in initiating, editing and producing the earlier editions, particularly Neil Warnock-Smith, Hilary Norman, Diane Chandler, Angela Leopard, Sián Cryer and Sue Hamilton; and, for this third edition, Fran Ford and the teams at Routledge/Taylor & Francis and Florence Production.

Thanks are due most particularly to my partner in several senses of the word, Patricia Macdonald, for her continued encouragement and for her expert assistance and scrutiny of many aspects of the text and illustrations.

Introduction

This book on architectural structures seeks to provide the reader with both the technical background required to appreciate the role of structure in architecture and a discussion of all aspects of this role, including the contribution of structure to architectural form and style and its importance in relation to questions such as environmental sustainability. The intention is to give insights into both the methodology of structural engineering in relation to architecture and its historical development.

Space does not permit that any of the topics be covered comprehensively. For example, the works of only a small number of the many engineers who have contributed prominently to Modern architecture have been included – chosen for their particular significance. Similarly, the discussion of structural theory covers only a few small aspects of that topic, again selected to allow broad conclusions to be drawn concerning the role of theory in the building process as a whole, and to give insights into its depths. The relationship between built form and environmental sustainability now influences every aspect of structural and architectural design and is discussed where relevant throughout the book. In addition, crucial aspects of the topic are considered in a separate chapter, but the coverage is necessarily limited and of a general nature. There are therefore many omissions, made necessary by the attempt to cover the full breadth and depth of a very large field. It is hoped that the book will nevertheless give the reader a wide appreciation of the particular contribution that structural engineering makes to architecture in all of its forms.

It has long been acknowledged that an appreciation of the role of structure is an attribute that is essential for the development of a proper understanding of architecture. It was Vitruvius, writing at the time of the founding of the Roman Empire, who identified the three basic requirements of architecture as *firmitas*, *utilitas* and *venustas* and Sir Henry Wotton (Wotton, 1624, 2013), in the seventeenth century, who translated these as 'firmness', 'commodity' and 'delight'. Subsequent theorists have proposed different systems by which buildings may be evaluated, their qualities discussed and their meanings understood but the Vitruvian ontology nevertheless still provides a valid basis for the examination and criticism of a building.

In the present day the question of which of the three Vitruvian qualities is the most important is controversial. For some, a building cannot be considered

Facing page: L'Oceanogràfic, Valencia, Candela/Calatrava. Photo: Sebastian Weiss.

to be satisfactory unless it fulfils its utilitarian functions well in respect of firmness and commodity. From such a viewpoint, there cannot be delight without well-designed structure and a set of spaces that function well for the intended purpose of the building. For others, these mundane functions are of secondary importance in relation to the aesthetic agenda which is considered overwhelmingly to be the source of delight. For much of the Modern period the latter view has tended to dominate architectural discourse and, as a consequence, many of its best-regarded buildings perform poorly in respect of firmness and commodity.

It is not the intention of this book to enter into the controversy that surrounds the relative importance of the three Vitruvian virtues but simply to offer criteria by which the structural qualities of a building – the basis of 'firmness' – may be judged. To be in a position to make such judgements the critic or observer must know something of the structural make-up of the building. This requires an ability to read a building as a structural object, a skill that depends on a knowledge of the functional requirements of structure and an ability to distinguish between the structural and the non-structural parts of the building. These topics are discussed here in Chapters 1 to 6.

Traditionally, the primary consideration, so far as the purely technical performance of a structure is concerned, was that it should fulfil its function with maximum economy of means in three respects: efficiency in the use of material, ease of construction and long-term durability. In this view, a structure should contain no more material than is necessary; it should be no more difficult to design and construct than is necessary and it should not require that excessive amounts of maintenance be carried out in order that it can continue to function adequately for its intended purpose. A recent addition to these traditional objectives, which arises from the increasing need for buildings to be designed for sustainability, is the requirement that a structure should not unduly disrupt the ecosystem in which it is placed. It should, in other words, have some of the qualities of a living organism, particularly with respect to its consumption of energy and materials and its suitability for recycling or re-use. All of the above desirable qualities are affected by the form that is adopted for the structure.

Perhaps the most fundamental consideration in relation to structural performance is with the relationship between structural form and structural efficiency. As is explained in Chapter 4, the principal single factor that affects this is the overall form of the structure in relation to the pattern of load that it supports, because it is the relationship between form and load distribution that determines the type of **internal force** that occurs in structures: axial-type internal forces can be resisted much more efficiently than those that derive from bending. In the case of architectural structures, which predominantly involve horizontal spans carrying distributed gravitational loads, the shapes that produce axial rather than bending-type internal forces are curvilinear – arches, domes, vaults, cable nets, fabric tents. These are the most efficient forms. The straight, horizontal spans of rectilinear frameworks produce predominantly bending-type internal forces that result in an inefficient use of structural material. Where, as is frequently the case, it is not practicable to adopt a curvilinear form, the efficiency of straight-sided arrangements can be improved by the use of complex cross-sections, such as the I-form or box beam, or by other devices such as triangulation of the internal geometry. The reasons for this are also explained in Chapter 4 where a classification system for structures is suggested. The fact that the performance of a structure is to a large extent determined by its form means that it is possible to make a meaningful assessment of its suitability from a purely visual inspection of its make-up. This technique of assessment is explained in detail in Chapters 4 and 6.

One of the most significant aspects of structural behaviour is that high efficiency requires high complexity: curvilinear forms are more efficient than those that are straight-sided; complex cross-sections are more efficient than solid circles or rectangles. Most structures involve a compromise between complexity of form, which improves efficiency, and simplicity of form, which makes design, construction and maintenance easier, and one of the most interesting aspects of the design of any structure is the nature of the compromise that has been achieved.

In making a judgement concerning the suitability of a chosen structural arrangement for a particular application, the important question is whether or not the level of complexity that is present is appropriate; whether or not the particular compromise that has been adopted is sensible, in other words. The various factors that influence this question are discussed in Chapter 6 where it is shown that the most important of these is *span*: the larger the span, the greater is the level of efficiency that is necessary and therefore of complexity that can be justified. Thus, large-scale enclosures usually involve the use of spectacular curvilinear forms or complex triangulated arrangements while those of modest scale are generally supported by simple, but inefficient, post-and-beam frames of various kinds. High complexity is rarely justified technically for structures of short or medium span. These, and other factors that influence the selection of structural form, are the subject of Chapter 8.

In the context of architecture, where the question of 'delight' becomes a major consideration, the relationship between structural design and architectural design can take many forms and the selection of structure type for a building is often influenced by the requirements of appearance and aesthetics rather than simply by technical performance. The role of structure can range from that of simply an agency that provides support for a building and whose visual qualities are of no particular significance, to one in which the structural elements contribute symbolic meaning and expression of various kinds to the architecture. This possible architectonic function of structure is discussed in Chapters 8, 9 and 10.

It is possible for an architect virtually to ignore structural considerations while inventing the form of a building and to conceal entirely the structural elements in the completed version of the building. Many buildings of the Modern period fall into this category, for example, the Walt Disney Concert Hall in Los Angeles (2003) by the architect Frank Gehry (Figures 0.1 and 0.2) and the Glasgow Transport Museum building (2012) by Zaha Hadid (Figures 1.9, 1.10, 10.25 and 10.26). Buildings such as these contain a structure but the technical requirements of the structure have not significantly influenced the form that has been adopted and the structural elements themselves are not direct or visible contributors to the aesthetics of the architecture. Structures that have been evolved in this way rarely perform well when judged by technical criteria. At the other extreme it is possible to produce a building that consists of little other than structure and where structural considerations

Figure 0.1 Walt Disney Concert Hall, Los Angeles; Frank Gehry (1929–), architect. An example of Late-Modern 'Digital Architecture'. The form of this building was little influenced by structural requirements.

Photo: Jon Sullivan/Wikimedia Commons.

have dominated the design. The masonry vaulted enclosure system that is under development by Afrotech and Foster & Partners for use in Africa as a terminal for a medical supply facility operated by drones is an example of this (Figure 0.3). Between these extremes many different approaches to the relationship between structure and architecture are possible. In the early Modern buildings of Walter Gropius, Ludwig Mies van der Rohe (Figure 0.4), Le Corbusier and others, the forms that were adopted were influenced by the types of geometry that were suitable for steel or reinforced concrete structural frameworks. In these cases structure and architecture were allowed to develop together. In another approach, structure can be allowed to dominate the appearance of a building for stylistic reasons and this often leads to the selection of a particular type of structure from consideration principally of its visual qualities rather than its technical performance – something that was common in the work of the so-called High-Tech architects of the late twentieth century (Figures 3.19, 9.28 and 10.7). As is discussed in Chapter 10, the relationship between structure and architecture can therefore take many forms and it is the purpose of this book to explore these against a background of information concerning the technical properties and requirements of structures.

Figure 0.2 Walt Disney Concert Hall, Los Angeles; Frank Gehry (1929–), architect. The supporting structural steel framework is highly inefficient. The overall cost of the building was $274 million, compared to $190 (equivalent) for three other halls on the same site that were built in the 1960s with conventional post-and-beam structures.

Photo: Cygnusloop99/Wikimedia Commons.

Figure 0.3 Droneport Prototype Building; Norman Foster Foundation, architects; Ochsendorf, De Jong and Block, engineers. The principal element of this building is a self-supporting (and therefore structural) multi-bay vaulted enclosure constructed from compressed earth bricks. Structural requirements have strongly influenced the choice of form and materials.

Photo: Sonia Millat/Foster & Partners.

Figure 0.4 Farnsworth House, Illinois, 1951; Mies van der Rohe (1886–1969), architect. This building is supported by a rectilinear steel framework structure. The form is appropriate in the context of an industrialised society and for the span involved.

Photo: Victor Grigas/Wikimedia Commons.

Whatever the relationship between structure and architecture, the form of a structural armature is inevitably very closely related to that of the building that it supports and the act of designing a building – of determining its overall form – is therefore, consciously or unconsciously, also an act of structural design. The potential conflict between the visual aspects of a work of architecture and the purely technical performance of its structure is one of the most controversial aspects of the relationship between structure and architecture and is particularly relevant in the context of design for environmental sustainability. The debate is often diminished by a degree of misinformation, or even simply a lack of understanding of structural principles, by the participants and this is one of the problems of architectural interpretation that it is the intention of this book to address. The author hopes that the book will be found useful by architectural critics and historians as well as by students and practitioners of the professions concerned with building.


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CHAPTER 1

The relationship of structure to building

The simplest way of describing the function of an architectural structure is to say that it is the part of a building that resists the loads that are imposed on it. A building may be regarded as simply an envelope that encloses and subdivides space in order to create a protected environment. The surfaces that form the envelope, that is the walls, the floors and the roof of the building, are subjected to various types of loading: external surfaces are exposed to the climatic loads of snow, wind and rain; floors are subjected to the gravitational loads of the occupants and their effects; and most of the surfaces also have to carry their own weight (Figure 1.1). All of these loads tend to distort the building envelope and to induce it to collapse; it is to prevent this from happening that a structure is provided. The function of a structure may be

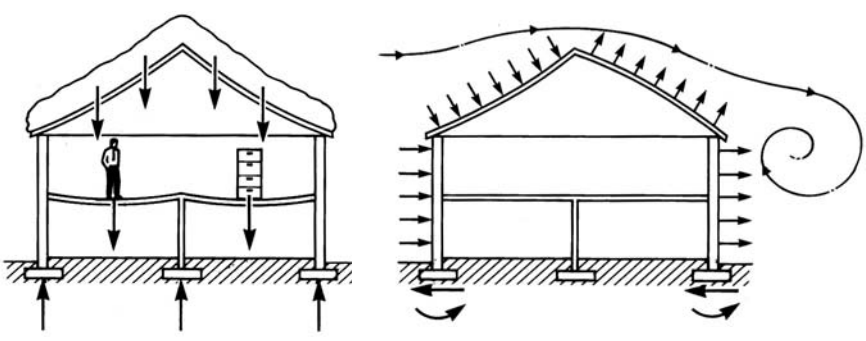

Figure 1.1 Loads on the building envelope. Gravitational loads due to snow and to the occupation of the building cause roof and floor structures to bend and induce compressive internal forces in walls. Wind causes pressure and suction loads to act on all external surfaces.

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Pantheon, Rome. Painting: Panini.

Figure 1.2 The igloo is a self-supporting compressive envelope.

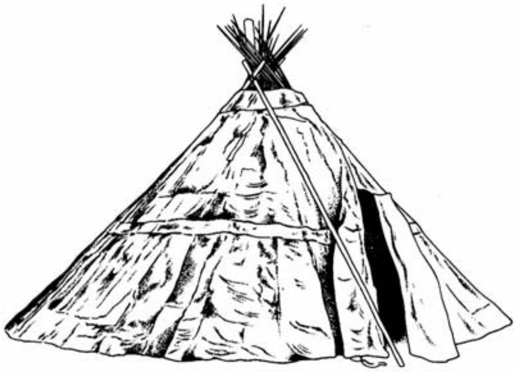

Figure 1.3 In the tepee a non-structural skin is supported on a structural framework of timber poles.

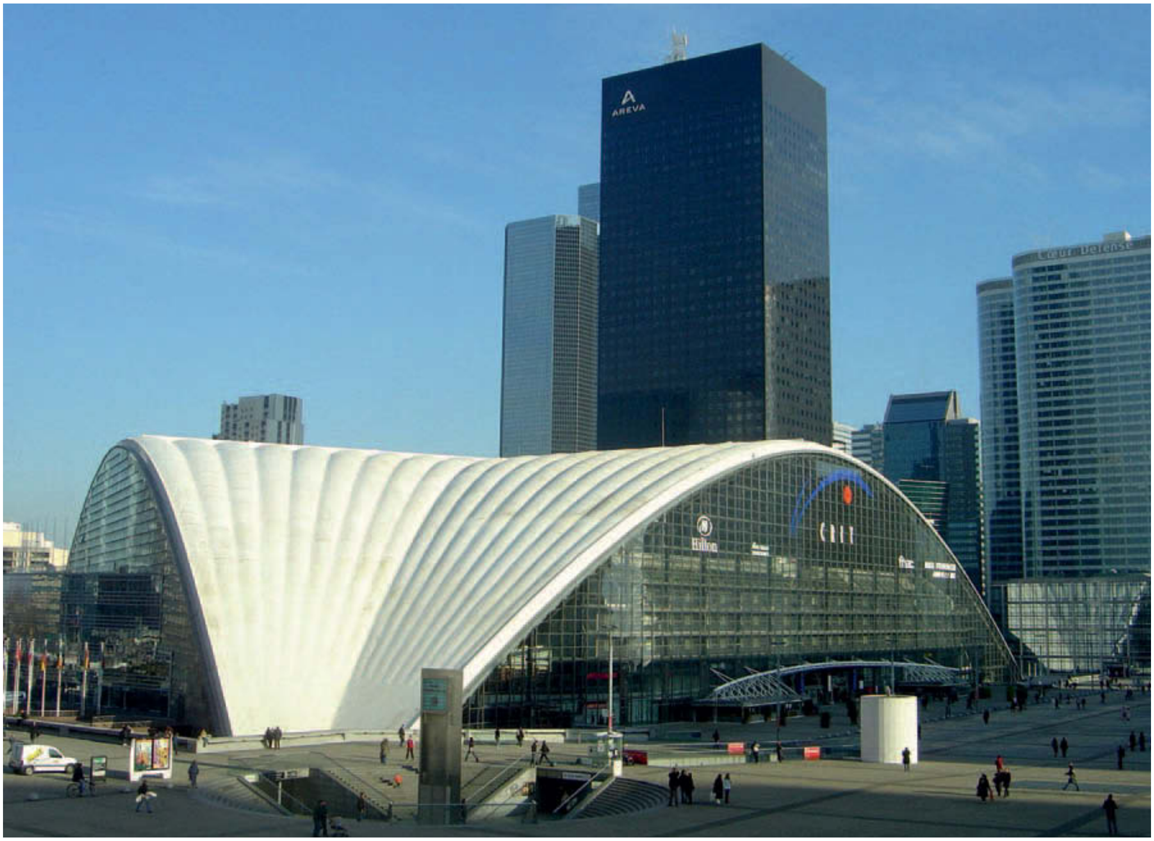

Figure 1.4 Exhibition Hall of the CNIT, Paris, 1958; Nicolas Esquillan, engineer. The principal element is a self-supporting reinforced concrete shell.

Photo: David Monniaux/Wikimedia Commons.

summed up, therefore, as being to supply the strength and rigidity that are required to prevent a building from collapsing. More precisely, it is the part of a building that conducts the loads that are imposed on it from the points where they arise to the ground underneath the building, where they can ultimately be resisted.

The location of the structure within a building is not always obvious because the structure can be integrated with the non-structural parts in various ways. Sometimes, as in the simple example of an igloo (Figure 1.2), in which ice blocks form a self-supporting protective dome, the structure and the space enclosing elements are one and the same thing. Alternatively, the structural and space-enclosing elements can be entirely separate. A very simple example is the tepee (Figure 1.3) in which the protecting envelope is a skin of fabric or hide that has insufficient rigidity to form an enclosure by itself and that is supported on a framework of timber poles. Complete separation of structure and envelope occurs here: the envelope is entirely non-structural and the poles have a purely structural function.

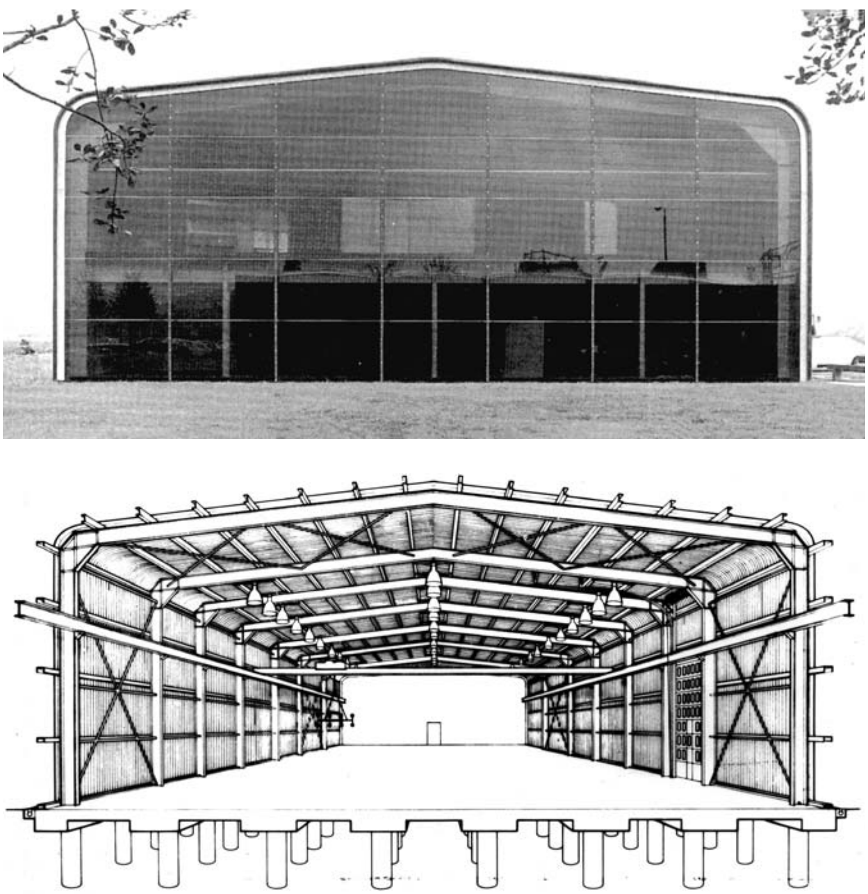

Figure 1.5
Modern Art Glass Warehouse, Thamesmead, UK, 1973; Foster Associates, architects; Anthony Hunt Associates; structural engineers.
A non-structural skin of profiled metal sheeting is supported on a steel framework, which has a purely structural function.
Photo: Andrew Mead.

The CNIT exhibition hall in Paris (Figure 1.4) is a sophisticated version of the igloo; the reinforced concrete shell that forms the main element of this enclosure is self-supporting and therefore structural. Separation of skin and structure occurs in the transparent walls, however, where the glass envelope is supported on a structure of mullions. The roof of the Centre Pompidou building at Metz (Figure 11.6), the overall form of which was largely determined by the requirements of its lattice-timber 'shell' structure, is similarly configured although in this case the timber structural elements are distinct from the enclosing roof surface that it supports and the building is therefore similar to the tepee in its separation of structural from enclosing elements.

The steel frame warehouse by Foster Associates at Thamesmead, UK (Figure 1.5), is almost a direct equivalent of the tepee. The elements that form it are either purely structural or entirely non-structural because the corrugated sheet metal skin is entirely supported by the steel frame, which has a purely structural function. A similar breakdown may be seen in later buildings by the same architects, such as the Sainsbury Centre for the Visual Arts at Norwich, UK (Figures 9.33 and 9.34) and the warehouse and showroom for the Renault car company at Swindon (Figure 3.19).

In most buildings the relationship between the envelope and the structure is more complicated than in the above examples and frequently this is because the interior of the building is subdivided to a greater extent by internal walls and floors. For instance, in Foster Associates' building for Willis, Faber & Dumas (WFD), Ipswich, UK (Figures 1.6 and 5.16) the reinforced concrete structure of floor slabs and columns may be thought of as having a dual function. The columns are purely structural, although they do punctuate the interior spaces and are space-dividing elements, to some extent. The floors are both structural and space-dividing elements. Here, however, the situation is complicated by the fact that the structural floor slabs are topped by non-structural floor finishing materials and have ceilings suspended underneath them. The floor finishes and ceilings could be regarded as the true space-defining elements and the slab itself as having a purely structural function. The glass walls of the building are entirely non-structural and have a space-enclosing function only.

The Solaris Building in Singapore by Ken Yeang, with Arups as engineers, (Figures 1.7 and 1.8) is also supported by a reinforced concrete structure. Here the **structural continuity** (see Glossary) and mouldability that concrete offers were exploited to create a complex juxtaposition of solid and void. The building is of the same basic type as the WFD building however: a structural framework of reinforced concrete supports cladding elements that are non-structural.

In the Centre Pompidou in Paris by Piano and Rogers a multi-storey steel framework is used to support reinforced concrete floors and non-loadbearing glass walls. The breakdown of parts is straightforward (Figs 9.28 to 31): identical plane-frames, consisting of long steel columns which rise through

Figure 1.6 Willis, Faber & Dumas Office, Ipswich, UK, 1974; Foster Associates, architects; Anthony Hunt Associates, structural engineers. The basic structure of this building is a series of reinforced concrete coffered slab floors supported on a grid of columns. The external walls are of glass and are non-structural. In the finished building the floor slabs are visible only at the perimeter. Elsewhere they are concealed by floor finishes and a false ceiling.

Photo: A. Hunt.

the entire height of the building supporting triangulated girders at each floor level, are placed parallel to each other to form a rectangular plan. The concrete floors span between the triangulated girders. Additional small cast-steel girders project beyond the line of columns and are used to support stairs, escalators and servicing components positioned along the sides of the building outside the glass wall, which is attached to the frame near the columns. A system of cross-bracing on the sides of the framework prevents it from collapsing through instability. In this type of building the structure not only provides support but makes a significant contribution to the visual aspects of the architecture.

The free form, in both plan and cross-section, of the Riverside Museum in Glasgow by architect Zaha Hadid (Figures 1.9 and 10.25 and 26), make it in some respects a complete contrast to the controlled order of the Centre

Figure 1.7 Solaris Building, Singapore, 2011; T. R. Hamzah & Yeang, architects; Arups, engineers. Ecological and sustainability considerations greatly influenced the design of this building. The structural armature is a reinforced concrete framework that allowed the creation of irregular plan-forms and facilitated the inclusion of green corridors and a passively ventilated atrium.

Photo: T. R. Hamzah & Yeang SDN. BHD; Photography credit: Albert Lim.

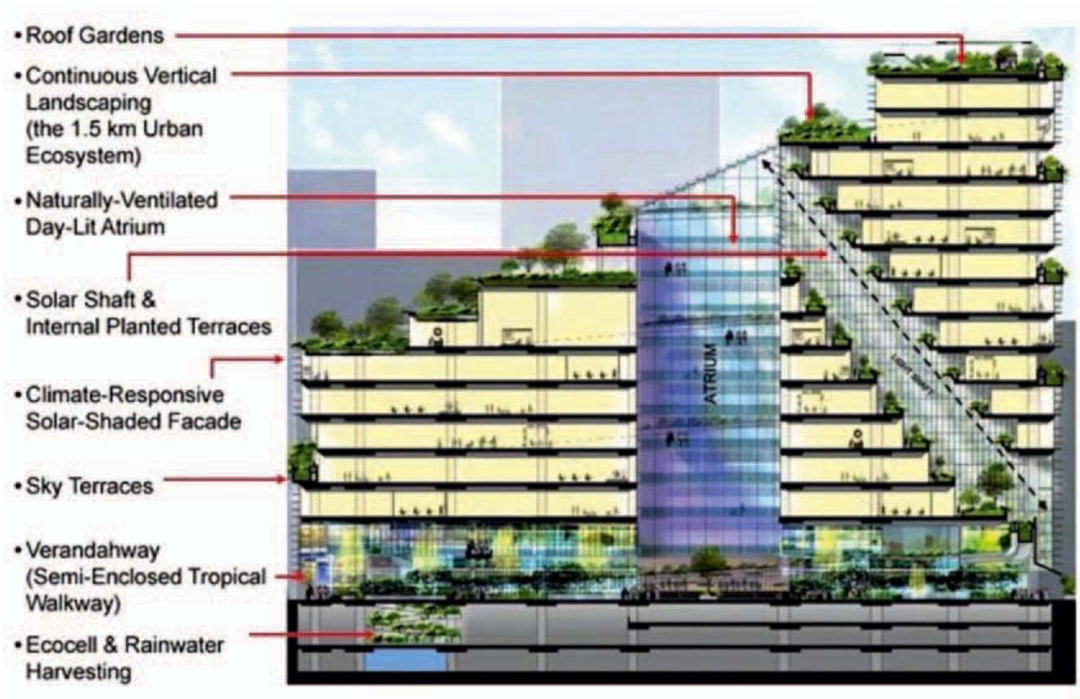

Figure 1.8 Solaris Building, Singapore, 2011; T. R. Hamzah & Yeang, architects; Arups, engineers. Cross-section. The structural continuity offered by the reinforced concrete framework allowed the creation of irregular, curvilinear plan-forms, cantilevered balconies and an internal atrium – all of which contributed to the passive system for environmental control.

Graphic: Courtesy of T. R. Hamzah & Yeang SDN. BHD.

Pompidou. Architecturally it is quite different, and the structural action is completely suppressed, but structurally the principal part of the building is similar to the extent that a metal skeleton frame-work supports a light, enclosing skin (Figure 1.10).

The house with masonry walls and timber floor and roof structures is a traditional form of building in most parts of the world. It is found in many forms, from the historic grand houses of the European landed aristocracy (Figure 1.11) to modern homes in the UK (Figure 1.12). Even the simplest versions of this form of masonry-and-timber building (Figure 1.13) are fairly complex assemblages of elements. Initial consideration could result in a straightforward breakdown of parts with the masonry walls and timber floors being regarded as having both structural and space-dividing functions and the roof as consisting of a combination of the purely supportive trusses, which are the structural elements, and the purely protective, non-structural skin. Closer examination would reveal that most of the major elements can in fact be subdivided into parts that are either purely structural or entirely non-structural. The floors, for example, normally consist of an inner core of timber joists and

Figure 1.9 Riverside Museum, Glasgow, 2012; Zaha Hadid, architect; Buro Happold Engineering, engineers. The principal space in this building is an S-plan single exhibition area, of serrated cross-section, that runs through its entire length. The supporting structure is a steel skeleton framework that supports non-structural cladding. The glazed end of the building illustrates its cross-sectional shape.

Photos: (a) E. Z. Smith/Hawkeye; (b) Bjmullan/Wikimedia Commons.

floor boarding, which are the structural elements, enclosed by ceiling and floor finishes. The latter are the non-structural elements which are seen to divide the space. A similar breakdown is possible for the walls and in fact very little of what is visible in the traditional house is structural, as most of the structural elements are covered by non-structural finishes. It should not be thought, however, that structural considerations do not make a significant contribution to architectural aspects of traditional loadbearing-wall buildings. Their overall form and general arrangements are in fact largely determined to satisfy structural requirements and the influence of structure on the traditional house, of whatever size and architectural style, was and is profound.

To sum up, these few examples of very different building types demonstrate that all buildings contain a structure whose primary function is to support the building envelope by conducting the forces that are applied to it from the points where they arise in the building to the ground below it where they are ultimately resisted. Sometimes the structure is indistinguishable from the enclosing and space-dividing building envelope, sometimes it is entirely separate from it; most often there is a mixture of elements with structural, non-structural and combined functions. In all cases the form of the structure is very closely related to that of the building taken as a whole and usually exerts considerable influence on the nature of that form. The structure may also make a significant contribution to the architectural vocabulary being employed. The elegance with which the structure fulfils its function is considered by many to be something that affects the quality of the architecture.

Figure 1.10 Riverside Museum, Glasgow, 2012; Zaha Hadid, architect; Buro Happold Engineering, engineers. Due to its unconventional structural configuration, a massively strong steel framework structure was required.

Photo: Hélène Binet.

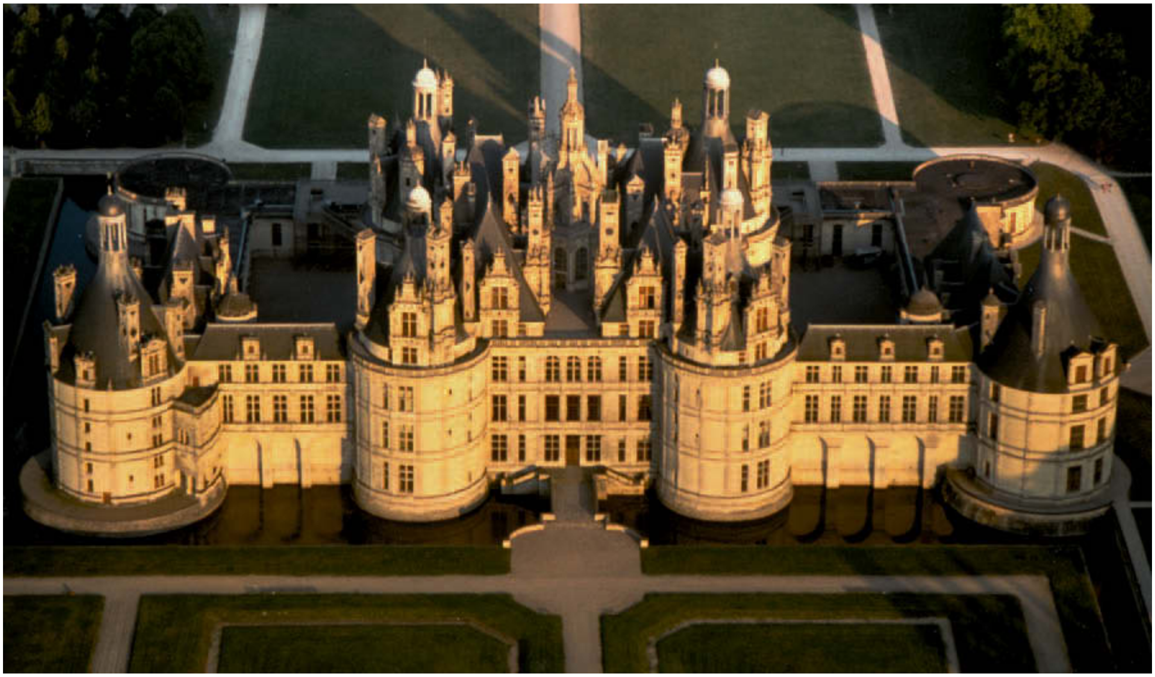

Figure 1.11 Chateau de Chambord, France, 1519–1547; Domenico da Cortona, architect; Pierre Nepveu, engineer. One of the grandest domestic buildings in Europe, the Chateau de Chambord has a loadbearing masonry structure. Most of the walls are structural; the floors are either of timber or vaulted masonry and the roof structure is of timber.

Photo: Patricia & Angus Macdonald/Aerographica.

Figure 1.12 Local authority housing, Haddington, Scotland, 1974; J. A. W. Grant, architects. These buildings have loadbearing masonry walls and timber floor and roof structures.

Photo: P. Macdonald.

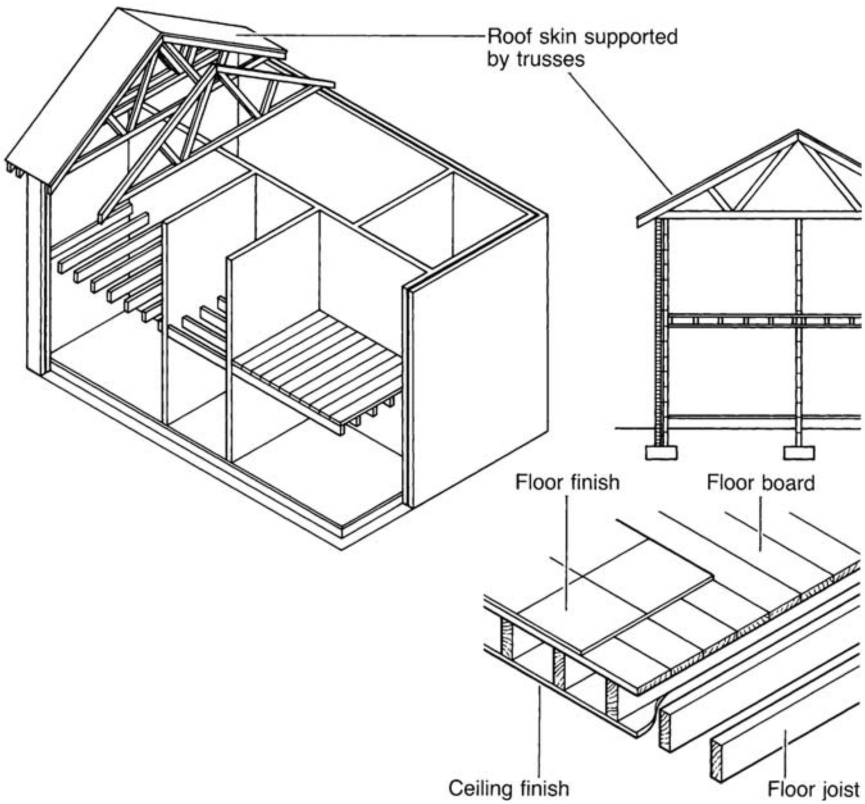

Figure 1.13
Traditional construction in the UK, in its twentieth-century form, with loadbearing masonry walls and timber floor and roof structures. All structural elements are enclosed in non-structural finishing materials.

CHAPTER 2

Structural requirements

2.1 Introduction

To perform its primary function of supporting a building in response to whatever loads may be applied to it a structure must possess four properties: it must be capable of achieving a state of static **equilibrium**, it must be stable, it must have adequate strength and it must have adequate rigidity. The meanings of these terms are explained in this chapter.

2.2 Equilibrium

Structures must be capable of achieving a state of static equilibrium under the action of applied load. This requires that the structure, taken as a whole, must be connected to its foundations in such a way that all possible applied loads are balanced exactly by **reactions** generated at its supports. Similarly, each element in the structure must be connected to the rest of the structure such that equilibrium is established under all possible loading conditions.

2.3 Geometric stability

Geometric **stability** is the property that preserves the geometry of a structure and allows its elements to act together to resist load. The distinction between stability and equilibrium is illustrated by the framework shown in Figure 2.1, which is capable of achieving a state of equilibrium under the action of gravitational load, but which is not stable because the frame will collapse if disturbed laterally. Stability can therefore be distinguished from strength or rigidity, because a system can become unstable even though its elements are sufficiently strong and rigid to resist the loads that are imposed on them.

This simple arrangement demonstrates that the critical factor, so far as the stability of any system is concerned, is the effect on it of a small disturbance. In the context of structures this is shown very simply in Figure 2.2 by

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the comparison of tensile and compressive elements. Both are capable of achieving equilibrium but, if the alignment of either is disturbed, the tensile element is pulled back into line following the removal of the disturbing agency but the compressive element, once its initially perfect alignment has been altered, progresses to an entirely new position. The fundamental issue of stability is demonstrated here, which is that stable systems revert to their original state following a slight disturbance whereas unstable systems progress to an entirely new state. The parts of structures that tend to be unstable are the ones in which compressive forces act and these parts must therefore be given special attention when the geometric stability of an arrangement is being considered. The columns in a simple rectangular framework are examples of this (Figure 2.1).

The geometric instability of the arrangement in Figure 2.1 would have been obvious if its response to horizontal load had been considered (Figure 2.3) and this demonstrates one of the fundamental requirements for the geometric stability of any arrangement of elements, which is that it must be capable of resisting loads from orthogonal directions (directions at right angles) – two orthogonal directions for plane arrangements and three for three-dimensional arrangements. This is another way of saying that an arrangement must be capable of achieving a state of equilibrium in response to forces from three orthogonal directions. The stability or otherwise of a proposed arrangement can therefore be judged by considering the effect on it of sets of mutually perpendicular trial forces: if the arrangement is capable of resisting all of these then it is stable, regardless of the loading pattern that will actually be applied to it in service. Conversely, if an arrangement is not capable of resisting load from three orthogonal directions then it will be unstable even though the load that it is designed to resist will be applied from only one direction.

It frequently occurs in architectural design that a geometry that is potentially unstable must be adopted in order that other architectural requirements can

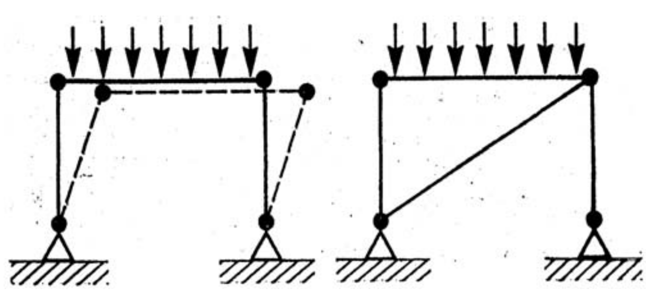


Figure 2.1 A rectangular frame with four hinges is capable of achieving a state of equilibrium under gravitational loading but is unstable because any slight lateral disturbance of the columns will induce it to collapse. The frame on the right here is stabilised by the diagonal element which makes no direct contribution to the resistance of the gravitational load.

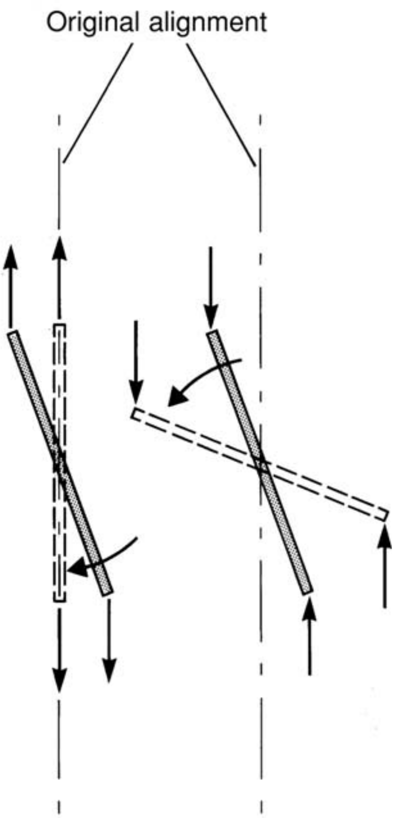


Figure 2.2 The tensile element on the left here is stable because the loads pull it back into line following a disturbance. The compressive element on the right is fundamentally unstable.

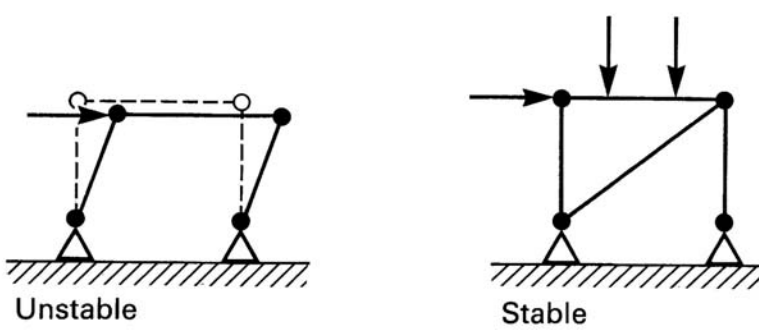


Figure 2.3 Conditions for stability of frameworks. The 2-D system is stable if it is capable of achieving equilibrium in response to forces from two mutually perpendicular directions.

be satisfied. For example, one of the most convenient structural geometries for buildings, that of the rectangular frame, is unstable in its simplest hinge-jointed form, as has already been shown. Stability can be achieved with this geometry by the use of **rigid joints**, by the insertion of a diagonal element or by the use of a rigid diaphragm that fills up the interior of the frame (Figure 2.4). Each of these has disadvantages. Rigid joints are the most convenient from a space-planning point of view but are problematic structurally because they are difficult to construct and because they can render the structure **statically indeterminate** (see Glossary). Diagonal elements and diaphragms block the framework and can complicate space planning. In multi-panel arrangements, however, it is possible to produce stability without blocking every panel. The row of frames in Figure 2.5, for example, is stabilised by the insertion of a single diagonal. Where frames are parallel to each other the three-dimensional arrangement is stable if a few panels in each of the two principal directions is stabilised in the vertical plane and the remaining frames are connected to these by diagonal elements or diaphragms in the horizontal plane (Figure 2.6). A three-dimensional frame can therefore be stabilised by the use of diagonal elements or diaphragms in a limited number of panels in the vertical and horizontal planes. In multi-storey arrangements these systems must be provided at every storey level.

None of the components that are added to stabilise the geometry of the rectangular frames in Figures 2.1 and 2.6 would make a direct contribution to the resistance of gravitational load (i.e. the carrying of weight), which would normally be the primary load on the structure. These elements are called **bracing** elements and most structures contain such elements, whose presence frequently affects both the planning and the appearance of the building that it supports.

Where, as is normal, a structure is subjected to loads from different directions, the elements that are used solely for bracing when the principal load is applied frequently play a direct role in resisting secondary load. The diagonal elements in the frame of Figure 2.6 for example, would be directly involved in the resistance of horizontal load caused by the action of wind. The diagonal or diaphragm bracing elements that are inserted into rectangular frameworks are often referred to as **wind bracing**, which gives the impression their sole function is to carry wind load. This is incorrect. These elements would be essential for stability even if wind was not a consideration in the design.

It is common practice to provide more bracing elements than the minimum number required for stability so as to improve the resistance of three-dimensional frameworks to horizontal load. The framework in Figure 2.6, for example, although theoretically stable would suffer considerable distortion in response to a horizontal load applied parallel to the long side of the frame at the opposite end from the vertical-plane bracing. A load applied parallel to the long side at this end of the frame would also cause a certain amount of distress as some movement of joints would inevitably occur in the transmission

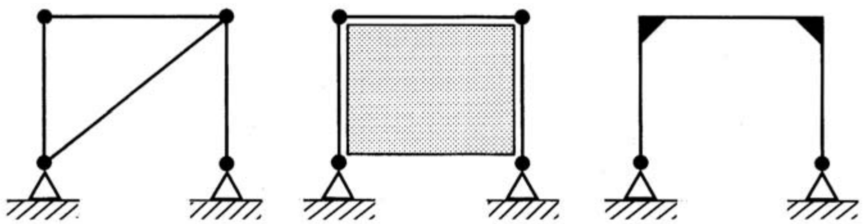


Figure 2.4 A rectangular frame can be stabilised by the insertion of a diagonal element or a rigid diaphragm or by the provision of rigid joints. A single rigid joint is in fact sufficient to provide stability.

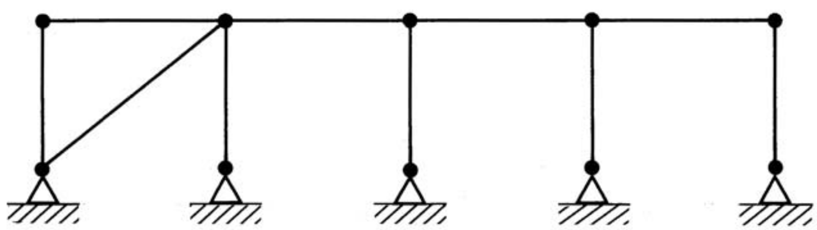


Figure 2.5 A row of rectangular frames is stable if one panel only is braced by any of the three methods shown in Figure 2.4.

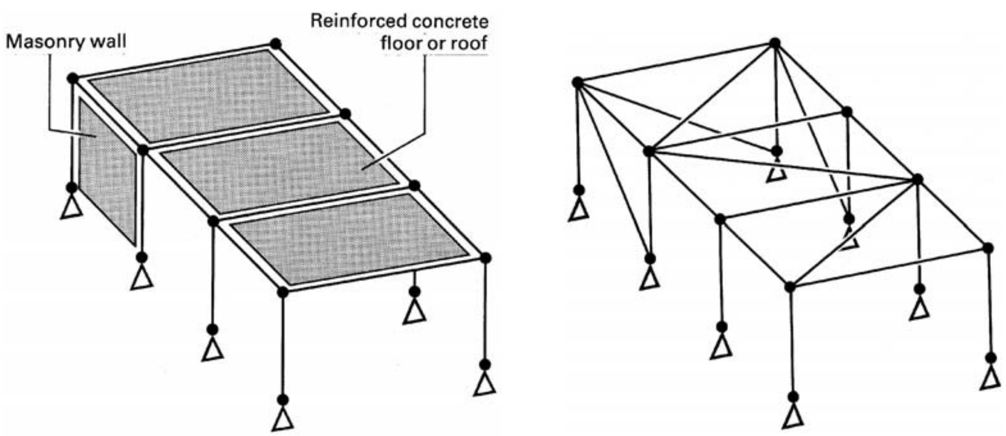


Figure 2.6 These frames contain the minimum number of braced panels required for stability.

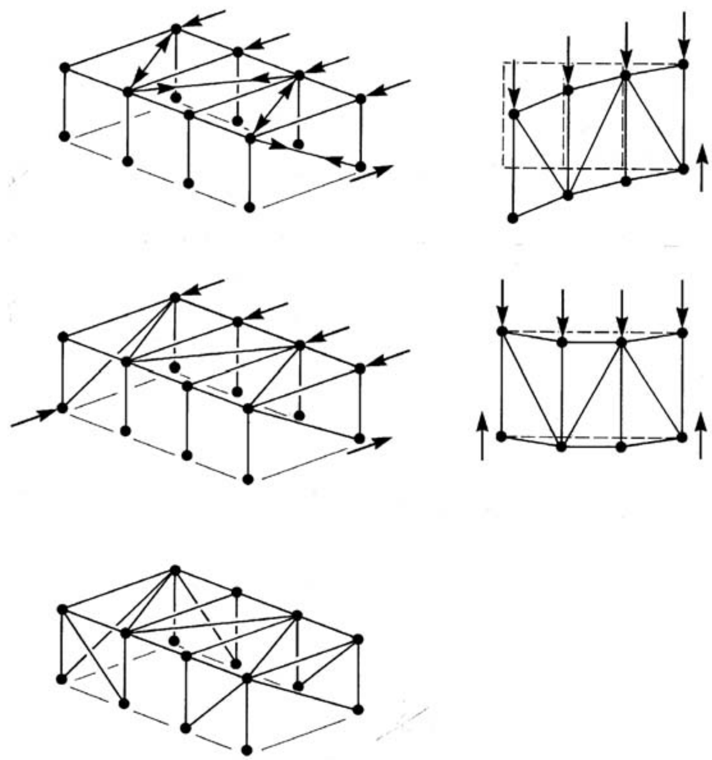


Figure 2.7 In practical bracing schemes more elements than are strictly necessary to ensure stability are provided to improve the performance of frameworks in resisting horizontal load. The frame at the top here is stable but will suffer distortion in response to horizontal load on the side walls. Its performance is enhanced if a diagonal element is provided in both end walls. The lowest framework contains the minimum number of elements required to resist effectively horizontal load from the two principal horizontal directions. Note that the vertical-plane bracing elements are distributed around the structure in a symmetrical configuration.

of it to the vertical-plane bracing at the other end. In practice the performance of the frame is more satisfactory if vertical-plane bracing is provided at both ends (Figure 2.7). This gives more restraint than is necessary for stability and makes the structure statically indeterminate but results in the horizontal loads being resisted close to the points where they are applied to the structure.

Figures 2.8 and 2.9 show typical bracing systems for multi-storey frameworks. Another common arrangement, in which floor slabs act as diaphragm-type bracing in the horizontal plane in conjunction with vertical-plane bracing of the diagonal type, is shown diagrammatically in Figure 2.10. Where the rigid-joint method is used it is normal practice to stabilise all panels individually by making all joints rigid. This greatly increases planning freedom by eliminating the need for bracing in the vertical planes. The rigid-joint method is the normal method that is adopted for reinforced concrete frames,

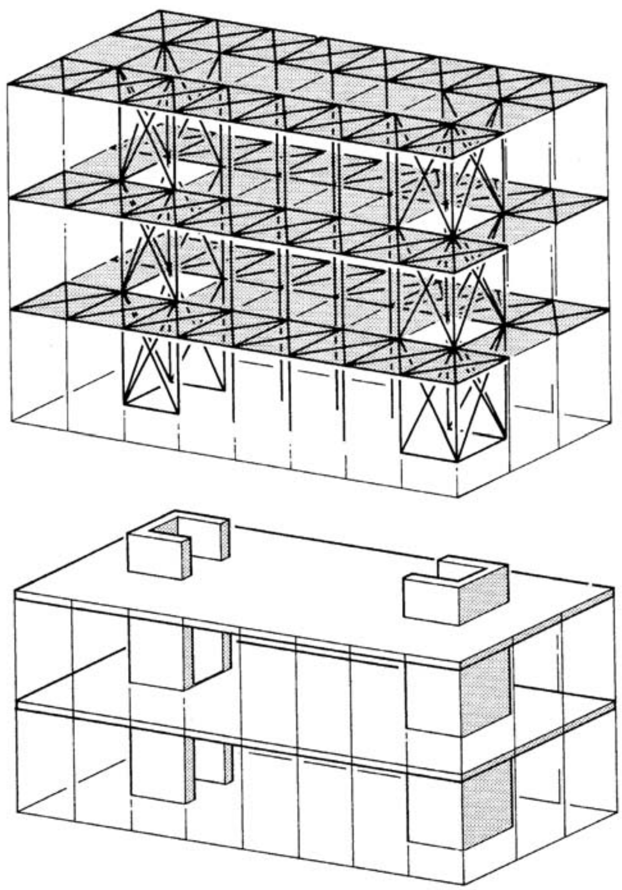


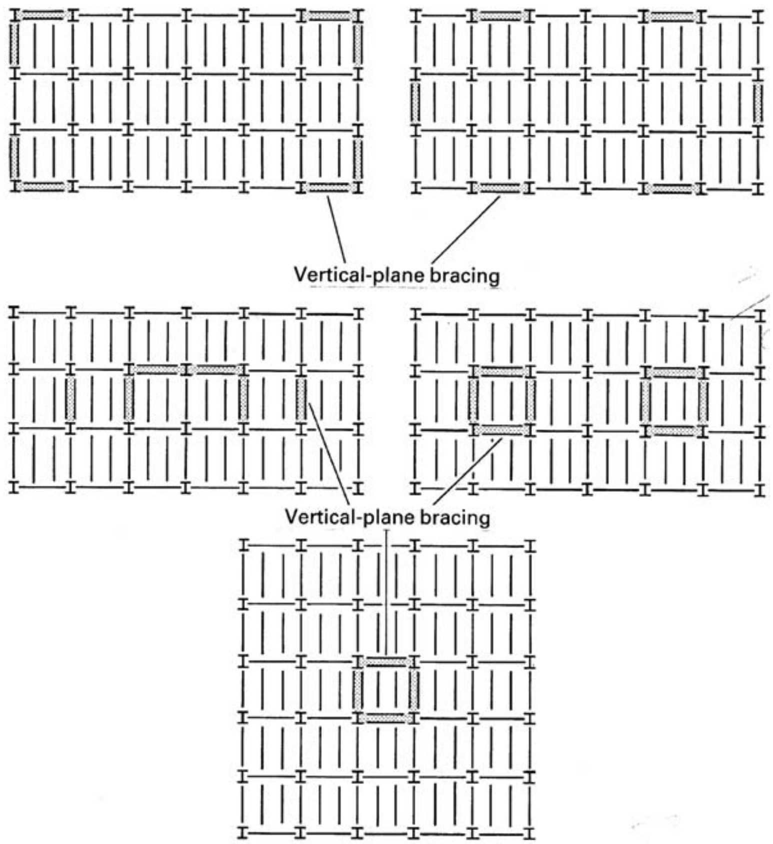
Figure 2.8
Typical bracing schemes for multi-storey frameworks. Vertical-plane bracing is provided in a limited number of bays and positioned symmetrically on plan. All other bays are linked to this by horizontal-plane bracing at every storey level.

in which continuity through junctions between elements can easily be achieved; diaphragm bracing is also used however in both vertical and horizontal planes in certain types of reinforced concrete frame.

Loadbearing wall structures are those in which the external walls and internal partitions serve as the vertical structural elements. They are normally constructed of masonry, reinforced concrete or timber but combinations of these materials are also used. In all cases the joints between walls and floors are normally incapable of resisting bending action (they behave as hinges, in other words) and the resulting lack of continuity means that rigid-frame action cannot develop. Diaphragm bracing, provided by the walls themselves, is used to stabilise these structures.

A wall panel has high rotational stability in its own plane but is unstable in the out-of-plane direction (Figure 2.11); vertical panels must, therefore, be grouped in pairs at right angles to each other so that they provide mutual support. Because loadbearing wall structures are normally used for multi-cellular buildings, the provision of an adequate number of vertical-plane bracing diaphragms in two orthogonal directions is normally straightforward

Figure 2.9
These drawings of floor grid patterns for steel frameworks show typical locations for vertical-plane bracing.



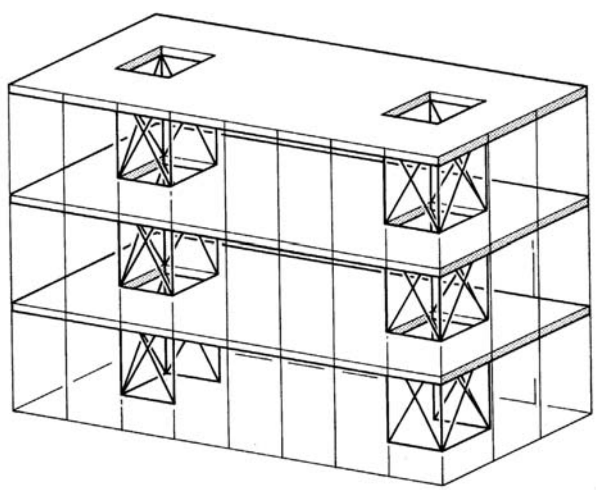


Figure 2.10 Concrete floor slabs are normally used as horizontal-plane bracing of the diaphragm type which acts in conjunction with diagonal bracing in the vertical planes.

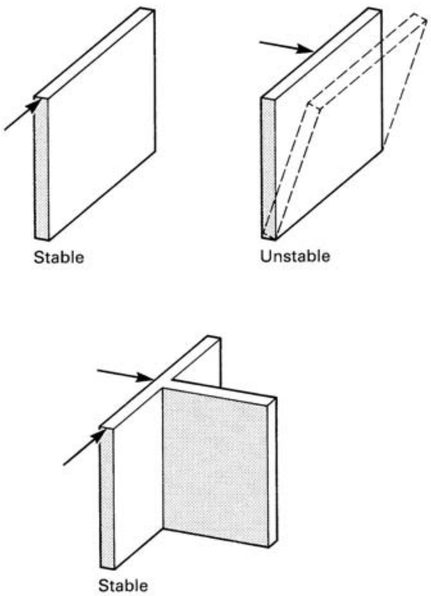


Figure 2.11 Walls are unstable in the out-of-plane direction and must be grouped into orthogonal arrangements for stability.

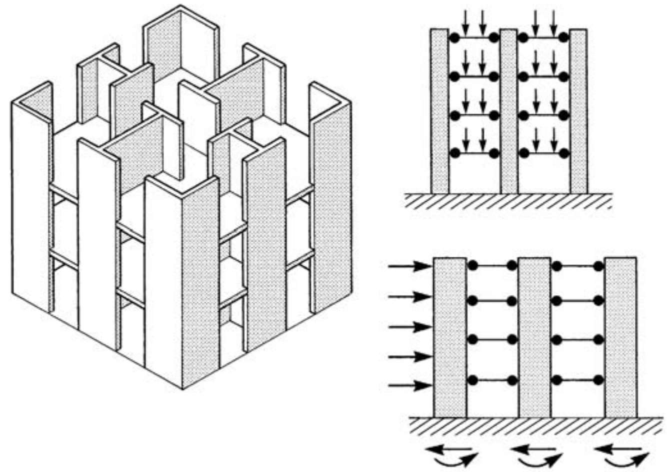


Figure 2.12 Loadbearing masonry buildings are normally multi-cellular structures that contain walls running in two orthogonal directions. The arrangement is inherently stable.

(Figure 2.12). It is unusual therefore for bracing requirements to have a significant effect on the internal planning of this type of building.

The need to ensure that a structure is stable is a factor that normally affects the internal planning of buildings. A basic requirement is that some form of bracing must be provided in two orthogonal directions on plan and, if diagonal or diaphragm bracing is used, this will affect wall arrangements. Because vertical-plane bracing is most effective when it is placed symmetrically, either in internal cores or around the perimeter of the building, this can restrict space-planning freedom, especially in tall buildings where the effects of wind loading are significant.

2.4 Strength and rigidity

2.4.1 Introduction

The application of load to a structure generates internal forces in the elements and external reacting forces at the foundations (Figure 2.13) and the elements and foundations must have sufficient strength and rigidity to resist these. They must not rupture when the peak load is applied; neither must the **deflection** that results from the peak load be excessive.

The requirement for adequate strength is satisfied by ensuring that the levels of stress that occur in the various elements of a structure, when the peak loads are applied, are within acceptable limits. This is chiefly a matter of providing elements with cross-sections of adequate size, given the strength of the constituent material. The determination of the sizes required is carried out either by using geometric rules (such as minimum ratios of span to depth for beams) or by structural calculations (see Chapter 7 for comparison of the two methods). The provision of adequate rigidity is similarly dealt with.

Structural calculations – the method most commonly used in the present day to determine suitable sizes for structural elements – allow the strength and rigidity of structures to be controlled precisely and must be preceded by an assessment of the load that a structure will be required to carry. The calculations may be considered to be divisible into two parts and to consist first, of **structural analysis**, which is the evaluation of the internal forces that occur in the elements of the structure, and second, the element-sizing calculations that are carried out to ensure that they will have sufficient strength

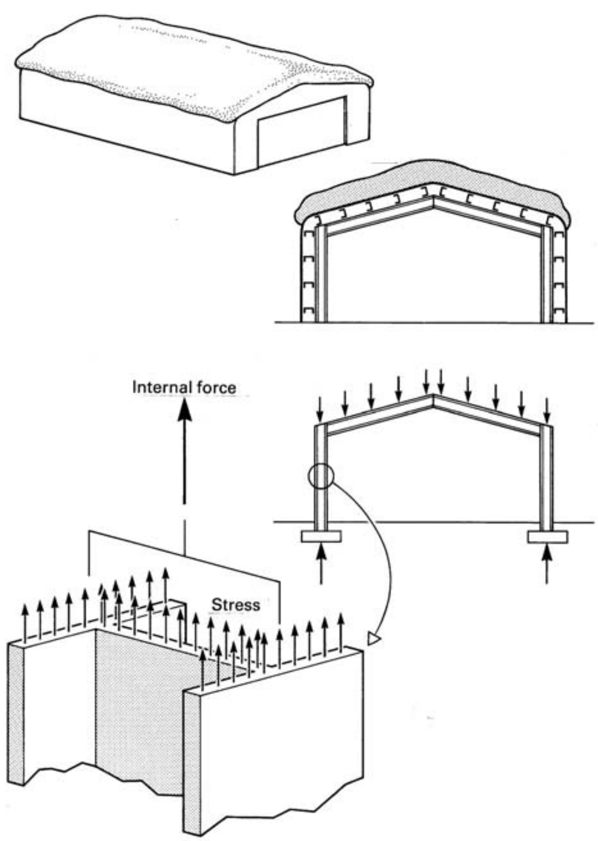


Figure 2.13 The structural elements of a building conduct the loads to the foundations. They are subjected to internal forces that generate stresses whose magnitudes depend on the intensities of the internal forces and the sizes of the elements. The structure will collapse if the stress levels exceed the strength of the material.

and rigidity to resist the internal forces that the loads will cause. In many cases, and always for **statically indeterminate structures**, the two sets of calculations are carried out together but it is possible to think of them as separate operations and they are described separately here.

2.4.2 The assessment of load

The assessment of the loads that will act on a structure involves the prediction of all the different circumstances that will cause the load to be applied to a building in its lifetime (Figure 2.14) and the estimation of the greatest magnitudes of these loads. The maximum load could occur when the building was full of people, when particularly heavy items of equipment were installed, when it was exposed to the force of exceptionally high winds or as a result of many other eventualities. The designer must anticipate all of these possibilities and also investigate all likely combinations of them. The evaluation of load is a complex process involving the statistical analysis of load data but guidance is normally available to the designer of a structure from loading standards (see Section 7.3.5).

2.4.3 The analysis calculations

The purpose of structural analysis is to determine the magnitudes of all of the forces, internal and external, that occur on and in a structure when the most

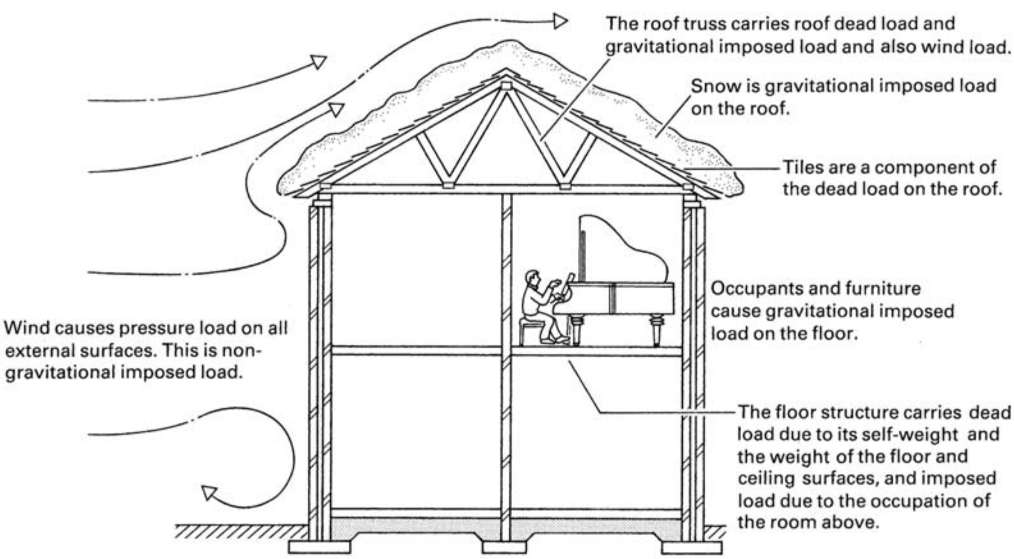


Figure 2.14 The prediction of the maximum load that will occur is one of the most problematic aspects of structural calculations. Loading Standards are provided to assist with this but assessment of load is nevertheless one of the most imprecise parts of the structural calculation process.

unfavourable load conditions occur. It is a procedure in which the external reactions that act at the foundations of a structure and the internal forces in its elements are calculated from the loads (Figure 2.15). This is a process in which the structure is reduced to its most basic abstract form and considered separately from the rest of the building that it will support.

The different types of internal force that can occur in a structural element are shown in Figure 2.16. As these have a very significant influence on the sizes and shapes that are specified for elements they will be described briefly here.

In Figure 2.16 an element is imagined to be cut through at a particular cross-section. In Figure 2.16a the forces that are external to one of the resulting sub-elements are marked. If these were indeed the only forces that acted on the sub-element it would not be in a state of equilibrium. For equilibrium the forces must balance and this is clearly not the case here: an

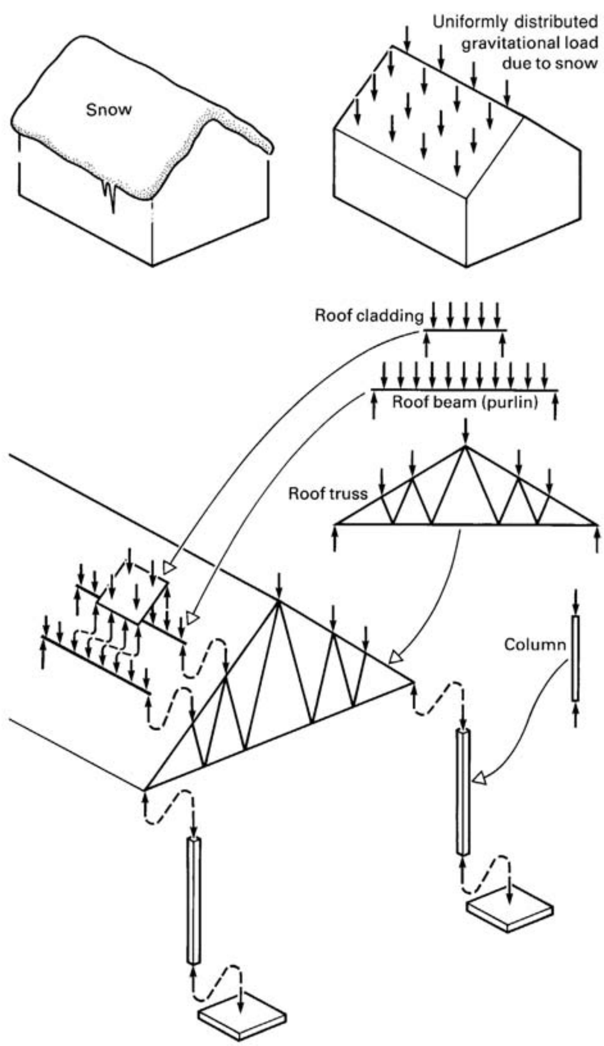


Figure 2.15 In structural analysis the complete structure is broken down into 2-D components and the internal forces in these are subsequently calculated. The diagram shows the pattern forces that result from gravitational load on the roof of a small building. Similar breakdowns are carried out for the other forms of load and a complete picture is built up of the internal forces that will occur in each element during the life of the structure.

additional vertical force is required for equilibrium. As no other external forces are present on this part of the element the extra force must act on the cross-section where the cut occurred. Although this force is external to the sub-element it is an internal force so far as the complete element is concerned and is called the **shear force** (see Glossary). Its magnitude at the cross-section where the cut was made is simply the difference between the external forces that occur to one side of the cross-section, i.e. to the left of the cut.

Once the shear force is added to the diagram (Figure 2.16b) the question of the equilibrium of the sub-element can once more be examined. In fact, it is still not in a state of equilibrium because the set of forces now acting will produce a turning effect on the sub-element that will cause it to rotate in a clockwise sense. For equilibrium an anti-clockwise moment is required and as before this must act on the cross-section at the cut because no other external forces are present. The moment that acts at the cut and that is required to establish rotational equilibrium is called the **bending moment** (see Glossary) at the cross-section of the cut. Once this is added to the diagram the system is in a state of static equilibrium, because all the conditions for equilibrium are now satisfied.

Shear force and bending moment are forces that occur inside structural elements and they can be defined as follows. The shear force at any location is the amount by which the external forces acting on the element, to one side

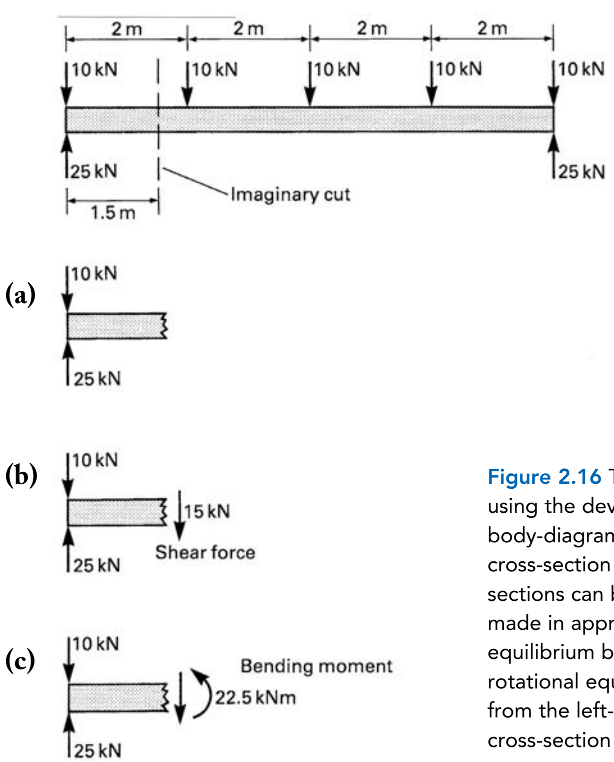
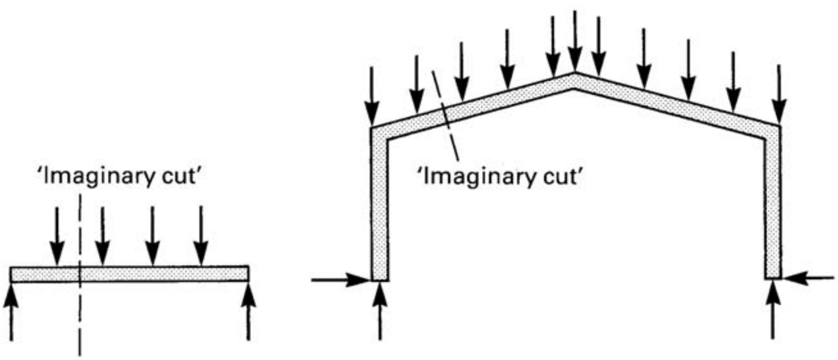


Figure 2.16 The investigation of internal forces in a simple beam using the device of the 'imaginary cut'. The cut produces a free-body-diagram from which the nature of the internal forces at a single cross-section can be deduced. The internal forces at other cross-sections can be determined from similar diagrams produced by cuts made in appropriate places. (a) Not in equilibrium. (b) Positional equilibrium but not in rotational equilibrium. (c) Positional and rotational equilibrium. The shear force on the cross-section 1.5 m from the left-hand support is 15 kN; the bending moment on this cross-section is 22.5 kNm.

of that location, do not balance when they are resolved perpendicular to the axis of the element. The bending moment at a location in an element is the amount by which the moments of the external forces acting to one side of the location, about any point in their plane, do not balance. Shear force and bending moment occur in structural elements that are bent by the action of the applied load. Beams and slabs are examples of such elements.

One other type of internal force can act on the cross-section of an element, namely **axial thrust**[1] (Figure 2.17). This is defined as the amount by which the external forces acting on the element to one side of a particular location do not balance when they are resolved parallel to the direction of the element. Axial thrust can be either tensile or compressive.

In the general case each cross-section of a structural element is acted upon by all three internal forces, namely shear force, bending moment and axial thrust. In the element-sizing part of the calculations cross-section sizes are determined which ensure that the levels of stress that these produce are not excessive. The efficiency with which these internal forces can be resisted depends on the shape of the cross-section (see Section 4.2).



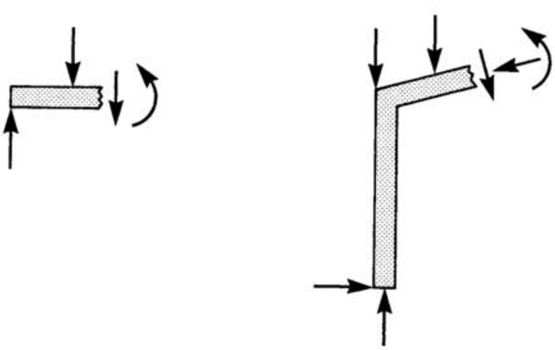


Figure 2.17 The 'imaginary cut' is a device for exposing internal forces and rendering them susceptible to **equilibrium analysis**. In the simple beam shown here, shear force and bending moment are the only internal forces required to produce equilibrium in the element isolated by the cut. These are therefore the only internal forces that act on the cross-section at which the cut was made. In the case of the portal frame, axial thrust is also required at the cross-section exposed by the cut.

The magnitudes of the internal forces in structural elements are rarely constant along their lengths and, once calculated, are normally presented graphically in the form of bending moment, shear force and axial thrust diagrams for each structural element (Figure 2.18). The shapes of bending moment, shear force and axial thrust diagrams are of great significance for the eventual shapes of structural elements because they indicate the locations of the parts where greatest strength will be required. Bending moment is normally large in the vicinity of mid-span and near-rigid joints. Shear force is highest near support joints. Axial thrust is usually constant along the length of structural elements.

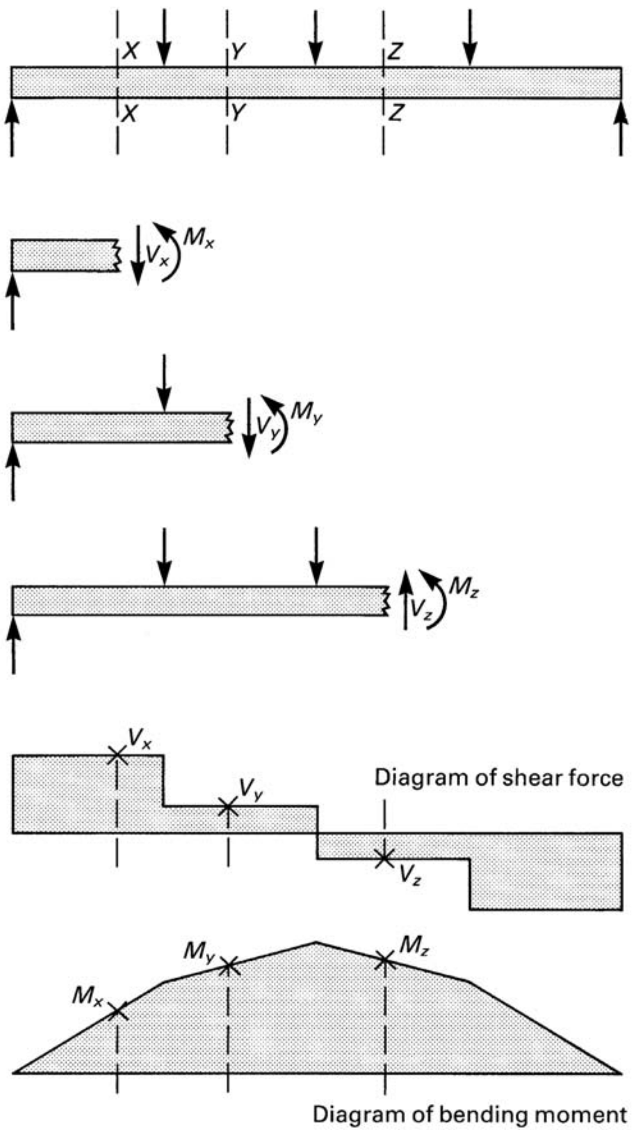


Figure 2.18 The magnitudes of internal forces normally vary along the length of a structural element. Repeated use of the 'imaginary-cut' technique yields the pattern of internal forces in this simple beam.

2.4.4 Element sizing calculations

The size of cross-section that is provided for a structural element must be such as to give it adequate strength and adequate rigidity: in other words, the size of the cross-section must allow the internal forces determined in the analysis to be carried without overloading the structural material and without the occurrence of excessive deflection. The calculations that are carried out to achieve this involve the use of the concepts of **stress** and **strain** (see Glossary).

In the sizing calculations each element is considered individually and an area of cross-section determined which will maintain the stress at an acceptable level in response to the peak internal forces. The detailed aspects of the calculations depend on the type of internal force and therefore stress involved and on the properties of the structural material. As with most types of design the evolution of the final form and dimensions of a structure is, to some extent, a cyclic process. If the element sizing procedures produce cross-sections that are considered to be excessively large or unsuitable in some other way, modification of the overall form of the structure will be undertaken so as to redistribute the internal forces. Then, the whole cycle of analysis and element sizing calculations must be repeated.

If a structure has a geometry that is stable and the cross-sections of the elements are sufficiently large to ensure that it has adequate strength it will not collapse under the action of the loads that are applied to it. It will therefore be safe, but this does not necessarily mean that its performance will be satisfactory (Figure 2.19). It may suffer a large amount of deflection under the action of the load and any deformation that is large enough to cause damage to brittle building components, such as glass windows, or to cause alarm to the building's occupants or even simply to cause unsightly distortion of the building's form, is a type of structural failure.

The deflection that occurs in response to a given application of load to a structure depends on the sizes of the cross-sections of the elements[2] and can be calculated once element dimensions have been determined. If the sizes that have been specified to provide adequate strength will result in excessive deflection they are increased by a suitable amount. Where this occurs it is the rigidity requirement that is critical and that determines the sizes of the structural elements. Rigidity is therefore a phenomenon that is not directly related to strength; it is a separate issue and is considered separately in the design of structures.

2.5 Conclusion

In this chapter the factors that affect the basic requirements of structures have been reviewed. The achievement of stable equilibrium has been shown to be dependent largely on the geometric configuration of the structure and is therefore a consideration that affects the determination of its form. A stable

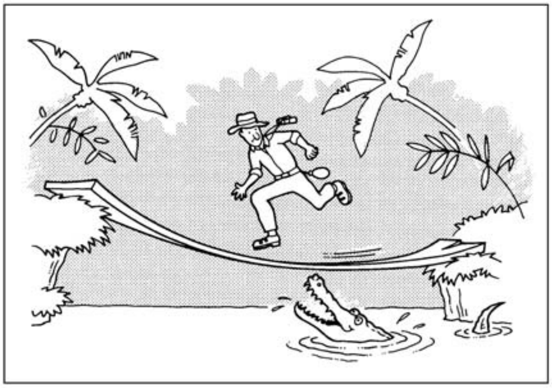


Figure 2.19
A structure with adequate strength will not collapse but excessive flexibility can render it unfit for its purpose.

form can almost always be made adequately strong and rigid but the form chosen affects the efficiency with which this can be achieved. The provision of adequate strength is accomplished by analysis of the structure to determine the types and magnitudes of the internal forces that will occur in all of the elements when the maximum load is applied and the selection of cross-section shapes and sizes which are such that the stress levels are maintained within acceptable limits. The amount of deflection that will occur under the maximum load can then be calculated and, if this is excessive, the element sizes are increased to bring the deflection within acceptable limits.

One final point worth noting is the effect of structural form on structural efficiency. A stable form can always be given adequate strength and rigidity simply by making individual elements large enough to ensure that the stresses are not excessive. It may be thought, therefore, that the provision of adequate strength and rigidity is not something that need be considered when evolving the form of a structure (and therefore of the building that it supports). However, the form selected directly affects the types and magnitudes of the internal forces and therefore of the strengths that are required of the structural elements and the quantities of material that must be provided to realise these strengths. Some forms generate much larger internal forces than others in response to the same applied load. The form that is selected therefore determines the efficiency with which the load can be resisted and is something that should be considered in the preliminary design of a building if wasteful use of material is to be avoided. An inappropriate form may even render the building structurally unviable.

Notes

1 Other types of internal force, such as torsion, can occur but are not considered here as they are not normally significant in architectural structures.
2 The deflection of a structure is also dependent on the properties of the structural material and on the overall configuration of the structure.

CHAPTER 3

Structural materials

3.1 Introduction

The selection of the material for a structure is one of the most crucial aspects of its design. It has consequences for the overall form of the structure, and therefore of the building that it supports, and also for several aspects of its aesthetic make-up. The strength characteristics of a material obviously affect the load-carrying potential of the structure and therefore the maximum height and spans that can be achieved. The physical properties of the material also determine the types of internal force that can be carried and therefore the categories of element for which it is suitable. Unreinforced masonry, for example, may only be used where compressive stress dominates. Reinforced concrete performs well when loaded in compression or bending but not particularly well in axial tension. Steel is the most suitable material for tensile elements.

The processes by which materials are manufactured and subsequently fashioned into structural elements also play a role in determining the shapes of elements for which they are suitable and influence the forms in which they are available to the builder. The properties of the structural material also have an important role in determining the visual qualities of a building. The slenderness of elements in high-strength materials such as steel contrasts with the massiveness of a masonry structure. The tactile quality, surface textures and colours of structural components can also affect the 'materiality' of architecture.

Another vital aspect of the specification of a material is its performance in respect of sustainability. The two principal considerations are the ecological footprint associated with the initial construction – as determined by such factors as embodied energy, carbon footprint and embodied water – and the potential of the material for recycling. The former is notoriously difficult to evaluate but must nevertheless be considered. It is discussed here in general terms only. Realistic concern for recycling requires that it be given serious

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Photo: Derek Skalko.

consideration at the design stage of a building and can affect the choice of material.

The various aspects of the influence of material properties on structural design are now discussed in relation to the four principal structural materials of masonry, timber, steel and reinforced concrete.

3.2 Masonry

Masonry is one of the ancient building materials that, over the centuries, has been used to construct some of the most spectacular structures of the Western architectural tradition, which have included very tall buildings and wide-span enclosures. Its strength properties are not ideal, however, and for the largest

Figure 3.1
Laon Cathedral, France, C12 and C13 CE. The Gothic church incorporates most of the various forms for which masonry is suitable. Columns, walls and compressive form-active arches and vaults are all visible here.

Photo: Mattana-Mattis/Wikimedia Commons.

structures in particular it has required that structural forms be adopted that eliminate tension. These include the vault and the dome, to achieve large horizontal spans, and thick, buttressed walls to allow great height to be provided safely.

Masonry is a composite material in which individual stones, bricks or blocks are bedded in mortar to form columns, walls, arches or vaults (Figure 3.1). The range of different types of masonry is large due to the variety of types of constituent. Bricks may be of fired clay, baked earth, concrete, or a range of similar materials, and blocks, which are simply very large bricks, can be similarly composed. Stone too is not one but a very wide range of materials from the relatively soft sedimentary rocks such as limestone to the very hard granites and other igneous rocks. These 'solid' units can be used in conjunction

Figure 3.2 Kharraqan Towers, Qazvin, Iran, C11 CE. These 15 m-high late-medieval brickwork structures demonstrate one of the advantages of masonry, which is that very large constructions with complex geometries can be achieved by relatively simple building processes.

Photo: Zereshk/Wikimedia Commons.

with a variety of different mortars to produce a range of masonry types. All have certain properties in common and therefore produce similar types of structural element. Other materials such as dried mud, pisé or even unreinforced concrete have similar properties and can be used to make similar types of structural element.

The fact that masonry structures are composed of very small basic units makes their construction straightforward. They are most commonly used in small-scale structural typologies as in Figures 1.12 and 1.13. Complex geometries can be produced relatively easily, however, without the need for sophisticated plant or techniques and very large structures can be built by these simple means (Figures 0.3, 3.2, 11.13 and 11.14). The only significant constructional drawback of masonry is that horizontal-span structures such as arches and vaults require temporary support until complete.

The physical properties of masonry are moderate compressive strength, minimal tensile strength, relatively high density and high thermal capacity. The very low tensile strength restricts the use of masonry to elements in which the principal internal force is compressive. Where horizontal spans are involved, tension can be eliminated by the use of form-active arrangements. Where significant bending movement occurs in masonry elements, for example from side thrusts on walls caused by rafters or vaulted roof structures, from out-of-plane wind pressure on external walls or from the tendency of compressive elements to buckle, the level of tensile **bending stress** is kept low by increasing their thickness. This can give rise to very thick walls and columns and therefore to excessively large volumes of masonry unless some form of 'improved' cross-section is used (see Section 4.3). Traditional versions of this are buttressed walls: those of medieval cathedrals or the voided and sculptured walls that support the large vaulted enclosures of Roman Antiquity (Figures 7.4, 10.18 and 10.19) are among the most spectacular examples. In all of these the volume of masonry is small in relation to the total effective thickness of the wall concerned. The fin and diaphragm walls of recent tall single-storey masonry buildings (Figure 3.3) are modern equivalents.

Due to the strength characteristics outlined above, the volume of material in a masonry structure is often relatively large and produces walls and vaults that can act as effective thermal, acoustic and weather-tight barriers and also as reservoirs of heat. Other attributes of masonry-type materials are that they are durable, and can be left exposed in both the interiors and exteriors of buildings. They are also, in most parts of the world, available locally in some form and do not therefore require to be transported over long distances. This, together with the fact that brick and block manufacture is generally a low-energy process, gives masonry a relatively small ecological footprint. Masonry is also a material that can be relatively easily recycled. Bricks, stones and blocks can be recovered from demolition processes and even where damaged can be re-used as aggregate for concrete or other building purposes. All of these characteristics make masonry an environmentally-friendly material whose

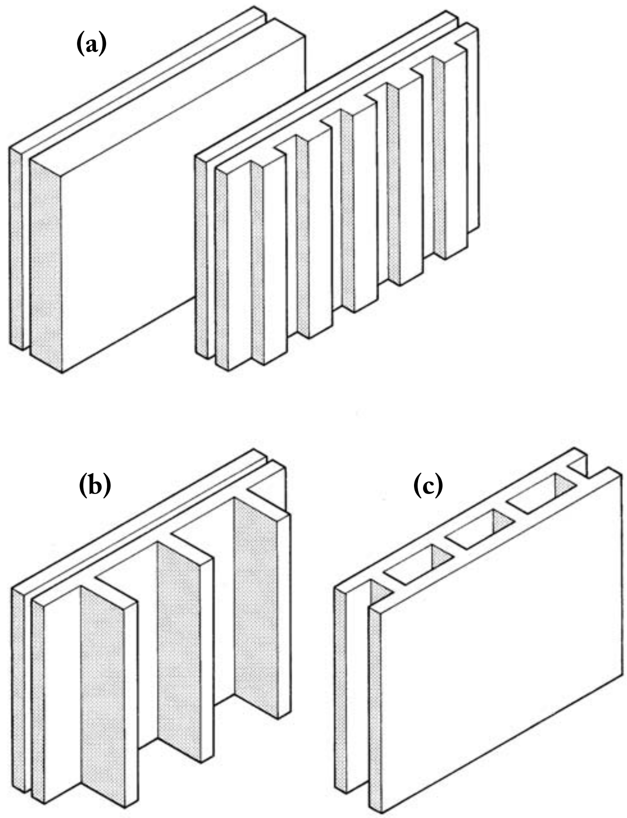


Figure 3.3 Where masonry will be subjected to significant bending moment, as in the case of external walls exposed to wind loading, the overall thickness must be large enough to ensure that the tensile bending stress is not greater than the compressive stress caused by the gravitational load. The wall need not be solid, however, and a selection of techniques for achieving thickness efficiently is shown here.

use must be expected to increase in future as the demand for sustainable forms of building become more pressing.

It is likely, therefore, that the use of masonry will increase and that it will be 'reclaimed' as a structural material that is suitable for large-scale buildings. This, in turn, is likely to have a significant effect on architectural style as the development of overall forms that are compatible with masonry construction are rediscovered and greater emphasis is placed on integrative design in which structure, environmental control and architectural style are evolved together.

3.3 Timber

Timber is, with masonry, one of the traditional structural materials but its strength properties are far superior as it can resist tension and compression with equal facility and therefore also bending. It is also a lightweight material with a high ratio of strength to weight. As with masonry, its use involves the acceptance of certain restrictions, such as those imposed by the forms in which it becomes available. It can, however, be relatively easily joined together which allows the build up of large structures, principally in the form

Figure 3.4 LeMay Museum, Tacoma, 2012; Large Architecture, architects. The principal structural elements here are laminated timber frameworks (1.3 m x 22 mm in cross-section) which span 32 m across the rectangular-plan interior.

Photo: Zheng Zhou/Wikimedia Commons.

of trussed arrangements, though the structurally weak nature of the joints imposes restrictions that have to be respected. Timber has nevertheless been used to create tall and also wide-span enclosures (Figures 3.4 and 11.5, 11.6).

Of the four principal structural materials timber is the only one that is sourced from raw material that is renewable and potentially inexhaustible provided that the forests from which it is extracted are appropriately managed. Timber components can also be re-used, if carefully removed from obsolete buildings, and are suitable for various forms of recycling. It is therefore likely that the importance of timber, as a structural material, will increase with the need to develop sustainable forms of architecture. As with masonry this will require that the vocabulary of timber forms be widened from the fairly limited range that has characterised its use in the Modern period to include more complex and efficient forms of structure (see Section 11.5), within the constraints imposed by the fundamental properties of the material.

The fact of timber having been derived from a living organism is responsible for the nature of its physical properties. The material is composed of long fibrous cells aligned parallel to the original tree trunk and therefore to the grain that results from the annual growth cycles. The constituent elements are of low atomic weight, which is responsible for its low density, but the lightness in weight is also due to its cellular internal structure which produces member cross-sections that are permanently 'improved' (see Section 4.3).

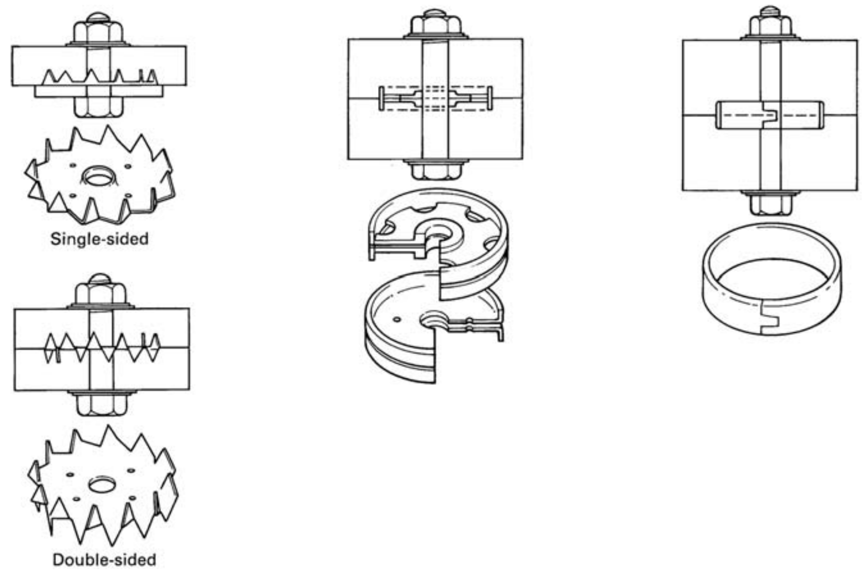


Figure 3.5 Timber connectors are used to increase the load-carrying capacity of bolted connections by reducing the concentration of stress. A selection of different types is shown here. Joint weakness is nevertheless a factor that limits the maximum size of built-up timber structures.

Parallel to the grain the strength is approximately equal in tension and compression so that planks aligned with the grain can be used for elements that carry axial compression, axial tension or bending-type loads as noted above. Perpendicular to the grain it is much less strong because the fibres are easily crushed or pulled apart when subjected to compression or tension in this direction.

This weakness perpendicular to the grain makes timber intolerant of the stress concentrations such as occur in the vicinity of mechanical fasteners such as bolts and screws and the difficulty of making satisfactory structural connections with mechanical fasteners (Figure 3.5) is a factor that limits the load carrying capacity of large-scale timber structures composed of many separate elements. The development, in the twentieth century, of structural glues for timber has to some extent solved the problem of stress concentration at joints but the curing of glue must normally be carried out under controlled conditions of temperature and relative humidity, which is impractical on building sites so that gluing has to be regarded as a pre-fabricating technique.

Timber suffers from a phenomenon known as moisture movement. This arises because the precise dimensions of any piece of timber are dependent on its moisture content (the ratio of the weight of water that it contains and its dry weight, expressed as a percentage) which is affected by the relative humidity of the environment, and therefore subject to continuous change.

It can cause joints made with mechanical fasteners to work loose. The greatest change to the moisture content occurs following the felling of a tree after which it undergoes a reduction from a value of around 150% in the living tree to between 10% and 20%, which is the normal range for moisture content of timber in a structure. The controlled drying out of timber, to avoid damage caused by shrinkage during this phase, is known as *seasoning*, a process in which the timber is physically restrained to prevent the introduction of permanent twists and other distortions caused by differential shrinkage.

The most basic timber elements are of sawn-timber, which is simply timber cut directly from a tree with little further processing other than seasoning, shaping and smoothing. These are normally relatively small (maximum length

Figure 3.6
The all-timber house is a loadbearing-wall form of construction in which all of the structural elements in the walls, floors and roof are of timber. An internal wall of closely spaced sawn-timber elements is here shown supporting the upper floor of a two storey building.
Photo: Angus J. Macdonald.

around 6 m and maximum cross-section around 75 mm × 250 mm) partly because the maximum sizes of cross-section and length are governed by the size of the original tree but also due to the desirability of having small cross-sections for the seasoning process. Sawn-timber elements can be combined to form larger, composite elements such as trusses with nailed, screwed or bolted connections. The scale of structural assemblies is usually modest however due to both the small sizes of the constituent planks and to the difficulty of making good structural connections with mechanical fasteners (Figure 3.6).

Timber is also available in the form of products that are manufactured by gluing small elements together in conditions of high quality control. They are intended to exploit the advantages of timber while at the same time minimising the effects of its principal disadvantages, which are variability, dimensional instability, the restrictions in the sizes of individual components and anisotropic behaviour. Examples of timber products are laminated timber, composite boards such as plywood, and combinations of sawn timber and composite board (Figure 3.7).

Laminated timber (Figure 3.7c) is a product in which elements with large rectangular cross-sections are built up by gluing together smaller solid timber elements of rectangular cross-section. The obvious advantage of the process is that it allows the manufacture of solid elements with much larger cross-sections than are possible in sawn timber. Very long elements are also possible because the constituent boards are jointed end-to-end by means of finger joints (Figure 3.8). The laminating process also allows the construction of elements that are tapered or have curved profiles. Arches (Figure 3.9) and portal frame elements (Figure 3.4) are examples of this.

Composite boards are manufactured products composed of wood and glue. There are various types of these including plywood, blockboard and particle board, all of which are available in the form of thin sheets. The level of glue impregnation is high and this imparts good dimensional stability and reduces the extent to which anisotropic behaviour occurs. Most composite boards also have high resistance to splitting at areas of stress concentration around nails and screws.

Composite boards are used as secondary components such as gusset plates in built-up timber structures. Another common use is as the web elements in composite beams of I- or rectangular-box sections in which the flanges are sawn timber (Figure 3.7b).

Because timber possesses both tensile and compressive strength it can be used for structural elements that carry axial compression, axial tension and bending-type loads. Its most widespread application in architecture has been in buildings of domestic scale in which it has been used to make complete structural frameworks, and for the floors and roofs in post-and-beam loadbearing masonry structures. Rafters, floor beams, skeleton frames, trusses, built-up-beams of various kinds, arches, shells and folded forms have all been constructed in timber (Figures 3.4, 3.6 and 3.9 to 3.13).

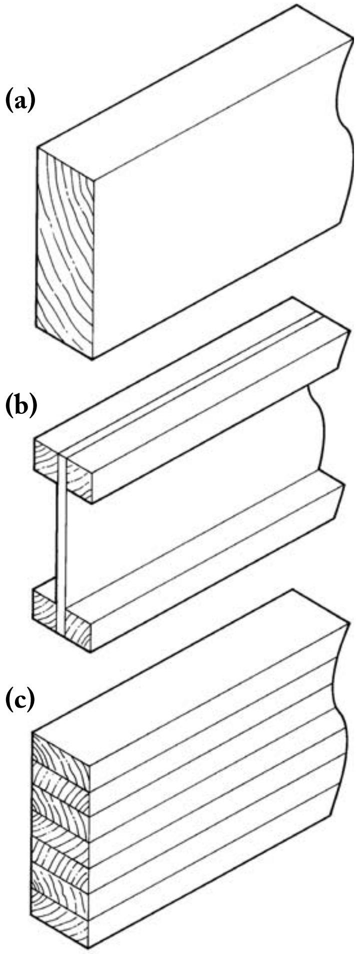


Figure 3.7 The I-beam with the plywood web (b) and the laminated beam (c) are examples of manufactured timber products. These normally have better technical properties than plain sawn timber elements such as that shown in (a). The high levels of glue impregnation in manufactured beams reduce dimensional instability, and major defects, such as knots, are removed from constituent sub-elements.

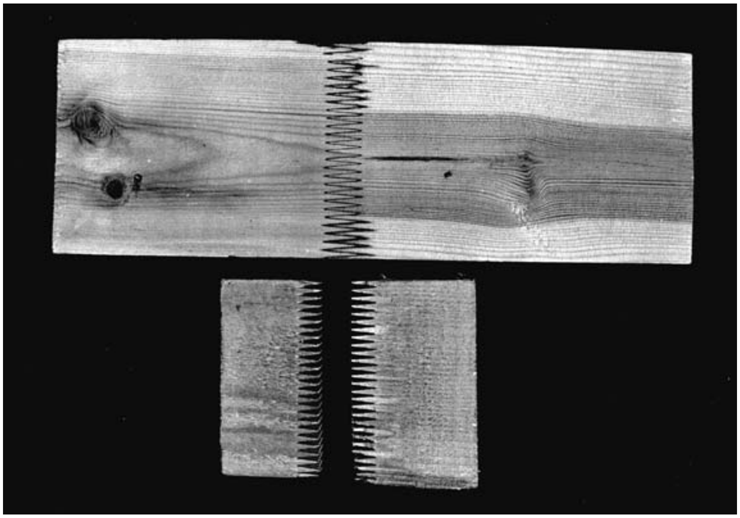


Figure 3.8 'Finger' joints allow the constituent boards of laminated timber elements to be produced in long lengths. They also make possible the cutting out of defects such as knots.

Photo: TRADA.

Timber is, therefore, a material that offers the designers of buildings a combination of properties that allow the creation of lightweight structures that are simple to construct. Its relatively low strength, the small sizes of the basic components and the difficulties associated with achieving good structural joints tend to limit the size of structure that is possible, however, and the majority of timber structures are small in scale with short spans and a small number of storeys. Currently, its most common application in architecture is in domestic building where it is used as a primary structural material either to form the entire structure of a building, as in timber wall-panel construction, or as the horizontal elements in loadbearing masonry structures. Its potential for use in larger structural typologies is, however, considerable (see Section 11.5).

Figure 3.9 Olympic Oval, Richmond, Canada; CannonDesign, architects. The principal structural elements of this building, which received a LEED award for its many environmentally sustainable features, are composite arches of laminated timber and steel spanning 100 m.

Photo: Duncan Rawlinson/Wikimedia Commons.

Figure 3.10 Savill Building, Windsor, UK, 2006; Glen Howells Architects, architects; Buro Happold Engineering and Haskins Robinson Waters, engineers. The primary structural element in this building is a timber grid-shell, spanning 90 x 25 m, constructed from locally sourced larch and oak.

Photo: oosoom/ wikimedia commons

Figure 3.11
Savill Building, Windsor, UK, 2006; Glen Howells Architects, architects; Buro Happold Engineering and Haskins Robinson Waters, engineers. Individual elements consist of two 80 x 50 mm laths separated by 50 mm or 75 mm shear blocks. The 24 mm-thick plywood skin provides stiffening and is therefore part of the structure. The configuration is similar to that used in aircraft construction (see Figure 4.15) but the fabrication is 'low tech'. It is an example of the type of innovation required for the creation of sustainable forms of building.

Photo: Glen Howells Architects.

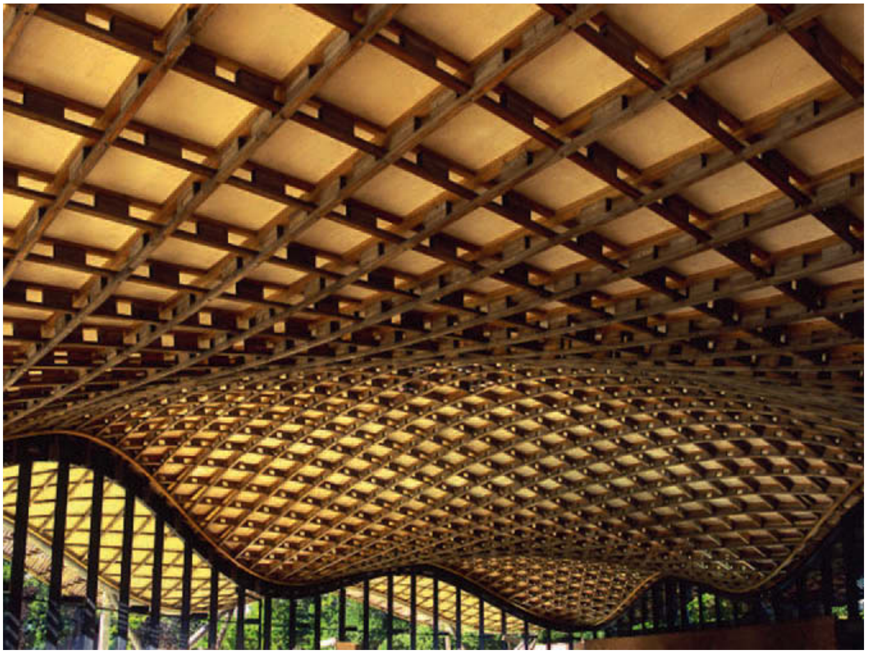


Figure 3.12
Living Planet Centre, WWF UK, Woking, UK, 2013; Hopkins Architects, architects; Expedition Engineering, engineers. This vaulted timber roof structure spans 80 x 37.5 m.

Photo: Morley von Sternberg.

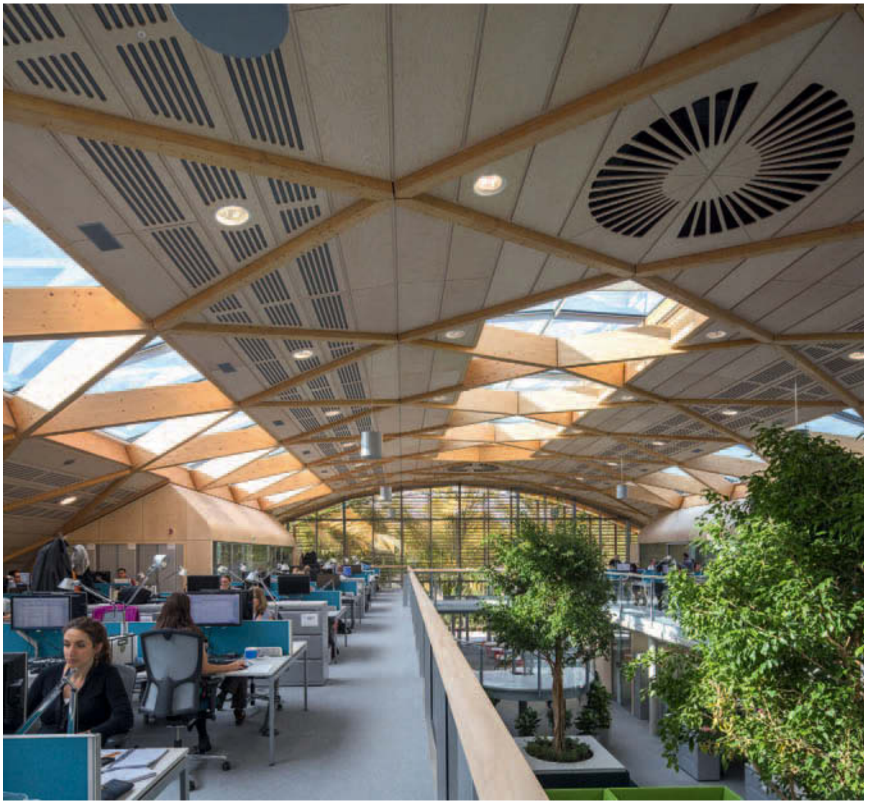


Figure 3.13
Living Planet Centre, WWF UK, Woking, UK, 2013; Hopkins Architects, architects; Expedition Engineering, engineers. Individual elements are of laminated timber and are 'improved' with built-in 'lightening' holes.

Photo: Morley von Sternberg.

3.4 Steel

Steel is the strongest of the commonly used structural materials, used for the tallest buildings and the longest spans. It has more-or-less equal strength in tension and compression and is therefore able to resist bending well. It can also be relatively easily jointed by welded or bolted connections. This combination of properties has allowed steel to be used in all types of structural configurations and, since its introduction at the beginning of the Modern period, has released architects from many of the constraints on form which had formerly been imposed by the limitations of the traditional structural materials. The glass-clad rectilinear steel skeleton framework has been one of the signature forms of Modern architecture and recent developments in steel fabrication technology has allowed its use to be extended to large-scale and very complex curvilinear shapes. Much of the free-form architecture of recent decades (see Figures 10.23 to 10.27) involves the use of inefficient semi-form-active structural configurations that would have required impossibly bulky elements for support were it not for the use of a very strong structural material. The great freedom of expression that has been enjoyed by certain 'starchitects' in the early twenty-first century has therefore been made possible largely by the advent of steel as a structural material that can now be fashioned into complex curvilinear forms.

It is also a material that carries a very high environmental cost, with a large carbon footprint and high embodied energy. It can be relatively easily re-used or recycled but the energy input required for the latter is considerable. Its usefulness, in both structural and all other current applications, is such that a significant reduction in society's dependence on steel is unlikely in the near future, but the environmental costs are such that this will come under increasing scrutiny. Given the alternatives that are available for most building applications, the use of steel as a structural material in architecture is likely to decrease in the medium to long term and this, in turn, will increase the influence of structural design on the development of architectural style as forms are adopted that are more suited to environmentally friendly materials (see Section 11.5).

The high strength and high density of steel favours its use in skeleton frame type structures in which the volume of the structure is low in relation to the total volume of the building that is supported but a limited range of slab-type formats are also used. An example of a structural slab-type element is the profiled floor deck in which a profiled steel deck is used in conjunction with concrete, or exceptionally timber (Figure 3.14), to form a composite structure. These have 'improved' corrugated cross-sections to ensure that adequate levels of efficiency are achieved. Deck units consisting of flat steel plate are uncommon.

The shapes of steel elements are greatly influenced by the process that is used to form them – hot-rolling, cold-forming and casting. Hot-rolling is a primary shaping process in which massive red-hot billets of steel are rolled between several sets of profiled rollers. The cross-section of the original billet, which is normally cast from freshly manufactured steel and is usually around 0.5 m × 0.5 m square, is reduced by the rolling process to much smaller dimensions and to a particular precise shape (Figure 3.15). The range of cross-section shapes that are produced is very large and each group requires its own set of finishing rollers. Elements that are intended for structural use

Figure 3.14
Hopkins House, London; Michael and Patty Hopkins, architects; Anthony Hunt Associates, structural engineers. The floor structure here consists of profiled steel sheeting that will support a timber deck. A more common configuration is for the profiled steel deck to act compositely with an in-situ concrete slab for which it serves as permanent formwork. The building also illustrates well the slender elements and low volume of structure that the great strength of steel makes possible and that is exploited here for visual effect.

Photo: Pat Hunt.

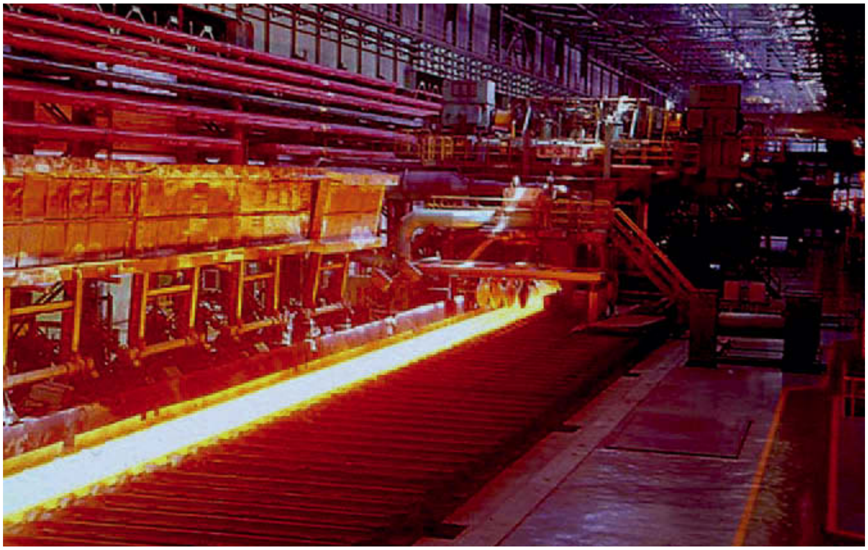


Figure 3.15 The heaviest steel sections are produced by a hot-rolling process in which billets of steel are shaped by profiled rollers. This results in elements that are straight, parallel-sided and of constant cross-section. These features must be taken into account by the designer when steel is used in building and the resulting restrictions in form accepted.

Photo: Univac Consulting Engineers.

have shapes in which the **second moment of area** (see Glossary) is high in relation to the total area (Figure 3.16). I- and H-shapes of cross-section are common for the large elements that form the beams and columns of structural frameworks. Channel and angle shapes are suitable for smaller elements such as secondary cladding supports and sub-elements in triangulated frameworks. Square, circular and rectangular hollow-sections are produced in a wide range of sizes, as are flat plates and solid bars of various thicknesses. Details of the dimensions and geometric properties of all the standard sections are listed in tables of section properties produced by steelwork manufacturers.

The other method by which large quantities of steel components are manufactured is cold-forming. In this process thin, flat sheets of steel, which have been produced by the hot-rolling process, are folded or bent in the cold state to form structural cross-sections (Figure 3.17). The elements that result have similar characteristics to hot-rolled sections, in that they are parallel sided with constant cross-sections, but the thickness of the metal is much less so that they are much lighter but have lower load-carrying capacities. The process allows more complicated shapes of cross-section to be achieved however. Another difference from hot-rolling is that the manufacturing equipment is much simpler than that used for hot-rolling and can produce tailor-made cross-sections for specific applications. Due to their lower carrying capacities cold-formed sections are used principally for secondary elements in roof structures, such as purlins, and for cladding support systems.

Structural steel components can also be produced by casting, in which case very complex tailor-made shapes are possible. The technique is problematic when used for structural components, however, due to the difficulty of ensuring that the castings are sound and of consistent quality throughout. In the early

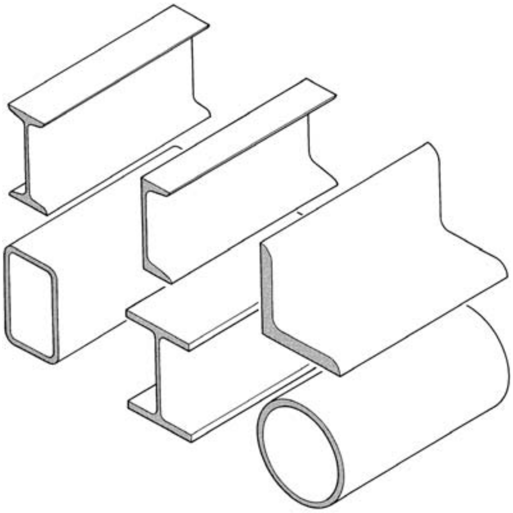


Figure 3.16 Hot-rolled steel elements.

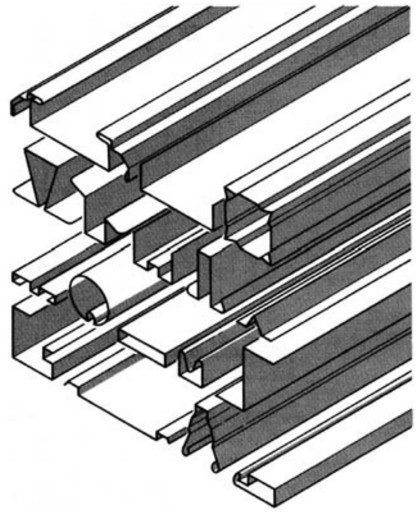


Figure 3.17 Cold-formed sections are formed from thin steel sheet. A greater variety of cross-section shapes is possible than with the hot-rolling process.

years of ferrous metal structures in the nineteenth century, when casting was widely used, many structural failures occurred – most notably that of the Tay Railway Bridge in Scotland in 1879 – and casting was discontinued as a method for shaping structural elements. The use of the technique for architectural structures was revived in the late twentieth century, largely due to the development of systems for proving the soundness of castings, a spectacular early example being the semi-cantilevered 'gerberette' brackets in the Centre Pompidou (Figures 9.30 and 9.31). The development of weldable cast steel, largely in connection with the offshore oil industry, has allowed the technique to be used for complex jointing components in space frameworks (Figures 10.4 and 10.5). Most of the structural steelwork used in building consists of elements of the hot-rolled type and this has important consequences for the layout and overall form of the structures. A consequence of the rolling process is that the constituent elements are prismatic (straight, parallel-sided with constant cross-sections) and this tends to impose a regular, straight-sided format on the structural forms for which it is suitable (Figures 3.19 and 5.10 to 5.14). In recent years, however, methods have been developed for bending hot-rolled structural steel elements into curved profiles and this has extended the range of forms for which it can be used.

Because steel structures are pre-fabricated, the design of the joints between the elements is an important aspect of the overall design that affects both the structural performance and the appearance of the frame. Joints are made either by bolting or by welding (Figure 3.18). Bolted joints are less effective for the transmission of load because bolt holes reduce the effective sizes of

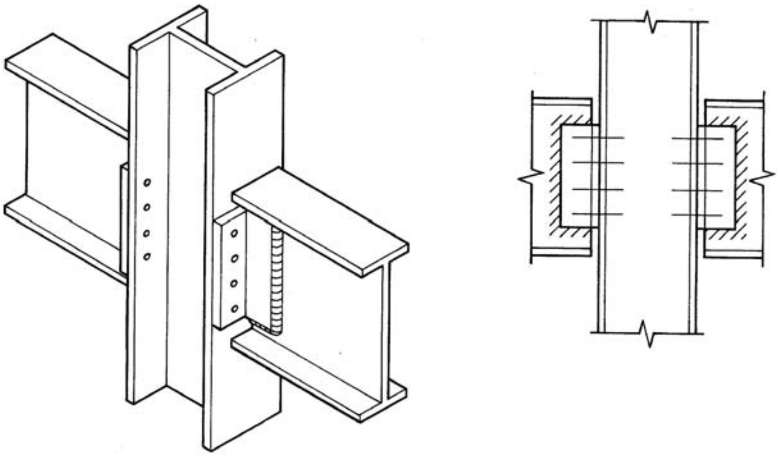


Figure 3.18 Joints in steelwork are normally made by a combination of bolting and welding. The welding is usually carried out in the fabricating workshop and the site joint is made by bolting.

element cross-sections and give rise to stress concentrations. Bolted connections can also be unsightly unless carefully detailed. Welded joints are neater and transmit load more effectively but the welding process is a highly skilled operation and requires that the components concerned be very carefully prepared and precisely aligned prior to the joint being made. For these reasons welding on building sites is normally avoided and steel structures are usually pre-fabricated by welding to be bolted together on site. The need to transport elements to the site restricts both the size and shape of individual components.

Two problems associated with steel are its poor performance in fire, due to the loss of mechanical properties at relatively low temperatures, and its high chemical instability, which makes it susceptible to corrosion. Both of these have been overcome to some extent by the development of fireproof and corrosion protection materials, especially paints, but the exposure of steel structures, either internally, where fire must be considered, or externally, where durability is an issue, is always problematic.

To sum up, steel is a very strong material with dependable properties. It is used principally in skeleton frame types of structures in which the components are hot-rolled. It allows the production of structures of a light, slender appearance and a feeling of neatness and high precision (Figure 3.19). It is also capable of producing very long span structures and structures of great height. The manufacturing process imposes certain restrictions on the forms of steel frames. Regular overall shapes produced from straight, parallel sided elements are the most favoured.

Figure 3.19
Spectrum building (formerly Renault Sales Headquarters), Swindon, UK, 1983; Norman Foster Associates, architects; Ove Arup & Partners, structural engineers. An example of steelwork used to create architectural effect as well as to provide support. All principal elements are standard hot-rolled sections. Tapering of I-section beams is achieved by cutting and welding of the parallel-sided originals.

3.5 Reinforced concrete

Concrete, which is a composite of fragments of stone or other inert material (aggregate) and cement binder, may be regarded as a kind of artificial masonry because it has similar properties to stone and brick (high density, moderate compressive strength, minimal tensile strength). It is made by mixing together dry cement and aggregate in suitable proportions and then adding water, which causes the cement to hydrolyse and subsequently the whole mixture to set and harden to form a substance with stone-like qualities.

Concrete has one considerable advantage over masonry which is that it is available in semi-liquid form during the construction process and this has three important consequences. First, it means that other materials can be incorporated into it easily to augment its properties, the most important of these being steel in the form of thin reinforcing bars which give the resulting composite material (reinforced concrete – Figure 3.20) tensile and therefore bending strength as well as compressive strength. Other materials, such as mineral fibre, plastics of various kinds, and fabric, can also be used as tensile reinforcement. Second, the availability of concrete in liquid form allows it to be cast into a wide variety of shapes. Third, the casting process allows very effective connections to be provided between elements and the resulting structural continuity greatly enhances the efficiency of the structure.

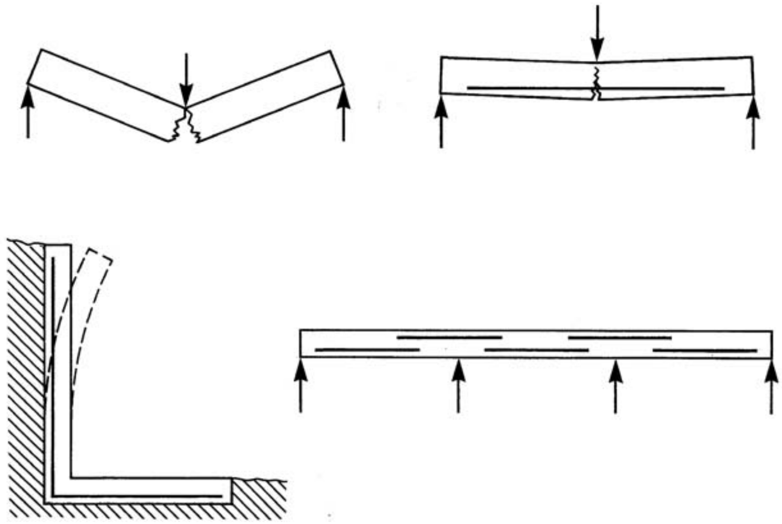


Figure 3.20
In reinforced concrete, steel reinforcing bars are positioned in locations where tensile stress occurs.

This combination of properties, and in particular the combination of high bending strength with mouldability, has allowed reinforced concrete to be used in a very wide range of forms. For the greater part of the Modern period it was the only material in which large-scale, free forms, involving semi-form-active arrangements, could be constructed. In these situations it was normally the difficulties of constructing the formwork on which the concrete would be cast rather than any constraints caused by the material itself that placed restrictions on the forms that were possible.

Although concrete can be moulded into complicated shapes, relatively simple shapes are normally favoured for reasons of economy in construction (Figure 3.21). The majority of reinforced concrete structures are therefore post-and-beam arrangements (see Section 5.2) of straight beams and columns, with simple solid rectangular or circular cross-sections, supporting plane slabs of constant thickness. The formwork in which such structures are cast is simple to make and assemble and therefore inexpensive, and can be re-used repeatedly in the same building. These non-form-active arrangements (see Section 4.2) are relatively inefficient but are satisfactory where the spans are short (up to 6 m). Where longer spans are required more efficient 'improved' types of cross-section (see Section 4.3) and profile are adopted. The range of possibilities is large due to the mouldability of the material. Commonly used examples are coffered slabs and tapered beam profiles.

The mouldability of concrete also makes possible the use of complex shapes and the inherent properties of the material are such that practically any shape is possible. Reinforced concrete has therefore been used for a very wide range of structural geometries. Examples of structures in which this has been exploited are the Wills, Faber & Dumas Building (Figure 1.6), where the mouldability of concrete and the level of structural continuity that it makes

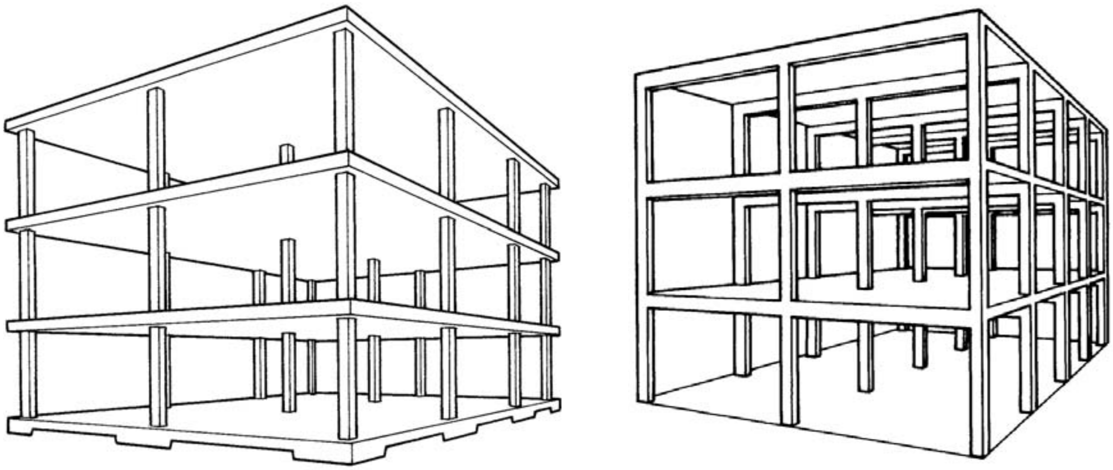


Figure 3.21 Despite the mouldability of the material, reinforced concrete structures normally have a relatively simple form so as to economise on construction costs. The two most commonly used configurations for multi-storey buildings are shown here: two-way spanning flat slab (*left*) and beam-column frame (*right*). The structural armatures of multi-storey reinforced concrete structures are normally variations of one or other of these two generic forms.

possible were used to produce a multi-storey structure of irregularly curved plan with floors that cantilevered beyond the perimeter columns, and the Lloyd's Building, in London (Figs 10.6 to 10.10), in which an exposed concrete frame was given great prominence and detailed to express the structural nature of its function.

In recent years the sculptural qualities of reinforced concrete have been exploited in the design of complex structural armatures for large building complexes so as to incorporate features that improve their environmental performance. The buildings of the Malaysian architect Ken Yeang, in which complex 'green' corridors are provided in configurations that spiral upwards through buildings, are examples (Figures 1.7 and 1.8).

Sometimes the geometries that are adopted for concrete structures are selected for their high efficiency. Form-active shells for which reinforced concrete is ideally suited are examples of this (Figures 1.4 and 9.14). The efficiency of these is very high and spans of 100 m and more have been achieved with shells a few tens of millimetres in thickness. In other cases the high levels of structural continuity have made possible the creation of sculptured building forms that, though they may be expressive of architectural meanings, are not particularly sensible from a structural point of view. A well-known example of this is the roof of the chapel of Notre-Dame du Haut at Ronchamp by Le Corbusier (Figure 10.22), in which a highly individual and inefficient structural form is executed in reinforced concrete. At the time of its construction, it would have been impossible to make this form in any other structural material.

3.6 Conclusion

This chapter has reviewed the essential structural properties of the four principal structural materials and discussed their applications. In the Modern period they have been used principally in various post-and-beam forms as has suited both the architectural aspirations of Modernism and the economic climate of the age. The need, in future, to evolve building forms that are environmentally sustainable is likely to have a significant effect on the selection of the materials for the structural parts of buildings. This is likely to result in an expansion in the use of the traditional materials of masonry and timber for types of building, such as inner-city office, retail and housing complexes, in place of the more environmentally damaging materials of steel and reinforced concrete. This, in turn, will produce the need for a reconsideration of the forms and styles of architecture that are considered appropriate for this type of building.

CHAPTER 4

The archetypes of structural form

The relationship between structural form and structural efficiency

4.1 Introduction

The term 'strong shape' is often used in discussions of structural form, especially in relation to spectacular curvilinear structures such as thin shells. There is, however, no such thing as a *shape* that is strong, because all shapes of structure can be provided with adequate strength if sufficient material is specified. Some shapes require less material than others to achieve a given level of strength, however, so the question, so far as the relationship between form and performance is concerned, is not so much one of strength as of the *efficiency* with which a particular level of strength can be achieved. This chapter is concerned with the relationship between **structural form** and **structural efficiency**.[1]

The shapes of structural elements, especially the shapes of their longitudinal axes in relation to the pattern of applied load, determine the types of internal force that occur within them and influence the magnitudes of these forces. These two factors – the *type* and the *magnitude* of the internal force created by a given application of load – have a crucial effect on the level of structural efficiency that can be achieved because they determine the amount of material that must be provided to give the elements particular levels of strength and rigidity.

A classification system for structural elements is proposed here, based on the relationship between form and efficiency. The concepts involved define the '**archetypes of structural form**' (see Glossary and Section 4.4).

Facing page:
Charles Kuonen Suspension Bridge, Randa, Swissrope. Photo: Valentin Flauraud.

The purpose of the classification system is to act as an aid to the reading of buildings as structural objects and to the assessment of the technical performance of structures. It is also intended to form a basis for the critical appraisal of structures.

4.2 The effect of form on internal force type

Elements in architectural structures are subjected principally either to axial internal force or to bending-type internal force. They may also be subjected to a combination of these. Other types of internal force, such as torsion and shear, do occur but are rarely critical in determining the overall sizes required for structural elements. The distinction between axial and bending is an important one, so far as efficiency is concerned, because axial internal force can be resisted more efficiently than bending-type internal force. The principal reason for this is that the distribution of stress that occurs within the cross-sections of an axially loaded element is more-or-less constant and this uniform level of stress allows all of the material in the element to be stressed to its limit. A size of cross-section is selected that ensures that the level of stress is as high as the material concerned can safely withstand and an efficient use of material therefore results because all of the material present provides full value for its weight. With bending stress, which varies in intensity in all cross-sections (Figure 4.1) from a minimum at the **neutral axis** to a maximum at the **extreme fibres** (see Glossary), only the material at the extreme fibres can be stressed to its limit. Most of the material present is understressed and therefore inefficiently used.

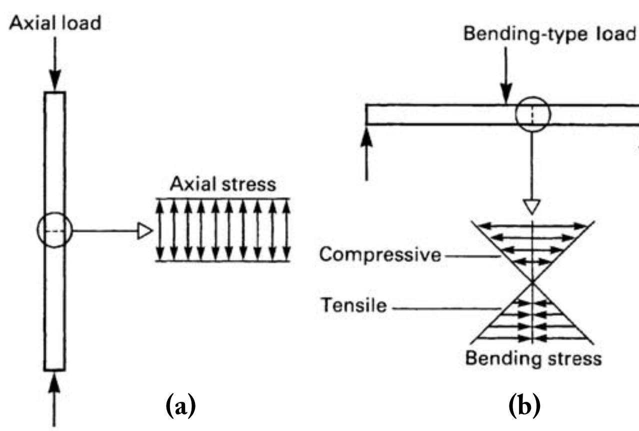


Figure 4.1 (a) Elements that carry purely axial load are subjected to axial stress whose intensity is constant across all cross-sectional planes. (b) Pure bending-type load (i.e. load that is normal to the axis of the element) causes bending stress to occur on all cross-sectional planes. The magnitude of this varies within each cross-section from a maximum compressive stress at one extremity (extreme fibre) to a maximum tensile stress at the other.

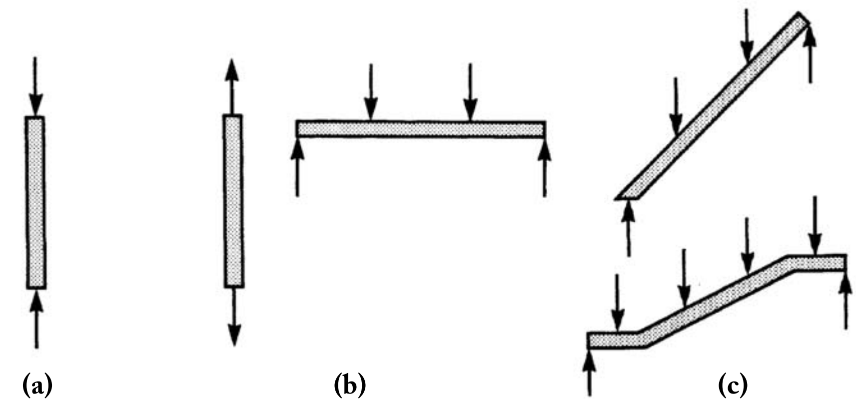


Figure 4.2 Basic relationships between loads and structural elements. (a) Load coincident with principal axis: **axial internal force**. (b) Load perpendicular to the principal axis: **bending-type internal force**. (c) Load inclined to the principal axis: **combined axial and bending-type internal force**.

The type of internal force that occurs in an element depends on the relationship between the direction of its principal axis (its longitudinal axis) and the direction of the load that is applied to it (Figure 4.2). If an element is straight, axial internal force occurs if the load is applied parallel to its longitudinal axis. Bending-type internal force occurs if it is applied at right angles to the longitudinal axis. If the load is applied obliquely, a combination of axial and bending internal force occurs. The axial-only and bending-only conditions are in fact special cases of the more general combined situation, but they are nevertheless the most commonly found types of loading arrangement in architectural structures.

If an element is not straight then it will almost inevitably be subjected to a combination of axial and bending internal forces when a load is applied but there are important exceptions to this as is illustrated in Figure 4.3. Here, the structural element consists of a flexible cable, supported at its ends, and from which various loads are suspended. Because the cable has no rigidity it is incapable of carrying any other type of internal force but axial tension; it is therefore forced by the loads into a shape that allows it to resist them with an internal force that is pure axial tension. The shape traced by the longitudinal axis is unique to the load pattern and is called the '**form-active**'[2] shape for that load.

As is seen in Figure 4.3 the shape that the cable adopts is dependent on the pattern of load that is applied; the form-active shape is straight-sided when the loads are concentrated at individual points and curved if the load is distributed along it. If a cable is allowed simply to sag under its own weight, which is a distributed load acting along its entire length, it adopts a curve known as a catenary (Figure 4.3).

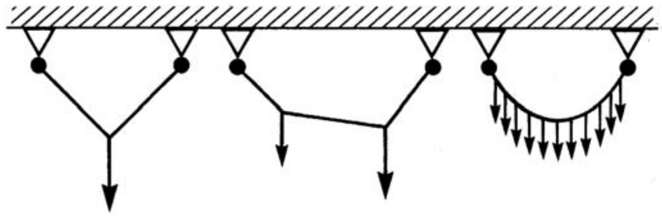


Figure 4.3 Tensile form-active shapes. Because it has no rigidity a cable must take up a shape – the form-active shape – that allows it to resist the load with a purely axial tensile internal force. Different load arrangements produce different form-active shapes.

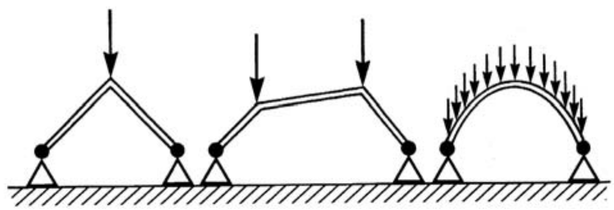


Figure 4.4 Compressive form-active shapes.

An interesting feature of the form-active shape for any load pattern is that, if a rigid element is constructed whose longitudinal axis is the mirror image of the form-active shape taken up by the cable, then it too will be subjected exclusively to axial internal forces when the same load is applied, despite the fact that, being rigid, it could also carry bending-type internal force. In the mirror-image form, all the axial internal forces are compressive (Figure 4.4).

The cable structure and its rigid 'mirror-image' counterpart are simple examples of a whole class of structural elements that carry axial internal forces because their longitudinal axes conform to the **form-active shapes** for the loads which are applied to them. These are called **form-active elements**.

If, in a real structure, a flexible material such as steel wire or cable is used to make an element, it will automatically take up the form-active shape when load is applied. Flexible material is in fact incapable of becoming anything other than a form-active element. If the material is rigid, however, and a form-active element is required, then it must be made to conform to the form-active shape for the load that is to be applied to it or, in the case of a compressive element, to the mirror image of the form-active shape. If not, the internal force will not be pure **axial force** and some bending will occur.

Figure 4.5 shows a mixture of *form-active* and *non-form-active* shapes. Three load patterns are illustrated and, for each of these, the elements in the top row have shapes that conform exactly to the form-active shapes of the loads. They are therefore *form-active* elements that carry axial internal forces

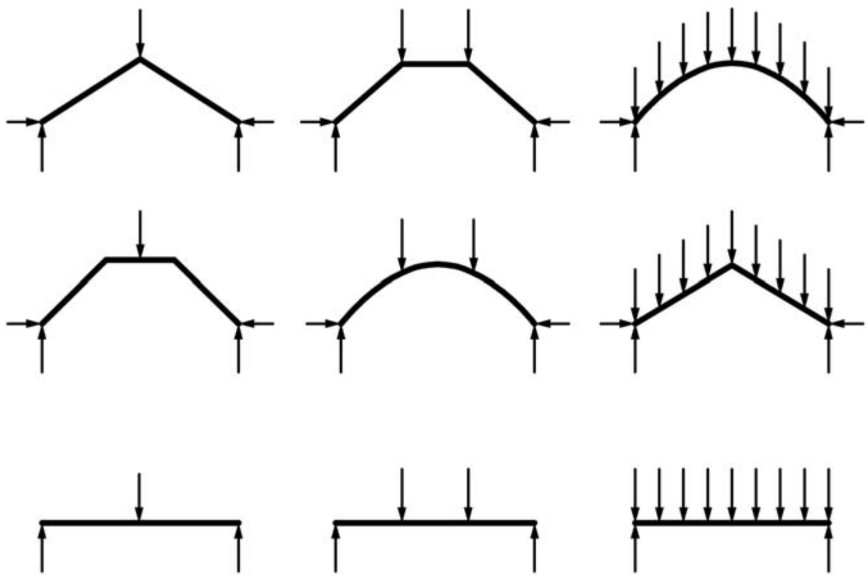


Figure 4.5 Examples of the relationship between element shape, load pattern and element type. The latter is determined by the relationship between the shape of the element and the form-active shape for the load pattern that it carries: top row – form-active (axial internal force only – archetypes of structural form); middle row – semi-form-active (combined bending and axial internal force); bottom row – non-form-active (bending internal force only).

Note that each of the shapes in the top and middle rows can be either form-active or semi-form-active depending on the load applied.

only; in each case the forces are compressive. The elements in the bottom row carry pure bending-type internal forces; no axial force can occur in these because there are no components of the loads that are parallel to their principal axes; they are *non-form-active* elements. The elements in the middle row do not conform to the form-active shapes for the loads shown applied to them and will not therefore carry pure axial internal force. Neither will they be subjected to pure bending; they will carry a combination of bending and axial internal force and are therefore *semi-form-active* structures.

So far as the shape of their longitudinal axes are concerned, structural elements can thus be classified into three categories: **form-active** elements, **non-form-active** elements and **semi-form-active** elements. Form-active elements are those that conform to the form-active shape of the load pattern that is applied to them and they contain axial internal forces only. Non-form-active elements are those whose longitudinal axis does not conform to the form-active shape of the loads and is such that no axial component of internal force occurs. These contain bending-type internal force only. Semi-form-active elements are elements whose shapes are such that they contain a combination of bending and axial internal forces.

Figure 4.6 The Charles Kuonen Suspension Bridge, Randa, Switzerland, 2017; Swissrope, constructor. The steel ropes that support the footway are form-active structures and demonstrate the very high structural efficiency that this typology makes possible.

Photo: Valentin Flauraud/ecophiles.

It is important to note that structural elements can *only* be form-active in the context of a particular load pattern. There are no shapes that are form-active *per se*. The cranked beam shape in Figure 4.5, for example, is a form-active element when subjected to the two concentrated loads but a semi-form-active element when subjected to the single point load.

Form-active shapes are potentially the most efficient types of structural element and non-form-active shapes the least efficient. The efficiency of semi-form-active elements depends on the extent to which they are different from the form-active shape.

The characteristic differences between form-active and non-form-active structures are readily demonstrated by simple examples. The steel rope bridge illustrated in Figure 4.6 achieves a span of 494 m with a very small amount of structural material. The quantity of steel that would be required to provide the same crossing facility with a rigid (non-form-active) girder would be several orders of magnitude greater. The rope structure also provides a simple demonstration of the 'active' principle. As can easily be imagined, the precise shape of the structure would undergo slight changes under the variation in the loading condition caused by the movement of pedestrians across it. The reinforced concrete envelope of the CNIT enclosure in Paris (Figure 1.4) achieves a span of 218 m with an overall shell thickness of 120 mm due to its having an overall shape that is form-active. In a non-form-active post-and-beam slab configuration in reinforced concrete a depth of around 500 mm would be required to achieve a span of as little as 10 m. The difference of efficiency between the form-active and non-form-active arrangements is again seen to be several orders of magnitude.

4.3 The concept of 'improved' shapes in cross-section and longitudinal profile

It will be remembered from the beginning of Section 4.2 that the main reason for the low efficiency of elements in which bending-type internal forces occur is the uneven distribution of stress that exists within every cross-section. This causes the material near the centre of the cross-section, adjacent to the **neutral axis** (see Glossary), to be under-stressed and therefore inefficiently used. The efficiency of an element can be improved if some of the under-stressed material is removed and this can be achieved by a judicious choice of geometry in both cross-section and longitudinal profile.

Compare the cross-sections of Figure 4.7 with the diagram of bending stress distribution. Most of the material in the solid rectangular cross-section is under-stressed; the load is actually carried principally by the material in the high stress regions of the cross-section that occur at its top and bottom extremities (the extreme fibres). In the I- and box-shaped cross-sections most of the under-stressed material is eliminated; the strength of elements that are given these cross-sections is almost as great as that of an element with a solid rectangular cross-section of the same overall dimensions; they contain significantly less material and are therefore lighter and more efficient.

A similar situation exists with slab-type elements. Solid slabs are much less efficient in their use of material than those in which material is removed from the interior, as can be demonstrated by carrying out a simple experiment with card (Figure 4.8). A flat piece of thin card has a very low bending strength. If the card is arranged into a folded or corrugated geometry the bending strength is greatly increased. The card with the folded or corrugated cross-section has a strength that is equivalent to that of a solid card with the same total depth; it is, however, much lighter and therefore more efficient.

In general, cross-sections in which material is located away from the centre are more efficient in carrying bending-type loads than solid cross-sections. Solid cross-sections are, of course, much simpler to make and for this reason have an important place in the field of architectural structures but they are poor performers compared to the I- or box-cross-section so far as structural

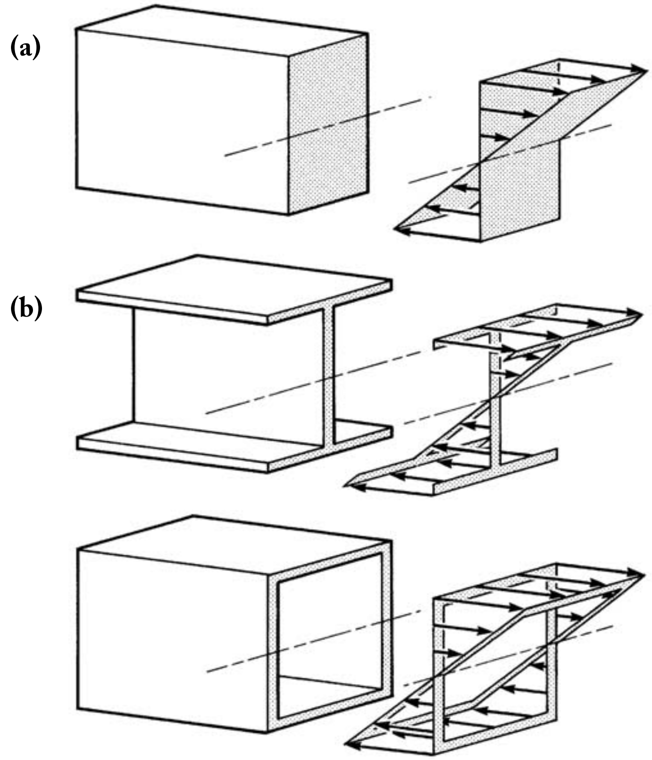


Figure 4.7 The effect of cross-section shape on the efficiency of elements that carry bending-type loads. (a) In an element with a rectangular cross-section, high bending stress occurs at the extreme fibres only. Most of the material carries a low stress and is therefore inefficiently used. (b) In 'improved' cross-sections, such as the I or hollow box, efficiency is increased by elimination of most of the understressed material adjacent to the centre of the cross-section.

efficiency is concerned. In the classification that will be proposed here in Section 4.4 these two categories of cross-section are referred to as 'simple solid' and 'improved' cross-sections.

The shape of an element in longitudinal profile can be manipulated in a similar way to its cross-section to improve its performance in resisting bending-type loads. The adjustment can take the form of alteration to the overall shape of the profile or to its internal geometry.

To improve efficiency the overall shape can be adjusted by varying the depth of the element: this is the dimension on which bending strength principally depends and if the depth is varied according to the intensity of bending (specifically to the magnitude of the bending moment) then a more efficient use of material is achieved than if a constant depth of cross-section is used. Figure 4.9 shows two beam profiles that have been '**improved**' in this way. They are deep at the locations where the intensity of bending is high and shallow where it is low.

The internal geometry of the longitudinal profile can also be 'improved' by altering it to remove under-stressed material from the interior of the element. Examples of elements in which this has been done are shown in Figure 4.10. As in the case of cross-sectional shape the internal geometry of the longitudinal

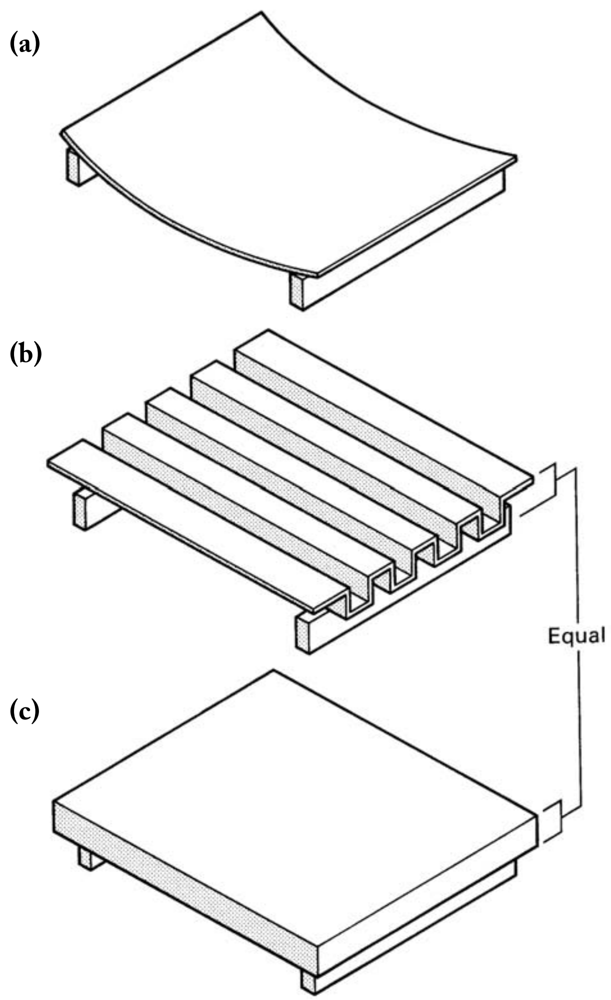


Figure 4.8 The effect of cross-sectional shape on the efficiency with which bending-type load is resisted: (a) thin card that has an inefficient rectangular cross-section; (b) thin card folded to give an efficient 'improved' cross-section; (c) thick card with inefficient rectangular cross-section and having equivalent strength and stiffness to the folded thin card.

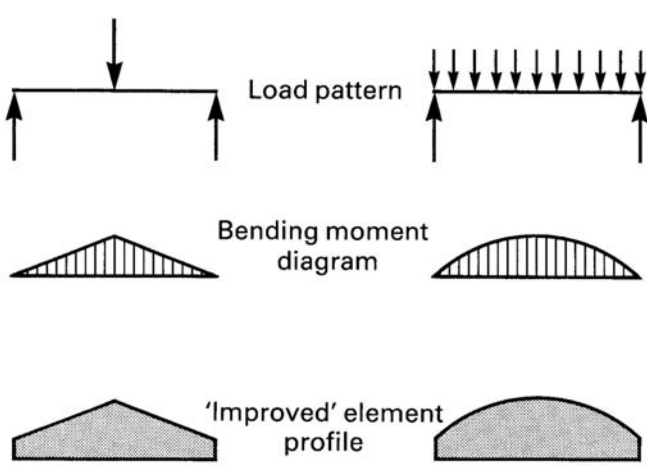


Figure 4.9 The efficiency of a non-form-active element can be improved if its longitudinal profile is adjusted to conform to the bending moment diagram so that high strength is provided only where the internal force is high.

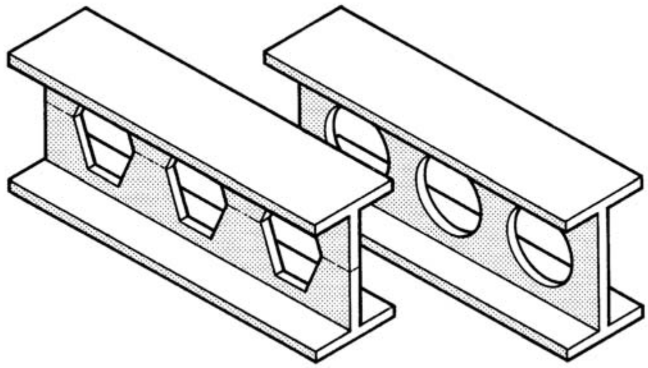


Figure 4.10
The efficiency of non-form-active elements can be improved by selecting a shape in longitudinal profile in which material is removed from the understressed centre of the element.

profile of an element will be referred to here as 'simple solid' or 'improved'.

One type of 'improved' profile that is of great importance in architectural as well as all other types of structure is the triangulated profile (i.e. the profile that consists entirely of triangles) (Figure 4.11). If an element of this type has loads applied to it at the vertices of the triangles only, then the individual sub-elements that form the triangles are subjected to axial internal forces only. This property is a consequence of a characteristic unique to the triangle among geometric figures, which is that its geometry can only be changed if the length of one or more of its sides is altered. (The geometry of any other polygon can be changed by altering the angles between the sides and maintaining the sides at a constant length – Figure 4.12.) The resistance that is generated by a triangulated structure to a potential alteration in geometry (which is what occurs when a load is applied) takes the form of a resistance to change in length of the sides of the triangles. This results in the sub-elements that form the sides of the triangles being placed into either axial tension or axial compression. The axial-stress-only state therefore occurs no matter what the overall form of the element, provided that its internal geometry is fully triangulated with straight-sided triangles and the load is applied only to the joints between the sub-elements. If a load is applied directly to one of the constituent sub-elements and not at a joint, as in Figure 4.13, then bending will occur in that sub-element. This applies no matter what the relationship is between the pattern of loads and the longitudinal axis of the element, taken as a whole.

By eliminating bending stress from non-form-active elements the triangulated internal geometry allows a high degree of structural efficiency to be achieved. The advantage of the triangulated element over the other class of element for which this is true – the form-active element – is that no special overall form is required to produce the axial-stress-only condition; all that is required is that the internal geometry be fully triangulated and the external load applied only at the joints. Triangulated elements do not, however, achieve quite such a high degree of structural efficiency as form-active structures due to the relatively high level of internal force that occurs.

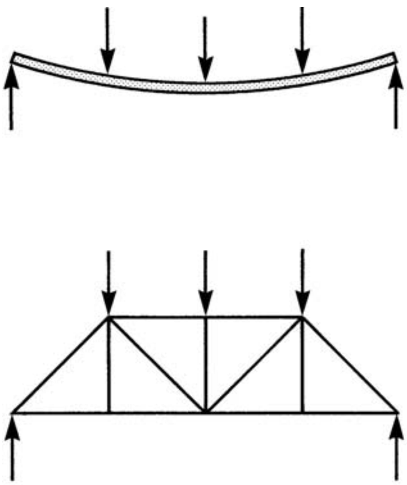


Figure 4.11
A solid beam is less strong and rigid than a triangulated structure of equivalent weight.

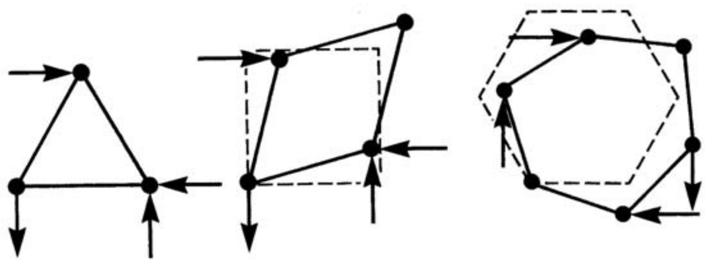


Figure 4.12 An alteration of the geometry of a triangle can only occur if the length of one of the sides changes. Application of load to a triangle, which tends to distort its geometry, is therefore resisted by axial internal forces in the elements.

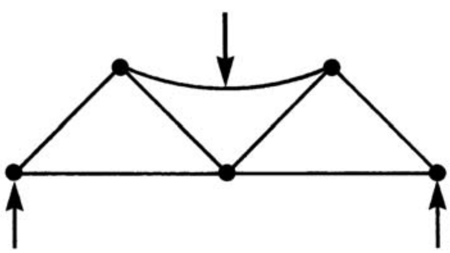


Figure 4.13 The axial-internal-force-only condition does not occur if load is applied to a triangulated structure other than at its joints.

The use of the techniques of 'improvement' is well illustrated in the field of aeronautical engineering, where lightweight structures are required in the context of overall forms that are not form-active. For example, in the case of the 'stick-and-string' biplane fuselage (Figure 4.14a), a high ratio of strength to weight was achieved through the principle of triangulation. As the size and speed of aircraft increased and stronger aircraft structures were required the change to an all-metal structure became inevitable. The non-structural fabric skin of the early biplane was replaced by sheeting of aluminium alloy and the internal structure of timber and wire by ribs and longitudinal stringers also of aluminium alloy. In this more sophisticated type of aircraft structure (Figure 4.14b), the metal skin acts with the ribs and stringers to form a

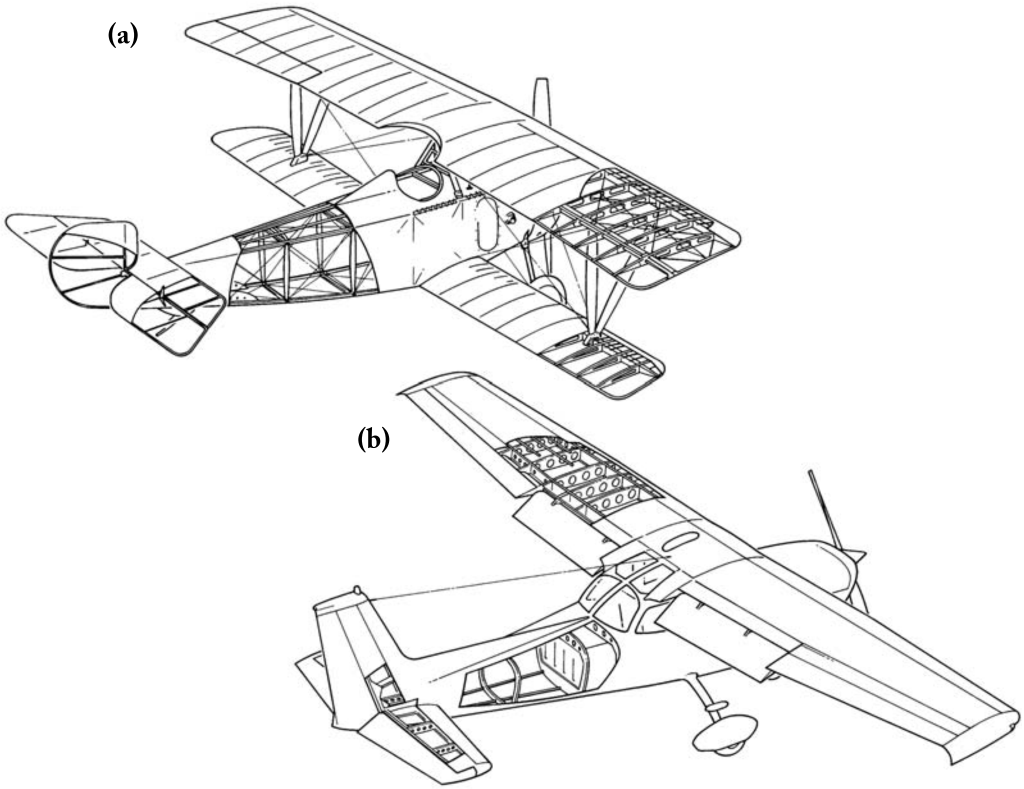


Figure 4.14 The overall shapes of aircraft are determined mainly from non-structural considerations, principally aerodynamic performance requirements. The supporting structures are therefore non-form-active, but the very high priority that must be given to saving of weight results in the adoption of configurations in which many ‘improvements’ are incorporated. (a) The fuselage and wings of the ‘stick-and-string’ biplane have triangulated structures of timber and wire. The fabric covering has a minimal structural function. (b) The wings and fuselage of the all-metal aircraft are hollow box-beams in which the skin plays an essential structural role.

composite structure called a stressed-skin semi-monocoque. (**Monocoque** construction is the term used where the element consists only of the stressed skin.)

In the semi-monocoque fuselage of an all-metal aircraft (Figure 4.14b), which is a **non-form-active structural element** with an ‘improved’ cross-section, a very thin stressed-skin is used which must be strengthened at regular intervals by ribs and stringers to prevent local buckling from occurring. The technique of ‘improvement’ may be seen to be operating at several levels. The fuselage, taken as a whole, is a non-form-active element with an ‘improved’ hollow-tube cross-section. Further ‘improvement’ occurs in the tube walls which have a complex cross-section consisting of the stressed-skin acting in conjunction with the strengthening ribs and stringers. These strengthening sub-elements are in turn ‘improved’ by having cross-sections of complex shape and circular holes cut in their webs.

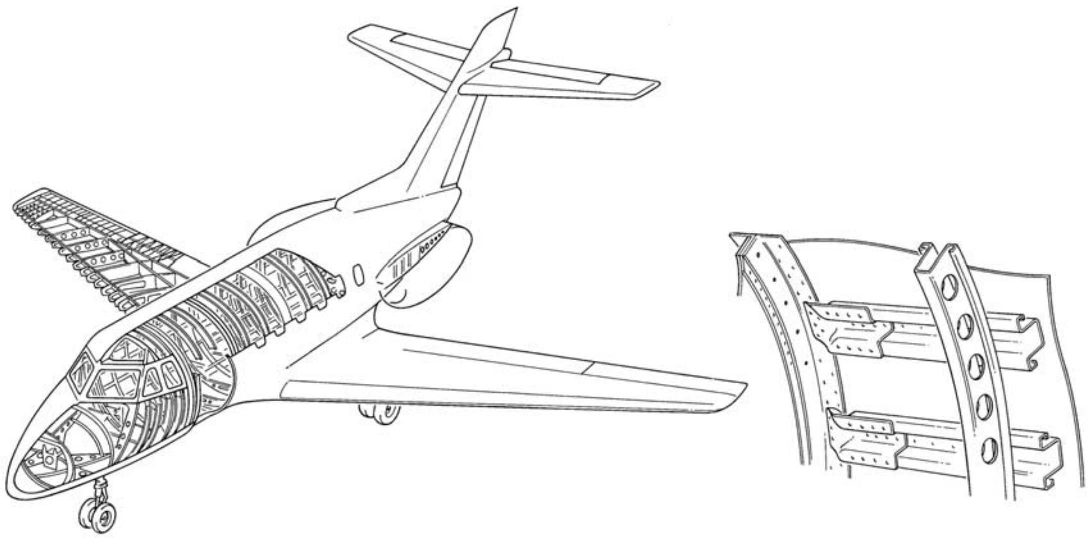


Figure 4.15 The fuselage of the all-metal aircraft is a non-form-active structure which is 'improved' at various levels. The fuselage, taken as a whole, is a hollow box-beam. 'Improvements' of several types are incorporated into the sub-elements that support the structural skin.

The all-metal aircraft structure (Figure 4.15) is therefore a complicated assembly of sub-elements to which the technique of 'improvement' has been applied at several levels. The complexity results in a structure that is efficient but that is very costly to produce. This is justified in the interests of saving weight; every kilonewton saved contributes to the performance of the aircraft and weight saving is therefore allocated a very high priority in the design.

A similar application of the features that save weight can be seen in the field of vehicle design, especially railway carriages and motor cars. The structure of the modern railway carriage consists of the metal tube that forms its skin, spanning as a beam between the bogies on which it is mounted. It is a non-form-active 'improved' box beam. The structure of a motor car is similar: the steel car body acts as a beam to carry the weight of the engine, occupants, etc. between the road wheels (Figure 4.16). As in the case of the aeroplane the overall forms of rail and road vehicles are determined largely from non-structural considerations but the need to save weight is given a high priority in the design. Again, the use of 'improved' non-form-active monocoque and semi-monocoque structures constitutes a sensible response to the technical problems posed.

The use of elaborate forms of improvement, such as semi-monocoque stressed skins, triangulation of profiles or elements with complicated cross-sections is rarely justified in architectural structures on purely technical grounds due to the added complexity in design and construction that their use implies. They may also give rise to long-term maintenance problems. An additional

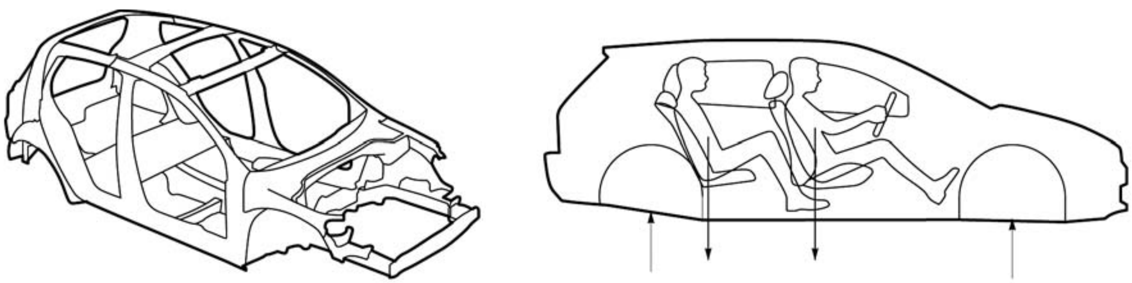


Figure 4.16
The metal body of a motor car is an 'improved' non-form-active beam which spans between the road wheels.

Line drawing: Andrew Siddall.

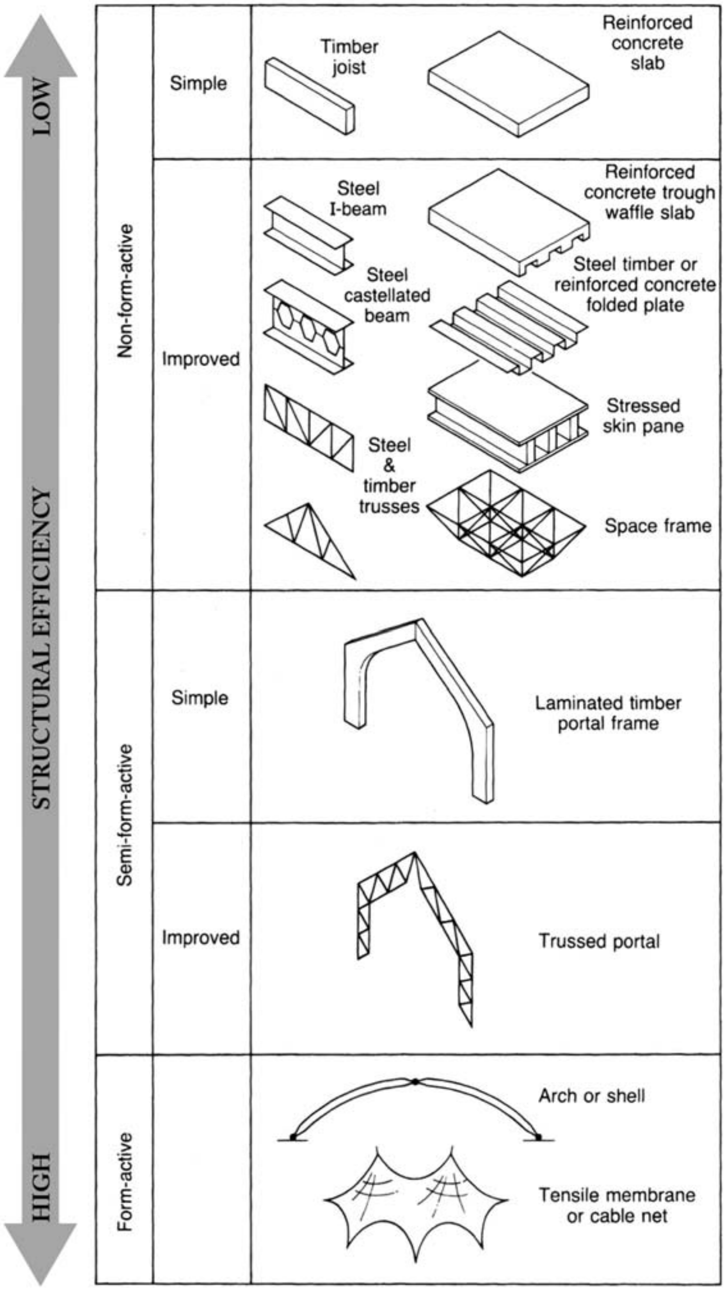
consideration is that inefficient, high-mass structures may actually improve technical performance in other ways. Their weight may counteract wind uplift and their high thermal mass may improve the environmental performance of the building that they support. The saving in material associated with the use of highly efficient structures is just one of the many factors that must be balanced in the design process.

The uses of the devices and configurations that produce efficient and therefore lightweight structures is not therefore always appropriate from the technical viewpoint in the context of architecture where they are justified technically only in situations in which an efficient, lightweight structure is a necessity (see Section 10.2.3.4). They can, however, have another architectural function which is to form a visual vocabulary of structure. The use of the devices associated with structural efficiency for stylistic purposes is discussed in Section 10.2.2.

4.4 Classification of structural elements – the archetypes of structural form

The principles outlined in the preceding sections, concerned with the various features that can be used to improve the efficiency of structures, can form the basis of a classification system for structural elements. This is illustrated in Table 4.1. The primary distinction is between form-active, semi-form-active and non-form-active elements because this is the most important factor in determining the level of efficiency which can be achieved. Elements are further classified according to the degree of 'improvement' which is present in their cross-sections and longitudinal profiles. These concepts define the **archetypes of structural form**. The number of combinations and permutations is very large and a selection only of possibilities is illustrated in Table 4.1 to show the general principles involved. The least efficient shapes (non-form-active elements with simple shapes in both cross-section and longitudinal profile) are placed at the top of the table and the degree of efficiency present increases towards the bottom, where the most efficient shapes – tensile form-active elements – are placed. A distinction is made between line elements, such as beams, in which one dimension is significantly larger than the other two, and

Table 4.1



surface elements, such as slabs, in which one dimension is significantly smaller than the other two.

The system links the form, and therefore the appearance, of a structure with its efficiency in resisting load and provides a basis for reading a building, or indeed any artefact, as a structural object. It is an important consideration for anyone involved with either the design of buildings or with their critical appraisal. It provides the essential link between the aesthetics of structures and their technical performance.

The system is based on the idea of efficiency: structural elements are classified according to the level of efficiency that they make possible in the resistance of load which is, of course, their principal function. The main objective of structural design, however, is the achievement of an appropriate level of efficiency rather than the maximum possible level of efficiency. The factors that determine the level of efficiency that is appropriate are discussed in Chapter 6. The discussion of whether or not an appropriate level of efficiency has been achieved cannot take place, however, in the absence of a means of judging efficiency. The system proposed here is intended to provide that means.

Appendix to Chapter 4

A note on the use of the term 'form-active'

A degree of confusion surrounds the use of the term '**form-active**'. It was first employed in the context of structural engineering by Engel in his book *Structure Systems* (1967) and has been used by a number of authors since but with slight variations in meaning. In Engel's original use it was applied to the group of structures based on flexible components such as cables and fabric membranes which, due to their lack of rigidity, can resist *only* pure axial tension when a load is applied to them. They therefore take up a particular form in response to load which creates internal forces that are purely tensile. An essential characteristic of these structures is that the form adopted is unique to the load and that, if the load changes, the structure adjusts its form to maintain the tensile-only condition. The structure is therefore *active* in the sense that it undergoes movement when changes to the load pattern occur.

A confusion occurs because Engel, in the same publication, refers to triangulated structures as *vector-active*. In this class of structure, the arrangements are rigid and have no ability to become *active* in the sense of adopting modified shapes in response to variations in load. Rather, they are *reactive* because what is being implied by the term *vector-active* is the type of internal forces that occur in the sub-elements of these structures so as to resist the load. The internal forces are either pure axial tension or pure axial compression. They are, in fact, vectors and the behaviour of the structures could be simulated abstractly by a diagram of vectors that replicated the internal forces in the individual sub-elements. In other words, the term *vector active* describes how the structures react to load and no movement of the structure is implied. *Active* therefore has a different meaning than when used in the term *form-active*. Engel's use of the term *surface-active* to describe compressive shell structures attributes yet another, this time slightly vague, meaning to the word *active*. In later editions of the book the terms *section-active* and *height-active* are used. The meanings of *active* in these expressions are again slightly different and imply a preferred kind of solution that the designers of the structures have devised in response to the problems that they pose.

In the continuing discourse on engineering these terms, particularly 'form-active', are frequently used but rarely accurately defined. In this book the terms **form-active**, **semi-form-active** and **non-form-active** have precise meanings and always describe the ways in which a structure reacts to the application of load because they refer to the type of internal force that occurs when load is applied. **Form-active** refers to a structure that, due to its overall form, is subjected to axial internal forces only. It is used here for both tensile and compressive versions and therefore includes cables, cable nets, fabric membranes, arches, vaults and compressive shells. In the case of the tensile versions, the structures, due to their flexibility (ability to change geometry under varying load) remain form-active under all load conditions. The compressive versions are only truly form-active (subjected to axial internal force only) in response to the single pattern of load for which their shape was designed. If the configuration of load on these structures changes, they will be subjected to some bending and will no longer be form-active structures (see Figure 4.5). The term '**non-form-active**' is used here to refer to structural arrangements in which only bending-type internal forces occur and where no axial force of any kind develops in response to load. As with *form-active* structures, these too have shapes that are unique for a particular pattern of loads. Structures whose overall form is such that they are subjected to a combination of axial and bending-type internal force are considered here to be '**semi-form-active**'. If a structure has not been tailored to a particular load pattern it will normally be semi-form-active.

These distinctions are *very* important because they have a significant effect on the efficiency with which load can be resisted.

Notes

1 **Structural efficiency** is considered here in terms of the weight of material that must be provided to carry a given amount of load. The efficiency of an element is regarded as high if the ratio of its strength to its weight is high.

2 '**Form-active**' was a term applied by H. Engel (1967) in his book *Tragsysteme* (*Structure Systems*) to a structural element in which the shape of the longitudinal axis, in relation to the pattern of applied load, was such that the internal force was axial. The expression has been much used subsequently in discourses about structural form but often with meanings that are not precisely defined. The meanings attributed to them in this text are explained in more detail in the Appendix above.

CHAPTER 5

Complete structural arrangements

5.1 Introduction

Most structures are assemblages of large numbers of elements and the performance of the complete structure depends principally on the overall form into which the elements are assembled and on the ways in which these are connected together. The classification of elements was considered in Chapter 4, where the principal influence on element type was shown to be the shape of the element in relation to the pattern of applied load. In the context of architecture, where gravitational loads normally predominate, there are three basic arrangements: **post-and-beam**, **form-active** and **semi-form-active** (see Chapter 4) (Figure 5.1). Post-and-beam structures are assemblages of vertical and horizontal elements (the latter being non-form-active); fully-form-active structures are complete structures whose geometries conform to the unique form-active shape for the principal load that is applied; arrangements that do not fall into either of these categories are semi-form-active.

The nature of the joints between elements (be they form-active, semi-form-active or non-form-active) significantly affects the performance of structures and by this criterion they are said to be either 'discontinuous' or 'continuous' depending on how the elements are connected. **Discontinuous structures** contain only sufficient constraints to render them stable; they are assemblies of elements connected together by **hinge-type joints**[1] and most of them are also **statically determinate** (see Glossary). Typical examples are shown diagrammatically in Figure 5.2. **Continuous structures**, the majority of which are also **statically indeterminate**, contain more than the minimum number of constraints required for stability. They usually have very few hinge-type joints and many have none at all (Figure 5.3). Most structural geometries can be made either continuous or discontinuous depending on the nature of the connections between the elements.

Facing page: David Mellor Factory, Hathersage, Michael Hopkins/Ove Arup & Partners. Photo: Carol Sachs.

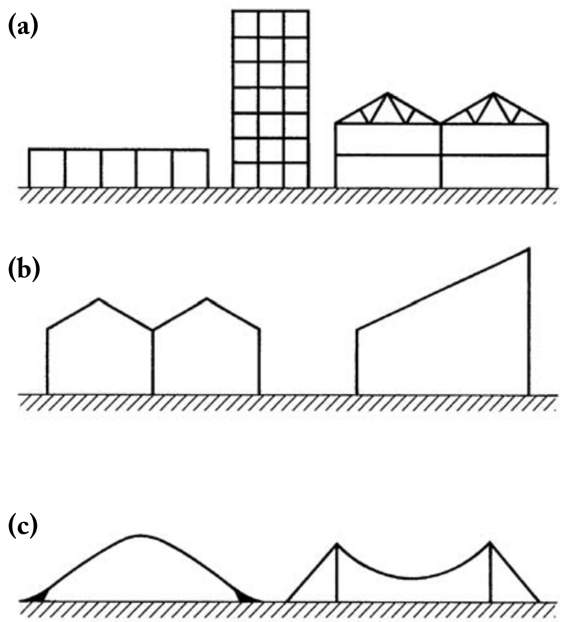


Figure 5.1 The three categories of basic geometry: (a) Post-and-beam; (b) Semi-form-active; (c) Form-active.

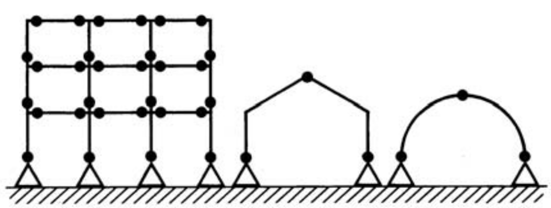


Figure 5.2 Discontinuous structures. The multi-storey frame has insufficient constraints for stability and would require the addition of a bracing system. The 3-hinge portal frame and 3-hinge arch are self-bracing, **statically determinate structures**.

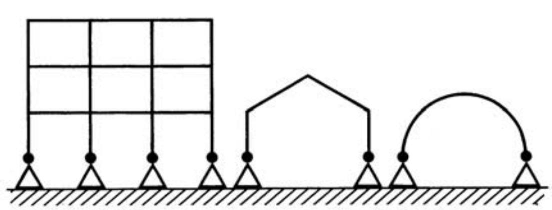


Figure 5.3 Continuous structures. All are self-bracing and statically indeterminate.

The principal merit of the discontinuous structure is that it is simple, both to design and to construct. Other advantages are that its behaviour in response to differential settlement of the foundations and to changes in the lengths of elements, such as occur when they expand or contract due to variations in temperature, does not give rise to additional stress. The discontinuous structure adjusts its geometry in these circumstances to accommodate the movement without any internal force being introduced into the elements. A disadvantage of the discontinuous structure is that, for a given application of load, it contains larger internal forces than a continuous structure with the same basic geometry: larger elements are required to achieve the same load carrying capacity and it is therefore less efficient. A further disadvantage is that it must normally be given a more regular geometry than an equivalent continuous structure in order that it can be geometrically stable. This restricts the freedom of the designer in the selection of the form that is adopted and obviously affects the shape of the building that can be supported. The regular geometry of typical steel frameworks, many of which are discontinuous (Figures 2.8 and 5.10) illustrate this. The discontinuous structure is therefore a rather basic structural arrangement that is not very efficient but that is simple and therefore economical to design and construct.

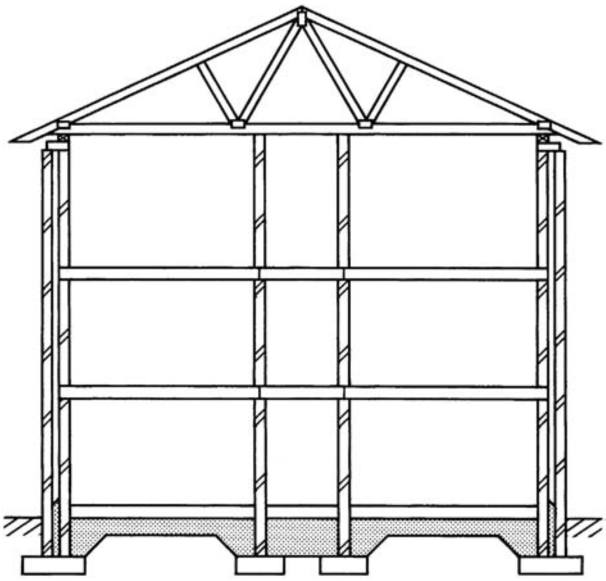
The behaviour of continuous structures is altogether more complex than that of discontinuous forms. They are more difficult both to design and to construct and they are also unable to accommodate movements such as thermal expansion and foundation settlement without the creation of internal forces that are additional to those caused by the loads. They are nevertheless potentially more efficient than discontinuous structures and have a greater degree of geometric stability. These properties allow the designer greater freedom to manipulate the overall form of the structure and therefore of the building that it supports. Figures 1.6 to 1.8 and 10.22 to 10.28 show buildings with continuous structures that illustrate this point.

5.2 Post-and-beam structures

Post-and-beam structures are either loadbearing wall structures or frame structures. Both are commonly used structural forms and, within each type, a fairly wide variety of different structural arrangements, of both the continuous and the discontinuous types, is possible. A large range of spans is also possible depending on the types of element that are used.

The loadbearing wall structure is a post-and-beam arrangement in which a series of horizontal elements are supported on vertical walls (Figure 5.4). If, as is usually the case, the joints between the elements are of the hinge type, the horizontal elements are subjected to pure bending-type internal forces and the vertical elements to pure axial compressive internal forces when gravitational loads are applied. The basic form is unstable but stability is provided by bracing walls and the plans of these buildings therefore consist

Figure 5.4
In the cross-section of a post-and-beam load-bearing masonry structure the reinforced concrete floors at first and second storey levels span one-way between the outer walls and central spine walls. Timber trussed rafters carry the roof and span across the whole building between the outer walls.



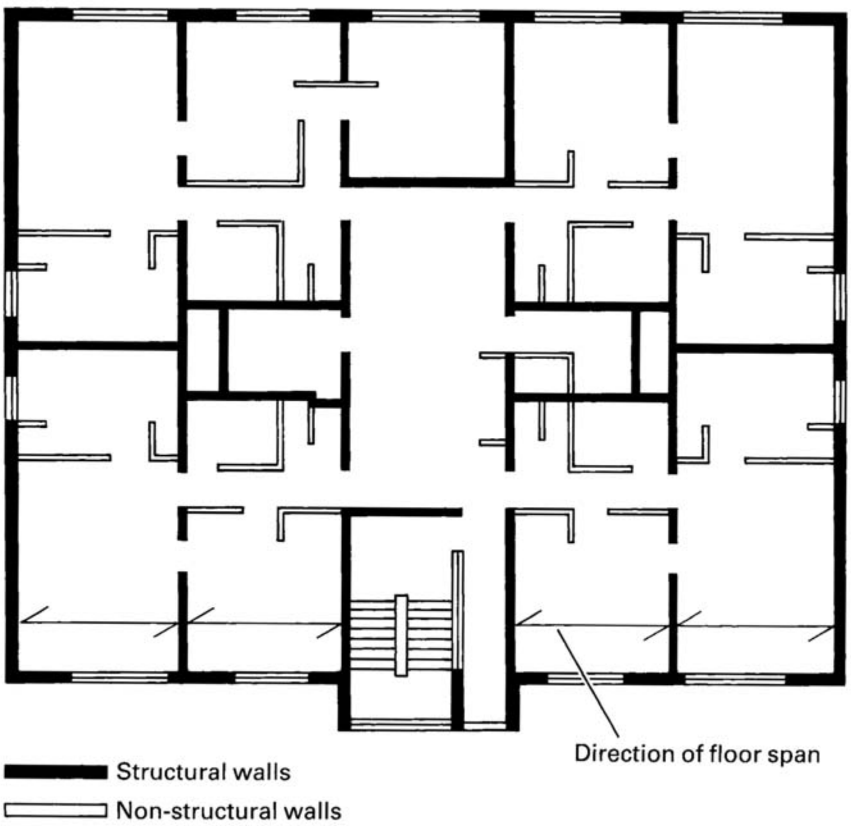


Figure 5.5
Typical plan of a multi-storey loadbearing-wall structure. The floor structure spans one-way between parallel structural walls. Selected walls in the orthogonal direction act as bracing elements.

Figure 5.6 Indian Institute of Management, Ahmedabad, India, 1974; Louis Kahn and Balkrishna Vithaldas Doshi, architects. Extensive use was made of loadbearing masonry in the structure of this building complex, which contains both multi-cellular and large single-cell interior spaces. Horizontal structures are of reinforced concrete.

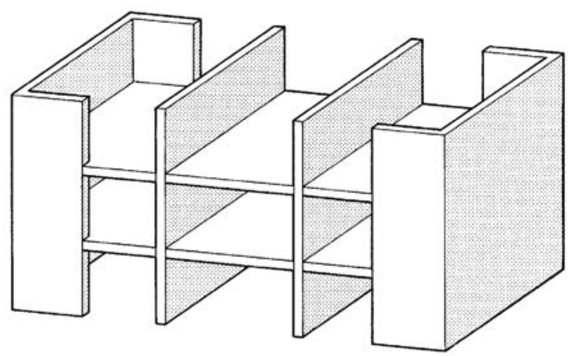
Photo: Dave Morris/Wikimedia Commons.

of two sets of walls, loadbearing walls and bracing walls (Figure 5.5). The arrangements work best if the loadbearing walls, which carry the weights of the floors and roof, are positioned more-or-less parallel to one another at approximately equal spacings and as close together as space-planning requirements will allow, to minimise the spans. The bracing walls are normally placed in a perpendicular direction and the interiors of the buildings are therefore multi-cellular and rectilinear in plan. In multi-storey versions the plan must be more-or-less the same at every level so as to maintain vertical continuity of the loadbearing walls.

Loadbearing wall structures are used for a wide range of building types and sizes of building (Figures 5.4 and 5.6 to 5.99 and 1.11 to 1.13). The smallest are domestic types of one or two storeys in which the floors and roofs are normally of timber and the walls of either timber or masonry. In all-timber construction (Figure 3.6), the walls are composed of closely spaced columns tied together at the base and head of the walls to form panels and the floors are similarly constructed. Where the walls are of masonry, the floors can be of timber or reinforced concrete. The latter are heavier but they have the advantage of being able to span in two directions simultaneously. This allows the adoption of more irregular arrangements of supporting walls and generally increases planning freedom (Figure 5.7). Mies van der Rohe's sketch for the unbuilt project for a brick house (Figure 5.8) shows the extreme possibilities for plan irregularity in the context of a loadbearing wall structure. The building is structurally feasible with a two-way spanning horizontal structure because the basic requirements (adequate walls for vertical support arranged in two orthogonal directions for stability) were satisfied.

Although beams and slabs with simple, solid cross-sections are normally used for the floor elements of loadbearing-wall buildings, because the spans are usually short (see 6.2), axially stressed elements in the form of triangulated trusses are frequently used to form the horizontal elements in the roof structures. The most commonly used lightweight roof elements are timber trusses (Figure 5.9) and lightweight steel lattice girders.

The discontinuous loadbearing wall configuration is a very basic form of structure in which the most elementary types of bending (non-form-active)



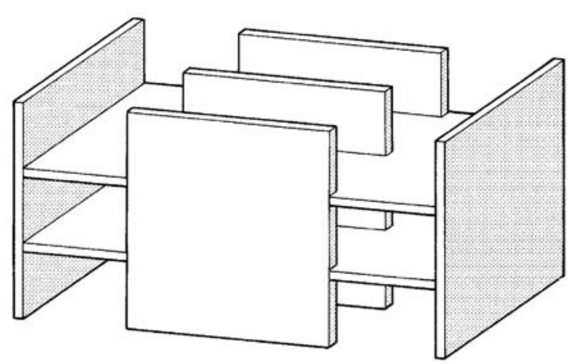


Figure 5.7 In these arrangements the floor structures are two-way spanning reinforced concrete slabs. This allows more freedom in the positioning of loadbearing walls than is possible with one-way spanning timber or precast concrete floors.

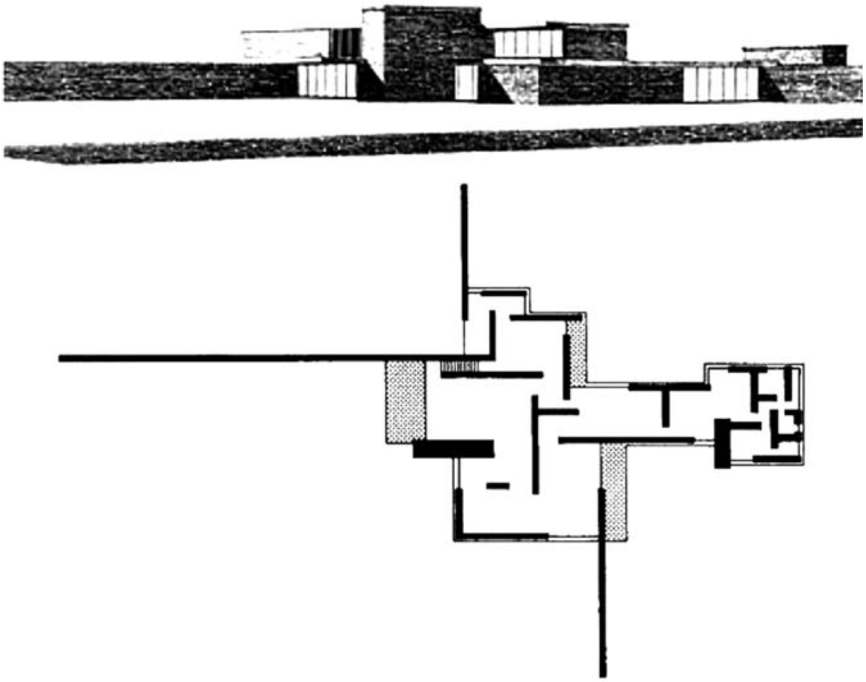


Figure 5.8 Plan, Brick Country House Project, 1924; Mies van der Rohe. This unbuilt project for a country house demonstrated the ultimate in plan irregularity for the loadbearing-wall typology. It is nevertheless feasible with a two-way spanning horizontal structure, such as a reinforced concrete slab, because it meets the basic structural requirements by providing adequate walls for vertical support arranged in two orthogonal directions for stability.

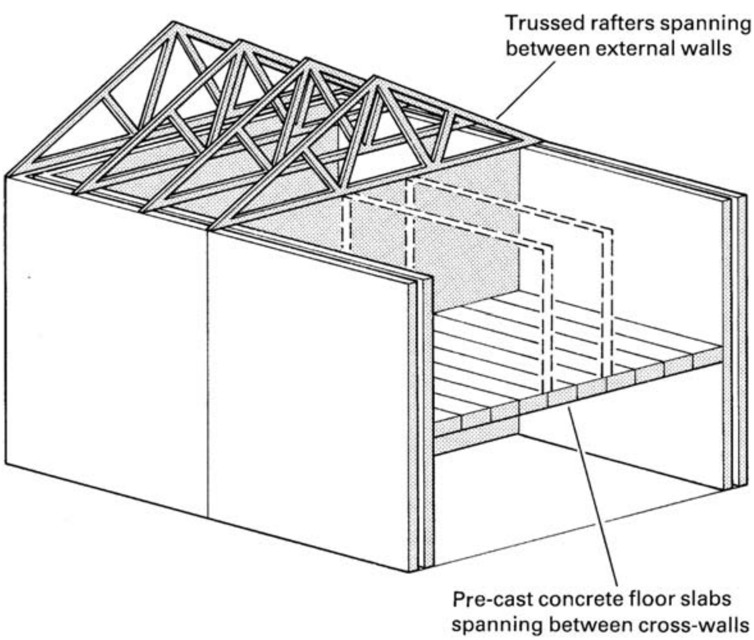


Figure 5.9
Typical arrangement of elements in traditional loadbearing masonry construction. Simple 'unimproved' floor beams are combined with 'improved' triangulated trusses for the more lightly loaded roof.

Figure 5.10 The typical multi-storey frame structure consists of a skeleton of steel beams and columns supporting a floor of reinforced concrete slabs. Walls are non-structural and can be positioned to suit space-planning requirements.
Photo: Dwight Burdete/Wikimedia Commons.

elements, with simple, solid cross-sections, are employed. Their efficiency is low and a further disadvantage is that the requirements of the structure impose fairly severe restrictions on the freedom of the designer to plan the form of the building – the primary constraints being the need to adopt a multi-cellular interior in which none of the spaces are very large and, in multi-storey buildings, a plan that is more-or-less the same at every level. The structures are, however, straightforward and economical to construct and, for these reasons, are widely used.

Where greater freedom to plan the interior of a building is required or where large interior spaces are desirable, it is usually necessary to adopt some type of frame structure. This can allow the total elimination of structural walls and large interior spaces can be achieved as well as significant variations in floor plans between different levels in multi-storey buildings.

The principal characteristic of the frame is that it is a skeletal structure consisting of beams supported by columns, with some form of slab floor and roof (Figure 5.10). The walls are usually non-structural (some may be used as vertical-plane bracing – see Figure 2.8) and are supported entirely by the beam-column system. The total volume that is occupied by the structure is significantly less than with loadbearing walls and individual elements therefore carry larger areas of floor or roof and are subjected to greater amounts of internal force. Strong materials such as steel and reinforced concrete must normally be used. Skeleton frames of timber (Figures 11.9 and 11.10), which is a relatively weak material, must be of short span (max 5 m) if floor loading is carried. Larger spans are possible with single-storey timber structures, especially if efficient types of element such as triangulated trusses are used, but the maximum spans are always smaller than those of equivalent steel structures.

The most basic types of frame are arranged as a series of identical '*plane-frames*'[2] of rectangular geometry, positioned parallel to one another to form rectangular or square column grids; the resulting buildings have forms that are predominantly rectilinear in both plan and cross-section (Figure 5.10). A common variation of the above is obtained if triangulated elements are used

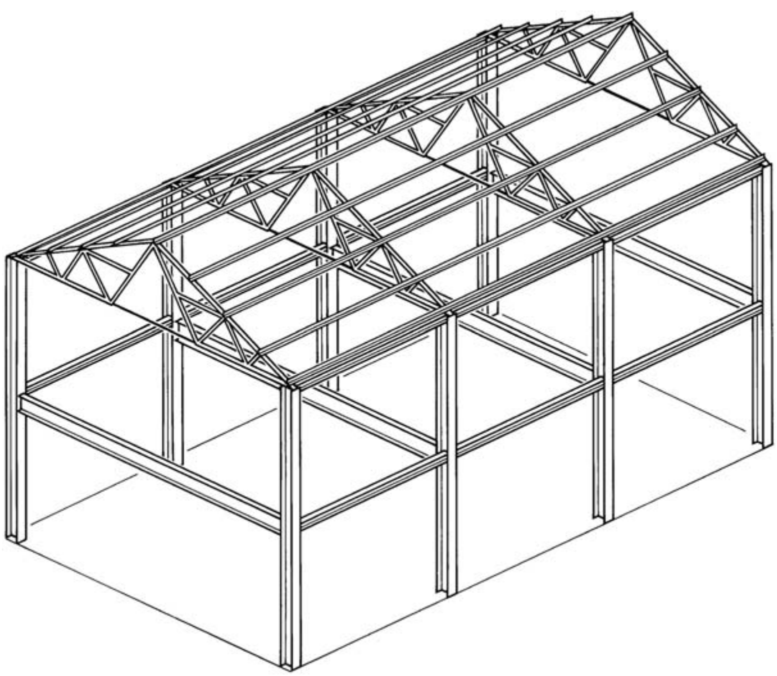


Figure 5.11 In this steel frame efficient triangulated elements carry the roof load. Floor loads are supported on less efficient solid-web beams with I-shaped 'improved' cross-sections.

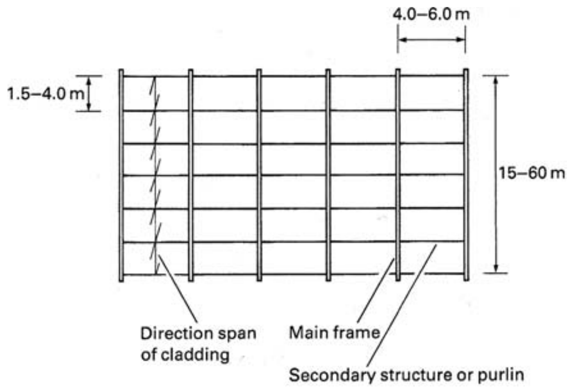


Figure 5.12 Generic plan for single-storey steel framework with 'strong' long-span primary elements acting in conjunction with short-span linking secondary beams. Typical examples of primary elements are portal frameworks or triangulated girders (see Figures 1.5, 5.17 and 10.4, 10.5).

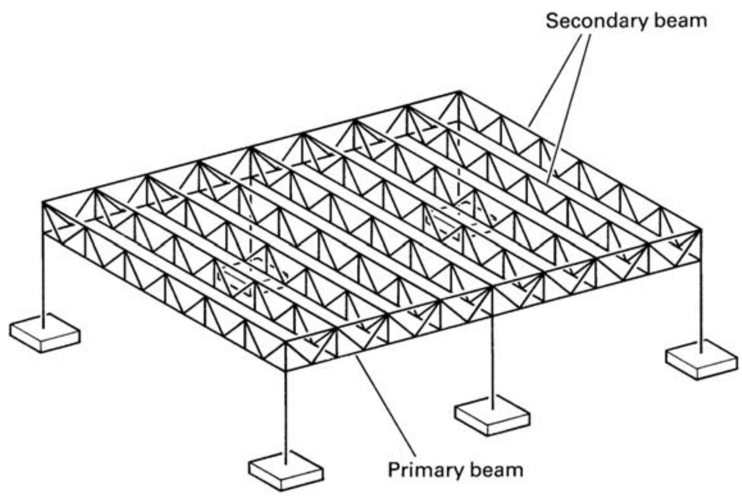


Figure 5.13 A typical arrangement of primary and secondary beams in a single-storey steel frame with lightweight triangulated elements.

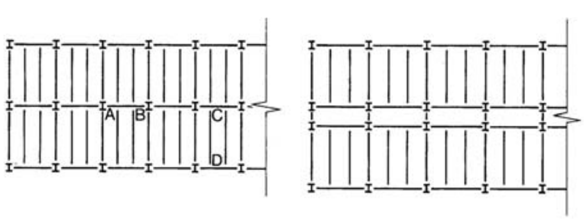


Figure 5.14 Typical floor layouts for multi-storey steel frames.

for the horizontal parts of the structure (Figure 5.11). Typical beam/column arrangements for single and multi-storey frames are shown in Figures 5.12 to 5.14. Figures 5.12 and 5.13 show the two generic forms for single-storey frameworks. In Figure 5.12 (see also Figure 1.5) strong primary elements are spaced at relatively large distances (around 6 m) with lighter secondary elements to carry the roof and wall skins. This arrangement is capable of producing wide-span buildings (Figure 10.4). The arrangement in Figure 5.13 uses lighter primary elements spaced sufficiently close together (1.5 m) to allow the cladding to be attached directly. It is normally used where column spacing is moderate (up to 20 m). Significant departure from these generic arrangements is, of course, possible, such as in the building illustrated in Figures 9.33 and 9.34, but the generic forms normally offer the best compromise between efficiency and simplicity (see Section 6.2) and significant variation from them normally involves a cost penalty.

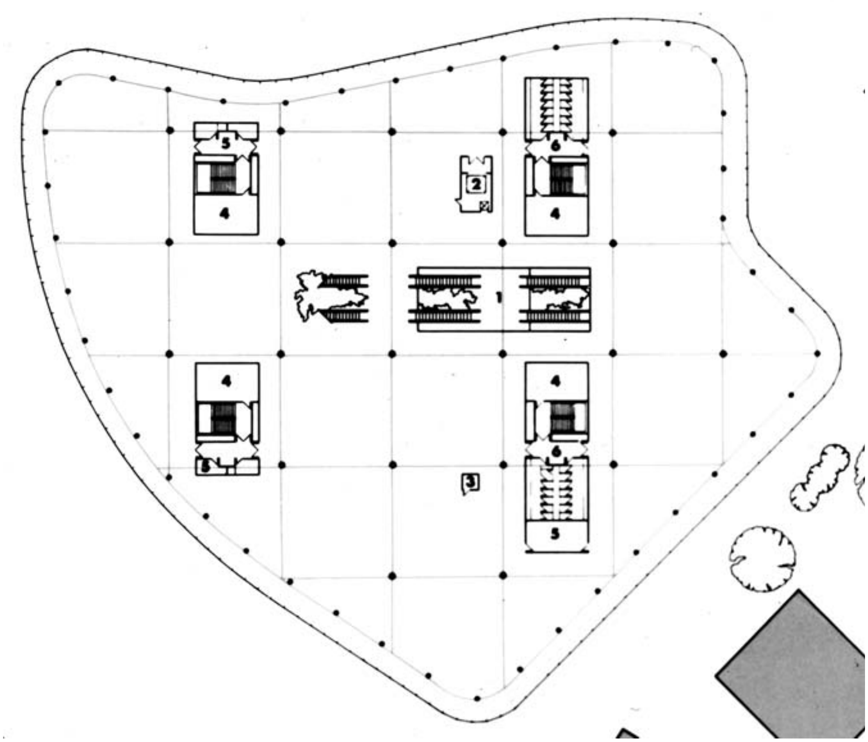


Figure 5.15 Willis, Faber & Dumas building, Ipswich, UK, 1976; Foster Associates, architects; Anthony Hunt Associates, structural engineers. The structural plan of this building, based on a square column grid, is an extension of the generic flat-slab arrangement (Fig 3.21). The structural continuity of this typology allows a curvilinear plan with floor slabs cantilevered beyond the 'necklace' of perimeter columns (see also Figure 1.6).

It will be noted that systems of primary and secondary beams are commonly used for both floor and roof structures in steel frameworks. These allow a reasonably even distribution of internal force to be achieved between the various elements within a particular floor or roof structure. In Figure 5.14, for example, the primary beam AB supports a larger area of floor than the secondary beam CD and therefore carries more load. The magnitudes of the internal forces in each are similar, however, because the span of AB is shorter.[3]

Due to the ease with which continuity can be achieved, in-situ reinforced concrete is a particularly suitable material for frames of complex geometry. The degree of continuity which is possible even allows the beams in a frame to be eliminated and a two-way spanning slab to be supported directly on columns to form what is called a 'flat-slab' structure (Figure 3.21). This is both highly efficient in its use of material and fairly simple to construct. The Willis, Faber & Dumas building (Figures 1.6, 5.15 and 5.16) has a type of flat-slab structure and this building demonstrates many of the advantages of

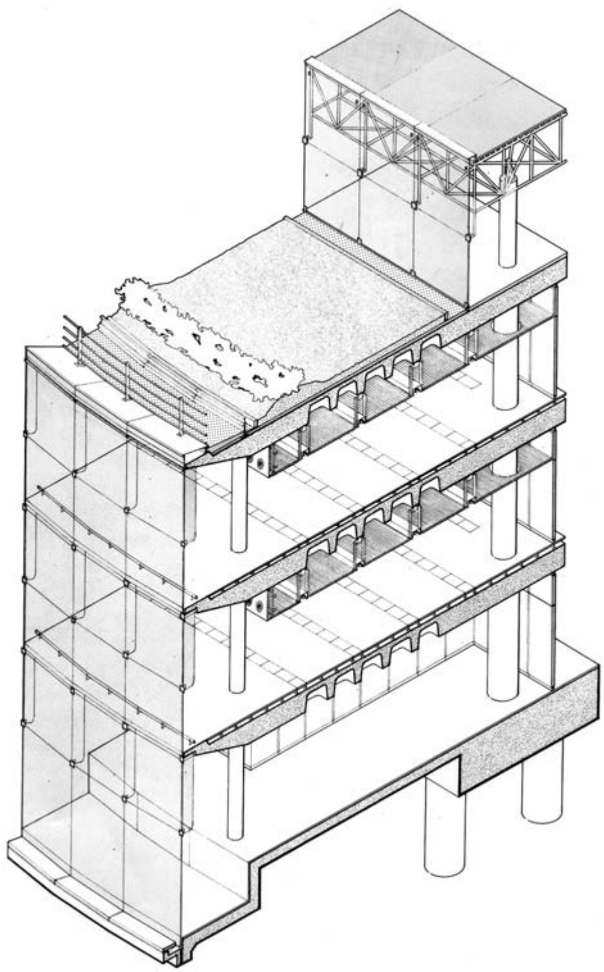


Figure 5.16
Willis, Faber & Dumas building, Ipswich, UK, 1976; Foster Associates, architects; Anthony Hunt Associates, structural engineers. The glass enclosing wall of the building is attached directly to the cantilevered edges of the floor slabs.

continuous structures; the geometric freedom which structural continuity allows is particularly well illustrated. The Solaris building (Figures 1.7 and 1.8) is a further demonstration of the sculptural treatment of the reinforced concrete frame typology made possible by the mouldability of the material and its ability to achieve structural continuity between the elements.

5.3 Semi-form-active structures

Semi-form-active structures have forms whose geometry is neither post-and-beam nor form-active (See Section 4.2). The elements therefore contain the full range of internal force types (i.e. axial thrust, bending moment and shear force). The magnitudes of the bending moments, which are of course the most difficult of the internal forces to resist efficiently, depend on the extent to which the shape is different from the form-active shape for the loads. The bending moments are significantly smaller, however, than those which occur in post-and-beam structures of equivalent span.

Semi-form-active structures are usually adopted as support systems for buildings for one of two reasons. Sometimes they are chosen because it is necessary to achieve greater efficiency than a post-and-beam structure would allow, because a long span is involved or because the applied load is light (see Section 6.3). Alternatively, a semi-form-active structure may be adopted because the shape of the building which is to be supported is such that neither a very simple post-and-beam structure nor a highly efficient fully-form-active structure can be accommodated within it.

The building in Figure 1.5 is a typical example of a type of semi-form-active frame structure which is frequently adopted to achieve long spans in conjunction with light loads. Note that it conforms to the generic arrangement shown in Figures 5.12 and 5.17. The type can be constructed in steel, reinforced concrete or timber (Figure 5.18). A variety of profiles and cross-sections are used for the frame elements, ranging from solid elements with rectangular cross-sections in the cases of reinforced concrete and laminated timber, to 'improved' elements (I-shaped cross-sections or triangulated profiles) in the case of steel. As with other types of frame, the range of spans which can be achieved is large.

The semi-form-active portal frame typology, with its generic plan-form, represents the best structural compromise (balance between complexity and appropriate efficiency) to achieve the ideal of economy of means for a range of mid- to long-span single-storey structures and contrasts with a different category of semi-form-active – those that have been adopted, not for structural reasons, but because an architectural form was required that had no structural significance. Most of the free-form architecture that became fashionable in the late twentieth and early twenty-first centuries (for example Figures 0.1, 1.9 and 10.22 to 10.28) falls into this category because its shapes are not related to structural function.

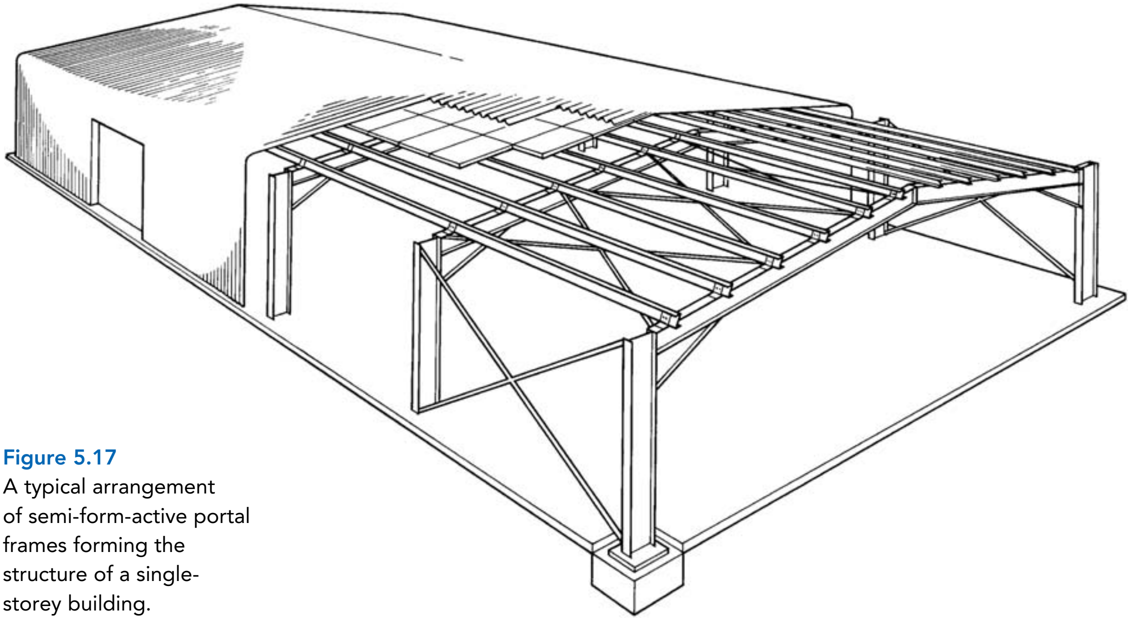


Figure 5.17
A typical arrangement of semi-form-active portal frames forming the structure of a single-storey building.

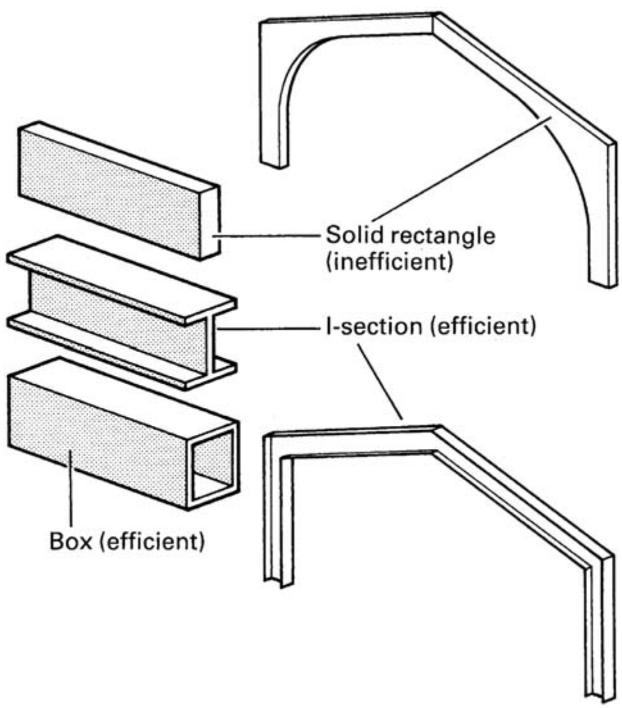


Figure 5.18 The efficiency of the semi-form-active portal frame is affected by the shapes of cross-section and longitudinal profile that are used. Variation of the depth of the cross-section and the use of I- or box-sections are common forms of 'improvement'. The structure type is highly versatile and is used over a wide range of spans.

5.4 Fully form-active structures

Fully form-active structures are normally used only in circumstances where a special structural requirement to achieve a high degree of structural efficiency exists, either because the span involved is very large or because a structure of exceptionally light weight is required. They have geometries that are more complicated than post-and-beam or semi-form-active types and they produce buildings that have distinctive shapes (Figures 0.3, 5.19 and 5.20, 10.11 to 10.13, 11.5 and 11.6).

Included in this group are compressive shells (including timber lattice 'shells'), tensile cable networks and air-supported tensile-membrane structures. In almost all cases more than one type of element is required, especially in tensile systems that must normally have compressive as well as tensile parts, and, in these cases, form-active shapes are frequently chosen for both the compressive and tensile elements (Figures 5.20 and 10.11). In the case of large building envelopes, the loads that are applied are predominantly of the distributed rather than the concentrated type and the form-active geometry is therefore curved (see Chapter 4). Although a certain amount of variety of shape is possible with this type of structure, depending on the conditions of support that are provided, the distinctive doubly-curved geometry of the form-active element is something that must be accepted by a designer who contemplates using this type of arrangement.

Form-active structures are almost invariably statically indeterminate and this, together with the fact that they are difficult to construct, makes them very expensive in the present age, despite the fact that they make an efficient use of structural material. The level of complexity that is involved in their design and construction can be appreciated by considering just a few of the special design problems that they create. The tensile envelopes, for example, always assume the form-active shape for the load that acts on them no matter what their initial geometry may have been. This is a consequence of their complete lack of rigidity and it means that considerable care must be taken in their manufacture to ensure that the tailoring of the membrane or network is correct. If this is not done and a membrane with a non-form-active geometry is produced initially it will nevertheless be forced into the form-active shape when the load is applied, causing folds and wrinkles to develop that are both unsightly and result in concentrations of stress. Many other technical difficulties, associated with the attachment of the membranes to their supports and with their behaviour in response to dynamic loads, also arise in connection with the design of tensile form-active structures.

In the case of the compressive version of the form-active structure, the penalty that is incurred if it is not given the true form-active shape for the load is that bending stress occurs in the membrane. If this happens unintentionally there is a risk of strength failure, and it is therefore desirable that the exact geometry of the true form-active shape should be determined

Figure 5.19 SkySong: ASU Scottsdale Innovation Centre, Arizona, USA, 2009; FTL Design Engineering Studio, architects. The canopy of this structure is a tensile membrane with a form-active geometry. Although flexible structures will always adopt the form-active shape for the load involved, thus restricting the choices of the designer, variations in form can be produced by manipulating the boundary (support) conditions, as here.

Photo: Cygnusloop99/Wikimedia Commons.

during the design process and that the structure be made to conform to it. Two problems arise, however. First, the geometry of the form-active shape is very complex and is difficult to determine accurately, and thus difficult to reproduce exactly in a real structure. In particular, the radius of curvature of the surface is not constant and this makes both the analysis of the structure and its construction difficult.

This difficulty has, to some extent, been overcome in recent years following the development of form-generating software. It must be borne in mind, however, that these systems are based on mathematical models that give only an approximation, albeit a very accurate one, to the behaviour of the physical

Figure 5.20 Copper Spur UL2 Tent. The backpacker's tent is an example of a short-span building for which the use of a highly sophisticated form-active structure is justified due to the need for minimal weight and therefore high structural efficiency. In this case the membrane is supported on compressive elements which are also form-active. A highly sophisticated structure of this type would not be justified for a building of this scale in which saving of weight was not critical.

Photo: CleverHiker.

structure (see Chapter 7). For this reason, some bending must always be expected to occur in response to the primary load condition in even the most carefully designed compressive form-active structure.

Second, real structures are always subjected to a variety of different forms of loading, which means that the required form-active shape changes as loads change. This does not present an insuperable problem in the case of tensile form-active-structures because these, being flexible, can simply adjust their geometry to take up the different shapes that are required. Compressive forms must be rigid, however, and so only one geometry is possible. Some bending stress will inevitably arise and the structure must therefore be given the strength (necessary thickness) to resist bending stress. Another problem associated with compressive form-active structures is the need to resist buckling which also requires that they have the ability to resist bending.

The fact that bending stress can never be totally eliminated from compressive form-active structures means that they are inevitably less efficient than their tensile equivalents. It also means that the adoption of a true form-active shape, with all the complications that this involves (such as varying radii of curvature) is rarely considered to be justified. A compromise is frequently made in which a doubly-curved shape, which is close to the form-active shape but which has a much simpler geometry, is adopted. These more practical shapes achieve greater simplicity either by having a constant radius of curvature, as in a spherical dome, or by being translational forms, which can be generated by simple curves such as parabolas or ellipses. The hyperbolic paraboloid (Figure 9.12) and the elliptical paraboloid are examples of the latter. These shapes are simpler to analyse and to construct than true form-active shapes and by adopting them the designer elects to pay the penalty of lower efficiency to achieve relative ease of design and construction.

An example of design excellence in the context of the compressive form-active structure is provided by the CNIT Exhibition Hall in Paris (Figure 1.4). The primary load on this structure is its self weight, the climatic loads of wind, rain and snow being small by comparison. The structure was given a parabolic profile rather than the catenary which would be the form-active shape for the primary load but whose geometry made the design and construction simpler. Two levels of 'improvement' were used to provide bending resistance efficiently. The shell consists of two 60 mm thick skins separated 1.5 m apart by diaphragms to provide an 'improved' hollow section. Bending performance is further enhanced by the introduction of slight corrugations. The compromises that have been made result in a structure that achieves a very high level of efficiency while at the same time being relatively simple to design and construct.

Another notable feature of the CNIT envelope is that it was assembled from pre-cast elements. This greatly simplified the provision of temporary supporting structures, which are normally a complicating feature of the construction of reinforced concrete shells if they are cast in-situ. Much use was made of pre-casting by Pier Luigi Nervi (Section 9.2.3), one of the early masters of the form-active structure in reinforced concrete, who was particularly concerned with the need to make the construction process for complex curvilinear structures as simple as possible. The more recent development of simple construction techniques, in the context of lattice-timber shells (Figures 11.5 and 11.6), is a further example of this type of thinking. The combination of highly efficient forms with simple erection techniques is likely to play a significant role in the future development of sustainable forms of building (see Section 11.5.2).

5.5 Conclusion

In this chapter the three basic types of structural arrangement have been described and a small selection of each has been illustrated. A great number of variations is possible within each type, depending on the nature of the elements of which they are composed. An ability to place a structure within the appropriate category forms a useful basis for assessing its performance and the appropriateness of its selection for a particular application.

Notes

1 A *hinge-type joint* is not literally a hinge; it is simply a joint which is incapable of preventing elements from rotating relative to each other; almost all junctions between elements in timber and masonry structures fall into this category; joints in reinforced concrete structures are mostly continuous; those in steel structures can be of either type.
2 A *plane-frame* is simply a frame with all elements in a single plane.
3 The critical internal force is *bending moment* whose magnitude depends on the span.

CHAPTER 6

The critical appraisal of structures

6.1 Introduction

This chapter outlines a method of assessing the structural performance of a building from a purely visual inspection of its form and general arrangement. The method requires an ability to 'read' a building as a structural object, as discussed in Section 6.2, and an appreciation of the archetypes of structural form (see Chapter 4). The critical appraisal of a structure involves an assessment of the appropriateness of its overall form and of the detailed aspects of its constituent elements, and, in particular, the shapes of their cross-sections and longitudinal profiles. The factors that influence these choices during the design of a structure are outlined in Section 6.3.

The topics considered in this chapter are concerned solely with the technical performance of a structure and not with questions of style or symbolic meaning. They are, however, especially relevant to the discussion of the relationship between structural form and architectural form presented in Chapter 10 and to the problems associated with environmental sustainability outlined in Chapter 11.

6.2 Reading a building as a structural object

The critical appraisal of structure, as an aspect of the general appreciation of a work of architecture, requires an ability to 'read' a building as a structural object. The classification system proposed in Section 4.4 provides a basis for this that is related to structural efficiency. The categorisation of an architectural structure is a three-stage process. It requires first that the structural parts of the building be identified and distinguished from the non-structural parts, as discussed in Chapter 1. Second, the basic overall structural type category (form-active, semi-form-active or non-form-active) must be determined.

Facing page:
Salginatobel Bridge, Schiers, Robert Maillart. Photo: Rama.

This will, in most cases, be related to the overall form of the building that it supports and is the most significant factor in determining the level of efficiency capable of being achieved. The third stage is to assess the degree to which 'improvements' have been used in the shapes of the longitudinal profiles and cross-sections of the individual elements.

The overall degree of efficiency likely to have been achieved can then be assessed. Simple non-form-active post-and-beam structures with simple 'non-improved' cross-sections are the least efficient structures, and fully form-active cable networks or thin shells the most efficient. In all cases the level of efficiency is affected by the extent to which 'improvements' – such as the use of complex cross-sections or triangulated longitudinal profiles – have been included.

6.3 The appropriateness of structural choices: complexity and efficiency in structural design

From a purely technical point of view, and as expressed by the twentieth-century 'philosophers' of structure, Pier Luigi Nervi and Eduardo Torroja (see Chapter 8), engineering is principally concerned with the achievement of '*economy of means*', and a structure may be considered to have been well engineered if it fulfils its function with a minimum input of materials, energy and other resources. This does not mean that the most efficient[1] structure, which produces the required load-carrying capacity with a minimum weight of material, is necessarily the most satisfactory; several other technical factors, including the complexity of the construction process, the subsequent durability of the structure and its performance in respect of sustainability, will affect the judgement of whether or not it performs its function well. Frequently, the technical requirements conflict. For example, as was seen in Chapter 4, efficient forms are invariably complex and therefore more difficult to design, construct and maintain than those that are simple but inefficient. For maximum economy of means, a sensible balance should have been struck between the complexity required for high structural efficiency and the ease of design, construction and maintenance that the adoption of a simple arrangement allows; the final geometry adopted is always a compromise.

It is not possible to specify precisely the level of efficiency that will produce maximum economy of means in a particular structure, such is the complexity of the interrelationships between the various factors involved. It is possible, however, by observation of extant structures, to identify two factors that seem to be the principal influences on this specification process, namely the *size of the span* that a structure must achieve and the *intensity of the external load* that it will carry. The longer the span, the greater is the need for high efficiency; the higher the level of load which is carried, the lower can be the efficiency.

The effect on efficiency of increasing span is demonstrated in the very simple example of a beam of rectangular cross-section carrying a uniformly

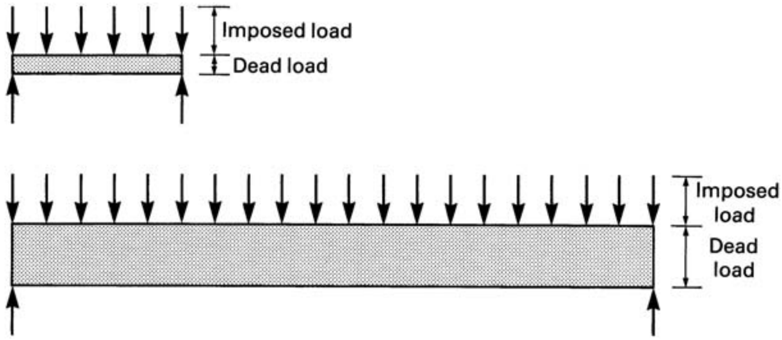


Figure 6.1 The weight of a beam is proportional to its depth, which must increase as span increases. Thus, the ratio of self-weight to **imposed load** carried per unit length becomes less favourable as span is increased.

distributed load (Figure 6.1). Two beams of different span are shown, each carrying the same intensity of load. The one with the longer span must have a greater depth so as to have adequate strength. The self-weight of each beam is directly proportional to its depth and so the ratio of load carried to self-weight per unit length of beam (the structural efficiency) is less favourable for the larger span. Thus, to maintain a constant level of efficiency (i.e. a constant ratio of load to self-weight) over a range of spans, more efficient types of structure must be specified as the span is increased.

A significant consequence of the relationship between span and efficiency is that it places an absolute limit on the maximum span possible for a given type of structural element. Consider, for example, a beam element with a particular cross-section across a range of spans. The strength of the beam – its **moment of resistance** (see Glossary) – would be constant. At small spans the maximum bending moment generated by the self-weight would be low and the beam might have a reasonable capacity to carry additional load. As the span was increased the bending moment generated by the self-weight would increase and an ever greater proportion of the strength available would have to be devoted to carrying the self-weight. Eventually a span would be reached in which all of the strength available was required to support only the self-weight.

Two generally applicable principles are demonstrated by these simple examples. The first is that the level of structural efficiency (the ability of a particular type of structural element to carry external load divided by its self-weight) steadily diminishes as span is increased. The second is that, for a given constituent material, every type of structural element has a maximum span that is reached when all of its strength is required to support its self-weight only. There is therefore a maximum possible span, for every type of structural element, which can never be exceeded.

The relationship between structural efficiency and intensity of applied load, which is the other significant factor affecting 'economy of means', can also be fairly easily demonstrated. Taking again the simple example of a beam with a rectangular cross-section (Figure 6.1), the weight of this increases in direct proportion to its depth, while its strength (moment of resistance) increases with the square of its depth (because bending strength is dependent on **section modulus** – see Glossary and Section 7.3.4). Thus, if the external load is increased by a factor of two the doubling in strength which will be required to carry this can be achieved by an increase in the depth that is less than a doubling (in fact by a factor of 1.4). The increase in the weight of the beam is therefore less than a doubling and the overall efficiency of the element carrying the double load will be greater. For a given span and shape of cross-section, the efficiency of the element therefore increases as the intensity of load increases, requiring larger cross-sections to be specified. Conversely, if a particular level of efficiency is required, this can be achieved with less efficient shapes of cross-section when heavier loads are carried. As with the relationship between span and efficiency, this is a general principle but, unlike that relationship, this principle applies only to structures in which bending is present – that is, to non-form-active and semi-form-active arrangements.

An examination of extant structures demonstrates that the majority are in fact designed in accordance with an awareness of the relationship between span, load and efficiency described above. This is particularly obvious in bridge engineering, as is illustrated in Figure 6.2, and can be demonstrated to be broadly true of architectural structures. It may be conjectured that the reason for this is to achieve overall economy of means.

From all of the foregoing it is possible to envisage a general governing principle of structural design in which the type of arrangement that would be most suitable for a particular application would range from the simplest post-and-beam, non-form-active types for very short spans, through a series of 'improved' non-form-active or semi-form-active types in the medium-span range, to form-active structures for the longest spans. The precise levels of span at which transitions from less to more efficient types of element would be appropriate would be affected by the load intensity: the higher the load carried, the longer would be the span at which the change to a more efficient type should occur.

One indicator of the extent to which the most appropriate balance between complexity (and therefore efficiency) and simplicity has been achieved is monetary cost because, although this is not strictly a technical aspect of the performance of a structure, it does give an indication of the level of resources of all kinds that will have been involved in its realisation. Cost is therefore an – admittedly fairly rough – measure of the level of economy of means that has been achieved and is frequently crucial in determining the appropriate balance of efficiency and complexity in a particular case.

Monetary cost, and in particular the relationship between labour costs and material costs in the economy within which the structure is constructed, strongly influences the ratio of load carried to self-weight (i.e. the level of

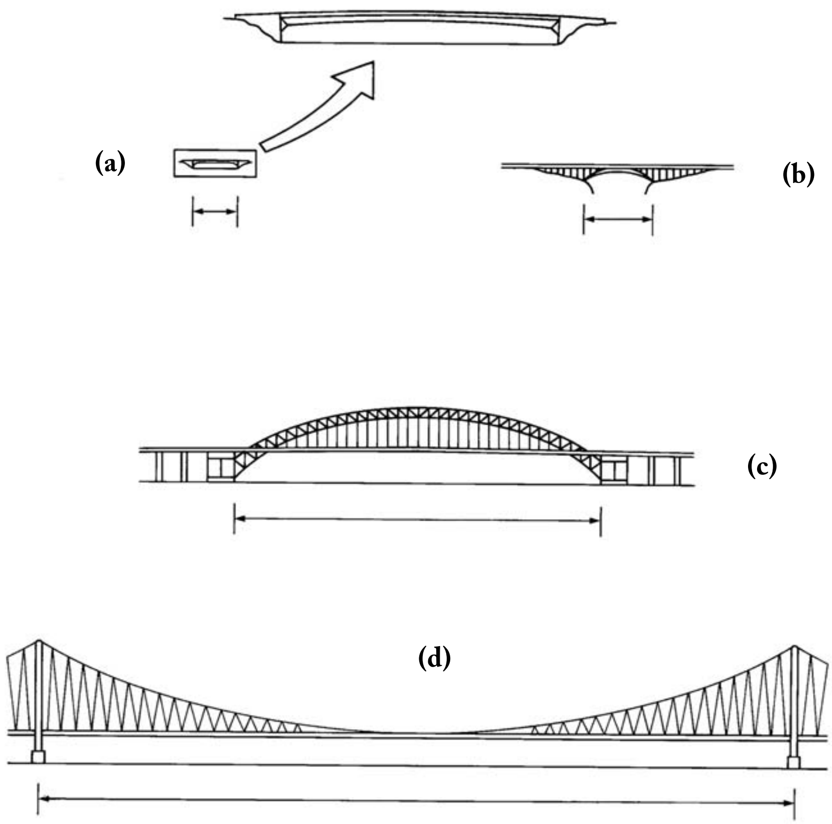


Figure 6.2 The four bridges illustrated here demonstrate the tendency for structural complexity to increase with span due to the need for greater efficiency. (a) Luzancy Bridge, France, 1946; Eugène Freyssinet, engineer; span 55 m, post-and-beam. (b) Salginatobel Bridge, Switzerland, 1930; Robert Maillart, engineer; span 90 m, compressive-form-active arch with solid cross-section. (c) Bayonne Bridge, USA, 1931; Othmar Ammann, engineer; span 504 m, compressive form-active arch with 'improved' triangulated longitudinal profile. (d) Severn Bridge, UK, 1966; Freeman, Fox and Partners, engineers; span 990 m, tensile form-active.

structural efficiency) that is appropriate in a specific case, and is a major factor in determining the spans at which the transition from less to more structurally efficient forms are made.

This situation may be illustrated by considering the relationship between material and labour costs for a particular structure. Consider, for example, the problem of a single-storey building of moderate span – an example might be the Spectrum Building at Swindon, UK (Figures 3.19 and 6.7). It might be assumed that, given its economic environment, a steel framework would be a sensible form of structure to support such an enclosure but the range of structural possibilities available to the designer is very large. Simple post-and-beam forms, with parallel sided beams, would be the least structurally efficient option. Semi-form-active **portal frameworks** with triangulated elements would be more efficient. A cable-supported structure or tent would give the greatest efficiency in the use of material. The higher the efficiency, the greater the complexity and therefore the higher would be the design and construction costs. As discussed in Section 6.4, the overall form of the arrangement that was adopted for this building was semi-form-active, with substantial 'improvement' in both the longitudinal profiles and cross-sections of the elements. A simpler alternative would have been a less efficient semi-form-active portal framework with minimal improvements (Figure 5.17). The question of which of these would have been more suitable is discussed in Section 6.4.

Returning to more general considerations, the relationship between material and labour costs of all kinds, for a particular structural application (span and load), is represented *diagrammatically* in Figure 6.3. The curve of material costs shows that these diminish as efficiency increases. Design and construction costs increase with a rise in efficiency due to the increase in complexity that this involves. The graph of total costs is obtained by adding these two curves together and this produces a new curve with a definite dip. The optimum level of efficiency corresponds with the minimum point in the total-cost combined curve, and this in turn corresponds to the particular type or types of structure that produce that level of efficiency.

Variations in labour costs, relative to material costs, affect the level of efficiency at which the overall cost is minimised. This accounts, to some extent, for variations in patterns of building in different parts of the world.

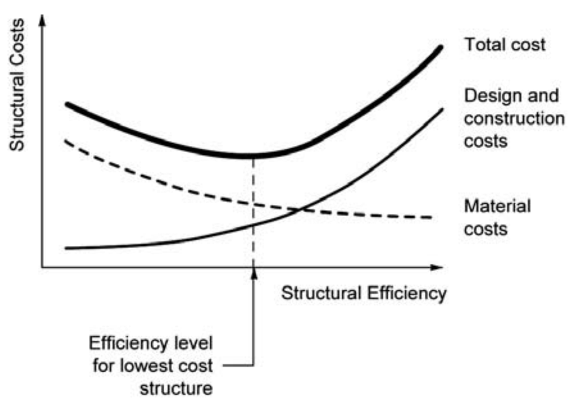


Figure 6.3 The relationship between structural efficiency and structural costs for a structure with a particular span and load condition are shown here diagrammatically. The quantity, and therefore cost, of material decreases as more efficient types of structure are used. The latter have more complex forms, however, so the cost of design and construction increases with increased structural efficiency. The curve showing total cost has a minimum point which gives the level of efficiency that is most cost effective for that particular structure.

Line drawing: Andrew Siddall after original by Angus J. Macdonald.

The higher the cost of materials in relation to labour, the greater is the incentive to achieve high efficiency and the smaller is the span at which the transition from less to more efficient, and therefore more complex, configurations is justified.

Extreme examples of the effects of specific relationships of these variables are found in nomadic societies, in which the economic conditions are such that very complex structural forms have traditionally been used for structures of relatively short span. The Bedouin tent, the igloo (Figure 1.2) and the yurt (Figure 6.4), all of which are form-active structures, may represent the very many examples that might be cited. The availability of ample reserves of labour to build and maintain complex structures, and the fact that they are the most effective ways of using locally available, and often scarce, materials, are responsible for this use of sophisticated, highly efficient structural forms for short spans. The need for light weight to facilitate portability is also a significant consideration.

Conversely, the situation in the industrialised societies of the developed world is that labour is expensive in relation to material. This favours the use of forms that are structurally inefficient but that are straightforward to build.

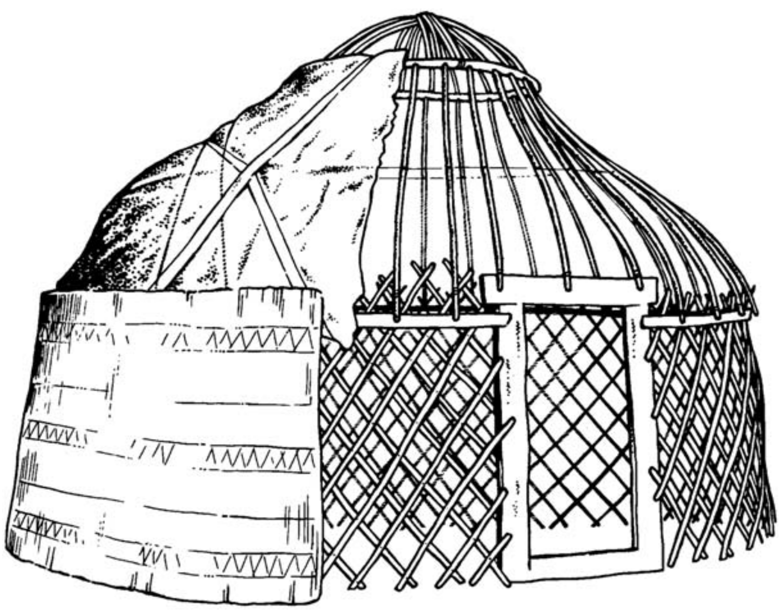


Figure 6.4 The yurt is the traditional house of the nomadic peoples of Asia. It consists of a highly sophisticated arrangement of self-bracing semi-form-active timber structural elements that support a non-structural felt skin. It is light and its domed shape, which combines maximum internal volume with minimum surface area, is ideal for heat conservation and also reduces wind resistance. When judged by purely technical criteria this building-type will stand comparison with many of those produced by the so-called technological societies of the Modern period.

The majority of the structures found in the developed world are inefficient post-and-beam types, an excellent example of the profligacy with material of present-day industrialised culture.

It is possible to suggest that, for a particular span and load requirement and within a particular set of economic circumstances, there will be a limited number of structure types that are the most appropriate. These will range from the simplest post-and-beam, non-form-active types for the shortest spans to form-active shells and cable structures for the largest spans. The majority of extant buildings conform to this pattern but there are exceptions. Some of these could be regarded simply as ill-considered designs. Others may be justified by special circumstances.

For example, if there is a specific requirement for a lightweight structure (as already discussed above in relation to traditional building types in nomadic societies), this would justify the use of a more efficient structural form than might otherwise be considered appropriate for the span. Perhaps the most extreme example of this is the backpacker's tent (Figure 5.20), an extremely short-span building for which a tensile form-active structure (the most sophisticated and most efficient type of structure) is used. The requirement for minimum weight is, of course, the justification in this case. Other examples are buildings that are temporary or that must be transported, such as those designed to house travelling exhibitions or travelling theatres – a circus tent being a historic example (see also Figure 10.17).

Another reason for adopting a structure type that might otherwise be considered inappropriate for the span or load involved might be that the building has to be built quickly. Where speed of erection is given the highest priority, a lightweight steel framework might be a sensible choice even though other considerations such as the shortness of the span might not justify this.

Where the structure is part of the aesthetic programme of the building, a structure type might be selected for its visual features rather than from a consideration of purely technical issues, as may have been the case at the Hopkins House (Figure 6.5), where the adoption of 'improved', triangulated steel joists for the horizontal structure would not normally be justified for such short spans. Many of the structures that are found in so-called 'High-Tech' architecture fall into this category. It is always possible to find examples of buildings in which a client was prepared to pay excessively and therefore commit excessive resources either in terms of materials or labour, in order to have a spectacular structure that would be unjustified on purely technical grounds.

A technical issue that should also form part of any thorough assessment of a structure is its durability: the structure should be capable of fulfilling the function for which it is designed throughout the intended life of the building, without requiring an unreasonable amount of maintenance. No definite best solution to this issue can be specified but an assessment of the implications for durability should form part of any serious assessment of the merits of a

Figure 6.5 Hopkins House, London, UK, 1977; Michael and Patty Hopkins, architects; Anthony Hunt Associates, structural engineers. The very short spans involved here would not normally justify the use of complex triangulated elements for the horizontal structure. Ease and speed of erection were the main technical reasons for their selection. The visual interest that they produce was nevertheless the principal reason for their adoption.

Photo: A. Hunt.

structure. If, for example, the material selected is steel – which, in its unprotected state is one of the least corrosion-resistant of materials – the problem of durability should be recognised and would mitigate against using steel exposed on the exterior of a building, especially in humid climates.

An increasingly important aspect of the judgement of whether or not true economy of means has been achieved, relates to the question of environmental sustainability. As shown diagrammatically in Figure 6.3, the optimum balance between complexity and efficiency for a particular structural application is determined by the relative costs of materials and labour. Monetary cost is, of course, an artificial yardstick that is affected by the ways in which a society chooses to order its priorities. In the future, these are likely to become more closely related to the realities of shortages of materials and energy, and to the need to reduce levels of industrial pollution – that is, to issues related to sustainability. Monetary cost, which, in the economic context of the Modern world of the twentieth century, was largely unrelated to these aspects of reality is likely, in the twenty-first century, increasingly to become aligned with them. This changed situation will have an effect on the balance of complexity versus simplicity that is considered to represent the best economy of means, and therefore on the choice of architectural as well as structural form.

6.4 Critical appraisal of structures

As discussed in Section 6.3, an important measure of a satisfactory structure is the nature of the compromise that has been made between complexity (for efficiency) and simplicity (for ease of construction and maintenance). A few examples of the critical appraisal of structures are now given in order to demonstrate the methodology described above; these show that it can be applied to any building from any time-period of architecture.

The temples of Greek Antiquity, of which the Parthenon in Athens (Figure 10.1) is the supreme example, are a very basic version of the post-and-beam arrangement. The level of structural efficiency in the Parthenon is low, and this is no doubt partly because the idea of achieving efficiency in a materialistic sense was probably the last consideration in the minds of its designers and builders when its dimensions were determined. This ancient and iconic building nevertheless stands up fairly well to purely technical criticism. The structure is of the post-and-beam non-form-active type with individual elements that have 'unimproved' solid rectangular or circular cross-sections. It is therefore a very simple form of construction but this is fully justified given the relatively short spans involved. No more elaborate configuration was necessary. The dimensions of the architrave beams that span between the perimeter columns may seem to be excessive, but this also is justified technically given the minimal tensile, and therefore bending, strength of stone. If more slender elements had been used, it is likely that cracks would have developed and that the building would have gradually collapsed during the many centuries in which it was neglected. The columns, which may appear excessively thick in comparison to those of a Modern structure, are also justified in the context of a material with little ability to resist bending and therefore buckling.

Moving to more recent times, the rectilinear form of the Reliance Controls factory in Swindon, UK (Figure 9.32) may appear to be configured similarly to the Parthenon but this is in fact a quite different type of structure. The principal structural elements of this building are multi-bay **portal frameworks** (see Glossary). Despite their post-and-beam appearance, these are semi-form-active structures (due to the rigid beam/column joints) to which mild 'improvement' in the form of the adoption of I-shaped cross-sections have been applied. The level of efficiency involved is relatively low but this is justified in view of the short spans (12 m). More elaborate 'improvements', such as those seen in the Spectrum building (reviewed below), would not have been appropriate.

Another building with an apparently similar basic form is the Sainsbury Centre for the Visual Arts (Figures 9.33 and 9.34). In this case the principal structural elements constitute a simple post-and-beam structure, rather than a semi-form-active portal framework, because the beam/column junctions are incapable of transmitting bending and therefore behave as hinge connections. The basic form consists of horizontal elements that are non-form-active and this is perhaps surprising in view of the relatively long span involved (35 m). The potential level of efficiency is low but this is mitigated to some extent by the adoption of a triangulated longitudinal profile. More elaborate 'improvements' might have been justified technically but other architectural considerations did not allow these to be used, with the result that the overall level of structural efficiency is lower than would be desirable for a building of this size (see Section 9.3 for a more detailed discussion).

The Centre Pompidou in Paris (Figures 6.6, 9.28 to 9.31) may also be read as a building with a simple post-and-beam form. As at the Sainsbury Centre, the connections between the principal floor beams and the columns behave as hinges, so that the floor girders are basic non-form-active elements and therefore potentially very inefficient, especially as the span involved is relatively large (48 m). The adoption, for the main girders, of a triangulated profile – which is one of the few forms of 'improvement' possible in the floor of a multi-storey building – compensates to some extent for the potential inefficiency. The only other option to reduce the total weight of steel required would have been to insert interior columns to reduce the spans. Architectural considerations ruled this out, however. The use of 'improved' shapes in cross-section and longitudinal profile of the cantilevered 'gerberette' brackets (Figures 9.30 and 9.31) reduced the potential inefficiency of these non-form-active elements, but the level of efficiency that was achieved by the structure, considered as a whole, was low. As discussed in Section 9.3, other aspects of the design of this building also cause it to perform rather badly when subjected to purely technical criticism. The technical compromises were necessary, however, in order to achieve the desired architectural effect. It is, of course, a matter of opinion whether the extravagant use of resources of all kinds was justified in the case of this building.

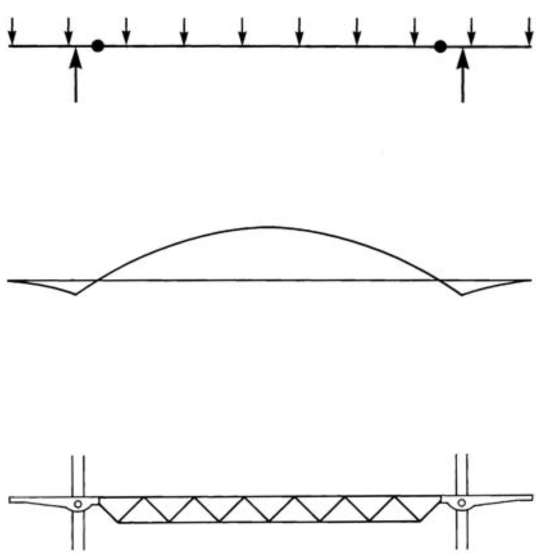


Figure 6.6 Load, bending moment and structural diagrams for one of the principal elements in the floor structure of the Centre Pompidou, Paris. This is a non-form-active beam but the relatively long span involved justified the incorporation of 'improvements'. Height restrictions prevented the matching of the longitudinal profile to the bending moment diagram, except in the cantilevered 'gerberette brackets' at the extremities of the structure. Triangulation was the only form of 'improvement' that was feasible here for the main element (see also Figures 9.28 to 9.31).

The structure of the Spectrum building (formerly Renault Sales Headquarters – Figures 3.19 and 6.7) may be read as a semi-form-active framework to which significant levels of 'improvement' have been applied in both the longitudinal profiles and cross-sections of the constituent elements. On preliminary inspection – as the basic form of the structure is rectilinear – the structure may appear to be a post-and-beam frame. As in the Reliance Controls building, the beam-to-column junctions are rigid, however (thus providing a degree of structural continuity), so that both horizontal and vertical elements are subjected to a combination of axial and bending-type internal force under the action of gravitational loads. The overall form is therefore semi-form-active. Because the basic shape of the structure is markedly different from the form-active shape,[2] the magnitudes of the bending moments are high and the structure is therefore potentially rather inefficient. The longitudinal profiles of the horizontal elements have, however, been 'improved' in a number of ways. The overall depth is varied in accordance with the bending-moment diagram and the profile itself is subdivided into a combination of a bar element and an I-section element, the relative positions of which are adjusted so that the bar element always forms the tensile component in the combined cross-section and the I-section the compressive element.[3] The circular cross-section of the bar is a sensible shape to carry the tensile load, while the I-section of the compressive part is a suitable choice in view of the need to resist compressive instability, which is a bending phenomenon. The cutting of circular holes in the web of the I-section is another form of 'improvement'. A similar breakdown of the cross-section occurs in the vertical elements, but in these the compressive components are circular hollow sections instead of I-sections. This is again sensible because these components are subjected to a greater amount of compression than their counterparts in the horizontal elements, and the circle is an ideal shape of cross-section with which to resist compression. The question of whether an appropriate overall level of efficiency has been achieved in this case is discussed below and in Section 10.2.2.

'Improvements' to element cross-sections in short-span post-and-beam arrangements are seen less often in buildings with reinforced concrete structures because concrete is both lighter and cheaper than steel, so there is not the same incentive to achieve even the moderate levels of structural efficiency of steel frameworks. Coffered slabs were used in the Willis, Faber & Dumas building (Figure 1.6 and 5.15, 5.16), however, and these are examples of 'improved' non-form-active elements in a post-and-beam, reinforced concrete arrangement. Versions of this type of 'improvement' are incorporated into most reinforced concrete structures if the span is greater than 6 m.

The timber roof structure of the Living Planet Centre (Figures 3.12 and 3.13) is a form-active vault that is supported continuously along the sides of the building. The overall thickness of the structural part of the vault is quite

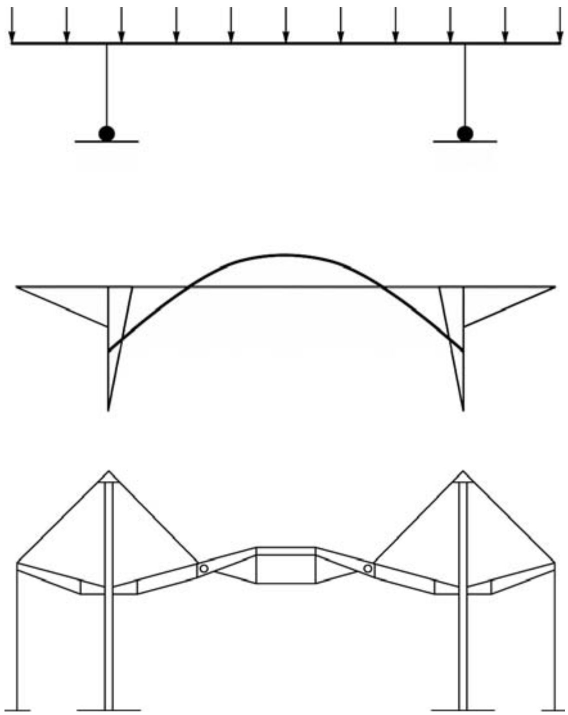


Figure 6.7 Load, bending moment and structural diagrams of the Spectrum building (formerly Renault Sales Headquarters), Swindon, UK; Foster Associates, architects; Arups, engineers. The basic form of this structure is a semi-form-active frame. 'Improvements' have been introduced at several levels: the overall profile of the structure has been made to conform to the bending moment diagram for gravitational load, the structure has been triangulated internally and some of the sub-elements have been further 'improved' by having I-shaped cross-sections and circular holes cut in their webs (see also Figure 3.19).

Line drawing: Andrew Siddall after original by Angus Macdonald.

large but this is necessary because, being a compressive form-active structure, it must be given some ability to resist buckling and therefore bending. The quantity of material involved is much reduced by the adoption of the lamellar principle, a form of 'improvement' that can be achieved with constructional efficiency due to the high degree of repetition in the sub-elements and connections.

The roof structure of the hangars at Orvieto (Figures 9.5 and 9.6) may appear to be similar to that of the Living Planet Centre but in fact is quite differently configured: the vault-like structure is not in this case supported continually by the side walls, but by transverse arches, one at each end of the building and one placed centrally. The lamella vault is in fact an 'improved' beam that spans longitudinally between the arches, the parabolic profiles of which make them form-active structures.

These few examples of structural classification (more are given in Chapters 8, 9 and 10) are intended to illustrate the use of the methodology described in Section 4.4 as a means of identifying precisely the type of structure that has been used to support a building, and therefore of assessing visually the level of efficiency that is likely to have been achieved. The structural critic must then decide whether or not the level of efficiency achieved is appropriate to provide overall economy of means, given the spans and loads involved, because it is the balance that has been struck between complexity for efficiency and simplicity for ease of construction that determines whether or not the chosen form is a sensible one technically.

A useful rough guide to the assessment of this question tends to be found in common practice. The critic should have an awareness of the span ranges that have normally been considered to be the most suitable for the various available structure types.

Taking again the example of the Spectrum building (Figures 3.19 and 6.7), the span involved was 24 m and the basic structural form adopted was that of a semi-form-active portal framework. The span range for which the portal frame is normally used is 20 m to 60 m so its use for the Spectrum building places it at the lower end of the span range at which few 'improvements' to longitudinal profile and cross-sections of elements might have been expected. The highly elaborate set of 'improvements' specified for the Spectrum building are therefore unlikely to have been technically justifiable, as shown by comparison with the much simpler type of configuration that is normally adopted for portal frameworks (Figures 1.6, 5.17 and 5.18). There is little doubt that the achievement of economy of means was not the primary consideration in the design of the Spectrum building (see Section 10.2.2 for further discussion of this topic). As an example of technology, the building does not therefore stand up particularly well to criticism. This is, of course, a separate issue from its quality as a work of architecture where other considerations than the achievement of overall economy may be given a higher priority.

6.5 Conclusion

Any formulation of the criteria by which the merits of a structure may be judged is inevitably controversial. The assessment of whether or not a reasonable level of economy of means has been achieved involves the examination of a number of different aspects of a design and is principally a matter of being satisfied that an appropriate balance has been struck between the quantity of material used, the complexity of the design and construction processes, and the subsequent durability and dependability of the artefact. Because these factors are interrelated in complicated ways, the overall judgement required is not straightforward. An important consideration is that the fundamental purpose of engineering is not image making; it is about the provision of artefacts that are useful. If the problem to be solved is not technically difficult – a short-span bridge across a stream, or a building of modest span, for example – the best engineering solution is likely to be simple. If it is well designed, from an engineering point of view, it will be considered satisfactory by those who appreciate engineering design.

In the context of architecture, many twentieth-century Modernists who believed that the 'celebration' of the 'excitement' of technology was a necessary part of architectural expression, often favoured the use of structural forms that, in engineering terms, were excessively complex. The Spectrum building

Figure 6.8 Salginatobel Bridge, Schiers, Switzerland, 1930; Robert Maillart, engineer.

(a) The design of the bridge was based on one of the archetypes of structural form: the profile of the arch contains, within its envelope, the form-active shapes for all of the principal load conditions, and the use of such a complex structure was justified for the 90 m span involved. The appearance of the bridge, which most people find to be very satisfying visually, was determined entirely from technical considerations.

Photo: Rama/Wikimedia Commons.

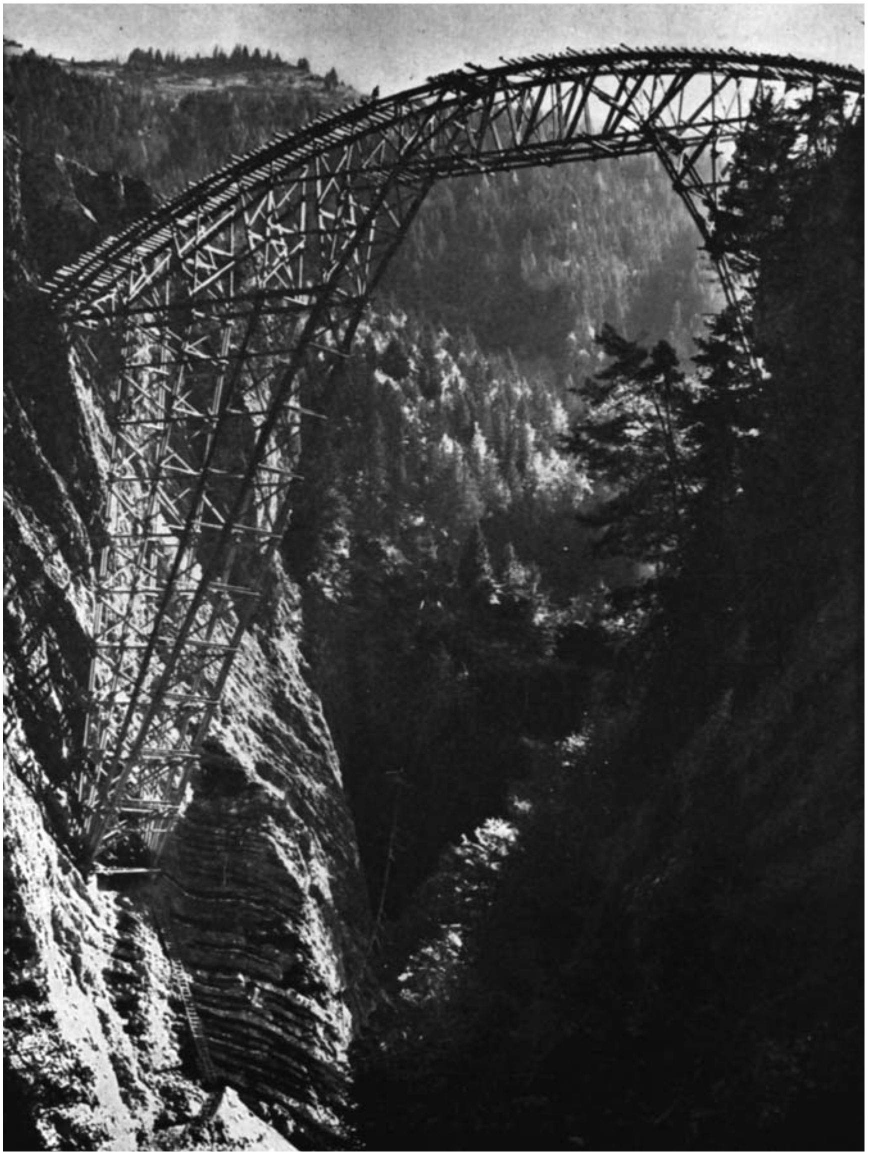


Figure 6.8 Salginatobel Bridge, Schiers, Switzerland – *continued*

(b) The elaborate support system for the timber formwork in which the concrete was cast (constructed by carpenter Richard Coray) was a considerable feat of construction in its own right. The fact that Maillart's design was the least expensive of the nineteen entries to the competition for its design indicates that overall economy of means was achieved. The bridge was of its time, however, and, due to the labour-intensive method of its construction, would be unlikely to constitute best overall economy of means in the present day, in which a simpler, less elegant but less efficient form that was easier to build would cost less under current economic conditions.

Photo: courtesy University of California Press.

is an example of this approach, which may be reasonable as an architectural design strategy but which should not be confused with what would have been most appropriate in purely engineering terms. The latter is likely to be accorded greater importance in future, however, as questions of environmental sustainability, and the avoidance of the wasteful use of resources, are inevitably given a raised priority.

In the case of complex problems, where sophisticated solutions are justified, architects and engineers can often agree on the merits of iconic solutions, such as those of the spectacular but classic bridges of Robert Maillart (Figure 6.8 a and b). Most would consider that his solution for the Salginatobel Bridge – a highly sophisticated, appropriate and efficient form-active structure – is also deeply satisfying in its elegant visual simplicity (although its means of construction was by no means simple (Figure 6.8b), and would not be carried out in the same way in the present day). This project represents, in its context, the achievement of economy of means.

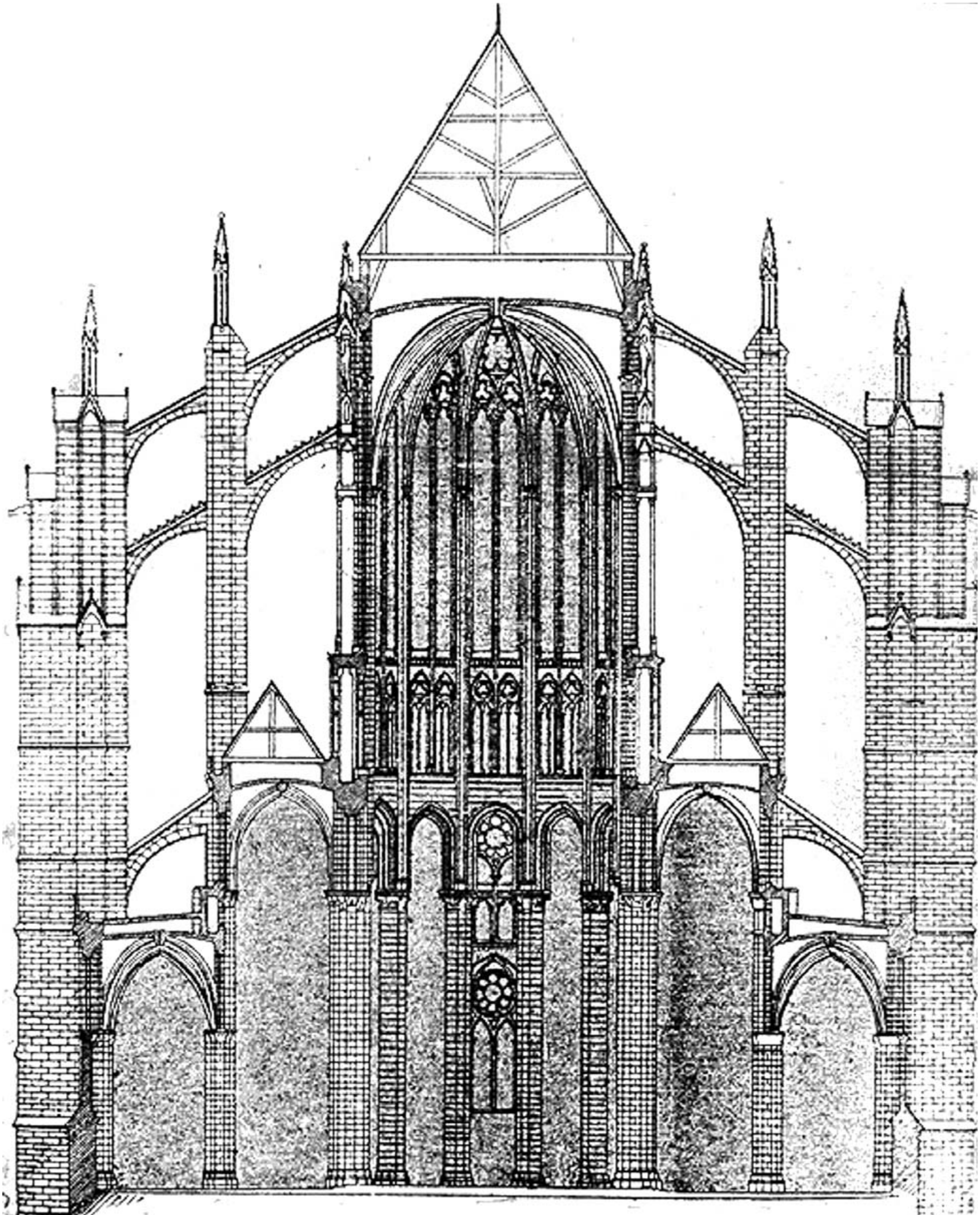
Other contexts, whether simple or complex, require other solutions. What is most needed today is probably equivalent deep thinking about contemporary problems, especially those that may seem structurally simple, and where there may therefore be a temptation on the part of designers to adopt dramatic solutions that are overly complex, thus failing to deliver economy of means.

Notes

1 As in Chapter 4, structural efficiency is considered here in terms of the weight of material that must be provided to carry a given amount of load. A measure of the efficiency of a structure is therefore the ratio of its strength (i.e. its total load-carrying capacity) to its self-weight. High efficiency is achieved if the strength-to-weight ratio is large.

2 The load pattern on the primary structure is a series of closely spaced concentrated loads. The form-active shape for this is similar to a catenary.

3 The bar element is sometimes above the I-section and sometimes below, depending upon the sense of the bending moment, and therefore upon whether the top or the bottom of the combined section is in tension.



CHAPTER 7

Theory of structures

7.1 Introduction

The term 'theory' has different meanings in the worlds of engineering and architecture. In engineering *theory of structures* is applied to a body of knowledge concerned with the understanding of the behaviour of materials and structures and which underpins the mathematical procedures used both in structural analysis (the process in which the forces that act on and within structures are evaluated) and in the sizing of structural elements (the large body of calculation methods by which suitable sizes are specified for these elements).

In the field of architecture the term *architectural theory* is used to describe sets of ideas, based largely on the philosophies of aesthetics, which inform both the creative activity of design and the critical discourses that surround it. In the field of engineering structures, the ideas that underpin the determination of form are more usually referred to as *philosophy of structures* rather than *theory*, and the volume of literature on this topic is small compared to that which exists for architecture.

As will be discussed here, the roles and objectives of architectural and structural theory have been quite different throughout the history of Western architecture. Architectural theory has been concerned principally with cultural issues while structural theory has dealt with physical realities. The distinction is an important one especially in relation to the increasingly important question of environmental sustainability (see Section 11.6).

In the present day, the design of a structure normally includes a complex set of processes in which several individuals or groups of individuals are involved, each bringing particular skills to the activity. The various aspects of structural design may however be subdivided into the two broad categories of *conceptual design*, the process in which the overall form and general arrangement of the structure are determined, and *design realisation*, in which the detailed design, including calculation of the sizes required for the structural elements, is carried out. In his thought-provoking book *Structural Engineering: the*

Facing page: Beauvais Cathedral, Beauvais. Image: after Benouville.

nature of theory and design (1990), William Addis referred to the second process as '*justification*', the 'proving' that a particular design will perform satisfactorily in practice. The two processes are often interlinked but are nevertheless quite distinct. Both are informed by considerable bodies of knowledge. The ideas that constitute *philosophy of structures* are largely concerned with conceptual design. It is design realisation (justification) that is informed by what is referred to, in structural engineering, as *theory of structures*.

In this chapter the field of theory of structures is briefly reviewed. The treatment is not comprehensive as this topic has been well covered by other texts (e.g. Kurrer (2008) and Addis (1990)). The principal purpose of this chapter is to explore the *role* of theory in structural design and the relationship between structural theory and architectural theory. Philosophy of structures, and *its* relationship to architectural theory, is the subject of Chapter 8.

From earliest times builders must have needed to 'justify' their designs for major and monumental public works, such as the Parthenon in Athens or the Colosseum in Rome, to their clients or patrons, as well as to themselves. In this context some form of structural theory must have been in use from the very beginning of constructed enclosure. In the present day the elaborate structural calculations that are carried out as part of the design of major structures are a form of justification – a component of the necessary demonstration that all steps have been taken to ensure that the building will function satisfactorily as a structure.

The procedures that have been used for the justification of structures fall into two broad categories: *geometric rules* (based on sizing purely by geometry, and sometimes called 'rules of thumb') and *grounded rules* (based on theories of structural behaviour). An example of a 'geometric rule' is the specification of a maximum ratio of span to depth for a floor beam, which might, for example, be a value of 15 for a timber beam in a house. A carpenter, wishing to determine the depth of beam required for a particular floor would, using this geometric rule, simply divide the span (the width of the room) by this number; if the room was 30 ft wide the required depth of beam would be 30/15 = 2 ft. This type of rule would traditionally have been derived empirically from the accumulated knowledge of long-term experience. It has obvious limitations, such as that it applies only to a particular type of element.

An example of a 'grounded rule' would be a formula for calculating the size of a beam from a known value of material strength and applied load (see Section 7.3.4). This method would be dependent on a knowledge of the relationship between the size of a beam and the stress that the load would generate within that beam, but it would be capable of more universal application than the 'rule of thumb'; it could, for example, deal with a range of materials, with different strength characteristics, and also be applied to more than a single type of structural element or a single type of building. Most structural design in the present day is based on justification by grounded rules rather than geometric rules.

To facilitate the broad discussion of structural theory under consideration here, two examples of theory will be described (one from each of the categories noted above): the first example is the theory that was traditionally used in the building of large-scale masonry structures, and that was of greatest significance in periods, up to the mid nineteenth century, when masonry was the principal structural material; the second is the more recent theory which is based on the concept of **elasticity**, on which large sections of present-day structural theory rely. Both the ability of elastic theory to provide insights into structural behaviour and the difficulties associated with its use.

7.2 Example 1: the use of 'geometric rules' – structural theory in Antiquity and the medieval period

7.2.1 Introduction

The origins of ideas concerned with selecting appropriate configurations for the structures that support buildings and for the selection of suitable sizes for structural elements must date back to the very earliest attempts of humans to construct shelter. Present-day knowledge in relation to historic masonry is sparse, however, even from times that are otherwise well documented, such as the periods of Greek and Roman Antiquity. What is almost certain is that, where large or monumental projects were involved, there was a highly developed organisation for both design and construction. In the words of J. J. Coulton (*Greek Architects at Work*, 1977), quoted in Addis (1990, p. 116):

> an architect . . . needs a technique of design, a technique which will allow him to visualise the finished building beforehand with sufficient accuracy to ensure that the lower parts of the building will suit the parts which are to be put on top of them, and that the whole building is satisfactory in form, function and structure.

The quotation refers to the monumental architecture of the Hellenic period in Greece but applies to large-scale works from any age. Formidable structures require a formidable degree of organisation if they are to be successfully executed. A necessary aspect of such organisation is an ability to plan a building so that it will perform as a structure, which implies, in turn, knowledge of a theoretical kind.

The study of the behaviour of masonry structures enables interesting comparisons to be made concerning the relationship between structural theory and architectural theory in pre-Modern times and the present day.

7.2.2 The structural theory of masonry

The monumental buildings of Greek and Roman Antiquity and of the Gothic period were built predominantly in stone or other forms of masonry. In his authoritative book *The Stone Skeleton* (1995), Jacques Heyman provided an excellent summary of the key factors that influence the behaviour of large masonry structures, and dispelled many of the myths and misconceptions that have accumulated through the centuries, in architectural history circles, about buildings such as Gothic cathedrals, and that were generated by commentators whose understanding of structural principles was slight. The key considerations identified by Heyman, for developing an understanding of the behaviour of large masonry structures, are:

1 that average stress levels in historic masonry structures are very low. Heyman demonstrated this by showing, by calculation, that a Gothic cathedral would have to be 2 km high before crushing stresses due to its weight (the principal load carried) approached the limiting values of masonry and that buildings of more 'human' scale were subjected to levels of average stress that were trivial. The significance of this finding is that levels of strain (deformation as a result of stress) of the individual building blocks are also minimal, so that treating buildings as assemblies of discrete blocks, each of which is totally rigid, was a reasonable assumption. A corollary of this is that conclusions about structural behaviour based on elastic analysis of arches (much carried out in the nineteenth century following the development of the **elastic bending theory** – see below) were largely irrelevant when applied to masonry structures;
2 that, as a consequence of 1, *geometric* procedures for determining the sizes and proportions of masonry structures constituted a valid method of design. A further corollary is that elements such as arches and buttresses will be in equilibrium so long as the *thrust line* (see box 'Thrust lines' and Figure 7.1) was contained within the envelope of the structure;

Thrust lines

Thrust line is a concept that provides useful insights into the structural behaviour of masonry elements that are subjected to a combination of axial thrust and bending. It is particularly relevant to the understanding of the factors that affect the equilibrium conditions for arches, flying buttresses and piers in medieval cathedrals, as is shown in Figures 7.1 to 7.3.

Where an element is subjected to axial force only (a simple example would be a block of masonry carrying its own weight – Figure 7.1a) the stress across every horizontal cross-section is distributed uniformly and the thrust force on each cross-section acts at the centre-line. (Note that, although stress levels in historic masonry are minimal, the presence of tensile stress is significant because it gives rise to cracking.) If bending is present (such as would occur if the block was acting

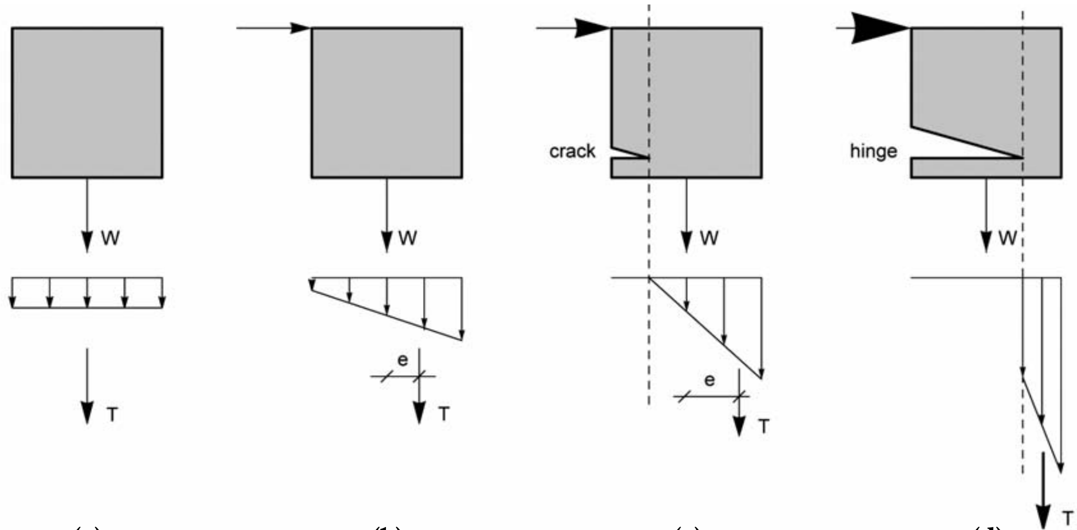


Figure 7.1 Eccentricity and hinge formation in masonry elements. The effects of combined axial and bending forces on a block of masonry (upper row), and the resulting distribution of stress at its base (lower row) (note that, although stress levels in historic masonry are very low, the presence of tensile stress is significant because it gives rise to cracking): (a) Under its own weight (W), the base of the block is subjected to a uniformly distributed stress and the accumulated thrust (T) acts on the centre-line. (b) Under the action of the combination of weight and a horizontal force, the stress distribution becomes trapezoidal and the thrust is displaced horizontally by an amount referred to as the eccentricity (e) of the system. Friction at the base of the block maintains horizontal equilibrium. (c) If the eccentricity exceeds approximately one sixth of the width of the cross-section, tensile stress will tend to develop. In the case of masonry, which has minimal tensile strength, this causes a crack to form. (d) As the eccentricity approaches half the width of the block, the cross-section behaves as a hinge. The concentration of compressive stress could now exceed the strength of the material and cause crushing.

Line drawing: Andrew Siddall after original by Angus J. Macdonald.

as part of the buttress of a vault and was subjected to a horizontal force at its top – Figure 7.1b), the stress pattern becomes trapezoidal and the position of the thrust force is displaced laterally by an amount known as the eccentricity of the system. Friction, acting at the base of the block, would also be required to maintain equilibrium.

If the amount of lateral force is sufficient to cause the eccentricity to be greater than one sixth of the width of the block, tension stress will tend to occur at one of its edges and, as masonry is incapable of resisting tension, a crack will form (Figure 7.1c). Redistribution and concentration of the compressive part of the stress group would also occur.

Under increasing levels of bending the eccentricity will extend to the edge of the block and the cross-section at its base will begin to behave as a hinge (Figure 7.1d). If this occurred in an element such as a flying buttress it could initiate collapse if other constraints were not present. If the eccentricity is allowed to exceed half the width of the pier, so that the thrust force would be required to act beyond the confines of the cross-section, collapse will almost certainly occur.

The line that traces the eccentricity of the individual cross-sections of an element is known as the **thrust line** (Figure 7.2 and 7.3). The task for the designer of the medieval cathedral (and

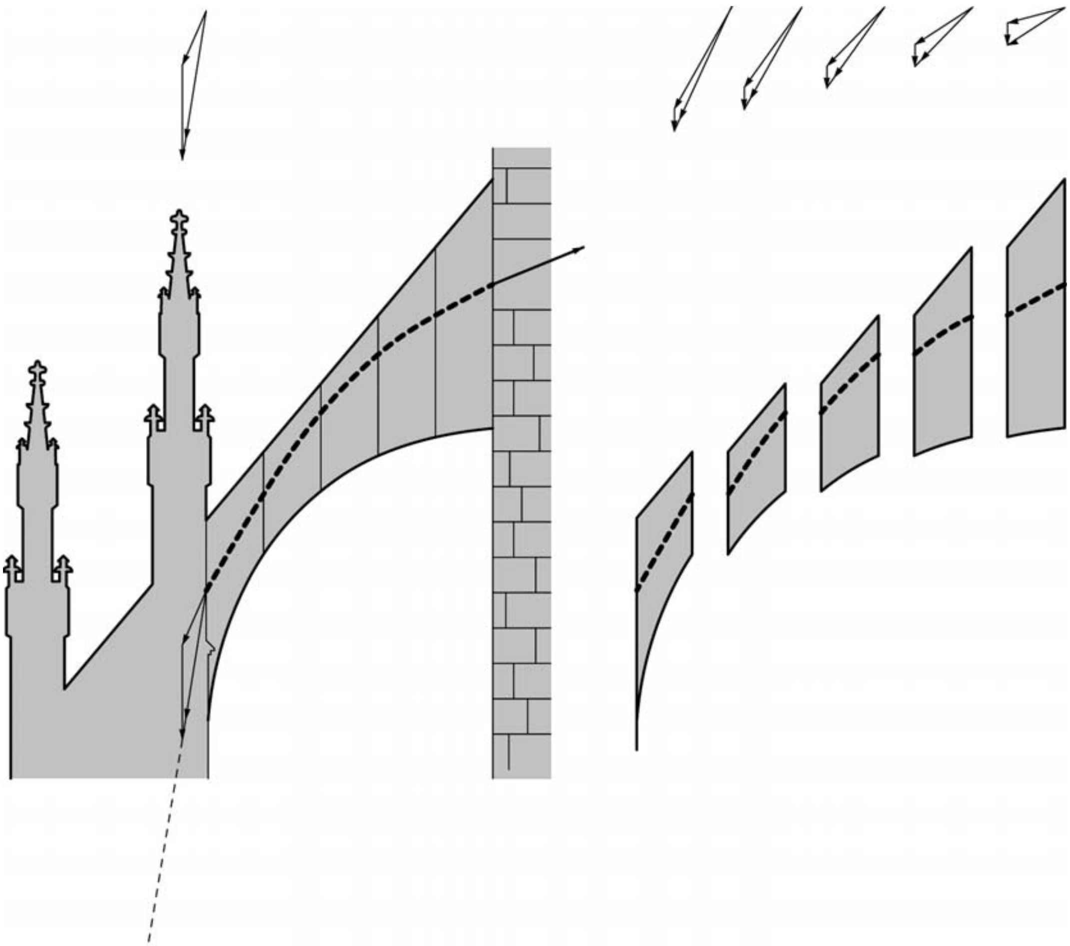


Figure 7.2 Thrust line in a flying buttress. Each block in the flying buttress is subjected to a combination of thrust from the vault which it restrains and the weight of the buttress itself. The cross-sections of the buttress are subjected to a combination of axial and bending forces that cause the distribution of stress to be similar to that at the base of the block shown in Figure 7.1. The row of force diagrams shows how the direction of the thrust is altered by the accumulated effect of the weights of individual blocks. This contains the eccentricity within the envelope of the buttress. The thrust line (shown dotted) traces the locations of the eccentricities in the individual cross-sections. At the left-hand end of the flying buttress the weight of the finial turns the direction of thrust downwards into the vertical part of the buttress system. (After Ungewitter, in Heyman, 1995.)

Line drawing: Andrew Siddall after original by Angus Macdonald.

indeed any masonry structure) is to arrange the geometry and thickness of piers, buttresses and arches (all of which are normally subjected to a combination of axial thrust and bending), such that the thrust lines are contained within their envelopes.

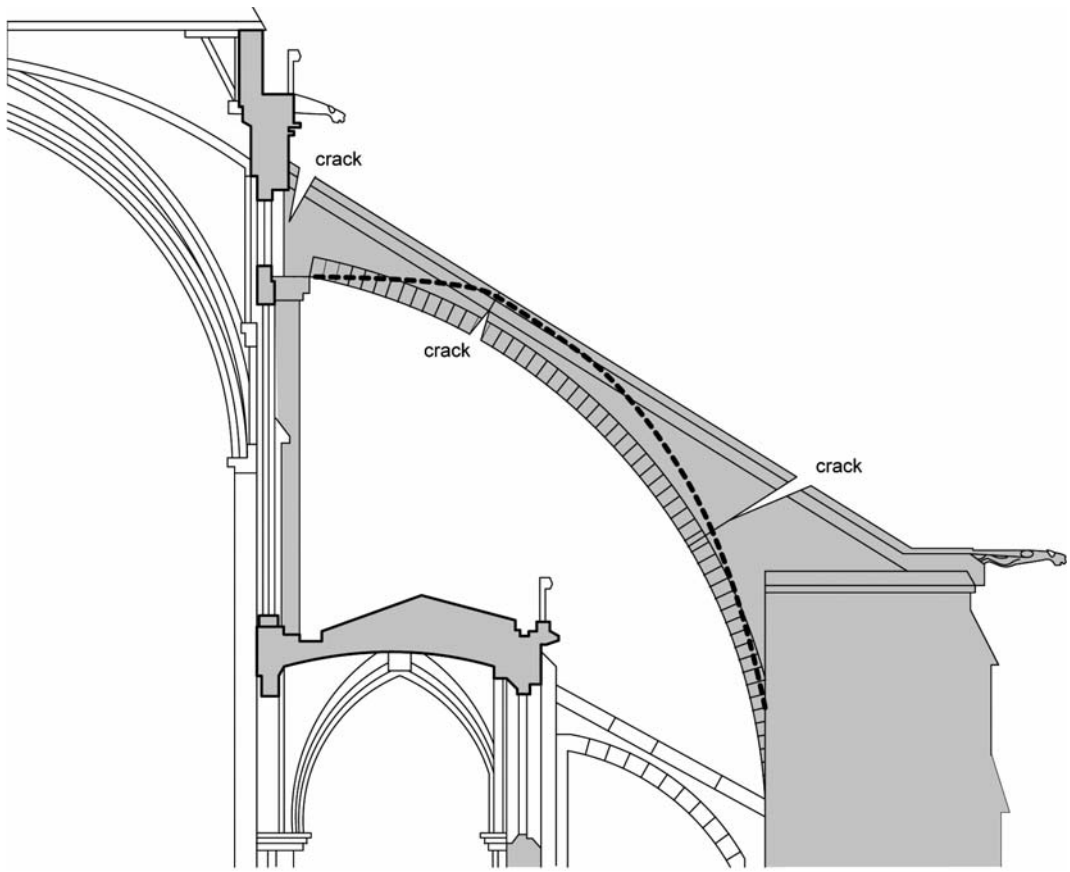


Figure 7.3 Hinge formation in a flying buttress. Crack formation occurs opposite locations where the thrust line deviates significantly from the centre-line of the buttress. If the thrust line approaches the edge of the buttress, hinge-type behaviour will occur. Individual elements can tolerate three hinges and remain stable. The presence of a fourth hinge would initiate collapse. Crack widths shown here are exaggerated for clarity. (Notre-Dame Cathedral, Paris; after Viollet-le-Duc.)

Line drawing: Andrew Siddall after original by Angus J. Macdonald.

3 that the aspects of geometry that were critical for stability and equilibrium of masonry structures were: first, the minimum thicknesses required to contain thrust lines within the masonry envelope of walls, arches and flying buttresses, and second, the appropriate configurations of the principal axes of these elements, which determined the pattern of thrust lines. Heyman also demonstrated that it was possible to determine *geometrically* the minimum depth of arch that was required to maintain the thrust line within its envelope, and therefore to define a *geometric factor of safety* which was the ratio of the actual thickness of an arch to the minimum thickness required to contain the thrust line.

Perhaps the most significant of Heyman's conclusions was, however, that it was possible to 'justify' the design of a masonry structure purely on the basis of its geometry;

4 that cracks will always occur in masonry structures. These are inevitable in a brittle material that is infinitely rigid (as described in 1 above) and are formed as the building settles, during construction, under the action of its accumulated weight. They will normally occur between stones but will also occur in potentially monolithic materials such as Roman concrete and adobe. They subdivide the structure into discrete rigid units held together by compressive forces and friction. At strategic locations they form the equivalent of hinges in the structure and determine the positions of the thrust lines (Figures 7.2 and 7.3).

As a footnote to his discussion on cracking, Heyman observed that the presence of cracks in a large masonry structure must be considered as normal behaviour and is not necessarily a sign of imminent collapse. Large cracks could, of course, cause the masonry to deteriorate through water penetration and are therefore normally pointed with mortar and could even be sealed with waterproof paper. As Heyman pointed out, Gothic cathedrals are one of the few instances in which apparently major problems can be resolved safely by 'papering over the cracks' (1995, p. 23);

5 that, due to the fact that individual blocks can be assumed to be infinitely rigid, design procedures based purely on geometry are independent of scale. Once satisfactory proportions have been determined for a proposed structure, it can be built at any scale from small timber-block models to full-size masonry structures. This means that the construction of small-scale block models gives an accurate representation of the behaviour of the full-size structure. This was a highly significant conclusion. Most aspects of structural behaviour are subject to a scale effect so that the results of tests conducted on models must be very carefully interpreted to allow for this. Heyman demonstrated that the scale effect does not apply in the case of the statics and stability of masonry structures. Use of models to test the validity of masonry structures in the medieval period would therefore have yielded reliable results even though scale effects may not have been understood at that time;

6 that masonry structures that are stable are likely to remain so indefinitely. Heyman coined the famous phrase 'if it will stand for 5 minutes (following the removal of temporary formwork used for construction) it will stand for 500 years' (1995, p. 24) – the so-called 'five-minute rule'. This rule applies so long as subsequent movement of the foundations does not occur, and such collapses as have happened to large masonry structures have usually been due to this cause rather than to any defect in the design of the masonry itself. The collapse of part of Beauvais Cathedral in 1284, which was caused by a detailing fault unrelated to the main design, is a notable exception (see Heyman, 1995, p. 113). It is the case, however, as Heyman

pointed out, that recent movement of an ancient structure is a cause for concern which is why glass 'tell-tales' are often to be seen fixed across cracks in old masonry in order to monitor movement. Recent or continuing movement is likely to have been caused by changes in soil conditions under the building, most probably due to variations in moisture content. It is often the case that changes in the water table due to adjacent building works or even drainage of land in the vicinity of the building are responsible. Unlike long-standing cracking, this is a phenomenon that should not be ignored by those responsible for caring for old buildings.

In identifying and clarifying the six essential characteristics of masonry structures noted above, Heyman drew attention to a fundamental difference between the design procedures that are appropriate for rigid materials, such as masonry, and those that must be used for materials that behave **elastically** (see Glossary and later in this chapter for an explanation of **elastic behaviour**), such as steel, reinforced concrete and timber. If the material is rigid, it is appropriate to base design on geometric rules because the only critical factors are stability and the ability to achieve a state of static equilibrium. Calculations of stress and strain are not required because the stress levels are very low. 'Modern' materials, such as steel or reinforced concrete, by contrast, are designed to carry high levels of stress and therefore behave elastically under normal load conditions. Design procedures involving numerical analysis and the calculation of stress and strain are required for these materials so as to check that stress levels will not be excessive and that the structure will not suffer undue deformation.

It is often assumed that the use of geometry *only* is an outmoded basis for structural design and that it was practised in medieval times because more rigorous, exact, 'scientific' methods of design were not available. What Heyman demonstrated is that geometric procedures are not only completely valid for traditional masonry structures but also that they are as relevant in the present day as they were in the Gothic period. It is the behaviour of the material that determines the method of design that is appropriate, not the state of human knowledge of structural behaviour at the time. The concluding sentence in Heyman's book aptly summarises the situation for traditional masonry structures: 'The key to the understanding of masonry is to be found in a correct understanding of geometry' (1995, p. 154).

Returning now to the consideration of what might have been the true state of structural theory at the time when the massive masonry structures of Antiquity and the Gothic period were being constructed, the earliest surviving treatise on Western architecture is *De architectura* by Vitruvius, dating from approximately 30 BCE. The matter of '*firmitas*' (firmness), the quality of being able to remain standing and to be robust in response to the various agencies that tend to cause a building to collapse or otherwise deteriorate, is discussed by Vitruvius but he had little specific to say about structure and, in particular, about procedures for producing configurations of elements that were stable. His remarks on building layout were principally concerned with the symbolic rather than the technical significance of number, and with the idea of *symmetria* – the relating of all of the dimensions in a plan or elevation to a single module or base-number through simple, whole-number ratios and the linking of these to ratios that were found in the natural world, especially in the human body. These ideas are architectural rather than technical because they are concerned with incorporating philosophical and theological considerations into the design of buildings. Vitruvius' ideas did not apply directly to such matters as the determination of wall and beam dimensions or arrangements that allowed buildings to achieve a state of static equilibrium in response to loads – the concern of structural theory. So far as can be determined, his rules were not based on any theory of structural behaviour and it is a matter of conjecture whether they were acceptable at the time as the sole justification for the proposed forms of large buildings. It is possible that additional technical justification was in fact required – see below. Vitruvius' treatise was, as is well known, subsequently widely promulgated throughout the medieval and Renaissance periods. The rules that it contained did have the virtue of being simple: as Heyman states, 'Vitruvius' rules were . . . so easy to grasp that even bishops could understand them' (1995, p. 2).

In the Roman Imperial period, the beginning of which coincided with the writings of Vitruvius, very large buildings were nevertheless successfully constructed, using sophisticated structural arrangements consisting of masonry vaults spanning between high walls that were also of masonry (Figure 7.4). (Many of the Roman vaults were in fact constructed in mass concrete but this is a material that has very similar structural properties to stone or brick masonry). Among the formidable technical problems with which the Roman builders had to contend was the possibility that the tall walls, being compressive elements, might become unstable and also that horizontal thrusts from the vaults which they supported might cause them to topple. The solution that they adopted was to make the walls very thick, both to minimise their slenderness, and to contain within their overall dimensions any thrust lines that might develop due to horizontal forces from the vault above. Their understanding of these problems must have been largely intuitive, however, as they could not have been aware of the concept of the thrust line. The builders *were* clearly aware, however, that although the walls had to be very thick they did not have to be solid and that great savings in material could be effected by incorporating voids of various kinds into the walls. The walls were given a constant thickness throughout their entire height but had large volumes extracted, thus producing an interesting architecture of the interior in the context of a building form in which a satisfactorily structural performance was achieved with great economy of means (see Figures 10.18 and 10.19).

The general principles that govern the equilibrium of large masonry structures were clearly well understood by the Roman builders and it is difficult to believe that they did not have rules of form-determination that were related to statics and stability – that they had, in other words, a body of knowledge that constituted structural theory and that was additional to anything described in Vitruvius.

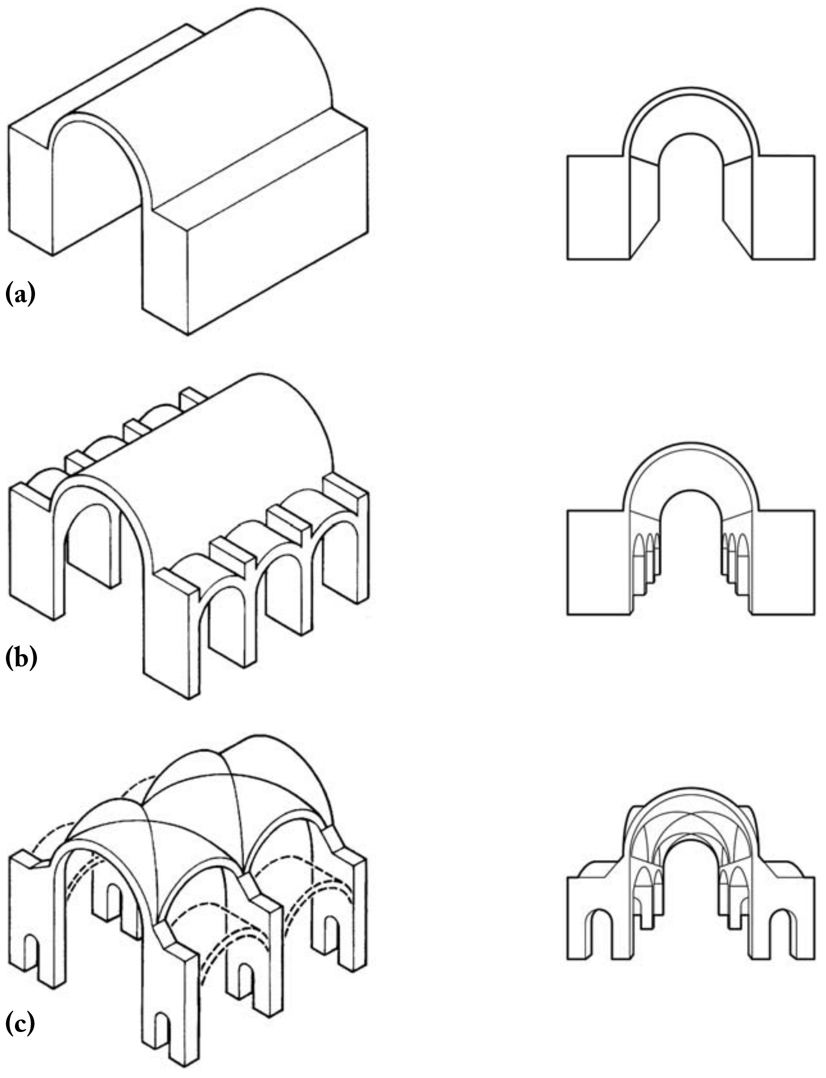


Figure 7.4 The evolution of the vault in Roman Antiquity. (a) Thick walls were required to support the barrel vault so as to contain the thrust lines within the structure. (b) The buttressing walls did not have to be solid. 'Improvement' of these semi-form-active elements (see Section 4.3) greatly reduced the volume of material required. (c) Use of cross-vaulting was a logical extension of the principle of 'improvement' applied to the walls. It had the added advantage of introducing flat areas above the supporting walls in which windows could be located (see also Figure 10.19).

Line drawing: Andrew Siddall after original by Angus J. Macdonald.

It seems likely that the Roman builders used geometric principles to achieve stability and equilibrium. These could not have been based on any systematic mathematically based theory of statics because such a theory did not exist at the time. They had presumably been determined empirically by codification of the dimensions of existing structures that were known to be successful, and probably also by the study of models. As Heyman pointed out, it is now known that the absence of scale effect would have made such a design method entirely feasible. Virtually nothing is known about the rules used by the Roman builders: what these consisted of, how they were formulated, or how they were promulgated. As Robert Mark states in his definitive book on early architectural technology, 'The best evidence for elucidating the early builders' knowledge and working methods remains the buildings themselves' (1993, p. 6). It may be conjectured, however, that codified rules did exist in Roman times and that these, rather than the number systems described by Vitruvius, were the *true structural theory* of the day. These are likely to have been the rules by which the structures were 'justified' technically. The distinction between these rules and the architectural principles expressed in Vitruvius is an important one because it draws attention to the probability that, even in this early period in which buildings of great architectural and technical sophistication were erected, architectural and structural theory were separate bodies of knowledge, concerned with different aspects of design. Architectural theory, such as Vitruvius' rules, was concerned principally with *appearance* and the philosophical preoccupations of the age – with architecture as a work of art; structural theory, such as it was, was concerned with *performance*, with determining arrangements that would guarantee *firmitas* – that is, with the creation of a building that worked well as a structure. It would appear, therefore, that this distinction between the intentions of structural and architectural theory has existed from earliest times.

One of the myths of architectural history has been the assumption that the methods used for determining the structural arrangements of large masonry buildings were derived by processes of trial and error. There is, however, little evidence that collapses of major structures actually did occur in Antiquity. Great pains must have been taken to avoid such disasters; apart from anything else they would have been extremely expensive. The builders of the early structures perhaps deserve more respect for their structural acumen than has been traditionally accorded to them, and as Addis has put it, their methods might be more aptly termed 'trial and success' rather than 'trial and error' (Addis, 1990, p. 188).

The several centuries that elapsed between the fall of Rome and the upsurge of architectural and structural creativity that produced the Gothic cathedrals were not a period of great innovation in the architecture of Western Europe. It is likely, however, that the knowledge of how to build large masonry structures somehow survived in the masonic lodge books and provided a basis for the upsurge of innovations that occurred in the Gothic period.

The building of the Gothic cathedrals was a period of extraordinary development in masonry construction in which large and very tall interiors, comparable in scale to those of Roman Antiquity, were constructed. These structures were notable for their geometric complexity and for the great economy that was achieved in the use of material. In the Gothic period, the structural vocabulary of the Romanesque period, of semi-circular barrel vaults supported on plain walls punctuated by small round-topped openings, was superseded by one of tall interiors spanned by vaults with pointed cross-sections and supported on filigree walls containing more void than solid, and buttressed by elaborate systems of flying ribs and arches (Figure 7.5). This extraordinary outpouring of structural creativity began in northern France with the cathedrals at Chartres and St Denis around 1130 CE, and within 200 years there were sixty of these remarkable structures in France and forty in England. The movement also spread across Europe, notably in Germany and Spain.

The builders of these structures demonstrated a deep understanding of the problems associated with the achievement of static equilibrium and stability in the context of a brittle material that had little ability to resist tension. As in the case of Ancient Rome, it seems inconceivable that they were not following codified rules and that the rules must have been evolved in the absence of anything resembling modern 'scientific' concepts such as force, centre of gravity or triangles of forces.

The master masons had to contend with the same problems as their predecessors in Roman Antiquity and responded with similar solutions – thick walls, voided this time with systems of flying buttresses to conserve material. The elaborate cross-sections of the medieval cathedrals (Figure 7.5), with their delicate systems of flying buttresses, are almost diagrams of the thrust lines produced by the vaults that they helped to support, and demonstrate a consummate understanding of structural behaviour on the part of the builders. The slenderness of the elements is remarkable and indicates that low levels of geometric factor of safety were achieved, presumably with confidence. The designers of these structures clearly knew how thrust lines would develop as the blocks of stone articulated by settlement during construction to create 'hinges' by crack formation. It seems improbable that such slenderness of masonry could have been achieved without the use of experiments with block models and there is some evidence that such devices were used. It is remarkable, however, that few such models survive and that so little written description of proven structural arrangements appeared in the literature; the lack of these is perhaps an indication of the secrecy with which the masons practised their craft.

As with Roman builders, we therefore look in vain for detailed rules that supported this achievement. The rules that *have* survived from the Gothic period consist of mere fragments of information contained in the notebooks of master masons such as Villard de Honnecourt, dating from the early thirteenth century. These demonstrate the use of geometric procedures for

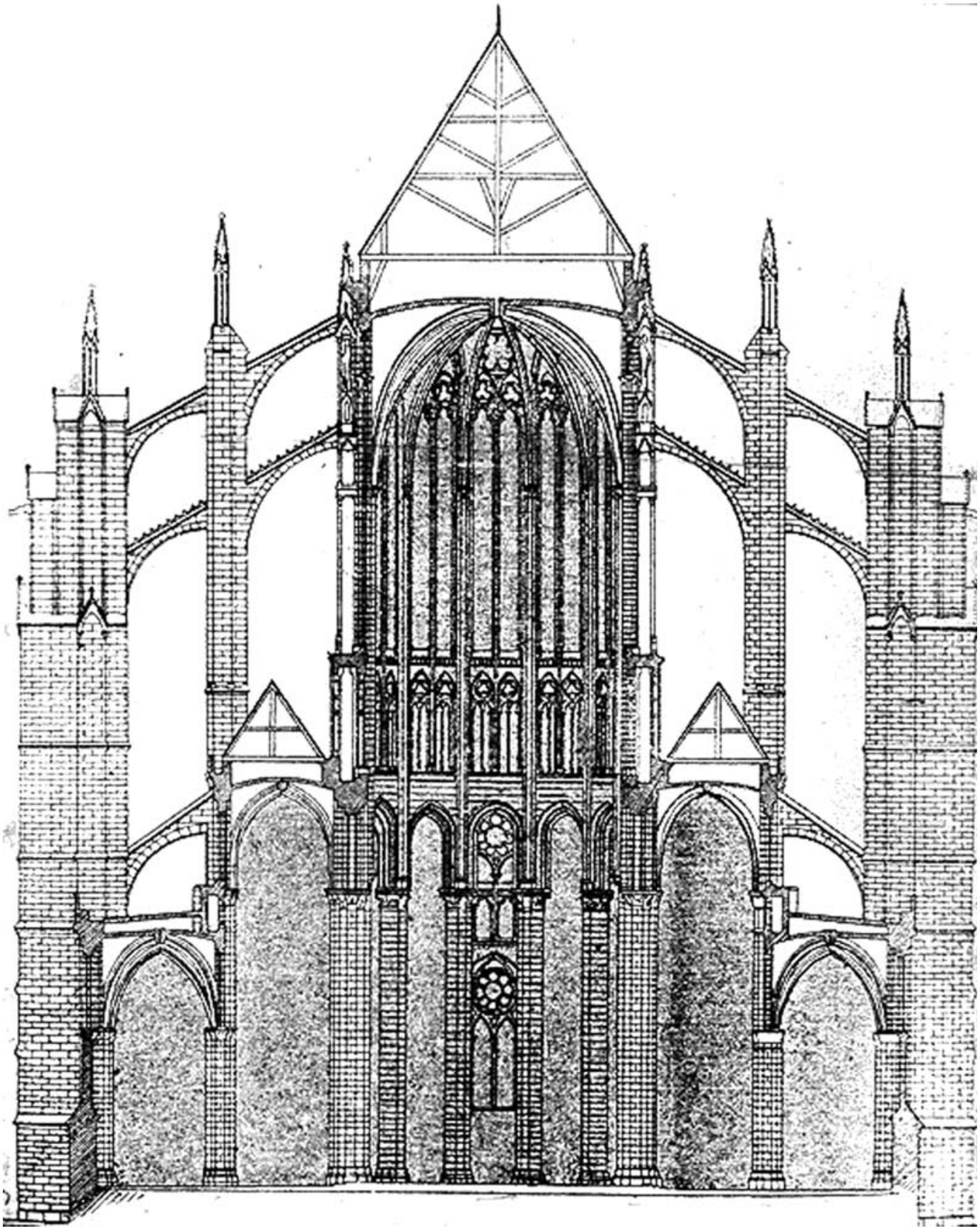


Figure 7.5 Cross-section of Beauvais Cathedral. Taken as a whole, the wall system supporting the vault is an 'improved' semi-form-active structure (see Section 4.3) subjected to a combination of bending moment (due to the vault thrust) and axial force (due to the combined weights of the vault and the wall system itself). Each individual cross-section in each of the constituent elements of the system is subjected to a combination of axial thrust and bending moment, and will therefore be subject to an eccentricity. The overall geometry of the system had to be such as to contain the thrust lines linking the eccentricities within the boundaries of the masonry elements. (After Benouville.)

Image: www.learn.columbia.edu; public domain.

setting out the planforms of buildings and the shapes of arches and vault cross-sections, and were almost entirely based on the most basic geometric figures of the square and the circle and their derivatives.

More complete presentations of rules for setting out masonry structures were published later by architectural scholars such as François Blondel (1683), and 'engineers' such as Bernard Forest de Bélidor (1729), the latter of whom compiled what is considered to be the first treatise on building engineering; these were again exclusively geometric procedures and, significantly, the rules were based on aesthetic considerations rather than those associated with stability or equilibrium.

Blondel's rules were probably the most influential of the early codifications that have survived and continued in use until the nineteenth century. They were remarkable for the absence of a direct connection to structural behaviour and were criticised by Bélidor for their lack of any basis related to technical performance. Blondel's rules were concerned principally with determining the shapes of parts of the structure that were visually significant, such as the *intrados* (profile of the underside) of arches, vaults and flying buttresses. The rules proposed for determining wall (buttress) thicknesses did have some connection with structural performance but yielded dimensions that were structurally conservative. The legitimacy of Blondel's rules, as justifiers for a design, seemed to rest on the belief that they were related in some way to the fundamental nature of the Universe (a core concept in Blondel's writings).

It was fortunate that, as Addis has pointed out, 'One of the advantages of the masonry arch is that it is actually quite difficult to build an arch that will fall down' (1990, p. 137). This should not be judged as a flippant remark as it encapsulates a fundamental property of masonry: the ability to bridge an opening without the support of a lintel. Such a property is demonstrated when an opening in a wall occurs unintentionally, for example in war zones where shell holes may occur in masonry walls without causing them to collapse. The mechanism that produces the 'bridge over unintended openings' is one of natural arch formation. The stones above the hole settle slightly under gravity and lock themselves together to form an arching effect that re-establishes equilibrium without the need for any particular profile along the upper edge of the opening.

The specification of the shape of the underside (*intrados* or soffit) of an arch using aspects of Euclidean geometry to provide semi-circles or other segmental derivatives of the circle such as the various versions of the Gothic pointed arch, which are described in manuals such as that of Blondel, is therefore largely irrelevant so far as structural performance is concerned. The careful shaping of *voussoirs* (wedge-shaped stones) may aid assembly and improve appearance and may carry symbolic meaning but is not necessary to produce a sound structure. Blondel's rules are therefore architectural rather than structural theory in the sense that they were chiefly concerned with appearance and only tenuously connected with technical performance.

Despite their lack of validity as guides to the technical performance of masonry structures, it appears that the geometric principles that were outlined in manuals such as Blondel's were accepted at the time by those to whom the design of the buildings had to be 'justified'. That the structures were sound and did not collapse, despite the remarkable slenderness of their elements was, however, presumably due to the understanding that the masons had of their material, rather than to the following of the 'theoretical' rules that existed in such manuals. The knowledge required to build a sound structure must have existed, but did not form part of the architectural theory of the day.

The recent analysis of masonry structures by Heyman (1995), described above, has demonstrated that geometric procedures *do* provide a valid method for determining the profile of an arch or flying buttress. The exact shape of the *intrados*, which was the main preoccupation of early guides such as Blondel, was not particularly significant but, if the arch was slender, it was important that its dimensions were sufficiently large to contain the thrust lines within its envelope. The theoretical demonstrations of this requirement were not developed until the seventeenth and eighteenth centuries, long after the Gothic cathedrals had been completed, by several subsequent investigators, notably Christopher Wren (1632–1723) and Robert Hooke (1635–1703) in England, who experimented with hanging chains to determine the profiles of thrust lines ('form-active' shapes – see Chapter 4) and the work of these practitioner-theorists greatly contributed to the understanding (in fact probably a rediscovery) of the behaviour of masonry structures. This enabled arches to be 'justified' and constructed with safety but there remained nevertheless much preoccupation, in the seventeenth and eighteenth centuries, with the question of the internal profile (*intrados*) which was in fact not critical structurally.

The work of Wren and Hooke, which culminated in the remarkable design for the dome of St Paul's Cathedral in London, was particularly significant in terms of structural engineering because it represented the beginning of a new approach to structural design, based on refining the understanding of the behaviour of structures through 'scientific' experimentation. Their methodology anticipated the modern era of structural design.

By the time that the behaviour of the masonry arch had been fully understood (or rediscovered) in the nineteenth century, and a theory based on technical performance developed, this structural form was being replaced by arches in iron, steel and reinforced concrete. As these carried significant levels of stress, and therefore strain, their justification had to be based on a theory that took account of the ways in which structures deform under load (elastic theory) and the use of purely geometric procedures was gradually replaced by calculations (grounded rules) for the determination of element sizes.

7.2.3 Conclusion

This short review of the role of structural theory in the evolution of the designs for the major structures of Antiquity and the medieval period has necessarily required that assumptions were made concerning the exact nature of such theory as was available, given the scarcity of the records that have survived. It seems reasonable, however, to conclude that a considerable knowledge base did exist concerning the technical behaviour of the massive masonry structures that were constructed during these periods and that this constituted the real structural theory of the time. Very little of this has survived in written form.

One of the most revealing conclusions that may be drawn from Heyman's penetrating analysis of the behaviour of masonry structures is that the procedures for the design of buildings that were advocated in the architectural treatises that have survived from Antiquity and from the medieval and early Renaissance periods, such as Vitruvius, Alberti, Palladio and Serlio, and later works such as that of Blondel, had only minimal relevance to structural performance. As Addis has remarked (2007, p. 198), these treatises were 'stylistic guides' concerned with the aesthetics of buildings rather than their technical performance. They were, in other words, *architectural* theory rather than *structural* theory and, despite the fact that they may have contained some references to technical matters, such as the selection and preparation of materials, they were not comprehensive or authoritative manuals for building, as has frequently been assumed in writings on historic architecture.

It is significant that, even in the pre-Renaissance period, when designers were apparently much closer to the workforce than was the case in post-Renaissance times, this distinction between architectural and structural theory appears to have been quite clear-cut. The distinction remains in the present day and has important consequences for the potential development of an architecture that is environmentally sustainable (see Section 11.6).

7.3 Example 2: the evolution of structural theory based on the use of 'grounded rules' – calculations based on elastic theory

7.3.1 Introduction

Attempts to base structural theory on knowledge of the physical behaviour of materials and structures have their origins in the development of the physical sciences generally from the time of the Italian Renaissance. In discussing the emergence of a 'scientific' theory of structures it is necessary to make a distinction between *engineering science* and *engineering practice*. Engineering science is one of the physical sciences and is concerned with 'understanding and explaining the world' (Addis, 1990, p. 36). Engineering practice is concerned with using the discoveries of engineering science as a basis for designing structures that will function satisfactorily in every way (i.e. that will be buildable, durable and perform their intended function with reasonable economy of means). As Addis has pointed out, the key difference between these two approaches lies in their aims. The objective of engineering science is *discovery* of how the world works; that of engineering practice is the *production* of useful artefacts. The field of **structural theory**, as the term is currently used, is concerned with employing the discoveries of engineering science in the service of engineering practice. To maintain an awareness of the scope and validity of any procedure it is, however, always necessary to bear in mind the different aims of engineering science and engineering practice.

The principal contribution that engineering science has made to the structural design process has taken the form of *grounded rules*, which have been defined by Addis as 'rules which were based on an explanatory theory of some kind' (Addis, 1990, p. 55). An example of such a **grounded rule** is the following formula, which allows the size required for a beam (given by Z_{req}) to be calculated from the applied load (which determines M) and the strength of the constituent material (from which σ_p is derived):

$$Z_{req} = M/\sigma_p$$

where

Z_{req} = the Section Modulus of a beam (a geometric property of the beam's cross section)
M = the bending moment caused by the load
σ_p = the maximum stress permitted in the beam.

It is the equivalent of the **geometric rule** ('rule of thumb') for determining beam depths (for example, span/depth ratios) discussed in Section 7.1. It is a much more useful procedure, however, because it can deal with any material whose strength is known and can be applied to any element in which bending occurs, not just to a single typology such as a floor beam, as is the case with most **geometric rules**. This particular grounded rule is derived from the Euler-Bernoulli Elastic Bending Equation (See Section 7.3.3).

It is, nevertheless, important to note that the engineering science on which most grounded rules are based relies on simplifications of the true, and extremely complex, behaviour of structures, rather than on exact simulations of it, because such simplifications were necessary to develop theories that could be described mathematically. When applying grounded rules, practitioners have to be aware that the theories on which they are based do not provide exact simulations of the 'real' world and to employ procedures, such as the use of factors of safety, to take account of the limitations of the theories (see Section 7.3.5). Before considering our example here of one such theory (the Elastic Bending Theory) it is also worth noting, as will be discussed later, that the problem just identified is only one of the various levels of uncertainty involved in the use of grounded rules.

The historical development of a numerical understanding of structural behaviour depended on the scientific definition of certain fundamental concepts such as force, elasticity and strength. The idea of force was discussed by Aristotle but its rigorous definition, in classical mechanics, was not formulated until the work of Isaac Newton in the late seventeenth century, despite the fact that the concept of a triangle of forces and the associated idea that two or more forces could be considered to have a single **resultant**, had been described by Leonardo da Vinci in the early sixteenth century. The development of calculus in the eighteenth century was also essential for the evolution of quantitative structural theory.

Theory concerned with the strength of beams originated with Galileo in the seventeenth century but the most significant contribution to the understanding of beam behaviour was the development of the **Elastic Bending Theory** by Leonhard Euler (1707–1783) and various members of the Bernoulli family in the mid-eighteenth century. Euler was also responsible for the extension of the beam theory to the important problem of **buckling** of compression elements.

The introduction of the discoveries of engineering science to engineering practice and the design of structures was slow and did not occur until the nineteenth century, when it became desirable in relation to the development of the new structural materials of iron and steel, and the rise of a consciousness of an obligation on the part of the designer to produce a structure that contained no more material than that required to provide adequate strength and rigidity, together with a reasonable degree of safety. Numerical methods for the analysis of triangulated frameworks and the evaluation of beam and column strengths were gradually introduced from the middle of the nineteenth century and had become more-or-less standard practice by its end.

As stated above, the grounded rules that have been developed by engineering practice from the theorems of engineering science give only an approximation to the true behaviour of structures. The uncertainty caused by the likelihood that calculated strengths might be significantly different from those that actually occur in practice is managed by the use of factors of safety.

7.3.2 The theory of elasticity and its applications

It is not an exaggeration to state that the one of the most important concepts in the field of structural theory is that of **elasticity** and, in particular, of the application of the ideas of elasticity to the understanding of the complex phenomenon of **bending**. Elasticity is concerned with the way in which materials behave in response to load and, in particular, with the relationship between load and deformation, and it was the study of this physical property of structures that enabled equations to be developed that linked load to internal force and stress.

The key concept in classical elastic theory is that the relationship between load and deformation is linear, which means that the amount of deformation that occurs when a load is applied to a material is directly proportional to the magnitude of that load. This is behaviour that can be described mathematically by equations that do not contain terms that are squared (x^2) or of higher powers (x^3, x^4, etc.) (that is, '**linear' equations**) and that produce straight-line graphs when plotted on Cartesian axes. The assumption of such a property places the elastic theory firmly in the realm of Newtonian physics, in which the behaviour of the physical world is considered to be governed by a small number of fundamental laws of nature, each of which can be described by a simple formula. Such ideas have contributed significantly to the development of the sophisticated technology of the modern world but recent thinking in the fields of mathematics and the physical sciences has shown that the physical world is very much more complicated than that described by classical physics and in reality often behaves in 'non-linear' ways that are more difficult to describe mathematically. This means that it should be accepted from the outset that the linear world of classical elastic theory, on which much of structural theory is based, is in fact an approximation only of what actually occurs in the physical world, a consideration that has significant consequences for structural engineering, and especially for structural practice and the development of grounded rules, as discussed here in Sections 7.3.4 to 7.3.6.

Two examples of the application of elastic theory to structural practice will now be discussed. The first of these is the use of the Euler-Bernoulli Elastic Bending Formula as a basis for sizing elements that undergo bending (Sections 7.3.3 and 7.3.8), and the second is a more general application of elastic theory to the analysis of structures (Sections 7.3.9 to 7.3.12).

7.3.3 The Euler-Bernoulli Elastic Theory of Bending (also known as Euler-Bernoulli Beam Theory, Engineer's Beam Theory and Classical Beam Theory)

Bending is a highly complex phenomenon in which the material at every location in an element is subjected simultaneously to tension and compression (stretching and squeezing) in two directions at right angles to each other (orthogonal directions). An indication of the level of complexity is given in Figure 7.6 in which the principal directions of tension and compression in a simply supported beam (perhaps the simplest of bending elements) are shown as hatched and solid lines respectively. These show only the *directions* of the stresses; the *magnitudes* vary both along the length of each line and between lines.

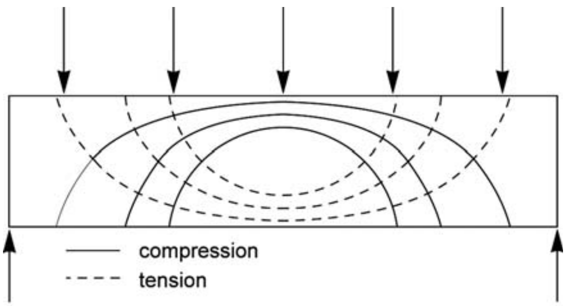


Figure 7.6 Principal stresses in a simply supported beam. At every location the material is subjected simultaneously to tensile and compressive stress acting in two mutually perpendicular directions. The lines indicate the directions only of these principal stresses; their magnitudes vary along the length of each line and between lines. The diagram illustrates the complexity of the bending phenomenon.

Line drawing: Andrew Siddall after original by Angus J. Macdonald.

The Euler-Bernoulli Theory allows every aspect of this highly complex behaviour to be described and provides an excellent example of the way in which engineering science employs mathematics as an aid – albeit partial – to the understanding of the physical world.

The Euler-Bernoulli Equation (see box, p. 139) is a fourth-level differential equation in which the fourth **derivative** (i.e. the result of four processes of **differentiation**) of the beam's deflection (w) is equated to the applied load (q). In accordance with the rules of calculus, the equation must be **integrated** four times to determine the deflection of the element (Figure 7.7). Every stage in the integration yields information which can be useful in design practice. The first two stages give the internal forces of shear force and bending moment, which are essential for beam-sizing calculations, such as the well-known beam-sizing formulae (grounded rules): $\sigma_y = My/I$ and $Z_{req} = M/\sigma_p$ (see Section 7.3.4). The third and fourth stages in the integration give the **slope** and deflection of the loaded beam and have been used as the basis for large bodies of structural analysis theory (see Section 7.3.9).

Both the brilliance of Euler's and Bernoulli's ideas and the power of mathematics to describe complex phenomena with simple equations, and thus provide aids to the understanding of them, are demonstrated in Figure 7.7. Each of the graphs shows how the magnitude of a particular quantity varies along the length of the beam and the sequence of diagrams gives information about how the various quantities are related to each other. In any one of the graphs, the magnitude of the quantity for a particular value of x is directly proportional to the gradient (slope) of the diagram immediately below. The rules of calculus tell us that these gradients are connected to rates of change. Thus, the shear force at any point in a beam is directly proportional to the rate at which the load is changing at that point, and the bending moment is proportional to the rate of change of shear force.

(a) Diagram of load (q per unit length)

(b)–(f) Structural parameters shown as functions of x (distance along beam):

(b) Load $q(x) = EI\, d^4w(x)/dx^4$

(c) Shear force $V(x) = EI\, d^3w(x)/dx^3$

(d) Bending moment $M(x) = EI\, d^2w(x)/dx^2$

(e) Slope $\theta(x) = EI\, dw(x)/dx$

(f) Deflection $w(x) = EI\, w(x)$

[Constants of integration not shown]

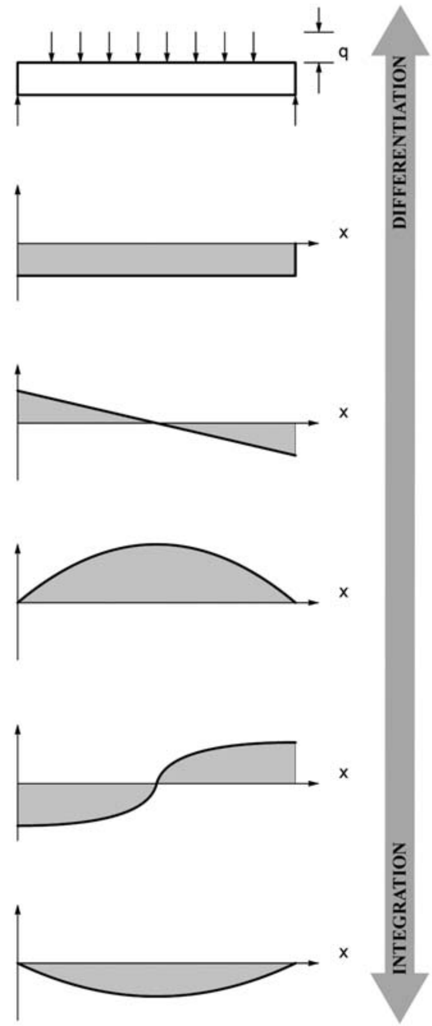


Figure 7.7 The Euler-Bernoulli Elastic Bending Equation. Successive integration of the equation (i.e. moving down this diagram) yields information on the significant parameters affecting the bending of a simply supported beam carrying a uniformly distributed load: (a) the load condition; (b) the basic version of the equation with the load condition expressed as a function of x; (c) first integration gives shear force; (d) second integration gives bending moment; (e) third integration gives slope of deflected form; (f) fourth integration gives deflected form.

The magnitude of each quantity, for a particular value of x (position in the beam), is directly proportional to the rate at which the quantity in the graph immediately below is changing at that location. In structural analysis, if any one of the quantities can be found as a function of x, all of the others can be derived by either integration (moving down the diagram) or differentiation (moving up the diagram).

The Euler-Bernoulli equation provides a good illustration of the power of mathematics to describe simply a highly complex phenomenon. The description is, however, an idealisation of the condition of a real structure.

Line drawing: Andrew Siddall after original by Angus J. Macdonald.

Euler-Bernoulli elastic bending equation

In its most basic form the Euler-Bernoulli Equation is:

$$EI\ d^4w(x)/dx^4 = q(x)$$

where x and w relate to a Cartesian co-ordinate system whose origin is at the end of the beam: x is the distance along the beam and w is the deflection at x due to bending. E is the Modulus of Elasticity of the material (**Young's Modulus**) and I is the Second Moment of Area of the beam's cross-section. I is a purely geometric property of the cross-section which depends on its size and shape. (See Glossary for more detailed explanations of these terms). q is the load on the beam. In the most general case E and I, as well as q, can vary with x (i.e. along the length of the beam) in which case the formula is written:

$$d^4w/dx^4 = q(x)/E(x)\ I(x)$$

The equation has to be integrated four times to calculate w, the deflection of the beam at any point x along its length.

The formula is based on the following simplifying assumptions:

- that the beam was originally straight;
- that cross-sections that were plane in the straight beam (before bending) are also plane in the bent form;
- that the amount of bending is small;
- that the material behaves elastically (linearly) in response to load, i.e. that the amount of deformation (squeezing and stretching) that occurs at any point as a consequence of the bending, is directly proportional to the intensity of the load causing the bending (spring-like behaviour).

None of these assumptions is strictly valid so the formula can never give other than an approximate representation of the behaviour of the beam.

7.3.4 Grounded rules based on the Euler-Bernoulli theory

Perhaps the most commonly used grounded rule that is derived from the Euler-Bernoulli Equation is the one that allows the stress at any point in the beam to be calculated, usually expressed as:

$$\sigma_y = My/I$$

where:

σ_y = the stress in the beam at a distance y from its Neutral Axis (centroidal axis)

(Note that y here does not relate to the co-ordinate system on which the Euler-Bernoulli Equation is based (both the position of the origin of the orthogonal axes, and the letters w, x, y, and z assigned to the Cartesian co-ordinates, are different in the two equations). This is an unfortunate potential source of confusion but these are the symbols that are traditionally used.)

M = the bending moment at the cross-section for which the stress is being calculated
I = the Second Moment of area of the beam cross-section about its Neutral Axis.

(Note also, that the derivation of the relationship between the quantity I, which takes account of the shape of the beam's cross-section, and the level of bending stress that is present, involves the assumption that the curved profile of the beam experiencing bending is a circular arc. This is obviously an approximation to the deflected shape defined by the Euler-Bernoulli Equation (and therefore an additional assumption) but for small levels of deflection the discrepancy is acceptable.)

The second important grounded rule that has been derived from the Euler-Bernoulli Equation is that which relates the load carried by a beam to the maximum stress that will result, and which is usually expressed as:

$$Z_{req} = M/\sigma_p$$

where σ_p = the maximum stress permitted in the beam.

$Z = I/y_{max}$ and, like I, is a geometric property of the beam's cross-section related to its size and shape.

(Note that this is, rather unfortunately, though by tradition, called the **Elastic Modulus of Section** (or simply **Elastic Modulus**) of the beam, and should not be confused with Modulus of Elasticity (E – Young's Modulus), which is a property of the material from which the beam is made).

y_{max} is the distance, in the cross-section, from the neutral axis to the extreme fibre.

As noted in the introductory Section 7.3.1, the second of these two formulae is particularly useful in design because it relates the load that the beam carries (which determines the level of the bending moment M) to the maximum stress that will result, through a quantity (Z) that is linked to the size of the beam. The formula can be used to select a size of beam that will ensure that, under the action of the maximum predicted load, the maximum **permissible stress** in the material (σ_p) will not be exceeded. For this reason it is one of the most commonly used formulae in the whole of structural engineering. It is an example of an ideal grounded rule: based on a theory of structural behaviour and simple to use to produce a reliable justification of a design.

7.3.5 The limitations of grounded rules and their consequences

The two examples quoted above are *grounded rules* based on the Euler-Bernoulli Elastic Bending Equation which was, in turn, derived from an idealised model of the highly complex behaviour of a material loaded in bending and which provides an approximation only to the true behaviour of a beam. The uncertainties caused by this idealisation are therefore built into the grounded rule at a fundamental level.

In design practice, uncertainties are also present in the estimation of the values for permissible stress (σ_p) and bending moment (M). σ_p is determined from the strength of the material – the value of σ (stress) at which failure will occur. The accuracy with which this can be known depends on the material. The strength of steel, which has consistent properties and which is manufactured under conditions of very strict quality control, is known with a fair degree of certainty, but those of timber or concrete much less so. The bending moment that occurs in a beam is calculated from an assumed value of the maximum load to which it will be subjected and this will depend on the function of the structure – for example, the floor of a warehouse is likely to be subjected to heavier loading than that of a house. Likely loads can be broadly quantified but the precise maximum load that will be applied to a particular floor throughout the lifetime of a building can never be known with certainty.

The use of grounded rules that are based on the Elastic Bending Equation therefore involves two different types of uncertainty. The first of these is due to the degree to which Euler-Bernoulli Bending Theory can simulate the true behaviour of a real structure. As will be discussed in Sections 7.3.9 to 7.3.12, this applies to the calculation of bending moment as well as to the evaluation of stress that results from it. The second is due to the difficulty of accurately estimating values of input quantities such as load and material strength.

In engineering practice, which operates at the interface between theory and reality, this problem is managed by the use of statistical procedures. Even if neither the load to which a structure will be subjected nor the strength of its material can be known with certainty, the *probability* that a design load will be exceeded or an assumed strength of material not reached *can* still be determined. This takes the evolution of grounded rules for structural design into the realm of *risk analysis*, in which the purpose of structural design calculations may be regarded as to control systematically the *level* of risk that a structure will fail. This is, in fact, an inevitable consequence of the use of numerical methods as the basis for justifying the design of a structure.

7.3.6 Risk analysis and factors of safety

A concept that is fundamental in risk analysis is that of *factor of safety*, the amount by which the actual strength of a structure should exceed its required strength so as to allow for the many uncertainties that exist in the design and construction processes, both those that are 'built in', due to the use of simplifying assumptions, and also those that occur due to statistically managed uncertainties such as load unpredictability. As with all aspects of safety management the desire for a high level of safety, which would favour the use of large factors of safety, must be balanced against the need for economy, which encourages a higher level of risk being taken and a lower factor of safety.

The purpose of employing a factor of safety is to try to ensure that the risk of failure is maintained at a known level that is acceptably low. There are three aspects to this: first, there is the question of the *level of risk* that is acceptable that a structure may fail; second, there is the matter of the *size of factor of safety* that is required to deliver a given level of risk; and third, there is the question of the *location of the factor of safety* in the calculation process.

The question of what level of risk is acceptable is a matter for society as a whole to determine, acting through its government agencies. The ultimate question is: to what level of risk should a person be exposed that they will be killed as a consequence of a structure malfunctioning? Various attempts have been made to answer this question – such as that the risk should be no greater than that they will die through 'natural causes' – a risk that can be evaluated actuarially. Such matters are not primarily the concern of structural theory and are not considered further here. The relationship between the sizes of the factors of safety that are used in calculations and the level of risk that these actually deliver, so that the level of risk deemed acceptable by society is achieved in practice, is a matter for statistical theory rather than structural theory and is also not considered further here.

The organisation of calculations so that they deliver a structure whose strength is greater than that required in service by the amount of the factor of safety is an aspect of risk management that impinges on structural theory because the value of the factor of safety that is actually achieved cannot be known unless the load required to cause the structure to collapse can be calculated. As is discussed in Section 7.3.8 below, this is something that is difficult to determine by the use of elastic theory only and it raises a fundamental difficulty associated with the use of elastic theory as the basis for a grounded rule for sizing beams.

7.3.7 Summary

Despite the uncertainties caused by the assumptions made in its derivation and those associated with its practical application, the development of grounded rules based on the Euler-Bernoulli Elastic Bending Equation was a very significant contribution to the theory of structures because it provided numerical methods by which the dimensions of elements loaded in bending could be justified, and it was especially relevant to materials that behave elastically such as timber or steel. In the context of these materials, it was a great advance on the geometric rules (rules of thumb) that had been used in the pre-Modern period for determining appropriate sizes for beams.

7.3.8 Ultimate Load Theory – a strategy for dealing with one of the limitations of the grounded rules derived from the Elastic Bending Equation

One of the simplest examples of the use of a grounded rule based on elastic theory, is the formula discussed earlier in Section 7.3.4, for determining the size required for a beam:

$$Z_{req} = M/\sigma_p$$

The factor of safety appears in the stress term σ_p, which is found by dividing the **yield stress** of the material (see Glossary) by the factor of safety. Use of the formula is intended to ensure that the actual stress that occurs under service loads is less than the yield stress of the material by the amount of the factor of safety. Achievement of the yield stress is thus used as the criterion of structural failure and the reason for this is that it is usually assumed (for a number of good reasons) that the performance of the structure will be unsatisfactory if the actual stress is allowed to exceed the yield stress value.

The basing of the permissible stress on the yield stress value is therefore a sensible procedure because it results in the calculation procedure simulating what will actually occur in the beam under service loading conditions. It is, however, problematic from the point of view of the rational management of risk because the beam would not actually collapse if the yield stress were to be reached and would in fact be capable of carrying a considerably greater load. The reason for this is that the stress at which the material actually fails structurally is significantly greater than the yield stress. The true factor of safety, and therefore the true degree of risk involved, is therefore unknown with this procedure and could only be known if the exact value of load at which the beam would collapse were to be calculated. This difficulty cannot be overcome simply by basing the permissible stress on the true failure stress of the material because, once the yield stress has been exceeded, the material no longer behaves elastically (linearly) and the elastic theory is no longer capable of accurately predicting its behaviour. Elastic theory cannot therefore be used to calculate the **collapse load** (strength) of the beam.

To address this problem a completely different approach was devised to justify the designs of beams in the context of rational risk management. This resulted in the creation of a new field of structural theory called **ultimate load theory** (also referred to as **load factor theory** and **plastic design**).

To evaluate the true factor of safety against collapse it is necessary to use a calculation procedure that is capable of simulating the behaviour of a beam at

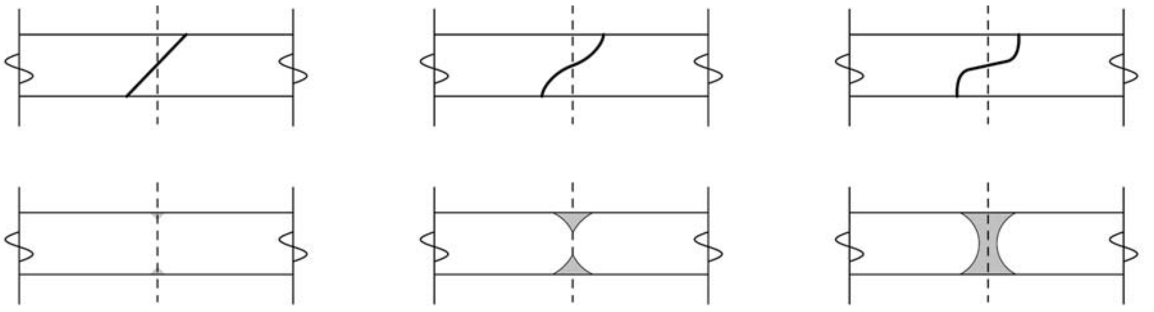


Figure 7.8 Plastic hinge formation. Upper row shows stress distribution; lower row indicates locations of material stressed above elastic limit (shaded). (a) Within the elastic range, the stress distribution in a beam cross-section is linear with maximum stresses at the extreme fibres. (b) If the load is sufficient to cause the yield stress to be exceeded at the extreme fibres, further increase in load does not cause increase in stress in the yielded material. Stress continues to rise in the unyielded material and the pattern of stress changes. (c) Under increasing load the yielded material causes the equivalent of a hinge to form.

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the point at which it actually collapses. This is difficult because the **non-linear behaviour** of most materials, as failure is approached, affects the distribution of forces within the structure. To illustrate the various difficulties that had to be overcome in this context the mechanisms by which steel structures collapse are considered here. Steel was one of the simpler materials to deal with, due to its consistency and isotropic behaviour, but, as will be seen, even with steel the prediction of the exact value of the load required to cause collapse was nevertheless a highly complex problem.

The key concept in the theory of ultimate load (plastic) design for steel frameworks is that of the **plastic hinge**, which simulates the behaviour of a beam once the yield stress has been exceeded and as the collapse state is approached. The sequence of the development of a plastic hinge is described in the box 'Concept of the plastic hinge' and Figure 7.8.

The 'plastic hinge' behaves like a real hinge but with a distinctive characteristic – it is not entirely free to rotate – it offers a constant level of resistance to rotation. It may be visualised as a hinge that is formed by clamping two steel plates together with a bolt. When the bolt is loose the two elements may rotate freely with respect to each other. When the bolt is tightened, they may still rotate but the contact surfaces offer a constant frictional resistance to rotation due to the tightening effect of the bolt. A plastic hinge behaves as though the bolt had been tightened to develop significant friction.

The concept of the plastic hinge allows the collapse sequence of a steel element to be simulated. A very basic simply supported beam carrying a uniformly distributed load demonstrates the principle. The simply supported beam has, in effect, hinge connections at its supports (Figure 7.9). It is also

The concept of the plastic hinge

At low levels of stress, where the material is behaving elastically, the Elastic Bending Equation provides a reasonably accurate prediction of the level of bending stress within the beam, which the equation shows to be varying constantly through each cross-section from a maximum tensile stress at one extreme fibre to a maximum compressive stress at the opposite extreme fibre (Figure 7.8a). If the load is increased the stress will increase uniformly in all parts of the cross-section and eventually the yield stress will be reached at the most highly stressed parts, at the extreme fibres.

Once the **yield point** is passed the increase in stress that occurs for a given amount of strain decreases markedly so that very much more strain is required to generate more stress. If the beam in which the yield point has been exceeded at the extreme fibres is subjected to yet more load (and therefore more strain), the increase in the strain that occurs at the extreme fibres does not produce more stress at that location. The stress at fibres away from the extreme fibres is still within the **elastic limit**, however, so more strain at these locations will continue to produce more stress. The stress distribution within the cross-section therefore changes shape once the yield point has been passed in the material in the extreme fibres (Figure 7.8b). This explains why the elastic bending formula does not accurately simulate the behaviour of the beam once the yield stress has been exceeded at the most highly stressed point. If the load is increased further, the locations at which the yield stress is exceeded migrate horizontally along the extreme fibres and also vertically down through the cross-section (Figure 7.8b).

A way of visualising this is to imagine that the material that has yielded has become soft. It still provides resistance when load (and therefore strain) is increased but this remains constant instead of increasing as the strain increases. Figure 7.8c shows the yielding material shaded and from this it can be imagined that a 'hinge' (a 'plastic hinge') has formed.

free to move horizontally at one of its ends at least. For it to collapse, a third hinge is required to convert it to a mechanism. Under an increasing load this will occur at the point of maximum bending moment (mid-span) due to the formation of a plastic hinge at that location. Calculation of the bending moment required to bring about the formation of a plastic hinge allows the collapse load to be evaluated. The true factor of safety of the system is the ratio of this calculated value of collapse load to the maximum load that the beam will be expected to carry in service.

A procedure for the allocation of sizes to beams can be based on the phenomenon of plastic hinge formation. It requires first, that the expected service load be multiplied by the factor of safety to give a factored **design load**. A beam size is then determined, using the concept of the plastic hinge, such that it will collapse at the level of the design load and its strength is therefore greater than the service load by the amount of the factor of safety.

One of the difficulties associated with the plastic design method is the problem of simulating the plastic hinge mathematically. This procedure is

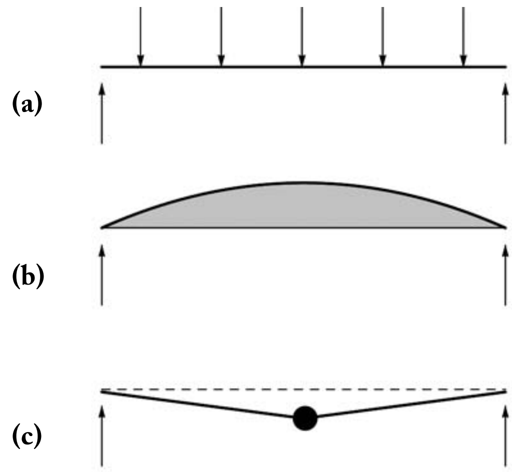

Figure 7.9 Under increasing load, a plastic hinge will form at the location of maximum bending moment (in this case mid-span). Collapse occurs when the load is sufficient to bring about full formation of the plastic hinge: (a) uniformly distributed load on a simply supported beam; (b) bending moment diagram indicating maximum bending at mid-span; (c) collapse initiated by formation of plastic hinge at location of maximum bending moment.

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required to provide a *grounded-rule formula* which links yield stress, load and the dimensions of the beam cross-section, at the point at which collapse is initiated. Among the problems associated with this is the fact that, at the point of formation of the plastic hinge, the relationship between stress and strain is non-linear. For this reason, the design formulae that are used in routine design are determined by extensive testing of prototype beams, of a large range of sizes and shapes. The design formulae contain empirically determined parameters which means that their application is restricted to the types of beam used in the testing. They are not based on a universally applicable theory – an example of the distinction between engineering science and engineering practice.

The design of a simply supported beam by the plastic method (discussed above) is perhaps the simplest example of its use. Its application to the design of the complicated three-dimensional frameworks used to support multi-storey buildings is of a different order of magnitude of complexity (see Section 7.3.10).

7.3.9 Use of the Euler-Bernoulli Equation for the analysis of structures

The techniques for the analysis of complex structural frameworks – the process by which internal forces such as bending moments (M) are calculated from loads, and which is an essential preliminary to the determination of sizes for elements, by whatever method – constitute a very large body of structural theory and space does not permit a comprehensive treatment of this here. The underlying principles on which it is based are, however, relatively straightforward and an explanation of these is now given, as this will help to contribute to the discussion of the role played by the Euler-Bernoulli Equation in structural design in the Modern period and in the present day.

In the case of large frameworks with many elements, the number of unknown bending moment values that have to be calculated is very large – in theory infinite because the bending moment normally varies continuously within any one element. Fortunately, the distribution of bending moment within an element can be evaluated if the values of bending moment at its ends are known. The critical number of unknowns for a complete analysis is therefore finite (two for every element in the frame). To analyse the structure fully, sufficient simultaneous equations must be generated to solve for this number of critical unknowns. The Euler-Bernoulli Equation can be used to generate the required equations (see box 'Elastic analysis of a large framework'), due specifically to its ability to allow the slope of the deflected form to be calculated.

The process that generates the simultaneous equations necessary to analyse the structure fully by this method is, however, one of trial-and-error, albeit of a relatively sophisticated kind. The reason for calculating the magnitudes of the internal forces is to allow suitable sizes to be allocated to the elements. Operation of the Euler-Bernoulli Equation for analysis (see box) is, however, dependent on knowing the value of EI, and therefore the size, of each element in advance. This conundrum is resolved in structural design by an iterative process in which trial sizes are used for an initial analysis and then adjusted subsequently, following calculation of the resulting internal forces, and the process is repeated until a satisfactory result is achieved.

When the elastic theory was first applied to the analysis of multi-storey frameworks, in the early decades of the twentieth century, one of the major problems was the solution, by hand calculation methods, of the very large number of simultaneous equations involved (literally hundreds in a frame of only moderate size). In design practice this daunting task was sometimes avoided altogether by the expedient of designing each beam as though it were a simply-supported beam. This allowed the bending moment to be calculated easily but was highly extravagant with material because it ignored the ability of joint continuity to reduce bending moment levels and seriously overestimated the level of bending moment that was actually present.

Various other methods were developed during the first half of the twentieth century in attempts to make the calculation process manageable without compromising accuracy, but these were often protracted when applied to large frameworks, and were usually abbreviated by expedients such as isolation of particular parts of the structure (for example by considering a single storey

Elastic analysis of a large framework

As was discussed in Section 7.3.2, the basis of the elastic analysis of structures is the idea that the amount of stress that occurs in the material of a structure depends directly on the amount of strain (deformation) that has occurred as a consequence of the application of load. This applies at the level of an individual piece of material and also to the behaviour of entire structures. Stress may be thought of as resistance to load and, because this is related to deformation, the manner in which internal forces (resistance) are distributed through a structure depends on the way in which it deflects in response to load and, in particular, on the relative stiffness of the elements; the stiffer parts attract a larger proportion of the load. It is this property of structures that forms the basis of elastic analysis.

To understand how this property affects the distribution of internal forces in large structures it is instructive to begin with a simple example, that of two vertical cantilevers, with differently sized cross-sections, which are connected together so that they are constrained to have the same deflection in response to load (Figure 7.10). According to Euler-Bernoulli Theory, the stiffness of each of the elements is given by the ratio EI/L where E is the modulus of elasticity of the material, I is the second moment of area of the element's cross-section (different in the two elements in this case) and L is the length of the element. If the two cantilevers were unconnected, the deflections that would occur in each would be determined by its respective value of EI/L. As a consequence of being constrained to undergo identical amounts of deflection, the two cantilevers share the load in proportion to the relative values of EI/L, with the stiffer element taking the greater share of the load.

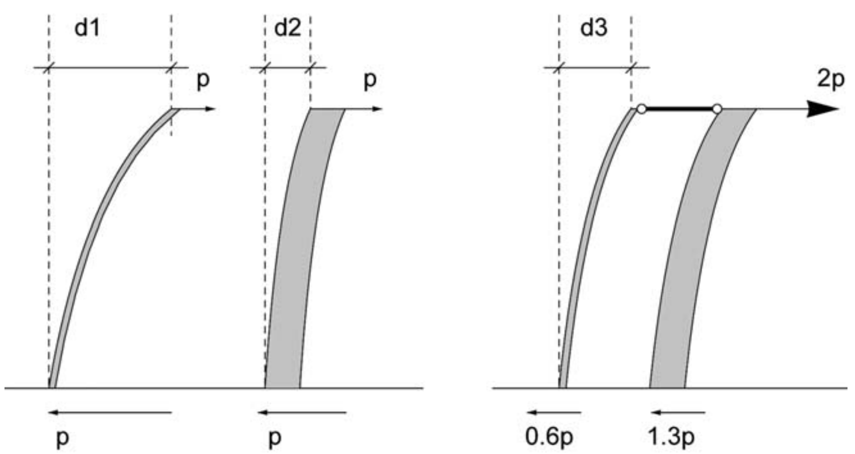

Figure 7.10 Principle governing the distribution of internal force during elastic behaviour. (a) When unconnected, the two dissimilar cantilevers (one twice as stiff as the other) undergo different amounts of deflection when equal amounts of load are applied. (b) When the cantilevers are connected, and must undergo an equal amount of deflection, part of the load passes across the connecting link and the cantilevers share the total load in proportion to their stiffnesses, with the stiffer cantilever carrying the greater share of the load.

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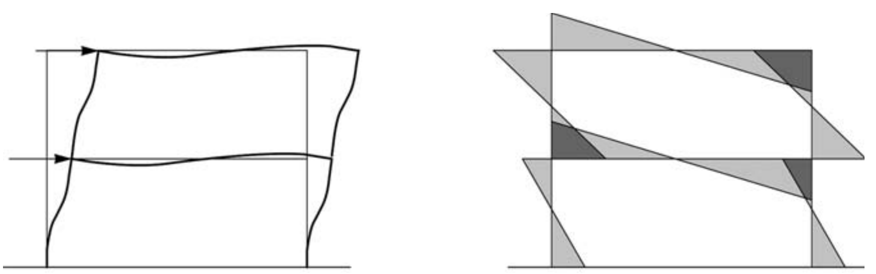
This simple idealisation demonstrates one of the fundamental characteristics of elastic behaviour of multi-element structures, which is that the stiffer elements attract a greater share of the load to themselves and the less stiff elements carry a smaller share. In complex frameworks the path taken by the load through the structure (the distribution of internal forces such as bending moment, in other words) is determined by the relative stiffnesses of the structural elements. This is one of the fundamental characteristics of structures that behave elastically, and one of the principles on which the elastic analysis of structures is based.

Consideration of the plane framework in Figure (7.11) reveals the principal features of the analysis of a relatively complex structure. It is assumed in this example that the joints between the beams and columns are fully rigid (constrained to remain right angles). As with the simple example of the linked cantilevers (Figure 7.10), and following the principles of elastic theory, the distribution of internal forces through the frame is determined by the manner in which it deforms. When the horizontal load indicated is applied (Figure 7.11a) the frame will sway sideways causing the joints between the elements to rotate slightly, while remaining right angles, and this rotation will introduce bending strain (and therefore bending moment and bending stress) into all of the elements – both the columns and the beams. Once sufficient strain has occurred to generate the stress required to resist the load the movement will cease and equilibrium will be re-established. The problem for the designer is to calculate precisely how the bending moments have been distributed through the structure. This will depend on the amount of deformation (bending strain) that has occurred which will, in turn, be dependent on the relative stiffness of the elements.

The equations required to calculate the distribution of internal forces in the framework are determined from its physical properties. One of these is equilibrium. For example, the sum of the moments that meet at each joint must balance, so a certain number of equations can be generated from this. The second physical property that is used to generate equations is the stiffness of the



(a) **(b)**

Figure 7.11 Elastic analysis of a multi-storey rigid framework. (a) When the frame with rigid joints is loaded horizontally the sway effect causes the rigid joints to rotate slightly, while remaining right angles, which introduces bending into all beams and columns. (b) The Euler-Bernoulli equation can be used to calculate the slope, and therefore bending moment, that occurs at the end of each element. The requirement for the moments to balance at each of the joints can then be used to create a set of simultaneous equations, the solution of which enables the magnitude of all of the moments to be calculated.

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elements (as determined, in accordance with the Euler-Bernoulli Equation, by their individual values of EI/L). One way of generating equations from this property is to consider the amount of rotation that occurs at each joint because this is affected by the relative stiffnesses of the elements that meet at that joint, and also by the amount of rotation that has occurred at adjacent joints. The influence of one joint on the next depends on the stiffness of the element that connects them. The precise orientations of the joints in the frame are therefore interdependent and controlled by the stiffnesses of the elements. This is the mechanism by which bending moments are distributed within the frame when the load is applied, and by setting up equations to calculate the rotations of each joint (possible from the Euler-Bernoulli Equation, which allows the slope of the deflected form to be evaluated (see Figure 7.7)) and comparing adjacent joints to ensure compatibility, sufficient equations can be obtained to solve for the critical number of bending moments. This is the basis of the elastic analysis of multi-element frameworks.

in isolation). The assumptions required to implement these simplifying procedures inevitably introduced approximations into the calculations that reduced their accuracy.

A significant breakthrough in structural analysis occurred in the 1960s with the introduction of digital computers. These made practicable the solution of multiple sets of simultaneous equations. This advance, together with the development of finite-element techniques (also in the 1960s onwards, and in fact simply a very sophisticated iterative procedure) has resulted in an ability, in the present day, to analyse fully the most complex of statically indeterminate frameworks. It was this revolution in structural analysis from the 1960s that was in part responsible for making possible the analysis of the highly complex structural geometries that are employed by some present-day architects.

These complex computer-aided techniques of structural analysis could not, however, eliminate the many uncertainties that were present in the calculation process, including those that were fundamental and a consequence of the difference between theory and practice (such as the assumptions on which elastic theory was based or the accuracy with which the behaviour of the junctions between elements could be simulated) and those that were statistical (such as the reliability with which loads and material properties could be predicted).

7.3.10 Ultimate load theory and the analysis of complex frameworks

The analytical methods discussed in Section 7.3.9 apply to structures in which elastic behaviour is occurring. If the load factor method is being used this adds a complication because it involves the prediction of the formation of plastic hinges, which in turn affects the distribution of bending moment within the frame as the collapse load is approached.

In the context of risk management, which is discussed here briefly in Section 7.3.6, a realistic assessment must be made of the load required to cause a structure to collapse. Even a relatively simple framework, such as that shown in Figure 7.12, is statically indeterminate with several degrees of redundancy (in this case 6). For such a framework to collapse under increasing load, sufficient plastic hinges (6) have to form to eliminate all the degrees of redundancy (indeterminacy), and convert the structure to a mechanism. To simulate the collapse, it is necessary to plot the bending moment diagram for every beam and column element in the frame so as to identify the location at which the first plastic hinge will form (more likely a group of hinges simultaneously). Once the first hinge(s) form, the distribution of bending moment changes and so the bending moments have to be recalculated to identify further plastic hinges, until a sufficient number of hinges have been created to cause collapse. Every time a new plastic hinge is formed, the

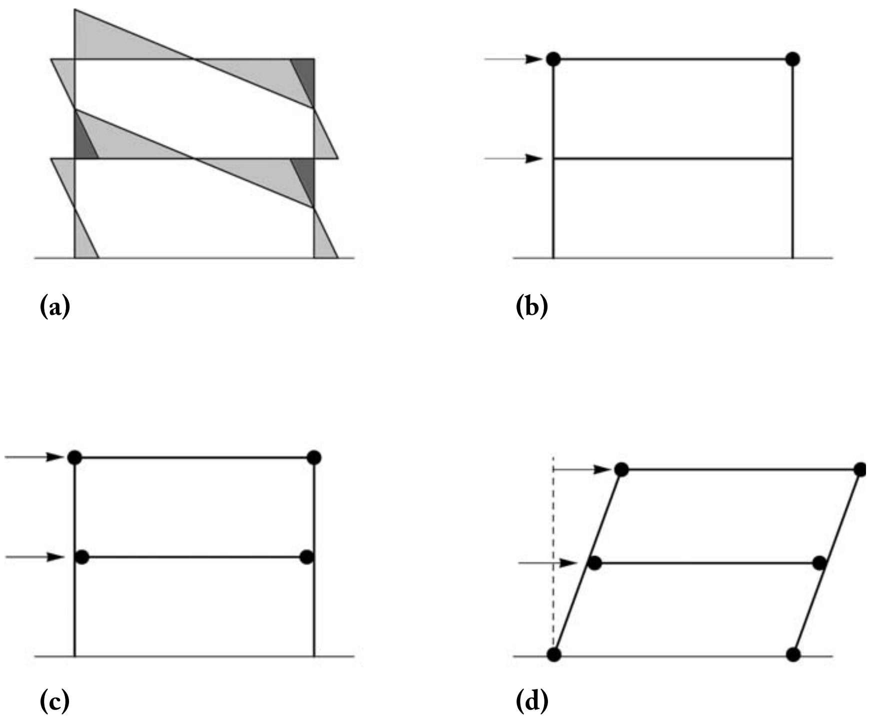

Figure 7.12 Evaluation of the load required to cause collapse: (b) and (c) show the sequence of formation of plastic hinges at the locations of peak bending moment as the load is increased; the collapse load is reached when sufficient plastic hinges have formed to convert the structure to a mechanism (d). The analysis outlined in Figure 7.11 can be extended to predict the sequence of plastic hinge formation. The calculations are complicated by the fact that the load-deformation behaviour becomes non-linear (inelastic) following the formation of the first plastic hinge.

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distribution of bending moments changes. The analysis of a large framework requires the solution of multiple (many hundreds) of simultaneous equations, and it was not until the late twentieth century that software was developed that could reliably evaluate the collapse load of a complex frame and, using that result, form the kind of realistic assessment of the true factor of safety achieved – the essential feature of rational risk analysis.

7.3.11 Limitations of elastic theory for structural analysis

All of the methods described in Sections 7.3.9 and 7.3.10 apply to the idealised world of structural theory. The extent to which they provide an accurate representation of what actually occurs in a real structure remains a concern for the practising engineer.

A particular area of considerable uncertainty relates to the behaviour of the joints between the elements. These are normally assumed to be either fully rigid or fully free (hinged with frictionless hinges). To qualify as fully rigid, a joint must permit no relative rotation to occur between the elements being joined. Even a very small amount of rotation (fractions of a millimetre) is sufficient to produce significant variations in the distribution of bending moment. In practice, most joints in a steel framework are neither fully rigid nor fully free. They are in fact semi-rigid, with the true degree of rigidity being unknown.

An insight into the effects of this uncertainty on the accuracy of the analysis of a multi-storey framework may be gained by imagining how it might behave in response to a horizontal load caused by wind. When horizontal load strikes a multi-storey framework it responds by swaying, as described above in Section 7.3.9. If there is variation in stiffness across the frame (due to variation in the rigidity of the joints) a greater amount of bending strain will develop in the stiffer parts for a given overall amount of deflection, due to slippage in the joints of the less stiff parts. The stiffer parts will, in other words, tend to attract a greater share of the load to themselves. The variation in deformation that then results will tend to redistribute the bending moment between elements so that further deformation, due to increasing load, will produce a different set of strains that will, in turn, redistribute the bending moments again. In this situation, no structural theory could predict precisely how the frame will respond to increasing load (necessary to determine the sequence of plastic hinge formation), due to the uncertainty concerning the precise degree of rigidity (or slippage) that is present in any of the joints. The successive redistributions will tend to be random due to the random nature of the uncertainties concerning joint rigidity. The system, given the random nature of the way in which it progresses from initial loading, through the successive formation of plastic hinges to collapse, makes it very sensitive to variations in the pattern of the applied load. A further complication therefore is that, because the wind loading is likely to be distributed across the face of the building in unpredictable ways, there will be a degree of uncertainty concerning the initial conditions of the load/deformation sequence. The system has in fact characteristics that are similar to those identified by the application of chaos theory to the study of systems that display 'extreme sensitivity to initial conditions', also known as the 'Butterfly Effect'. This problem can be eliminated in the analysis of structures by making the assumption that all joints are fully rigid, which is another example of the discrepancy between theory and reality.

7.3.12 Elastic theory – conclusion

The purpose of this discussion of the various aspects of the application of Elastic Theory to structural design has not been to provide a comprehensive treatment of the topic itself but simply to illustrate both its considerable usefulness and also the difficulties that it presents in the context of real structures. Even relatively small frameworks are in fact highly complex systems that can behave in non-linear ways in response to load. The theoretical simulations, such as those obtained by using the Elastic Bending Theory, are based on linear equations that provide a fairly crude representation of this complex and subtle non-linear behaviour, which is further complicated by uncertainties concerning the detailed behaviour of joints, the assessment of loads and material strengths, and many other factors.

Similar amounts of uncertainty are present in most sectors of structural analysis. The prediction of compressive buckling, the theory of which is also related to the elastic bending theory and which is an instability phenomenon, is notoriously difficult; it affects the design of all parts of structures that are loaded in compression including columns, walls, the compression elements in triangulated frameworks, the compression flanges of beams and girders, and the compression parts of beam and plate girder webs. The analysis of triangulated frameworks, which is also a non-linear problem if the effects of deflection and joint behaviour are allowed for, is another example of an area where simplifying assumptions, needed to make the calculations practical, corrupt the accuracy with which the real behaviour is simulated.

Questions such as these, at the interface between theory and practice, have been a major concern for the engineering profession in the period, from the mid-nineteenth century onwards, in which justification of structures has been based largely on numerical methods. Throughout this period engineers have been under pressure to use numerical methods, such as those discussed above, to produce structures that make a significantly more economical use of material than was the case in the earlier eras of masonry and timber construction, in which designs were justified by non-grounded rules based on geometry. This change, to the general use of grounded-rule-based operative methods, has been, to a large extent, accomplished and the structures that are built in the present day occupy significantly less volume than those of historic architecture.

The difference in slenderness between the columns of the Parthenon in Athens and those of a Modern steel framework are not accounted for solely by the different strengths of the constituent materials or even by a different concept of how columns should be treated aesthetically. The steel columns are also more slender because they are the result of a design process that was intended to match their strength to the loads that they had to carry.

That the numerical approach to the design of structures was introduced without a high incidence of failure is a tribute to the competence with which the situation was managed by the engineering profession. In view of the uncertainties that exist at the interface between structural theory and structural practice, the number of serious structural failures that have occurred, in relation to the total number of structures that have been constructed in the Modern period, is very small, and most of these were not attributable to deficiencies in structural theory. The low failure rate has been accomplished by the maintenance of an awareness of the large wider picture, in relation to structural design; by judicious use of factors of safety; and also by a conservative attitude to innovation, something that is a characteristic of the structural engineering profession.

The use of digital computers in structural analysis, together with the development of highly sophisticated computer-aided techniques of component manufacture in recent years, has enabled structures of great complexity and high degrees of statical indeterminacy to be designed with safety. The uncertainties associated with the behaviour of joints, and of stress distribution during flexure, cannot be entirely eliminated, however, and the profession must be continually vigilant so as not to be lulled into a sense of false security by the use of systems of highly sophisticated analysis which actually rest on foundations of (necessary) assumptions concerning parameters impossible to specify with absolute precision.

7.4 The role of structural theory – overall conclusion

This section has attempted to review very briefly the important role in the process of structural design of structural theory – that body of knowledge and techniques (based in the Modern period on numerical methods) that has been used to demonstrate that designs are safe, reliable and economical. Two quite different types of structure have been chosen to illustrate the principal *types* of problem that arise, these being the great masonry structures of Antiquity and of the Gothic period; and the complex frameworks of more recent times.

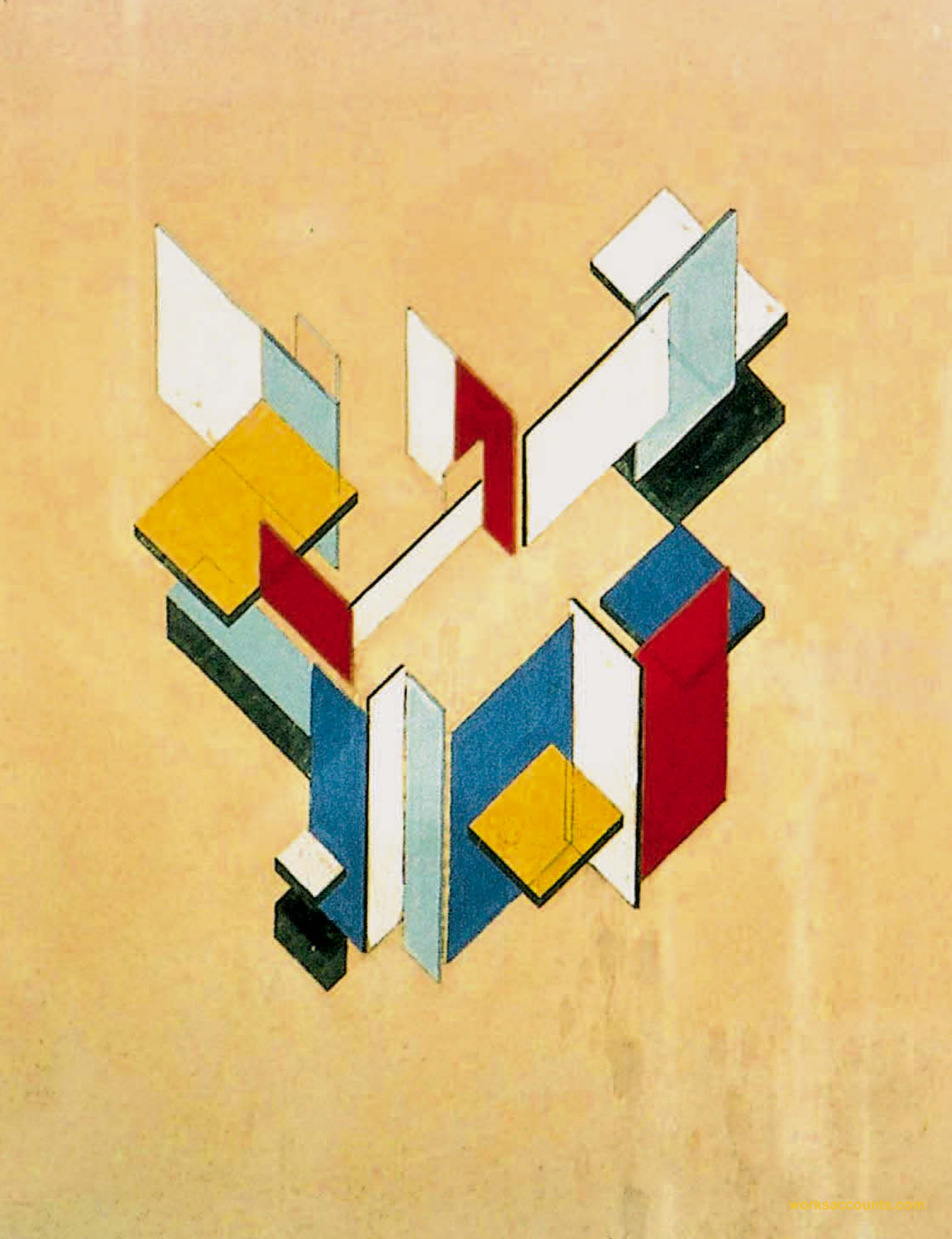
As described in this chapter, in the pre-Modern period – before the development of mathematically described engineering science – the methods used to design structures were based on geometry and not on concepts such as force and strength; these procedures were entirely appropriate when applied to masonry structures, as was demonstrated by Heyman. It was noted that the structural theories that underlay the design of the Gothic buildings have largely been lost, perhaps because of masonic secrecy; and also that very little of the true structural theory of the time found its way into the contemporary literature of architectural theory (such as the treatises of Vitruvius and Alberti). The early architectural treatises were, as Addis has pointed out (1990), stylistic guides rather than manuals of building, concerned principally with the appearance of buildings rather than with their technical integrity.

This chapter has also described how modern structural theory, based on engineering science, despite its usefulness and sophistication, presents significant difficulties for the design engineer, largely because real structures are highly complex systems that behave in non-linear ways, and that are extremely difficult to simulate mathematically. Attention has been drawn, therefore, to the difficulties that surround the application in engineering practice of theories that have been evolved to explain physical phenomena and that have necessarily been shorn of the complexities that exist in the real world, in order to render them manageable.

It is this liminal zone between the idealised theories of engineering science, which seek to explain the physical world, and the practical realities of designing structures for use in the real world, with its myriad complexities, that is inhabited by the practising engineer. The engineer must take a broad view of the scope of any theory used in design and must understand its limitations as well as its usefulness. Because the consequences of structural failure are potentially disastrous, a theory cannot be used unless it has been proved to be effective and its limitations fully understood.

This is one of the greatest differences between structural theory and architectural theory. An engineer cannot take the risk that a theory may not produce the desired performance. In architecture, theory is often experimented with freely in practice, and ill-conceived theory, based on the flimsiest of theoretical underpinnings provided by one of the para-philosophers in the field, may result in architecture whose success or failure, either as a building or as a work of art, is the subject of considerable controversy. Conversely, in the field of engineering, there is rarely any argument concerning the success or failure of structural design. If an engineer fails to appreciate the limitations of structural theory the result is likely to be catastrophic, and the structural collapse of a building is rather difficult to explain away by means of polysyllabic discourse.

The distinction between the aims and objectives of architectural and structural theory that have been identified in this chapter are very significant in relation to the development of forms of architecture that are sustainable, as is discussed here in Section 11.6. Architectural theory is concerned with aspects of design that are largely cultural; structural theory is concerned with managing physical realities. Both are vital but the relative importance of each is likely to change as the requirements for sustainability, which are largely concerned with physical realities, rise in importance.



CHAPTER 8

Philosophy of structures and its relationship to architectural theory in the Modern period

8.1 Introduction

As discussed briefly at the beginning of Chapter 7, the term *philosophy of structures* is used for a body of ideas concerned with conceptual design – the determination of the overall forms and general configurations of structures – and is distinct from that identified as *theory of structures* which refers to ideas involved with the realisation of structural form and with their 'justification'. *Philosophy of structures* may be regarded as the equivalent in structural engineering to what is termed *theory* in the architecture field. The comparison is not exact, however, because philosophy of structures is principally concerned with the technical aspects of design and largely ignores the cultural and iconic significance of form, which is the principal concern of architectural theory. In the Modern period, during which the relationship between architecture and technology has been a major preoccupation, various attempts have been made to incorporate structural philosophy into architectural theory, often with confusing results.

This chapter begins with a discussion and summary, in Section 8.2, of the ideas that are generally accepted as being fundamental to the philosophy of structures and that inform the approach to design that is adopted by most engineers. The ambivalent treatments of technology that are evident in early theories of architectural Modernism are outlined in Section 8.3, and the consequences of the variations between structural philosophy and architectural theory for the collaborations between architects and engineers in the design of buildings are discussed in Section 8.4.

Facing page: Counter Construction, van Doesburg.

8.2 'Building correctly' – the writings of Torroja and Nervi

8.2.1 Introduction

The term *philosophy of structures* was the title of the English edition of the classic book by the eminent twentieth-century professor of engineering, Eduardo Torroja (1899–1961) (Torroja, 1957, *Razon y Ser*, Instituto de la Constructión y del Cemento, Madrid; Torroja, 1958, *Philosophy of Structures*, University of California Press) (Figure 8.1a). In proposing a philosophy of structures, Torroja was concerned with the idea of 'building correctly' and with the consequences of this for structural, and therefore architectural, form. The other prominent philosopher of structures of the twentieth century was the renowned practitioner Pier Luigi Nervi (1891–1979) who, like Torroja, wrote extensively on the underlying principles of structural design. The ideas

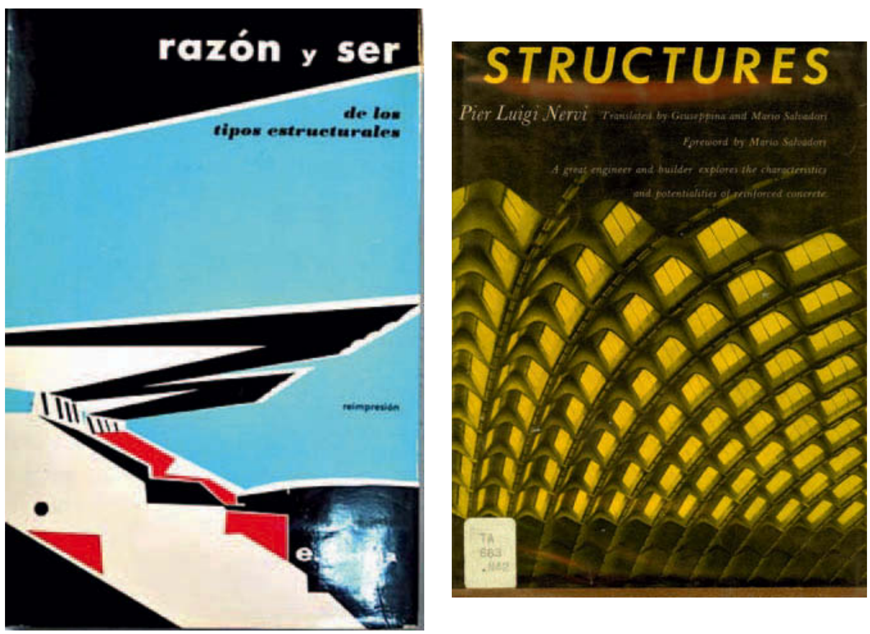


Figure 8.1 Covers of two of the most influential books of the Modern period on structural philosophy: (a) *Razon y Ser (Philosophy of Structures)* by Eduardo Torroja, first published 1957; (b) *Structures* by Pier Luigi Nervi, first published 1956.

Figure 8.2 (*Facing page*) Torino Exposizioni (Exhibition Hall), Turin, 1949; P. L. Nervi architect/engineer. The principal structural element of this building is a form-active vault spanning 100 m. The corrugations and other detailed aspects of the form were 'improvements' that enhanced the stiffness of the basic form giving it the ability to resist bending and buckling efficiently. The complex geometry contained considerable repetition and was constructed economically by a combination of in-situ casting with pre-cast sub-elements (acting as permanent formwork) in ferro-cement. In form and detail the building conforms to the 'rules' for 'building correctly' expressed by both Nervi and Torroja.

described by Torroja and Nervi are in fact timeless, because they are concerned with the fundamental relationship between structural form and structural behaviour, as already described in Chapters 4 and 6. Torroja's and Nervi's treatment placed these ideas in the context of the early Modern period, but they are as relevant in the present day as they were when they were written.

Nervi and Torroja were each also responsible for the design of a number of buildings that contributed forms to Modern architecture that were highly original and that helped to create a strand of architecture in which architectural form was harmonised with structural form (Figure 8.2). The close connection of these forms to engineering, a field of fascination to many Modernist architects, gave the buildings a particular significance and design integrity. These structures attracted the attention of the architectural media and found their way into the Modernist discourse on architecture. Their forms were frequently imitated by architects, although often without a proper understanding of their true structural characteristics.

8.2.2 Nervi's and Torroja's philosophy of structures

Although Torroja and Nervi employed approaches to design that were very similar, neither formulated their beliefs into a codified set of design principles. Had they done so they might have been summarised thus:

- that a building or structure should perform its intended function well in every respect;
- that the structural form adopted for a building should be appropriate for the span and load involved;
- that the form should be appropriate for the material used;
- that the building or structure should be as simple to construct as possible;
- that the finished building or structure should be durable.

Torroja and Nervi each identified, in slightly different ways, sets of criteria by which the appropriateness of a structure might be judged and that were capable of serving both as aids to design and benchmarks for structural criticism. They provided a basis for decision making in relation to structural design by defining a set of requirements that ought to influence the initial idea for the design and serve as guidance as a design was progressed to its final form.

These principles, as summarised above, might be described collectively as rules for 'building correctly' which was the title (in English translation) of the opening chapter of Nervi's remarkable book *Structures* (1956) (Figure 8.1b) in which he outlined his approach to structural and architectural design. This was a methodology that was shared by Torroja, and that was concerned with producing structures and buildings that not only fulfilled their function well, but were also economical to construct and were not wasteful of resources of

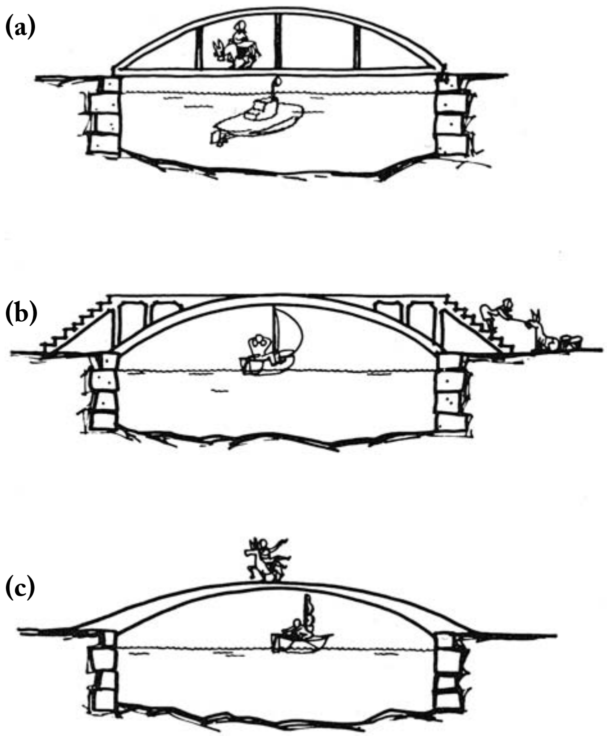


Figure 8.3 Alternative designs for a bridge (from Torroja, *Philosophy of Structures*). Torroja used this engaging sketch to illustrate his approach to design. To be satisfactory the bridge must function well for all of its users in addition to being sensible structurally.

Image: courtesy University of California Press.

material, energy or human endeavour. It had an ethical dimension because it was concerned with serving the needs of society rather than solely with the particular agendas of the designer or client.

Torroja and Nervi argued that the forms chosen for structures, and therefore buildings, should primarily be appropriate for their structural and programmatic function, and that the materials of which they were composed should be used in forms that were suited to their properties. They were advocates of a kind of ideal, 'total design', in which all of the functions of a building were accorded equivalent priority in the design process and were satisfied in equal measure in the final form (Figure 8.3). They also encouraged the belief that the best way of achieving this aim was to concentrate initially on satisfying the requirements of programmatic function and technical performance, arguing that if these criteria were satisfied, aesthetic and symbolic meaning would gracefully follow. It is noteworthy that this is virtually the opposite approach to architectural design from that followed by most of the prominent architects of the Modern period – a point that will be further explored later in this book.

In his book *Structures*, which was illustrated almost entirely with examples of his own designs (see Section 9.2.3), Nervi explained his approach to structural design and dealt with all aspects of the topic. He discussed the need for an education system for architects and engineers, based on academic institutions, that would allow them to develop the understanding required to produce well designed buildings:

> I believe that the schools of architecture should, above all, teach structural correctness, which is identical with functional, technical and economic truthfulness, and is a necessary and sufficient condition for satisfactory aesthetic results. The aesthetic results achieved by these means usually suffice, even if they do not reach the supreme heights of art.
>
> (Nervi, 1956, p. 26)

He discussed what he considered to be the impossibility of teaching someone to be an artist which he considered to be a 'state of grace', because any attempts to teach it: 'are bound to be negative, since the scholastic schematisation of art leads to formal imitation, to academic rhetoric and impotence, as evidenced by all beaux-art schools everywhere and at all times' (Nervi, 1956, p. 25).

His belief was that the only aspect of design that could be taught was technique, which gave the artist the means of expression, and he therefore adopted a very definite, and some would say naive, position in a 'time-honoured' debate with much relevance for architecture.

Nervi was critical of the 'rhetoric' that, in his view, typified the majority of works designed by architects, and which he considered to produce buildings that were 'aesthetically bankrupt, insufferably rhetorical and offensively vulgar' and that led to 'poor functionality, and waste of precious materials'. He advocated a method of design based on the 'satisfaction of functional, statical, constructional and economical needs and the creation of a well balanced organism'. Such an architecture, he states, 'may be aesthetically insignificant or expressively beautiful, depending upon the actual or unconscious capacity of its designer, but will never be aggressively annoying' (Nervi, 1956, p. 27).

Such ideas about design contrasted significantly with those of contemporary architectural theory (see Section 8.3) and produced a type of architecture that was different from that being created by the so-called 'masters' of mainstream Modernism.

Eduardo Torroja's book *Philosophy of Structures* (1958) provided a systematic account of the behaviour and properties of structures and materials. He devoted separate chapters to consideration of the various elements of structure – arches, vaults, beams and trusses – and to the different structural materials – timber, steel, reinforced concrete, stone and brick. In each case he described the basic properties of structural type and material and discussed the forms for which they are most appropriate. He also discussed basic aids to structural understanding such as the concepts of stress, strain and structural continuity. The book is generously illustrated with sketches in Torroja's own hand

(Figures 8.3, 9.9 and 9.11) and he used descriptions of structures and buildings that he had himself designed (described later in Section 9.2.3) as examples of what he regarded as good structural practice.

Torroja cautioned against the blind following of rules: 'No rules can be enunciated which, if followed, will yield the best possible structure. Hence everything depends, far more than on anything else, on the personal criterion and imagination of the designer' (Torroja, 1958, p. 347).

Torroja was, however, careful to point out that, in order to exercise appropriate creative judgement, the designer had to undergo a rigorous training and possess a thorough understanding of structural behaviour and knowledge of the properties of structural material.

Torroja devoted a whole chapter to the subject of aesthetics. Central to his belief was the idea that structures and buildings should be functional: 'The beauty of a structure is immanent in its structural form . . . and essentially resides in its structural quality' (Torroja, 1958, p. 287).

Torroja also cautioned against the pursuit of originality for its own sake: 'Is originality merely a desire to be different? If so it ceases to be a positive merit . . . and is no more than an incongruent and perverted mentality' (Torroja, 1958, p. 284). Above all, Torroja valued integrity on the part of the designer so as to avoid: 'the danger of inverting our sense of values to give priority to our own showmanship . . . over the sincere desire to solve, without glamorous vanity, the actual problem set before us' (Torroja, 1958, p. 350).

Sage advice indeed, for both engineers and architects! Torroja was clearly directing his observations at the manner in which Modern architecture was developing and, in particular, at the rise of star architects intent on developing distinctly individual styles producing spectacular buildings that functioned poorly in terms of both structure and programme. This process had begun in the early days of Modernism with the rise of the 'modern masters' such as Walter Gropius, Ludwig Mies van der Rohe, Le Corbusier and Frank Lloyd Wright, and gathered pace in the 1950s with such figures as Eero Saarinen, Louis Kahn and Paul Rudolph in the USA, and Alison and Peter Smithson in the UK.

In contrast, Nervi's and Torroja's ideas belonged to a functional tradition that was almost devoid of influence from art and architectural theory and of the idea of personal style and that therefore might be considered to represent a type of vernacular. This tradition belonged to 'building' rather than to architecture and was part of the genre that included the works of the nineteenth-century engineers who built the train sheds, mills and warehouses of the first industrial revolution and that was continued into the twentieth century by figures such as Robert Maillart, Owen Williams, Eugène Freyssinet, Nicolas Esquillon, Felix Candela, Eladio Dieste and Heinz Isler – all of them engineers who worked mostly *as* architects rather than *with* architects. Many of these individuals, including Nervi and Torroja, have been considered to be masters of the 'art' of engineering but few would have considered themselves to be 'artists'. Nervi and Torroja certainly did not; they were content simply to produce buildings that were useful, economical, without pretension and above all without being 'aggressively annoying' (Nervi, p. 27) or containing the 'academic rhetoric' (Nervi, p. 25) which they identified in many of the works of the architecture profession.

Nowhere did they introduce complexity into structures, either for its own sake or for purely visual effect. Always, their complexities were both fully justified technically and capable of being constructed economically. The vaulted enclosure of the Turin Exhibition Hall by Nervi (Figure 8.2) is typical. Its curvilinear form-active overall shape was fully justified for the span and loads involved. The corrugated and articulated detail was also justified in a compressive form that had to be capable of resisting buckling, and therefore bending, and the use of the technique of pre-casting with ferro-cement enabled the structure to be built economically. If the building has beauty or even artistic quality, these stem from its functionality. There was no other formal, conscious artistic input.

One last observation that might be made concerning Torroja and Nervi is that they both actively practised what they preached. It would be difficult to find an example, in the work of either of them, of a building or structure that did not conform to their declared philosophies of design, and neither did they ever find it necessary to be economical with the truth when asked to justify their designs. This is somewhat in contrast to many architects who have written about their design methodology, as discussed further here in Section 8.3 and also in Chapter 10.

As already stated the ideas of Nervi and Torroja on engineering design and its relationship to architecture are as relevant in the present day as when they were written. In the words of Cecil Balmond, one of the most creative architectural engineers of the late-twentieth and early-twenty-first centuries:

> With little understanding of the motivation of form, modernism runs into minimalist dead ends and by continuing to look to the outside the seduction with objecthood and architecture as art is perpetuated. Geometry is not invoked; no one peers within and asks questions about the archetypes of form. These are forgotten. Instead, instant realisations are sought from computers with form-finding that is software dependent.

The **archetypes of form** are, as expressed and discussed in this book (see Chapter 4), concepts such as 'form-active', 'non-form-active' and 'improvements' to cross-sections. As discussed in Chapter 11, it is the proper understanding and application of these fundamentals, so well described by Nervi and Torroja, that are likely to lead the way to the development of a future architecture that is environmentally sustainable.

8.2.3 Influences on architecture

The buildings of Nervi, Torroja, Candela, and the other architect-engineers, were much admired in the world of architectural Modernism and found their way into both its literature (see, for example, Section 8.3 for accounts by Giedion) and its visual vocabulary. They were much imitated, often with indifferent results, in terms of homage at least (as at the Sydney Opera House or the TWA Terminal in New York (see Chapter 9)), due mainly to a preoccupation with visual qualities coupled to a neglect, apparently through lack of understanding, of their structural properties. The singling out of the visual aspects of exposed structures and their quotation in inappropriate contexts, and to the detriment of their function, was a structurally unsatisfactory trend that found its way into many strands of Modern architecture.

8.2.4 Conclusion

In this short section, a *philosophy of structures* has been discussed, the basic principles of which were summarised in the first paragraph of Section 8.2.2. Most engineers would probably be uncomfortable in describing this discourse as philosophy, however; it was simply an approach to design that was concerned with producing buildings and structures that served the needs of both clients and society and that avoided the wasteful use of resources of all kinds. Nervi and Torroja each stressed that such a methodology was dependent on the rigorous application of technical knowledge and understanding rather than a desire to adhere to a theory of architecture that was principally concerned with aesthetics.

As applied by expert practitioners such as Nervi, Torroja, Candela and others, this approach produced some of the most memorable structures of the Modern period, which were regarded by their creators simply as modest attempts to produce artefacts that were useful in every sense, rather than as examples of an 'art of engineering', as they have sometimes been described. It is an approach to design that is not currently favoured in architectural circles, but that may have to be re-visited if society is not to continue to waste its energies on projects of dubious real worth requiring excessive consumption of resources of all kinds. There now exists a powerful argument for its return as the need to develop sustainable forms of architecture becomes more urgent (see Chapter 11).

8.3 Structure in relation to architectural theory: technology treated as a 'style'

8.3.1 Introduction

The relationship between structure and architecture has been an uneasy one in the Modern period and nowhere is this more evident than in the theoretical writings of the two disciplines. As discussed in Section 8.2, the engineers who committed their thoughts to paper were able to formulate a relatively simple set of guidelines for design and they themselves actually followed these. They were, of course, really doing nothing more than setting down the general principles of good engineering that engineers had been using for centuries and that were concerned with producing sensible, practical structures and buildings that functioned well in every sense and were economical to build. Their approach was therefore modest, although they nevertheless produced some of the most memorable buildings, structures and indeed iconic images of the Modern period; it contrasts somewhat with that of some of those who attempted to formulate an overarching theory of architecture for the Modern period.

8.3.2 Theories of Modernism – contradictions and mythologies

As Reyner Banham (1942–1988) pointed out in his *Theory and Design in the First Machine Age* (1960), there was in fact no coherent theory of Modern architecture. This is perhaps not surprising because, although Modernism is a recognised condition in the societies of the post-industrial age, Modernism in architecture was primarily a reactive phenomenon concerned with rejecting what was perceived to be the stifling effects of continuing adherence to the styles that had dominated in the preceding centuries. It is perhaps to be expected therefore that the reaction took different forms and was perceived differently by different practitioners, and that the prodigious quantity of theory that it produced contains inconsistencies and even outright contradictions.

Perhaps the greatest generator of inconsistencies was the *idea* of '*function*', something that was obviously crucial in the field of technology and that was considered by many to be an essential quality in any new architecture appropriate for the Modern age of machines and industry. The idea that buildings should perform equally well in respect of both function and aesthetics was, however, never accorded a high priority by the architects of the early Modern Movement, such as Walter Gropius or Ludwig Mies van der Rohe. Theirs was principally an architecture based on aesthetics as was well articulated by Charles Jencks in his perceptive critique *Modern Movements in Architecture* (1973, p. 189). Quoting from Paul Rudolph, the head of the school of architecture at Yale in the 1960s and a pupil of Gropius, Jencks drew attention to the non-functionality in the work of Mies van der Rohe: 'Mies . . . makes wonderful buildings only because he ignores many aspects of a building. If he solved more problems his buildings would be far less potent.' The aspects that were 'ignored' were mostly concerned with function. Jencks also drew attention to the views of Philip Johnson, another guru of architectural Modernism, whom he described as having 'quite candidly denounced the tendency of functionalism to degenerate into sterility, and reasserted the primary value of architecture as art' (p. 189).

This is a view with which most Modern architects would have concurred but it did present a problem, which was that Modern architecture was intended to be celebrative of technology, a field in which the proper functioning of a designed object was regarded as essential. It was deemed necessary, therefore, to produce buildings that functioned well in addition to satisfying the necessities of an artform, and this required combination of criteria led the theorists of Modernism in architecture into all kinds of difficulty. It was, however, aesthetics that ultimately triumphed over function as the dominating influence on Modern architecture. So far as the relationship between architectural and structural design is concerned this outcome resulted in the approach to the design of buildings of architects and engineers becoming distinctly different. Whereas most engineers were concerned with functionality, in all its aspects, the architects remained concerned principally with the visual qualities of architecture as an artform.

A building that – in its influence on later discourse and practice – provides an excellent illustration both of the many inconsistencies that exist in Modernist architectural theories and of the differences of approach to design that they represent, when compared to the structural philosophy outlined here in Section 8.2, is the Crystal Palace, in London (Figures 8.4 and 8.5). This building, which was perhaps the greatest glass-clad enclosure in the entire history of architecture, produced an iconic image that features in almost every account of the history of Modern architecture, due to its role as an exemplar for the creators of the new style of architectural Modernism. Consideration of the circumstances of its design and its performance as a building reveals much concerning the contradictions present in the Modernist approach to the relationship between the visual and the technical in architectural design.

It was inevitable that the Crystal Palace would be attractive to the advocates of Modernism in architecture: it was entirely new and without precedent as an architectural concept; it was composed principally of the then 'new' materials of iron and plate glass; and its technical configuration was novel for a large building as it consisted of a skeleton framework, which occupied a minimal volume, enclosed in a non-structural cladding. The building was entirely the product of industry, made up from components that were fabricated by production-line methods in factories and with minimal dependence on hand crafting, and the on-site building process therefore consisted of the assembly of pre-fabricated components. But most of all, its imagery was what appealed – that of a 'cathedral' in glass and iron – stark, modern, devoid of ornamentation and of any references to previous styles of architecture. Clearly, the theories of Modernism in architecture had to accommodate this – in its time – ground-breaking and futuristic building.

Figure 8.4 The Crystal Palace, London, 1851; Joseph Paxton, designer. It required both a new technology and a purely functionalist approach to design to create this enormous building. Both of these were alien to mainstream architecture of the period, which was largely concerned with the manipulation of images from previous eras. It was, however, the 'new' imagery (i.e. that of the glass-clad framework) created at the Crystal Palace, rather than the functionalist design methodology that produced it, which would serve as one of the architectural precedents for the Modern period.

Image: J. McNeven/Wikimedia Commons.

Figure 8.5 The Crystal Palace, London, 1851; Joseph Paxton, designer. The building performs well as a structure. The non-form-active, post-and-beam typology, with 'improved' triangulated horizontal elements, is entirely appropriate for the spans involved.

Image: J. McNeven/Wikimedia Commons.

One of the most significant features of the Crystal Palace, for the Modern architect, was the distinction made in it between the functions of structure and enclosure. These functions had been united in the pre-Modern period of Western architecture in the form of the masonry wall but the appropriateness of this was challenged in the 'new' vision of architecture expressed by Gottfried Semper (1803–1879) in his influential work *The Four Elements of Architecture* (1851), a work that was an important precursor of Modernist architectural theory. Semper considered that the distinction between structure and enclosure was fundamental and identified woven fabric (the means of enclosure) as one of the fundamental 'primitive' elements of architecture. Semper's re-formulation of how architecture should be perceived added to the attraction of the glass-clad framework as an exemplar for a new visual vocabulary because it enabled it to represent the clearest visual expression of the separation of enclosure from structure. A building typology consisting of a fragile and transparent membrane supported on a minimalist framework, and its adoption as an archetype by Modern architects, conveyed the idea that the architecture of Modernism was new, of its time, and also an original formulation of something that was fundamental and therefore of lasting validity.

But the Modernists of the twentieth century, who were so keen to take ownership of the Crystal Palace as a precedent for the new architecture, failed to accommodate in their various theories a number of aspects of its design and performance that were inconvenient for their cause. Perhaps the most obvious of these were the implications of the fact that the building was a work of almost pure engineering which was designed more-or-less in direct accordance with the functionalist principles that would be codified nearly 100 years later by Torroja and Nervi. This approach to design had been made necessary by the uniqueness of the design problem that the project posed, which was to produce a building of cathedral-like dimensions that was capable of being constructed in less than a year and subsequently easily dismantled. The then current practices of mainstream architecture, which were largely concerned with manipulation of visual motifs derived from previous styles, were incapable of addressing this design challenge, which was met instead by the adoption of a purely functionalist approach.

Proper appreciation of this outcome should, in fact, have assisted the cause of Modernism in architecture because the methodology – due to its operation from first principles in the quest to satisfy functional requirements – was clearly demonstrated to be capable of creating new imagery, as it was to again in the hands of later engineers such as Nervi and Torroja. Among the many commentators who subsequently drew attention to this situation was the twentieth-century engineer Edmund (Ted) Happold (1930–1996) who argued, in his presidential address to the UK Institution of Structural Engineers in 1986 (*The Structural Engineer*, Volume 4, 1986), that the true creators of the new images of Modern architecture were the engineers because they worked from first principles to provide original solutions to new problems. Buildings such as the Crystal Palace provided evidence in support of his argument.

Such a potential change in methodology, away from the visual to the technical, as the principal generator of form, was ultimately a change too far for the architects; they were not only unwilling to abandon the manipulation of images as the principal technique of architectural design, but also to abandon the link with cultural continuity that a change to pure functionalism, as the principal generator of architectural form, would involve.

It is well known that the engineer's functionalist methodology was in fact rhetorically encouraged by Le Corbusier in his great polemical work of Modernist architectural theory, *Vers Une Architecture* (1923) (*Towards a New Architecture* (1927)). As Charles Jencks has pointed out: 'It is the rare architect who, like Le Corbusier, depicts the collaboration of architect and engineer as two interlocking hands, as a partnership between equals.'[1] What Le Corbusier described was in fact what Ove Arup would later repeatedly refer to as 'total design' (See Section 9.3). It is significant, however, that neither Le Corbusier himself, nor his followers, actually *adopted* this methodology. Instead, they continued to use the practices that had in fact been current in architecture since the time of the Italian Renaissance, and that were vilified in their writings by Le Corbusier and other Modernist thinkers, namely those of simply manipulating visual images. The only real innovation introduced by the Modernists was that the *images* used in their form of new architecture –

many of which had been created by engineers – were different from those of the traditional 'styles'. Thus, one of the greatest lessons that could have been learned from consideration of the Crystal Palace – that in order to create *fundamentally* new images it was desirable to adopt a new *methodology* – was actually missed by architects, certainly in so far as its application to practice was concerned.

There were several other aspects of the Crystal Palace design that were ignored by the theorists and historians of Modernism: aspects connected to the technical performance of a glass envelope as effective cladding for a building. The most obvious of these is its poor performance, as a thermal barrier, in providing adequate separation between the internal and external environments, and the related problem of solar heat gain – problems that were well known to horticulturalists concerned with rearing plants in glasshouses. In the case of the Crystal Palace – a temporary building designed primarily for use over a single summer – these were not critical deficiencies. Overheating due to solar gain could, for example, be overcome simply by increasing natural ventilation, and the poor thermal performance of the glass envelope was not therefore a significant problem for the Crystal Palace building itself. It would, however, become a serious problem for the many extensively glazed offices, schools and domestic buildings created in an approximation of its image in the subsequent age of Modern architecture.

A further potential problem with glass envelopes is their lack of durability. Glass, being brittle, must be mounted in a flexible material that accommodates the relative movement caused by thermal effects and load-induced deformations, that occurs between it and the supporting structure. In the nineteenth century the flexible medium used was linseed-oil putty. In the twentieth century various forms of synthetic rubber gasket have been employed, all of which deteriorate in response to sunlight and therefore cause glass envelopes to leak. The best efforts of the materials technology industry have failed to eliminate completely this problem, which is a continuing concern for the maintenance and upkeep of buildings with extensive areas of glazing.

Despite its technical shortcomings, which were not actually significant in the context of a temporary building, the Crystal Palace may nevertheless be regarded as a genuine technical marvel. Its technology enabled a building of enormous proportions to be designed and constructed with incredible speed and to be rapidly dismantled subsequently.

It was, however, the *image* of a 'palace of crystal' that was of greatest interest to Modern architecture; the tendency that this implies for technical deficiencies to be ignored so that exciting images could be manipulated was something that was to haunt architects throughout the Modern period. In the heroic days of Modernism, in an architecture that was intended to be celebrative of technology, such problems were merely a somewhat embarrassing inconvenience that was either quietly ignored or simply explained away by apologists in the architectural media. It is not therefore surprising that significant contradictions are to be found in the early theoretical works of Modernism concerning the relationship between aesthetics, function and technology.

Perhaps the most extreme disdain of technical performance in the service of 'pure imagery' is to be found in the writings of Bruno Taut (1880–1938), one of the most influential of the early Modernist theorists. Taut expressed views that encouraged the complete disregard of technical considerations in the creative moment:

> Let the dusty, matted, gummed up world of concepts, ideologies and systems feel our north wind! Death to concept-lice! Down with everything serious!
>
> Hurray for a kingdom without force! Hurray for the transparent, the clear! Hurray for purity! Hurray for crystal! Hurray and again Hurray for the fluid, the graceful, the angular, the sparkling, the flashing, the light – hurray for everlasting architecture!
>
> (Bruno Taut, *Die Gläserne Kette* (*The Crystal Chain*, 1920), quoted in Whyte, 1985)

Taut also declared that his 'Glashaus had no other purpose than to be beautiful . . . [and that] glass symbolised the purified mankind of the future'.

Concerns for such matters as human well-being and the responsible use of materials and energy, which were just two of the many difficulties associated with buildings that had all-glass walls, were by no means evident in this ecstatic vision.

At the other extreme, Adolf Loos (1870–1933), in his essay *Ornament und Verbrechen* (*Ornament and Crime*, 1910) advocated a purely functionalist approach, stating: 'architecture is not art' – 'a house has nothing to do with art' – 'architecture must serve public needs' (Glück, 1962).

The practising architects of the early Modern period, if they sought theoretical guidance, were therefore presented with a rather conflicting and therefore baffling range of passionately advocated polemical advice.

A more considered view on the principles that should underpin Modern architecture, and that is generally acknowledged to have been one of the most influential bodies of ideas, emerged from the Bauhaus School, which encouraged the idea that a fusion of art and craft, and its extension to include industry, should be the foundation of Modern architecture. The Bauhaus programme was greatly influenced by the ideas of its famous directors, two of whom, Walter Gropius (1883–1969) and Ludwig Mies van der Rohe (1886–1969), would be recognised historically as 'masters' of the Modern Movement in architecture.

Gropius was dismissive of the role of technology in architectural design and expressed a view that directly conflicted with those of Adolf Loose, of Torroja and of Nervi:

> Structures created by practical requirements and necessity do not satisfy the longing for a world of beauty built anew from the bottom up, for the rebirth of that spiritual unity which ascended to the miracle of the Gothic cathedrals.
> (Essay by Gropius in catalogue of exhibition for the *Arbeitsrat für Kunst*, Berlin, 1919)

Gropius was attracted to the idea of the medieval craft guild as a model for the education of architects: 'In the medieval guilds it was from the close emotional commitment of artists of all levels that Gothic cathedrals arose' (*Der freie Volksstaat und die Kunst*, ms., 1922, cited in Kruft, 1994, p. 384). In deference to the idea that the architect should be a combined artist and craftsman, Gropius established the famous workshops at the Bauhaus School in which the students learned craft skills. However, as was pointed out by Millais in *Exploding the Myths of Modern Architecture* (2009), the Bauhaus students were merely dabbling in craftsmanship, as it is generally considered to take a dedicated five-to-seven year apprenticeship and around 10,000 hours of hands-on experience to develop genuine craft skills. The value of the type of 'flirting' with craftsmanship at the Bauhaus, and in many schools of architecture since, was questionable in that it encouraged an inflated belief in the level of expertise and real knowledge that was gained. It did, however, often instil a respect for the value of craft skills that it would be hard to replicate without any hands-on experience.

Other aspects of the Bauhaus system were also derived from Gropius' conception of the medieval guild model. Tutors at the school were encouraged to act as 'masters', and students as their unquestioning apprentices, in a relationship which simulated that of the craft apprenticeship system. This was, however, a false analogy. Most of the tutors were not actively practising the craft of architecture, with student apprentices at their elbow learning the craft as it was being carried out, in the manner of the medieval model. Most were in fact full-time educators, many of them from a background in fine art, and often with little practical experience of architecture.

The Bauhaus system also had a tendency to give architectural education the ambience of a quasi-religious initiation. Students undertook a 'cleansing of the mind', which was intended to rid them of prejudices accumulated from their past experiences. To reinforce this idea the study of history was prohibited. All of this tended to foster the idea that architecture was fundamentally different to other professions and led to the isolation of architects from the rest of society, something that has had unfortunate consequences both for the profession itself and for the society that it has sought to serve.

The idea that the mainstay of architectural education in the Modern period should be a simulated craft apprenticeship, and that the practising architect was the equivalent of a medieval craftsman, was in reality a highly romantic notion that, with the benefit of nearly a century of hindsight, may be seen to have served architecture rather badly. The ideology promoted by the Bauhaus lacked consistency and even integrity. Medieval craftsmen had, of course, been principally concerned with 'practical requirements and necessity' and not with 'building anew from the bottom up'. The quest to satisfy the 'longing for a world of beauty' was in fact principally based, in the studios of the Bauhaus, on a preoccupation with aesthetics rather than on the methodology of the craftsman. Flawed and inconsistent as its ideas may have been, the Bauhaus set a pattern for architectural education that became universal in schools of architecture in the second half of the twentieth century and that persists into the present day. It is against the general ambience created by the Bauhaus School that the relationship between architectural theory and structure must be considered.

The two treatises of architectural theory that probably had most influence on the Modern Movement were those by Le Corbusier and Sigfried Giedion and it is worth noting that each encapsulated the same inconsistencies and illogicalities that characterised the system of education being promoted in the Bauhaus. Both ostensibly found much that was positive in the idea that structural considerations should exert an influence on the new architecture, and each also, in fact, sidelined that idea in favour of the promotion of a design methodology that was primarily based on visual aesthetics.

Perhaps the greatest work of architectural polemic (if not theory) of this period was Le Corbusier's *Vers Une Architecture* (1923) (*Towards a New Architecture* (1927)). Le Corbusier set the scene for a theory of Modern architecture rather well in his opening sentence by identifying, perhaps unconsciously, the dichotomy that would characterise one of its major problems: 'The Engineer's Aesthetic, and Architecture, are two things that march together and follow one from the other . . .'

What Le Corbusier was saying, in this most revealing opening passage, was that it was the *aesthetic* of engineering rather than its *methodology* that was of primary importance for the new architecture. However, in a curious foretelling of the views expressed later by Happold (discussed above), Le Corbusier identified that it was by thought processes like those employed by engineers, working from first principles, that meaningful novel forms and images were created and he advocated this methodology for use in architectural design. He then undermined his message by flooding his book with 'technical' images – motor cars, aeroplanes, steamships and parts of these (Figure 8.6). He thus encouraged the architects to plunder the world of engineering for images rather than to adopt its methodology, and this is exactly what they did. Despite what he preached, and as discussed above, even Le Corbusier himself operated largely as a manipulator rather than a creator of images and did not in fact use the methodology of engineers. Le Corbusier, one of the great gurus of Modern architecture, therefore, in both his writings and his practice, encouraged the same kind of ambivalence to the relationship between technology and architecture that was embedded in the Bauhaus system.

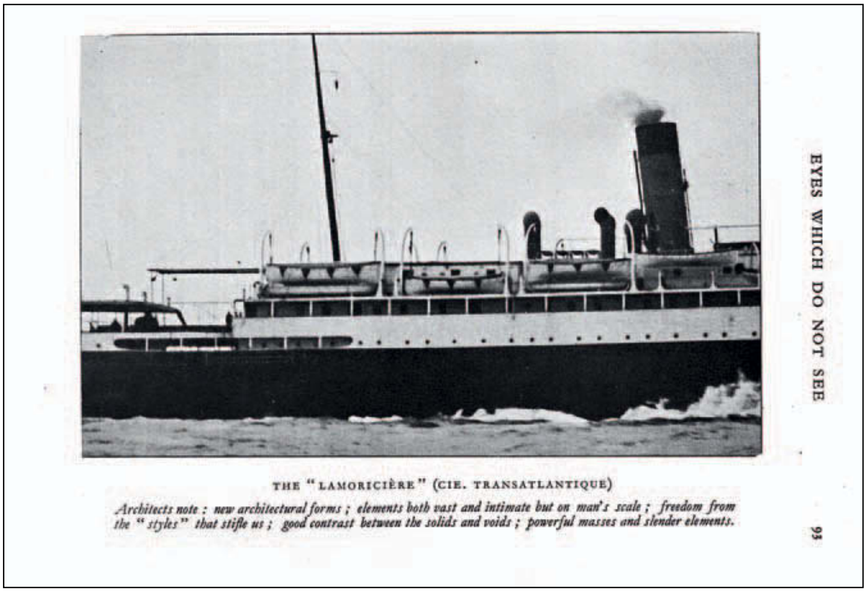


Figure 8.6 Illustration from *Vers Une Architecture* (1923); Le Corbusier. The 'engineer's aesthetic' of the ocean liner was a purely functionalist 'architecture' in the context of the most advanced marine technology of its age. Had the design problem been to produce a building in reinforced concrete, rather than a steel ship, the 'engineer's methodology' would have produced a somewhat different shape. It was, however, the imagery rather than the design methodology that created it that would serve as the precedent for Le Corbusier and his acolytes in Modern architecture.

It is ironic that, in the context of Modern architecture, the methodology involved in the creation of the 'Engineer's Aesthetic' was actually being practised by engineers such as Eduardo Torroja, Robert Maillart and Eugène Freyssinet. The failure of the architects to adopt the principles of engineering design, as advocated by Le Corbusier though not adopted by him personally, was not therefore due to a lack of availability of the knowledge in question. If they had adopted the methodology of engineers, they would, of course, have produced buildings similar to those of Nervi and Torroja, which might not have satisfied other aspects of the Modernist agenda.

In addition to Le Corbusier's polemical book, the other seminal work of early Modern architecture theory was Giedion's *Space, Time and Architecture* (first published by Harvard University Press, 1941). This was not so much a work of polemic as a compendium of Modernist thinking in relation to architecture. According to Kruft (1994, p. 435) 'from the moment of its publication it defined for a generation or more what constituted "modern architecture"'.

Sigfried Giedion's project was to provide both a history and a justification of Modern architecture and city planning. *Space, Time and Architecture* was first published in 1941 and updated by Giedion several times until his death in 1968, and then subsequently by his heirs and collaborators. It could be described as the Modern architect's bible. The text is notable, however, for its attempts, often by means of questionable reasoning, to reconcile the aesthetic aspirations of Modernist architectural theory with the new visual imageries being created by structural technology.

Giedion began his account with a fairly straightforward history of the precursors of Modern architecture in the late-nineteenth century and of the early Modern buildings of the twentieth century. He also sought out the visual sources of Modern architecture and attempted to provide a philosophical justification for their use as a basis for architectural expression. He attempted a rationale for reconciling the potential conflict between two of the goals of Modern architecture: that it should be a means of artistic expression and, at the same time, an example of functional and technical proficiency. For this reason Giedion's book may be considered to be a work of architectural theory as well as a history.

It was perhaps inevitable that Giedion should have looked to innovative developments in structural technology as potential sources for the new visual vocabulary of Modernism, and this makes consideration of his observations and conclusions particularly relevant here. The two aspects of structural technology that Giedion identified as being of crucial importance to the development of Modern architecture were the metal framework, as exemplified in the great exhibition buildings of the late nineteenth century – in particular the Crystal Palace in London (1851) and the Galerie des Machines in Paris (1889) (Figure 8.7) – and the concrete architecture of the Swiss engineer Robert Maillart. Giedion connected each of these to parallel developments in conceptions of space and time in the worlds of both fine art and theoretical physics, in an attempt to link architectural theory with the most advanced thinking of the age.

Giedion identified what he considered to be the two most essential characteristics of the glass framework, so far as the development of architecture was concerned, namely its potential for artistic expression and the methodology by which such images were created. He compared the visual qualities of the Crystal Palace to those evoked in the paintings of J. M. W. Turner in which 'all materiality blends into the atmosphere' and use is made of

> a humid atmosphere to dematerialise landscape and dissolve it into infinity . . . The Crystal Palace realises the same intention through the agency of transparent glass surfaces and iron structural members . . . an equivalent insubstantial and hovering effect is produced . . . to make up parts of a dream landscape.
> (1941, pp. 254–255)

Of the 1889 Galerie des Machines, in Paris, Giedion stated that it 'represented an entirely unprecedented conquest of matter' (1941, p. 270). He thus

Figure 8.7 Galerie des Machines, Paris Exposition, 1889; Ferdinand Dutert, architect; Victor Contamin, engineer. The principal structural element of this building was a 115 m-span, three-hinge, triangulated steel portal framework. The use of an 'improved' semi-form-active structure was entirely justified for the span involved. Giedion correctly identified that the structural typology was distinctly different from the post-and-beam arrangement used for the smaller spans at the Crystal Palace. His conclusion that with this structure 'iron vaulting has found its true form' and had 'obliterated the division between load and support' is a poetic interpretation that adds drama to the pragmatism of the engineering.

Image: Library of Congress/Wikimedia Commons.

described one of the desired characteristics of the new Modern architecture using language reminiscent of that of Bruno Taut.

In a sentence that expressed a similar idea to those of Le Corbusier, Giedion explained the origins of these ideas in built form: 'From now on, development will come . . . at the hands of the engineer. He will achieve the new solutions' (1941, p. 255). In an echo of what Torroja and Nervi would express nearly two decades later Giedion stated, of the glass exhibition buildings, 'Construction passes over into expression. Construction becomes the form giver' (1941, p. 275).

In the case of the Galerie des Machines, Giedion drew attention to what he believed to be its most salient features, namely the extreme slenderness of the framework elements and the elimination of the distinction of what he termed 'load' and 'support' in its principal structural members. He correctly identified that the principal reason for the delicacy of the framework was that it was constructed in structural steel – a 'new' material that was significantly stronger than iron and that therefore allowed the thickness of the elements to be reduced. He failed to appreciate, however, that the slenderness of the principal members was also due to their being semi-form-active (as opposed to the non-form-active elements in the post-and-beam arrangement of the iron framework at the Crystal Palace). For him, the significance of the portal framework arrangement of the principal elements was that they 'obliterate the division between load and support' with the result that 'iron vaulting has found its true form. The last hint of the antique column has disappeared . . . we may regard this vaulting as our equivalent of the caryatid' (1941, p. 273).

Giedion's choice of words is revealing. By using the terms 'load' and 'support' for elements that were in fact *beams* and *columns* respectively in a post-and-beam arrangement he revealed that he was thinking visually rather than in terms of structural function. The beams and columns actually act together as part of the structure, and each contributes to the provision of support for the applied load. Giedion was here feeling his way towards an understanding of the fundamental structural difference between post-and-beam and semi-form-active arrangements and their implications for design, but apparently lacked sufficient technical knowledge to articulate this accurately.

Giedion failed to mention, or perhaps failed to appreciate, that the suitability or otherwise of a technology is dependent on the circumstances of the application and that the glass-clad framework, while it may be ideal in the context of a temporary exhibition building, may nevertheless be entirely unsuitable for a different type of building. The many disadvantages of such an arrangement for more 'normal' types of building such as houses, schools and offices have already been pointed out. As with many writers on Modern architecture, it was the visual image and impression of the glass houses rather than their technical performance that were of greatest interest.

The Swiss engineer Robert Maillart (1872–1940) was a pioneer of reinforced concrete construction. His bridges are rightly admired for their elegance and fitness for purpose and they would, undoubtedly, satisfy all of the criteria of good engineering design advocated by Torroja and Nervi. It was not surprising that the stark functionality of their bare and unadorned concrete should appeal to the sensibilities of the early Modernists because these structures did represent an apparently effortless fusion of aesthetics and technology (see Fig 6.8).

Giedion's descriptions of the technical behaviour of Maillart's structures was perceptive and largely accurate. He identified correctly that one of the 'new' features which was offered by reinforced concrete was structural continuity and that this was fully exploited by Maillart. In particular, Maillart used the benefits of continuity to break away from structural forms based on linear elements (such as the beam/column arrangements used in timber and steel and adopted by that other pioneer of reinforced concrete, François

Figure 8.8 Schwandbach Bridge, Berne, 1933; Robert Maillart, engineer. The principal structural element of the bridge is a 37 m span, 200 mm thick, polygonal slab-form arch that supports the deck via 160 mm thick cross-walls. The polygonal profile of the slender arch, which is stiffened against buckling by the deck slab, is form-active in response to the concentrated loads transmitted by the cross-walls. In its form and simplicity the structure is entirely functional and devoid of ornamentation. For Giedion, it was a prime example of functional design but the transfer of the underlying design methodology to architecture was problematic, mainly because it lacked a cultural dimension, something that was not acknowledged by Giedion.

Photo: Chriusha/Wikimedia Commons.

Hennebique) and to extend the structural vocabulary to include the slab (plate-like elements) which Maillart used to good effect for both bridges and buildings. Giedion did not draw attention to the other significant property of the reinforced concrete slab, which is its ability to resist bending, and therefore out-of-plane loads. This is an important distinguishing feature of such a slab from earlier slab-like elements, such as the masonry wall, because it allows it to be used in semi-form-active arrangements.

Maillart's use of slab forms is well illustrated in the design for the Schwandbach Bridge, near Berne, 1933 (Figure 8.8) with its slab-form arch supporting a slab deck through slab-like cross-walls. His two-way-spanning flat-slab structures for mills and warehouses (Figure 8.9) became prototypes for a system of construction that has become universal for multi-storey building structures.

Figure 8.9 Flat-slab structure, Grain Depot, Altdorf, 1912; Robert Maillart, engineer. The flat-slab system, now one of the commonest forms of multi-storey structure, was developed by Robert Maillart. In its most economic form it is based on a regular square column grid but its two-way spanning capability can allow the slabs to be supported on an irregular basis. It was the planning freedom and sculptural possibilities that this enables that attracted the attention of Giedion.

Photo: Chriusha/Wikimedia Commons.

But it was not only the structural properties of Maillart's reinforced concrete slabs that interested Giedion. He was also attracted by their visual qualities and by the possibilities that they offered for creating a new type of architectural space; he drew parallels between Maillart's structures and the activities of contemporary artists such as Cézanne, Manet, Picasso and Matisse. He identified two aspects of the work of these artists as being particularly relevant to these comparisons. The first was the idea of *surface*. 'Surface . . . has now become the basis of composition, thereby supplanting perspective' and 'With the cubist's conquest of space . . . surface acquired a significance it had never known before' (1941, p. 462). Giedion pointed out that the linking of such ideas to architecture is perhaps best exemplified in the work of the De Stijl Group, as explored by Theo van Doesburg (1883–1931) in compositions such as *Relation of horizontal and vertical planes* (1923, Figure 8.10) which were described by Giedion as 'an attempt to present the elementary forms of architecture'. Giedion further comments on 'how the enormous amount of contemporary architecture which has since appeared acknowledges this version of space' (1941, p. 442). Maillart's reinforced concrete slabs made it possible to express the sorts of arrangement envisaged by van Doesburg in the form of the physical reality of a building.

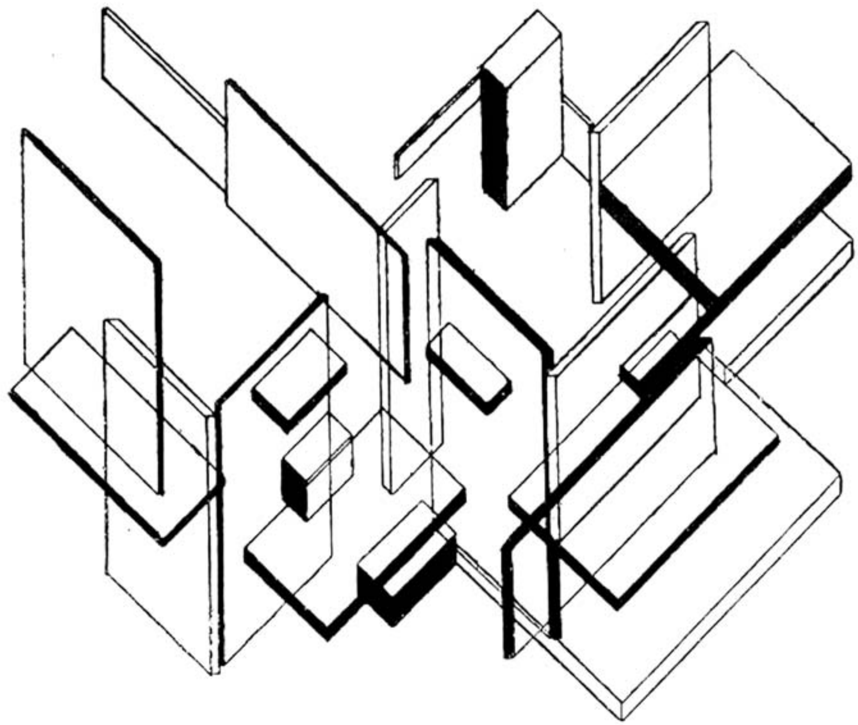


Figure 8.10 Relation of horizontal and vertical planes, Indian ink and paper, 1923; Theo van Doesburg.

Image: *De Stijl. Complete reprint.* Amsterdam: Athenaeum, Bert Bakker, Polak & Van Gennep, 1968, vol. 2, p. 399/Wikimedia Commons.

The visual similarities of the works of the engineer and artist held a particular fascination for Giedion:

> [J]ust as a great constructor transformed it [the slab surface] into a medium for solving structural problems that had always been considered insuperable, so the development of surface into a basic principle of composition in painting resulted in opening up untapped fields of optical expression. This is no longer a fortuitous optical coincidence, as might be objected, but a definite parallelism of methods.
>
> (1941, p. 463)

> Modern art has reached the same results as modern science by entirely independent intuitive steps. Like science it has resolved the shape of things into their basic elements with the object of reconstituting them in consonance with the universal laws of nature.
>
> (1941, pp. 464–465)

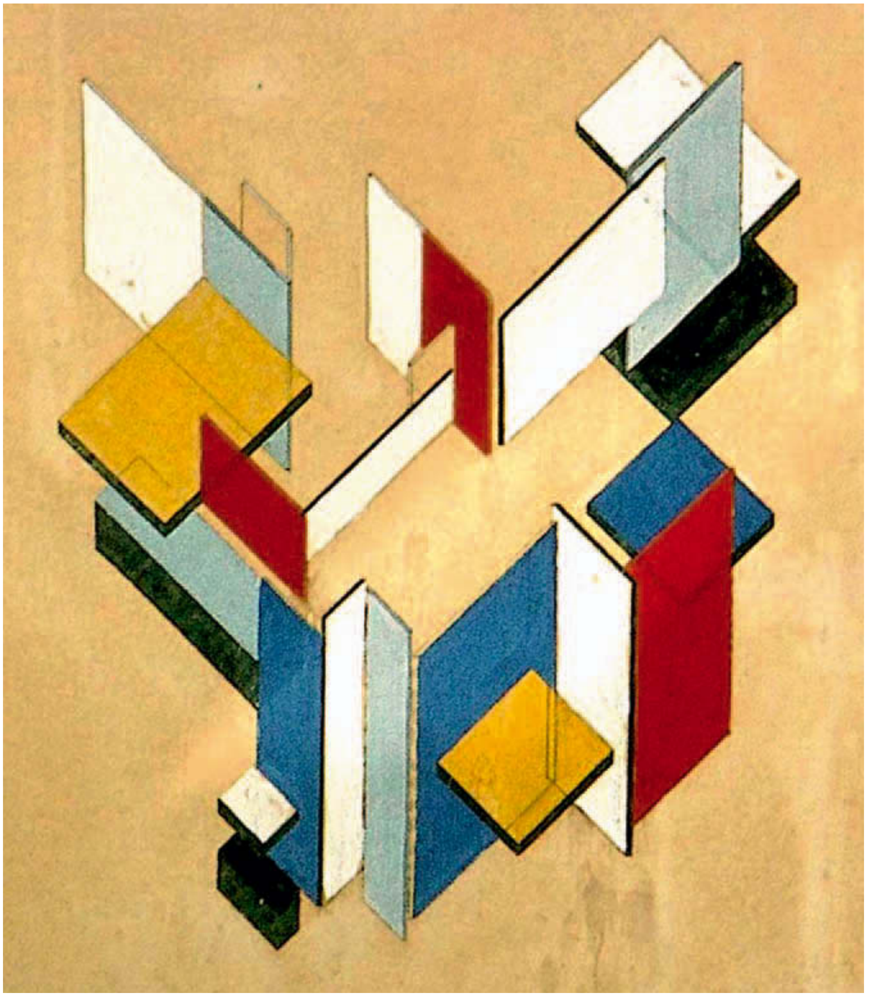


Figure 8.11 Counter-construction, 1923; Theo van Doesburg. This graphic composition of horizontal and vertical planes could be the design for a building. With two-way-spanning slabs the arrangement would be structurally feasible despite the obviously irregular pattern of support provided by the vertical elements. (Gouache and heliography on paper: Van Moorsel donation to Dutch State, 1981.)

Photo: geheugenvannederland.nl/Wikimedia Commons.

By suggesting that painters and engineers were working along similar lines, or at least achieving similar results, a legitimacy was added to the idea of using images generated by engineers such as Maillart in the art of architecture. In Maillart's hands, the slab forms clearly 'worked' – the bridges fulfilled their function – and were therefore 'valid'. It did not follow, however, that such forms were also appropriate for other types of application. Houses with intersecting walls and free-flowing space, arranged in the manner of van Doesburg's image (Figure 8.11), gave rise to many difficulties of inhabitation of a purely practical nature, and also lacked the structural logic of a Maillart building. Their irregular patterns of support resulted in high internal forces and less efficient structures than would have occurred with more conventional arrangements. By implicitly denying this Giedion was elevating image over functional performance in a way that was similar to that already observed in the case of the reaction to the glass-clad frameworks.

It is also the case that, while the reinforced concrete slab is an ideal form of construction for buildings in which the plans consist of irregularly intersecting planes, it is not essential. Two of the most famous iconic buildings

Figure 8.12 Schröder House, Utrecht, 1924; Gerrit Rietveld, architect. Although apparently suitable for realisation in slab-form concrete, this building is in fact a composite construction of brick masonry, timber and steel, with only minimal use of reinforced concrete slabs for the external balconies. A clever constructor can always find a way of making a building of this small size, without the need for the recourse to sophisticated reinforced concrete typologies implied by Giedion's advocacy of a necessary connection between avant-garde design and cutting-edge technology (see main text).

Photo: Basvb/Wikimedia Commons.

of early Modernism, which exemplify the use of free-flowing space (the Barcelona Pavilion (1929) by Mies van der Rohe and the Schröder House (1924) (Figure 8.12) by Gerrit Rietveld) are each based on steel-skeleton frameworks rather than slab-form structures. The latter is in fact a composite construction of brick masonry, timber and steel with only minimal use of reinforced concrete slabs (for the external balconies). Mies van der Rohe's brick house project (Figure 5.8) is a further example of a slab-like form that was *not* based principally on reinforced concrete. There is therefore a degree of post-rationalisation in Giedion's celebration of the reinforced concrete slab form as an example of an harmonious relationship between structural technology and visual art. The artists were in fact concerned principally with the visual result rather than with any 'poetic' fusion of art and technique and accorded scant attention to structural and constructional functionality. This was a characteristic of Modern architecture that Giedion was loath to acknowledge.

In this respect Giedion's approach was fundamentally different to that of Torroja or Nervi, neither of whom would ever have placed visual appearance above all other design considerations, and especially over practicality. Giedion's seminal work, like that of Le Corbusier and the ideas of Gropius, therefore encouraged architects to elevate the importance of the visual over the technical and discouraged any serious attempts to reconcile the conflicting requirements of aesthetics and function.

8.3.3 Summary – the conflicted confusions of Modernist architectural theory

This short section has drawn attention to a fundamental contradiction that has existed in the various architectural theories of Modernism that evolved in the twentieth century and that arose due to the elevation, by both the writers of theory and the architects themselves, of visual criteria above those concerned with function of all kinds. A consequence has been that, while the best Modern buildings have been visually exciting and expressive in various ways of the ideals of architectural Modernism, they have almost all been seriously deficient in terms of structural function and often, also, of living function. They were not, at the same time, *both* means of artistic expression *and* examples of technical excellence. An unresolved conflict between the visual and the practical is evident in all of the principal works of architectural theory, as well as in the built forms themselves. This situation has been in stark contrast to the writings and the built work of the 'philosophers' of structure which have had the virtue of being consistent and in which serious attempts have been made, usually with some measure of success, to create an architecture that was truly functional.

The approach of most Modern architects to design has not in fact been that of the engineer, as suggested by Le Corbusier, or been based on a Modern version of the craft apprenticeship, as advocated by Gropius and his Bauhaus system. Throughout the Modern period, architects have rather given visual criteria a significantly higher priority than those concerned with technology or function, while at the same time claiming that Modern architecture was celebrative of technology and functionalism. In this sense, Modern architecture has suffered from a lack of consistency that has characterised it at a fundamental level.

8.4 Structural technology and Modern architecture

The architecture that emerged in the second half of the twentieth century as a consequence of the various 'experiments' in practice and theory of the early Modernists took a variety of forms, the most common being the unadorned rectilinearity of International Modernism. Of the various sub-movements, a less severe version was practised in Scandinavia and a particularly harsh version, 'New Brutalism', in the UK. All of these were regarded as '*functional*', for example by critics and historians of theory such as Kruft (1994). They were not, however, truly functional, other than in a very general sense and the term was in any case applied almost exclusively to the space planning and general arrangement of buildings rather than to technical function. As pointed out above, much of the theory was contradictory; there was always present the idea that architecture should be a form of artistic expression, and always, also, a tension between the attempts to reconcile the conflicting requirements of symbolism, psychological perception and actual function in all of its aspects: space planning, structure, construction and environmental control.

The idea that function should not, in fact, be accorded a high priority in architectural design was advocated by the early leaders in the field, such as Gropius and Mies van der Rohe, as has been discussed, above (at the beginning of Section 8.3.2). This idea has been a significant characteristic of virtually all new architecture in the Modern period and continues into the present day. A serious critique of almost any of the buildings that have contributed to the architectural discourse in the Modern period would reveal considerable discrepancy between the satisfaction of both aesthetic and functional requirements, as discussed in Chapter 10. A single example serves here to illustrate the point: the Hunstanton School, in the UK (1954), by the architects Alison and Peter Smithson (Figure 8.13). This is an iconic building from the second wave of Modern architecture, from the post second-world-war period, and illustrates both the consequences of giving function a low priority in design and the nature of the resulting differences of approach to design, which were adopted at the time by architects and engineers.

This building has featured as an exemplar of functionalism in most histories of Modern architecture. It is rectilinear and consists of a steel-skeleton framework supporting non-structural external walls, principally of glass and brickwork masonry, together with non-structural internal partitions. One of

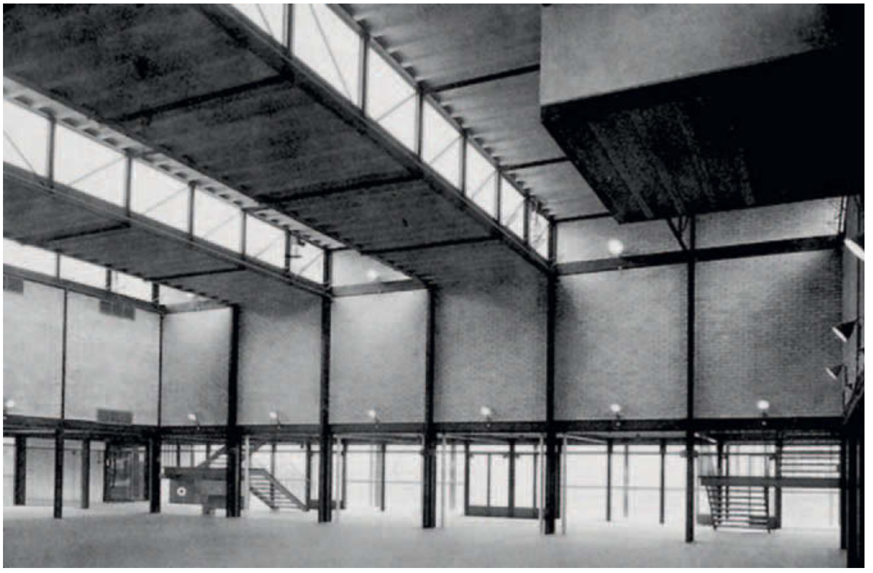


Figure 8.13 Hunstanton (Smithdon High) School, England, 1954; Alison and Peter Smithson, architects; Ove Arup & Partners, engineers. Listed in 1993, the building is an icon of early Modernism in Britain. It was heavily influenced by the work of Mies van der Rohe but was considered to have greater 'honesty' due to the full exposure of its constituents including its steel framework. The latter, which was designed by Ove Arup & Partners along plastic design principles, functioned well; the use of a post-and-beam arrangement with 'improvement' by the use of triangulation and I-sections, was entirely justified by the spans and loads involved. The building functioned less well as a school and the architects were criticised for their having made 'no claim to understand what teachers wanted'. Visual considerations were the highest design priority and it is significant that, at the architects' insistence, the early photographs of the building, such as that shown here, were made without occupation by people or furniture.

Photo: RIBA.

its themes is 'honesty' as expressed by the exposure of the materials from which it is constructed. It never functioned well for its principal intended purpose, that of a secondary school. Like most glass-walled buildings it was a 'freezing cold box in winter and a sweltering greenhouse in summer' (Malcolm Millais, *Exploding the Myths of Modern Architecture* (2009), p. 260), and it had many other functional shortcomings ranging from poor internal planning, which rendered many of its spaces unfit for purpose, to poor detailing, which caused rapid deterioration of its fabric. Millais (2009) also observed that its 'multiple functional shortcomings . . . were well known . . . but this was of little interest to architectural writers who were solely interested to see how the icon complied with the Modern Movement belief system' (p. 250). He quoted an example of a typical description from the architectural media 'technically it was almost perfect. Aesthetically the most distinguished of buildings of the time' (Dennis Sharp, *A Visual History of Twentieth Century Architecture* (1972)).

The Hunstanton School serves here as a prominent example of the discrepancy that existed in discussions of mainstream architecture between the sycophantic praise that certain buildings attracted in the architectural media and the reality of their functioning as useful components of the building stock, and indeed of places that could be congenially occupied by human beings. The functional shortcomings of the Hunstanton School were in fact fairly typical of the iconic buildings of early Modernism and it is well known that buildings such as Le Corbusier's Villa Savoye, Mies van der Rohe's Farnsworth House and many others, performed badly in respect of their primary function as dwelling places.

Ironically, and indeed significantly for the main topic of this chapter, one of the few parts of the Hunstanton School that did function well was its structure. Its post-and-beam arrangement was sensible for the spans and loads involved and the use of 'improved' I-section beams for the floor structures and triangulated girders for the roof were entirely appropriate. This was also true of many of the other iconic buildings of Modernism which, though they functioned badly in many respects, were usually based on structural systems that performed reasonably well with respect to the criteria outlined by Nervi and Torroja.

There were several reasons for this good structural functionality. The first was largely a result of a coincidence rather than a deliberate intent to reconcile the visual and technical agendas: the rectilinearity favoured by architectural theory, for purely stylistic reasons, happened to coincide with the non-form-active, post-and-beam structural arrangements that are most appropriate for short-span structures (see Chapter 6). The second was that, however badly a building might perform in other respects, it had to function as a structure; the scope for compromising the structure so as to meet other design objectives was therefore limited. The third was that the engineers would normally have been striving to achieve structural functionality as their main priority and were therefore working to a different agenda from the architects, whose principal concern was with aesthetics.

The true nature of the relationship between aesthetics and technology in Modern architecture, and therefore between the principal objectives of architects and engineers respectively, became more obvious in the various reactions to early Modernism that emerged in the last quarter of the twentieth century. These included so-called Postmodernism, characterised by the (often ironic) re-introduction of traditional symbols and figures of ornamentation; High-Tech, a Late-Modern style that featured a particularly overt visual use of structural symbolism; Deconstruction and Neo-Modernism, the latter in several forms. All of these reactions have conformed – despite their variously revolutionary rhetoric – to the dominating principles of early Modernism and could be considered to be simply extensions of Modernism in the broad sense rather than anything fundamentally new: they have all involved an adherence to the visual as the principal determinant of form, and a susceptibility to influence from a range of often contradictory 'philosophies' and 'theories' of varying levels of validity.

The discrepancy between the different weight accorded to visual expression and technical performance became ever wider towards the end of the twentieth century, as structural technology was developed to the point at which buildings of virtually any shape could be constructed and architects exploited fully the freedom of expression that this allowed, obvious examples being the designs of architects such as Zaha Hadid and Frank Gehry. Such architects have used methods that disdain any influence, at the form-determination stage of design, from considerations of careful or economical (responsible) use of material and energy – methods that invite comparison with the fanciful 'visions' of early Modernist thinkers such as Taut – but with less justification. Taut had at least the excuse that he was striving to break architecture free from the stultifying grip of nineteenth-century revivalism.

8.5 Conclusion

This chapter has discussed the relationship between structural technology, structural 'philosophy' and architectural 'theory'. It has argued that, unlike the fairly straightforward philosophies of structures described by engineers such as Nervi and Torroja and reiterated in the context of recent mathematical thinking by Balmond (see Section 8.2.2), the architectural theory of the Modern period has been highly contradictory – seeking architectural and visual vocabularies that on the one hand were intended to be celebrative of technology but that on the other placed visual considerations well above technical performance as the primary objective of design.

One of the ironies of Modern architecture is that, far from adopting a revolutionary new design methodology appropriate for the 'new age of technology', the architects have in fact prolonged the methods being taught in the Beaux Arts schools which were so vilified by Le Corbusier and other Modernist thinkers. They have continued in reality to be principally, like their predecessors, manipulators of visual images and symbols, simply substituting the steel I-section, plate glass and board-marked concrete for the classical column, the Gothic stained-glass window and polished ashlar masonry.

Throughout the Modern period structural technology has played several major roles: it has produced new systems of support based on skeleton frameworks, it has created a range of new images that were exploited and manipulated by Modern architects and it has freed architects from the constraints on form that were imposed by the technical limitations of the traditional building materials and technologies of the pre-Modern age.

So far as theoretical underpinnings are concerned, philosophies of structures have principally been directed at fostering approaches to design that result in structures that are appropriate for their function and that make economical use of materials and other resources. Architectural theory has been principally concerned with the art of architecture: with architecture as an art form, building as art. In the Modern period it has been concerned almost entirely with the aesthetics of architectural form in all of its aspects. A complication of Modernist architectural theory, which arose from the idea that the modern aesthetic should be celebrative of technology, was the idea that buildings should be functional in a purely practical way as well as being means of artistic expression. This has caused much of Modern architecture to lack overall integrity due to the many conflicts that have arisen between the requirements of art and of functionality. In much of the prominent architecture of the early twenty-first century, however, the pretence of functionality as a primary influence on form determination has largely been abandoned.

This consideration of the roles and purposes of structural and architectural theory has served to illustrate that engineers and architects have tended to approach the design process with very different objectives. It explains, in part, the disjunction that often exists between these two sets of contributors to the design of buildings. A better mutual understanding (or even a better appreciation) of the different priorities of the two groups would perhaps lead to the fostering of a more harmonious relationship.

Note

1 In his preface to Balmond, C., 2002, *Informal*, Prestel.

CHAPTER 9

The engineers – their role in developing the imagery of Modern architecture

9.1 Introduction

The introduction of the 'new' structural materials of steel and reinforced concrete in the late nineteenth century had a profound influence on both the forms of architecture which became possible and the nature of the processes by which buildings were designed. This chapter explores the roles of engineers in both of these developments which were so crucial to the evolution of Modern architecture. It begins, in Section 9.2, with an account of engineers who worked largely outside the world of architecture, mostly in the design of industrial buildings, and who devised entirely new forms of building typology, such as the glass-clad framework and the thin concrete shell, which contributed a range of new images that were subsequently incorporated into architecture. This group includes the great architect/engineers of the nineteenth century, such as Joseph Paxton and William Henry Barlow, and continues into the twentieth century with figures such as Pier Luigi Nervi, Eduardo Torroja and Felix Candela. Santiago Calatrava has continued this tradition into the present day. Section 9.3 is devoted to a second group of engineers who worked in design teams with architects. This group may be further subdivided, first, into engineers who worked as facilitators contributing expertise that allowed architects, as the leaders of design teams, to explore fully the sculptural possibilities of the new materials but often in forms that were less than ideal structurally; Peter Rice and, in the present day, Cecil Balmond, fall into this sub-group. A second sub-group are engineers, such as Anthony Hunt, who

Facing page:
Chords Bridge, Jerusalem, Calatrava. Photo: Leinad.

worked in collaborative partnerships with architects to evolve buildings in which visual and technical performance were accorded equal priority.

Another important development in the Modern period was the emergence of a profession that was new in the context of architecture, that of the independent consulting structural engineer. A significant figure in this context was Ove Arup who, in addition to being a highly competent design engineer, was responsible for founding one of the most successful of this new type of firm.

What follows here is not a complete listing of prominent engineers or a comprehensive account of the development of architectural engineering in the Modern period – space limitations do not permit this. The intention is simply to illustrate the role of engineers in the development of the imagery of Modern architecture, the types of collaboration that they formed with architects, and the nature of their contribution to the architectural design process.

9.2 The engineer/architects – their role in the creation of new images for architecture

9.2.1 Introduction

The tradition of the engineer/architect in the Modern period begins with the designers of the monumental buildings and structures of the first industrial revolution. Many of their creations had significant architectural qualities, such as the spacious interiors of the long-span train sheds, or the images of transparency achieved with the great exhibition buildings, as outlined earlier in Section 8.3. At the time of their construction the architectural qualities of these buildings were not generally recognised. As the Modern period became established, in the early twentieth century, illustrations of architectural engineering appeared in the writings of polemicists such as Le Corbusier, and the individuals themselves were championed by historians such as Sigfried Giedion. Only then did the architectural significance of figures such as Joseph Paxton (1802–1865), Isambard Kingdom Brunel (1806–1859), Gustave Eiffel (1832–1923), William Henry Barlow (1812–1902), Lewis Cubitt (1799–1883) and others, all of whom were well known in the engineering field, become recognised. Almost none of the individuals concerned had received any kind of architectural training and they therefore approached the task of designing buildings from a position of complete freedom from formalist or stylistic theories of architecture. They have been categorised, by architectural historians, as *structural functionalists*, and this epithet is justified, but only if the term is used to have the same precise meaning as is defined here in Section 8.2, rather than in the much looser way in which the term 'functionalism' has been commonly used in the literature of architectural history, as is discussed in Section 8.3. Their principal contributions to architecture were a methodology for design (described in Section 8.2) and a number of significant and influential images (discussed below).

9.2.2 The separation of structural and enclosing functions – the glass-clad framework

The glass-clad framework, which was perhaps the supreme icon of architectural Modernism, was originally derived from a building typology that was innovative in the nineteenth century and that was developed almost entirely in the world of engineering for use in industrial buildings. It had its origins in the idea of the metal skeleton framework (of steel in its most recent version) which could form the entire structural support for a building and relieve walls of all structural function. The history of its development in architecture, pioneered by figures such as William Le Baron Jenney (1832–1907) and Louis Sullivan (1856–1924), and evolved into the International Style by architects such as Ludwig Mies van der Rohe (1886–1969), is well known and will not be described here, where the interest is specifically in the individuals who originally devised its basic technology.

Perhaps the most influential of the great glass enclosures of the nineteenth century was the Crystal Palace in London (1851) (Figures 8.4 and 8.5), which is described in Section 8.3. Its principal designer was Joseph Paxton, whose background was actually in horticulture. Following training as a 'garden boy', he was employed at the gardens of the Royal Horticultural Society in London where he was 'spotted' by the Duke of Devonshire, as a result of which he became, at the very young age of 20, the head gardener at the Duke's estate of Chatsworth, which was considered at the time to have one of the finest designed landscapes of the age. Clearly a highly talented individual, Paxton became involved with the design of glasshouses, then in their infancy in horticulture, and was responsible for the innovative use of iron frameworks, plate glass and techniques of modularisation and the mass-production of frame components. The Crystal Palace, his supreme achievement and built to house the Great Exhibition in London of 1851, encapsulated his innovative glasshouse technology and was a work of pure engineering, designed to meet a very testing combination of requirements – a very large enclosure, capable of being erected in less than a year and, subsequently, easily dismantled. It was a major contribution to the development of the technology of the structural framework, its most novel feature being the standardisation and mass-production of the major elements of the structure.

Another prominent nineteenth-century engineer was William Henry Barlow (1812–1902) who, as the principal designer (assisted by Rowland Mason Ordish) of the train shed at St Pancras Station in London (1862–1869), may also deserve architectural credentials. With a clear span of 73 m (240 ft), the St Pancras train shed (Figure 9.1) was the longest-spanning iron and glass structure of its time and a magnificent architecture of the interior. Among his

Figure 9.1 Train shed, St Pancras Station, London, 1868; William Henry Barlow and Rowland Mason Ordish, engineers. The clear span across the entire width of the platforms was justified here by operational requirements. At 73 m it was the largest in the world when constructed. The use of a form-active parabolic arch profile was appropriate as was the 'improvement' by triangulation of the principal structural elements. The resulting striking architectural space was generated from the satisfaction of purely functional requirements.

Photo: Przemyslaw Sakrajda/Wikimedia Commons.

other claims to significance, Barlow had assisted Paxton with the structural calculations for the Crystal Palace and he was also responsible for the design of other notable structures such as the replacement Tay Railway Bridge (1882–1887). He was a considerable figure in the world of nineteenth-century engineering, a fellow of the Royal Societies of London and Edinburgh and an innovator and experimenter who was active in promoting the introduction of steel as a structural material. His education was entirely in engineering. The other London railway terminus of architectural significance, King's Cross, was designed by another engineer who had received no architectural training, Lewis Cubitt (1799–1883), the son of a Norfolk carpenter.

The three buildings described above were selected here because they all appear regularly as illustrations in works of architectural history dealing with the period leading up to the introduction of Modernism. They are prime examples of a body of architectural engineering that was created throughout the industrialised world and that constituted a major influence on both the imagery of Modern architecture and its underlying technology.

It is sometimes suggested, for example by Andrew Saint (*Architect and Engineer: a study in sibling rivalry*, Yale, 2007), that architects were involved in many of these projects, and this is to some extent correct, but the role of the architects in these cases was almost always as advisors on ornamentation rather than as collaborators in the evolution of the design concept. The aspects of the buildings which were truly innovative and of significance for the development of architecture were of purely engineering origin, designed by engineers acting as architects.

9.2.3 The iconography of reinforced concrete

One of the other significant technical developments of the nineteenth century, so far as Modern architecture was concerned, was that of reinforced concrete. As with steel, it was of enormous practical significance as it provided supporting structures for the rectilinear architecture of the International Style. Less well understood is its role in the iconography of Modern architecture – the creation of new images.

The significant properties of reinforced concrete as a structural material were its *strength characteristics* (particularly its ability to resist both tension and compression, and therefore *bending*), which allowed it to be used for every type of structural element; its *mouldability* which, together with the ease with which *structural continuity* could be achieved, allowed almost any shape to be constructed; and its *durability*. It was in fact one of the greatest innovations in building technology of all time.

Reinforced concrete added three distinct forms to the vocabulary of architectural engineering: the continuous beam/column framework; the two-way-spanning flat slab (Figure 8.9); and the thin shell (Figures 1.4, 9.4 and 9.7), which was suitable for applications such as the form-active dome and vault, and therefore of structures of very high efficiency and long-span capability. All three forms emerged in the world of pure engineering and all were introduced to architecture by structural engineers, working as architects and largely without architects.

By the end of the nineteenth century, the beam/column framework in reinforced concrete had been developed into the form that was to become ubiquitous in the Modern period. Many of its features were evolved simultaneously by different inventors, particularly in France and the USA, but the most complete early system was that of François Hennebique (1842–1921) (Figure 9.2), a self-taught builder whose importance was due to his work not only as an innovative engineer but also as a businessman. From the 1890s, Hennebique was highly successful in promoting his system both through his own company and through licensing arrangements with other firms in France, Belgium, Germany and the UK. The brothers Albert and Julius Kahn developed an improved system of reinforcement for concrete in the USA around 1902–1905 and this led to its widespread adoption in that country.

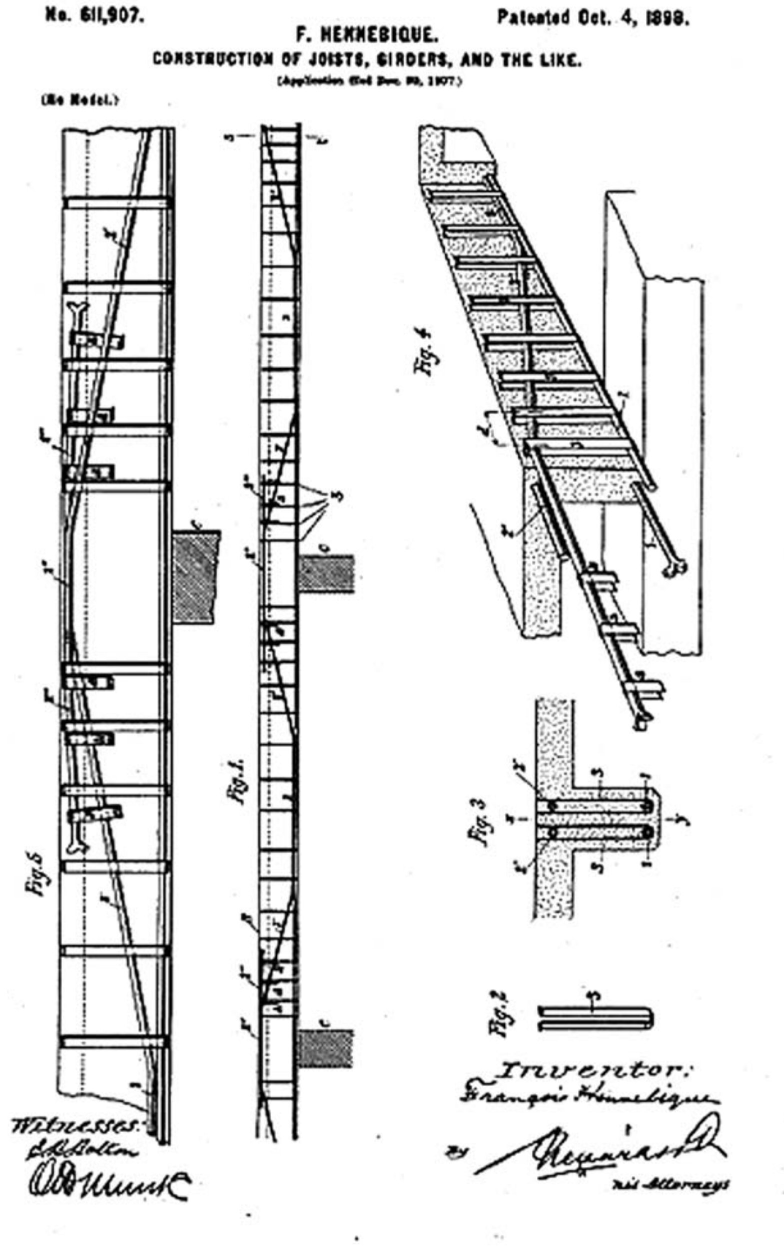


Figure 9.2 Patented system for multi-storey reinforced concrete framework, 1902; François Hennebique. Hennebique's system was a beam/column framework in which a pattern of steel reinforcement was used to give the elements bending strength. Continuity was achieved through in-situ construction that increased efficiency. More than 7,000 buildings, based on this system, were constructed between 1892 and 1902, which established the reinforced concrete framework as a standard technique for multi-storey buildings.

Image: Inventricity.

As a result of the activities of these pioneers, buildings based on rectilinear reinforced concrete frameworks began to appear in many countries on both sides of the Atlantic Ocean in the early decades of the twentieth century and affected the appearance of buildings as well as their structural make-up.

It was the developments in reinforced concrete just described (together with parallel advances in steel technology) that brought into being one of the most significant constructional arrangements of Modern architecture, that of the building with a skeleton-frame structure supporting walls that were entirely non-structural. This was a configuration that accommodated well the revised vision of architecture expressed by Gottfried Semper (see Section 8.3.2), and the fact that both steel and reinforced concrete frameworks were easily constructed in rectilinear arrangements also made them compatible with the Modernist architectural theory of the early twentieth century, which favoured rectilinearity for reasons other than the practicalities of construction.

The reinforced concrete flat-slab system, developed by Robert Maillart (1872–1940) (Figure 8.9), also in the early decades of the twentieth century, was a further addition to the structural vocabulary that made possible the glass-walled architecture of Modernism. In addition, and as was discussed by Giedion (see Section 8.3), the plate-like quality of the reinforced concrete flat-slab, together with the structural continuity offered by the material, allowed the creation of building forms that were reminiscent of the spatial concepts of fine-art movements such as Cubism. Thus was a new sculptural possibility added to the vocabulary of architecture.

A quite different strand of architectural engineering made possible by reinforced concrete was the long-span single-storey enclosure, based on the form-active dome or vault. The principal load carried by these structures was their own weight, with the result that the form-active geometry was curvilinear (see Chapter 4). The resulting three-dimensional shapes – thin *shells* – which were distinctively different from those of the semi-form-active domes and vaults of traditional masonry construction, were highly seductive and introduced an exciting new set of images to the visually focused world of architecture.

These thin shells offered astonishing levels of structural efficiency. For example, a properly designed shell of 100 mm thickness could easily achieve a free span of 60 m. By comparison, a horizontal flat-slab with a thickness of 500 mm could barely span 10 m and would therefore require five intermediate supports as well as five times the volume of concrete to cover the same area as the equivalent shell. To build thin-shell structures economically, however, two quite formidable problems had to be overcome. The first was the analysis of their complex forms: in order to build thin-shell structures safely it was necessary that the levels of internal forces be calculated in advance so that an appropriate thickness of shell could be specified. The second problem was that of constructing economically the complex formwork (usually of timber) on which the liquid concrete was cast.

The first successful reinforced concrete shells were developed in Germany by three engineers, Franz Dischinger (1887–1953), Ulrich Finsterwalder (1897–1988) and Hubert Rüsch (1903–1979), all of whom worked for the contractor Dyckerhoff and Widmann, who actually built the shells (Figure 9.3). The earliest shells were hemispherical domes constructed by erecting a geodesic framework of identical 600 mm long steel rods supporting wire mesh, on to which fine-aggregate concrete was sprayed. This procedure eliminated the need for temporary formwork and the system was developed to include other geometries based on simple polygonal figures. Dischinger, Finsterwalder and Rüsch solved the structural analysis problem by developing sophisticated theoretical calculations, the results of which were verified by a rigorous system of testing of scale models and, occasionally, of full-size structures. They thus developed a highly efficient system for the design and construction of thin shells and, throughout the 1920s and 30s, built many hundreds of examples worldwide. Their knowledge and experience were widely disseminated in technical journals and it was largely by extending the results of their pioneering work that the spectacular structures of the acknowledged masters of this form of architecture such as Nervi, Torroja, Candela and others, were achieved.

A related, but slightly different approach to that of Dischinger, Finsterwalder and Rüsch was pioneered by Eugène Freyssinet (1879–1962) in the

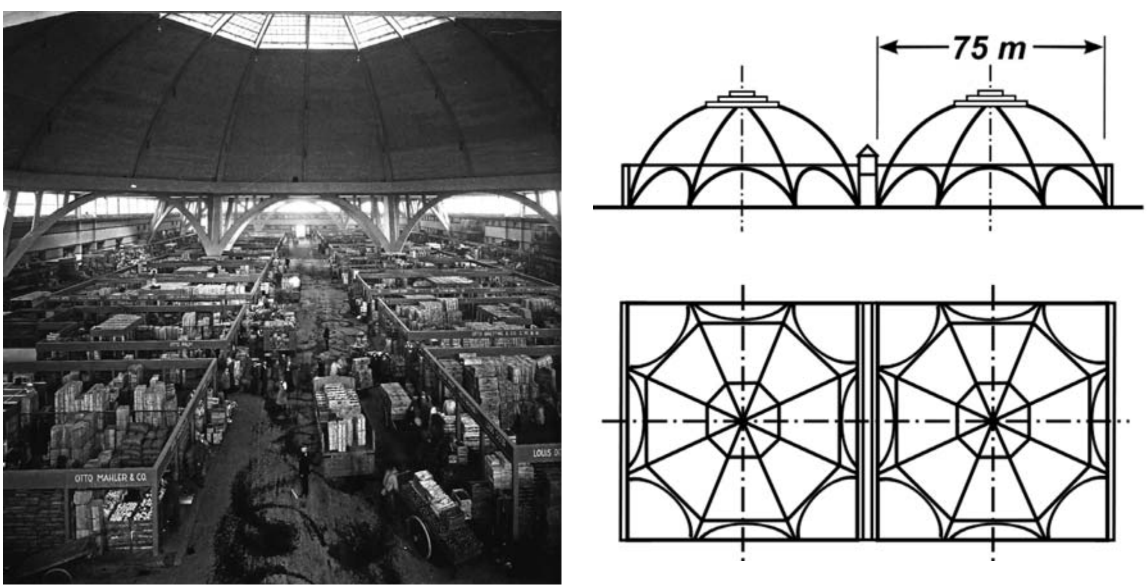


Figure 9.3 Reinforced concrete shell, Leipzig market hall, 1929; Franz Dischinger and Hubert Rüsch, engineers. This early reinforced concrete shell has a span of 65.8 m with a thickness of 90 mm. The geometry was complex, based on a polygonal arrangement, and the shell was stiffened with ribs and a supporting ring beam. The economy achieved in the use of material was nevertheless remarkable.

Photo: Atelier Hermann Walter/Wikimedia Commons; Drawing: Egdir/Wikimedia Commons.

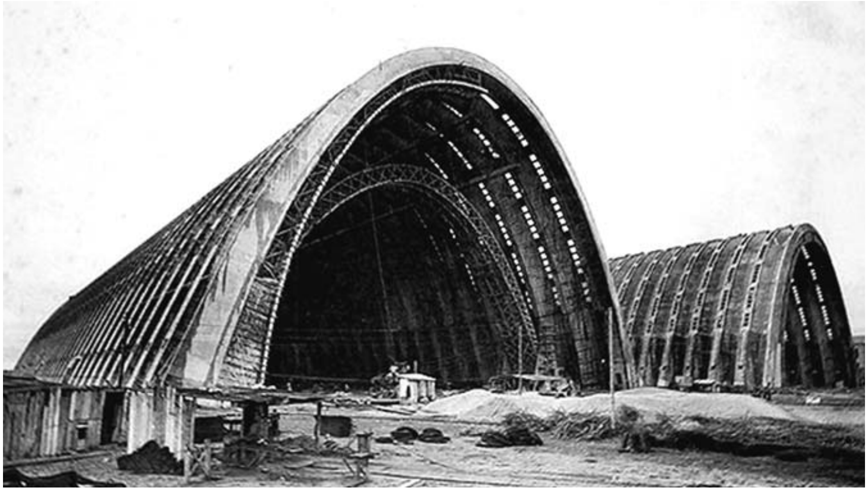


Figure 9.4 Airship hangars, Orly Airport, Paris, 1923; Eugène Freyssinet, engineer. The basic form of this structure is a barrel vault with a form-active parabolic profile spanning 75 m. Corrugations were used to give the vault the required stiffness while minimising the volume of material required. The identical sub-sections were cast in-situ using a moving formwork (just visible within the enclosure). Economy of means was achieved in terms both of the material consumed and of the simplicity of the construction process – a mark of excellence in structural design.

Photo: arquiscopio

famous airship sheds at Orly Airport, Paris (1923) (Figure 9.4). The basic form of these buildings was a single-curvature barrel vault of parabolic (form-active) cross-section. Freyssinet's Orly hangars were supreme examples of structural functionalism. The parabolic profile of the vaults minimised undesirable bending moments under the action of the principal load carried (the self-weight of the structure), and the corrugated ('improved') cross-section of the shells provided resistance to local buckling and ensured that such bending as did occur, due to variations in load, was resisted efficiently. The material was appropriately used, its mouldability being exploited to the full, and the construction sequence relied on efficient re-use of movable formwork.

The Orly hangars, which had a clear span of 75 m (250 ft), together with the thin-shell structures of Dischinger, Finsterwalder and Rüsch, were the equivalent, in reinforced concrete, of the iron and steel train sheds and exhibition buildings of the nineteenth century, and were the precursors of a whole series of similar buildings built during the mid-decades of the twentieth century by engineer/architects such as Nervi, Torroja, Candela and Nicholas Esquillan.

Pier Luigi Nervi (1891–1979) was educated at the School of Engineering at the University of Bologna. As a designer of buildings he operated as an *ingegnere edile* (a building engineer) and for most of his projects he acted as both the designer of the structure and the contractor responsible for its construction, and he was respected for his rigorous organisation of construction sites. It was no doubt this combination of roles which made his buildings remarkable for both their structural appropriateness and their ease of construction. Nervi was always concerned to achieve the best performance from minimal means, in terms of both material used and design and construction effort. Many of his most famous designs were for long-span enclosures, which justified the use of complex form-active structures. Nervi also employed a variety of 'improving' strategies (see Chapter 4), in the form of sets of intersecting ribs, to further enhance the efficiency with which material was used. The resulting highly complex and elaborate forms were constructed economically through the use of ingenious systems of standardisation and modular construction. All of these features may be seen to have come together in one of his earliest works, the last of a series of aircraft hangars at Orvieto (1942–destroyed 1944) (Figures 9.5 and 9.6).

Figure 9.5 (*facing page*) Aircraft hangar, Orvieto, 1935; Pier Luigi Nervi, engineer. The vault-like free-standing roof structure of this building, seen here in a partially completed state, is actually an 'improved' beam that spans longitudinally between three parabolic arches, one at each end and one located centrally. The width of the building is 44.8 m and its length is 120 m, giving a principal span between the arches of 60 m. Subdivision of the vault-like canopy into ribs on the lamellar principle, with sub-elements that were further 'improved' by triangulation, resulted in a very efficient use of material. The high degree of repetition in the structure facilitated simple manufacture of elements by pre-casting and resulted in a very economical construction process. Use of the relatively complex parabolic cross-section was justified in the interests of making the supporting arches conform to a form-active geometry.

Photo: Pier Luigi Nervi Project/Wikimedia Commons.

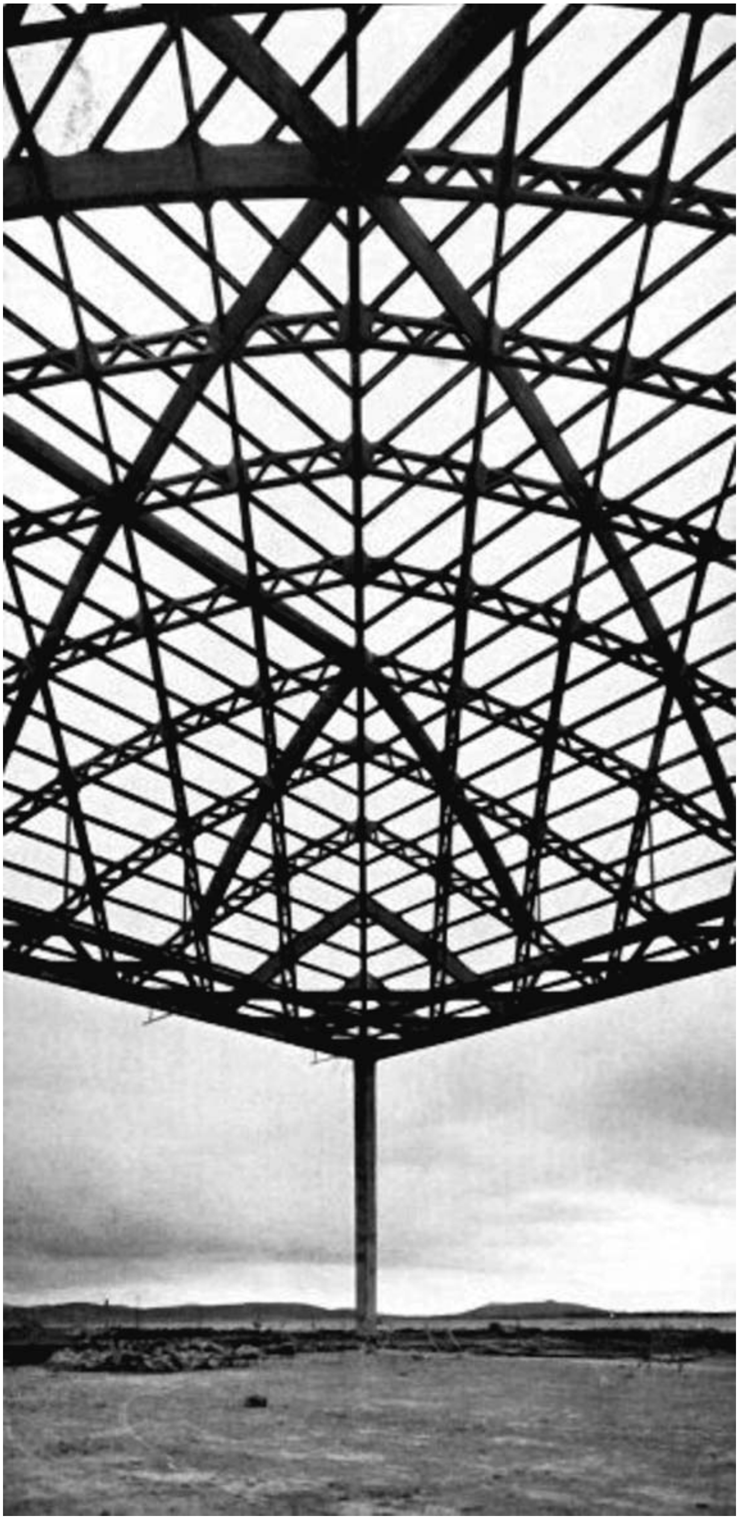


Figure 9.6 Aircraft hangar, Orvieto, 1935; Pier Luigi Nervi, engineer. The economy of material required for this long-span structure is evident in this view.

Photo: Architecturefarm.

The principal structural element of this building was a vault-like 'improved' beam that spanned between three arches, one at each end of the building and one placed centrally. The roof structure was thus supported at six locations and the walls of the building were entirely free of structural function and could therefore accommodate the large doors required for the ingress and egress of aircraft. The arches had parabolic (form-active) profiles.

The roof canopy consisted of a series of intersecting lamellar ribs that were further 'improved' by internal triangulation. The use of multiple levels of 'improvement' was similar to that used in aircraft construction (see Figure 4.15), but, unlike in the symbolic expression of complexity seen later in High-Tech (Figure 3.19), the 'improvements' in Nervi's hangars were fully justified on technical grounds.

The key to making the highly complex geometry economically buildable was the use of the lamellar system that subdivided the roof into small sub-units that had identical overall dimensions and that could be mass-produced by pre-casting. A further ingenious feature was that, by making slight adjustments to the pre-casting moulds, the minor dimensions of the sub-units could be varied to give a variety of strengths – necessary to accommodate variations in the magnitudes of the internal forces across the span. The sub-units were constructed from *ferro-cement*, a type of reinforced concrete based on very fine aggregate and wire-mesh reinforcement, which allowed very delicate shapes to be cast. Nervi made much use of this system to simplify the construction of many of his subsequent buildings (Figure 8.2).

It took Nervi's particular combination of skills and aspirations to produce the aircraft hangar design – a structure with levels of complexity that were both entirely justified technically and buildable economically. Nervi was awarded the contract to build these hangars because they were cheaper than the more conventional alternatives that were considered, rather than for their highly innovative design qualities, which would be so much admired subsequently in the worlds of both architecture and engineering.

Another notable feature of the aircraft hangars was the techniques that were used in the structural analysis – another extension of the design methodology pioneered by Dischinger, Finsterwalder and Rüsch. The delicacy and refinement of the lamellar ribs could not have been achieved safely without a reasonably accurate knowledge of the levels of internal forces involved. As these were highly **statically indeterminate structures** (see Glossary), accurate analysis was beyond the capabilities of the calculation techniques available at the time. In the manner of Dischinger, Finsterwalder and Rüsch, approximate calculations were carried out and the results verified using scale-modelling techniques, in collaboration with Professor Arturo Danusso (1880–1968) of the Polytechnic of Milan (see Addis, 2007, p. 491). Dimensionless ratios, first advocated by the hydrodynamic engineer William Froude (1810–1897), were used to allow for the effects of scale.

For the construction of his later vaults and domes, Nervi introduced yet another innovative feature, and one of his most ingenious techniques: that of standardised pre-cast concrete sub-elements as permanent formwork. Like the sub-elements of the aircraft hangars, these were cast in ferro-cement. They acted compositely with cast-in-situ concrete to form highly efficient structures that were economical to construct (Figure 8.2). They also eliminated the need for timber formwork, and the limitations to form that this implied. As Nervi himself stated: 'From a construction viewpoint, . . . my efforts as designer and builder have been directed towards removing the economic and shape limitations imposed by wooden forms' (Nervi, 1956, p. 100).

Nervi's buildings were remarkable for their combination of structurally meaningful complex forms that produced very efficient uses of structural material with simple constructional schemes, which allowed them to be built cheaply. Their apparently free-form shapes and ambience of advanced technology were found highly seductive by architects, but imitations were often flawed due to lack of understanding of their essential qualities. They provide a striking contrast with designs, such as that for the Sydney Opera House (see Section 9.3), in which shapes were derived from purely aesthetic considerations, devoid of structural meaning, resulting in requirements for excessive volumes of structural material and occasionally, as at Sydney, building designs that were impossible to construct without considerable modification.

Eduardo Torroja (1899–1961) was responsible for the design of a large number of reinforced concrete buildings that were constructed around the mid-twentieth century and that contributed to the genre of long-span, curvilinear and *apparently* free-form structures that were prominently featured in the architectural media at that time. He was a person of wide-ranging interests that included the aesthetics of structural form, investigations of the properties of materials and the education of both architects and engineers. As the author of *Philosophy of Structures* (1958) (see Section 8.2), he was responsible for one of the best accounts given of the methodologies of *structural functionalism*. This was an approach to design that he followed rigorously and his many built works are exemplars of the resulting types of building and structure.

Space limitations here permit the brief description of only three of his buildings. All were designed in collaborations with architects but the lack of any hint of formalism suggest that it was Torroja's ideas that dominated the evolution of their forms.

The shell canopy for the marketplace at Algeciras (1932–1933) (Figure 9.7) was a very early thin-shell building, contemporary with those of Dischinger, Finsterwalder and Rüsch in Germany. Its form was determined entirely from structural and constructional considerations. The doubly-curved surface of the principal shell element formed part of a sphere, to facilitate construction and rudimentary calculations; the shell was stiffened to resist buckling at its edges by mini-cylindrical canopies, and a set of tie cables, encased in concrete, was provided around the perimeter, both to prevent horizontal thrusts being

Figure 9.7 Algeciras market hall, 1934; Eduardo Torroja, engineer; Manuel Arcas, architect. Using a spherical approximation to the form-active shape, a span of 47.7 m was achieved with a maximum shell thickness of 100 mm. The shell is stiffened by cylindrical mini-canopies at its perimeter. Outward thrusts are absorbed by a tie beam at the tops of the supporting columns.

Photo: Creación propia/Wikimedia Commons.

imposed on the supporting columns and to absorb tensile hoop stresses in the shell itself. The span of 47.6 m was achieved with a maximum shell thickness of 100 mm, giving remarkable efficiency in the use of material.

The highly innovative form of the Frontón Recoletos building in Madrid (1935–1936 – demolished 1973) (Figure 9.8) was an example of the generation of a novel building shape from purely technical considerations. The building was designed to accommodate a court for the popular Spanish spectator sport of pelota, a game similar to squash (although the court is considerably larger) in which the playing surfaces are the end walls, floor and one side wall of a rectangular space, with the spectators being located on the other long side.

The remarkable roof of Torroja's building consisted of a thin reinforced concrete shell that spanned longitudinally between the end walls. The basic configuration is similar to that which Nervi used for his aircraft hangars (Figure 9.5). In cross-section, the roof consisted of two intersecting circular arcs, and although its appearance was similar to that of a vault, it was in fact an 'improved' beam (see Chapter 4) that derived only minimal support from the side walls. The use of circular arcs greatly simplified the construction and the use of a constant cross-section for the building allowed the formwork to be fabricated from straight timber planks, thus avoiding the complexities of formwork which are usually associated with concrete shells. This arrangement made possible the complete absence of internal structure that would have compromised the sightlines of the spectators. Torroja's sketch from *Philosophy of Structures* (Figure 9.9) demonstrates the structural principle on which the

Figure 9.8 Frontón Recoletos, Madrid, 1935; Eduardo Torroja, engineer; Secundino Zuazo, architect. The roof of this building spans 55 m longitudinally between the end walls in an 'improved' beam configuration similar to that used by Nervi for the Orvieto Hangars. The shell thickness was 80 mm. Use of a simple cylindrical configuration resulted in a relatively simple construction process. A more complex profile, such as that used by Nervi with the Orvieto hangars, would not have been justified in this case.

Photo: ArtChist/Enrique Pérez Rodero.

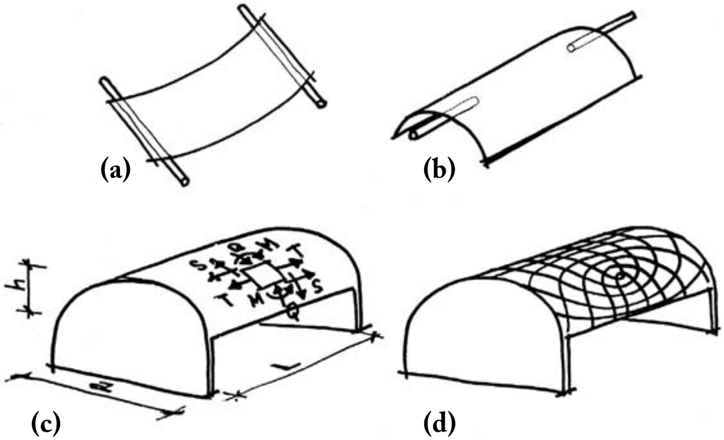


Figure 9.9 This sketch, which appeared in Torroja's book *Philosophy of Structures*, demonstrated the 'improved-beam' structural action of the Frontón Recoletos building.

Image: courtesy University of California Press.

Figure 9.10 Zarzuela Hippodrome (racecourse) Pavilion, Madrid, 1935, Eduardo Torroja, engineer; Martín Dominguez Esteban and Carlos Arniches, architects. The oversailing reinforced concrete canopies are non-form-active cantilevers that have been given 'improved' cross-sections in the form of curved thin shells, greatly increasing their structural efficiency.

Photo: Ximo Michavila/Wikimedia Commons.

design was based. The overall configuration and structural action were nevertheless fairly complex, thus posing difficulties of analysis. Torroja constructed a simple model, consisting of curved cardboard supported on timber end walls, to confirm that the idea was feasible and then used a simplified mathematical model as a basis for calculating the internal forces. The results were confirmed by testing a 1:25 scale-model, using the methods developed by Dischinger, Finsterwalder and Rüsch.

The grandstand at the Zarzuela Hippodrome (Racecourse) in Madrid (1935) (Figure 9.10), which Torroja designed in collaboration with the architects Martín Domíngues Esteban (1897–1970) and Carlos Arniches (1895–1958), provides a further example of the integrity of his design methodology. The building is notable for the seemingly effortless combination that was achieved of structural integrity and programmatic function, as is demonstrated by Torroja's sketch of its cross-section (Figure 9.11).

These three buildings clearly demonstrate Torroja's approach to design. Their concepts were entirely original but not unnecessarily so. The designs were informed by a deep understanding of how structures and materials

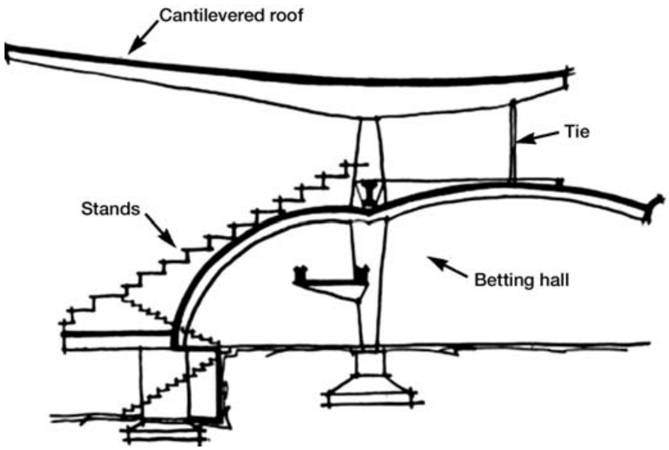


Figure 9.11 Zarzuela Hippodrome (racecourse) Pavilion, Madrid, 1935; Eduardo Torroja, engineer; Martín Dominguez Esteban and Carlos Arniches, architects. The sketch from Torroja's *Philosophy of Structures* demonstrates the integration of structural and space planning, both of which were truly functional.

Image: courtesy University of California Press

behave; the buildings were straightforward to construct and made a highly efficient use of material; and the final results were entirely fit for purpose. The buildings were remarkable examples of the creation of entirely novel forms, in response to particular sets of programmatic requirements, using the imaginative combination of knowledge of both structural behaviour and material properties.

Félix Candela (1910–1997) was a Spanish architect/engineer who was educated at the Escuela Técnica Superior de Arquitectura in Madrid and subsequently in Germany. He served as an engineering officer on the Republican side in the Spanish Civil War (1936–1939) and, following a period as a political prisoner, was deported to Mexico in 1939. Candela quickly found work there as an architect, engineer and constructor, and over the next three decades he was responsible for the design and construction of several hundred buildings, ranging from small enclosures to large factory complexes and major churches. Almost all of these were based on thin-shell structures using varieties of the geometry of the hyperbolic paraboloid. He emigrated to the USA in 1971 where he became a full professor at the University of Illinois.

Although Candela was trained as an architect, he had little interest in formalist approaches to design and 'protested against being associated with the formal intentions of such men as Eero Saarinen, Oscar Niemeyer and Jørn Utzon' (quoted in Enrique X. de Anda Alanís, *Candela*, Taschen, 2008, p. 7). Like Nervi and Torroja, he committed himself to designing and building structures that functioned well and that were economical to build. He was in this sense a structural functionalist. He became an expert in the calculation of membrane stresses in thin shells and, through knowledge gained by building test models and from experience of full-scale structures, developed an intuitive awareness of how to minimise the quantity of material required to produce safe structures.

Candela was intrigued by the remarkable geometric and structural properties of the hyperbolic paraboloid (**hypar**) shape (Figure 9.12). The hypar is a doubly-curved saddle-shaped surface that is generated by moving two mutually perpendicular parabolas over one another (Figure 9.12a). The result is an

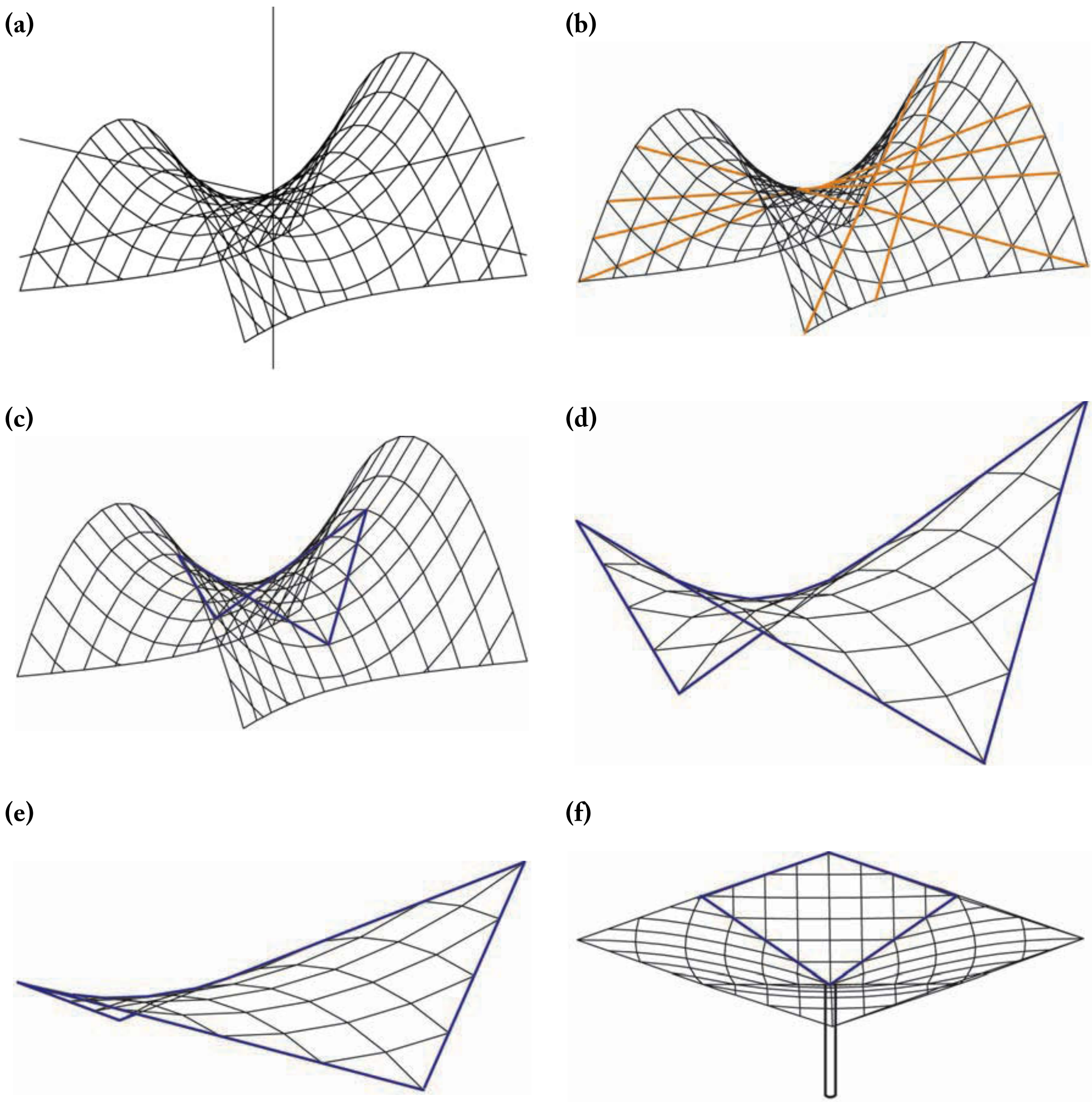


Figure 9.12 Geometry of the hyperbolic paraboloid. (a) The saddle-shaped hyperbolic paraboloid surface is generated by moving one parabola over another. The anticlastic form produces tension and compression stresses at each location, in two mutually perpendicular directions, and the tension stabilises the surface (see Figure 2.2) and inhibits buckling. (b) A characteristic of the shape is that two sets of straight lines may be inscribed on its surface which simplifies formwork and allows the shell to be cut into straight-sided portions (c), (d) and (e). (f) Straight-sided portions can be combined to form a roof canopy.

Line drawings: Andrew Siddall after originals by Angus J. Macdonald.

anticlastic (meaning doubly curved in opposite directions) translational shell. The shape is defined in the x,y,z Cartesian axis system by the equation:

$$z = x^2/a^2 - y^2/b^2$$

where a and b are constants that define the shapes of the generating parabolae. The equation can also be written:

$$z = (x/a + y/b)(x/a - y/b)$$

The fact that such a complex shape could be so simply described mathematically gave it two enormous advantages for the constructor: it greatly simplified (even made possible) the calculation of its internal forces; it also facilitated the setting out of the structure on the building site and the subsequent control of its geometry as construction proceeded.

The mathematically aware will have appreciated the significance of the (second quoted) 'factored' version of the hypar equation. The expressions within the brackets are the equations of straight lines which means that two sets of intersecting straight lines can be inscribed on the doubly curved surface. This is of enormous significance: it allowed the shell to be 'cut' into sub-shells that had straight edges (Figure 9.12 d, e and f). This property was exploited by Candela to produce buildings that had straight-edged plans, and also to evolve systems of enclosure based on combinations of straight-edged shells to cover large areas with structures the overall form of which was not significantly different to that of the post-and-beam framework, thus giving the advantages of shell architecture (very high efficiency) without one of its principal disadvantages – that of the necessarily high, curving form-active shape. Candela exploited this property both for the creation of highly practical enclosures for factories (Figure 9.13) and in the creation of expressive forms for church architecture (Figure 9.14). The second advantage of the straight-line characteristic of the hypar was that its formwork could be assembled from straight planks of timber, thus greatly simplifying its construction.

It was largely through Candela's work that the range of possibilities offered by the hypar class of shells was demonstrated to the world. The intriguing forms that could be produced resulted in their being featured in the architectural media and another set of images with a 'techy' feel was therefore added to the visual vocabulary of Modern architecture. The strict geometric discipline required by the hypar forms and its variations was not, however, found congenial by the architects who wished to break free from the Modernist tyranny of the rectangular box and the forms themselves did not offer sufficient visual excitement. The hypar was therefore relegated to the fringes of that part of the architectural world which was interested in curvilinear 'free' form. As Saint (2007 p. 410) remarked: '[the hypar] came into architectural vogue for [only] a generation.'

Figure 9.13 Umbrella hypar roof canopy, Mexico City, 1955; Felix Candela, engineer. Straight-sided elements of hyperbolic paraboloid shells are combined here to make a highly efficient roof canopy.

Photo: Revistacodigo.

This statement reveals once again what was and remains a typical difference in the approaches to design of architects and engineers. For Candela, the hypar shell did not represent a 'vogue'. It was, for him, a highly practical and efficient way of providing the envelope for a building.

In the canopies, based on hypar umbrellas, that Candela created for factory buildings, we catch a glimpse of the kind of approach to design that might produce a truly sustainable architecture – the provision of enclosure with maximum economy of means in the consumption of resources, ease of construction and subsequent durability. The design of this type of architecture must, of course, be based on technical knowledge rather than on architectural fancy, and questions of whether or not a shape is 'in vogue' do not arise.

Space does not permit the inclusion of more examples of the results of the methodology of structural functionalism. There were many other such practitioners, most notably Nicholas Esquillan, Riccardo Morandi, Heinz Isler and Eladio Dieste. In concluding this section, it may be noted that the works of Nervi, Torroja and Candela were representative of an approach to architectural design in which a constructional technology was allowed strongly to influence the overall concept, so as to produce a building that satisfied programmatic requirements and whose fabric fulfilled its function with maximum economy of means. As with the shells of Dischinger, Finsterwalder and Rüsch, these were truly 'High-Tech' buildings. These thin-shell enclosures also introduced a new building type and a new set of images to the world of architecture and were to be much imitated, often without a proper understanding of their structural characteristics. Their curvilinear forms were not arbitrary: they were selected to comply with structural requirements, most significantly the need to have form-active geometries (or at least shapes that

Figure 9.14 Church of Our Lady of the Miraculous Medal, Mexico City, 1955; Felix Candela, architect/engineer. A highly architectural use of the hyperbolic paraboloid geometry.

Photo: Wikimedia Commons.

were close to being form-active) so as to minimise bending moments, and also shapes that could be easily described mathematically to make the calculations of structural analysis manageable. The shapes were also devised to be highly practical in respect of the construction process, enabling the doubly curved surfaces to be built economically. All of these features are evident in the works of the engineer/architects who pioneered this particular class of built form.

As feats of construction the works of Nervi, Torroja and Candela also stand in marked contrast to the designs of a number of architects whose work they may have influenced, such as Eero Saarinen and Jørn Utzon. Of Saarinen's TWA terminal (Figure 9.15), Saint (2007) observed:

> The shift from the cardboard models of TWA terminal to the formwork on which the concrete was poured was to move from the exhilaration of studio

Figure 9.15a TWA Flight Centre, Idlewild (Kennedy) Airport, New York, 1962; Eero Saarinen, architect. The formalist free-form geometry of this building was related neither to structural function nor to simple mathematical description. The resulting semi-form-active structure generated large bending moments. The reinforced concrete envelope, which is often referred to erroneously as a 'thin shell', was problematic to construct and required large volumes of material to give it sufficient strength, in contrast to the lightweight shells designed by engineers such as Torroja and Candela. The building is no longer used for its original purpose and now serves as a 500-bedroom hotel.

Photo: Cameron Blaylock.

> design to a nightmare of complexity and cost. Apprehensions over formwork were among the reasons for delay at Sydney [Opera House]. They help to explain why concrete shells fell from favour after their short spell in the architectural sunshine.

Thus was a very valuable structural typology condemned (it is to be hoped temporarily) to the dustbin of architectural ideas.

It was not, however, the geometric complexity of the true curvilinear shell that led to the demise of this most useful structural form. Nervi, Torroja and Candela had clearly demonstrated that, with proper attention to the possible associated problems of design and construction, shells could be economically manufactured. It was, rather, the free experimentation with shell-like forms, by architects such as Saarinen and Utzon, in the glare of the publicity that customarily surrounds large architectural projects – but in the absence of any true understanding of the meaning of the forms created by the engineers – that was responsible for the constructional problems that caused excessive

Figure 9.15b TWA Flight Centre, Idlewild (Kennedy) Airport, New York, 1962; Eero Saarinen, architect. The overall form of the building has no structural meaning and is therefore non-form-active. The long spans involved generated high bending-type internal forces that could only be resisted by the use of large volumes of structural material.

Photo: Wikimedia Commons.

expense and delay. It was design incompetence rather than anything essentially problematic in the nature of true shells as a class of structure that led to their falling from favour, due to the erroneous belief that they were impossibly difficult to build.

In more recent times, the works of the architect/engineer Santiago Calatrava (1951–) have contributed significantly to the visual vocabulary of both engineering and architecture. He is one of the few practitioners who received a formal education in both architecture and engineering and who, as a consequence, unlike most of the present-day architects who experiment freely with built form, actually understands their technical behaviour and the implications, for their structural feasibility, of the forms that he creates. Calatrava freely confesses to a fascination with the visual excitement offered by arrangements of mass and line that apparently defy the rules of stability and equilibrium and create a *feeling* of movement in an artefact that must be a structure and therefore static. He uses various devices to create these effects, often based on subverting visually the role of key elements.

At the Campo Volantin (Zubizuri – Basque for 'white bridge') Bridge in Bilbao (1997) (Figure 9.16), for example, a disorienting effect is produced by varied lateral displacement, from the supporting over-sailing arch, of the deck and the pairs of hangers by which it is suspended. The deck structure acts compositely with a secondary arch concealed under its surface (Figure 9.17), to enable this lateral displacement – and causes a spectacular effect of seemingly impossible equilibrium when viewed longitudinally from within the network

Figure 9.16
Campo Volantin (Zubizuri) bridge, Bilbao, 1997; Santiago Calatrava, architect/engineer. The seemingly impossible equilibrium of this ingenious structure produces an exciting, disorienting effect.

Photo: Didier Descouens/Wikimedia Commons.

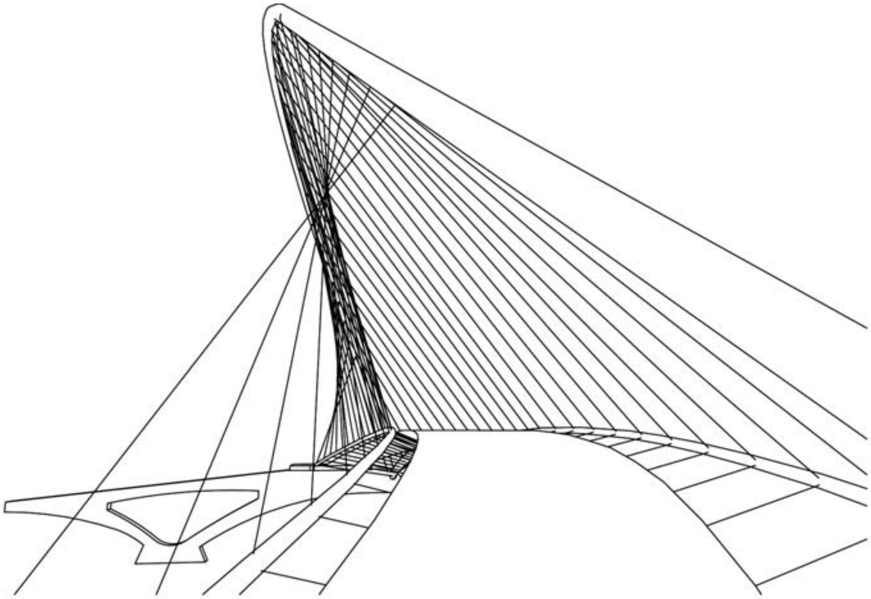
of suspending ties. The superimposed force diagram in Figure 9.18 demonstrates how equilibrium is achieved.

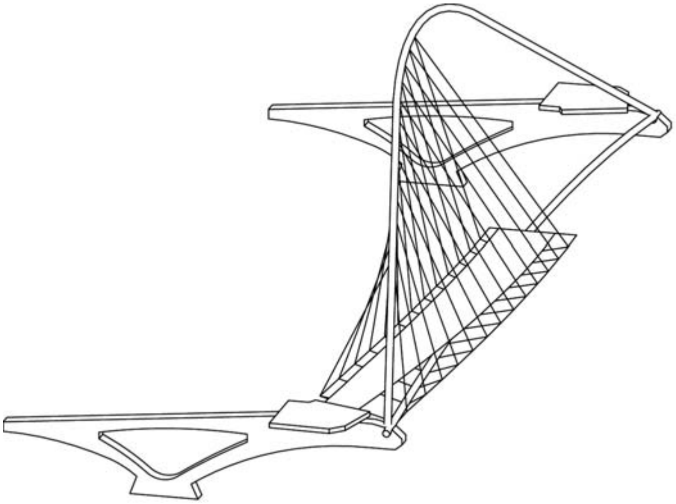
A conventional design, based on the arch principle, would have consisted of two parallel arches in the vertical plane braced together for stability (Figure 9.18). Calatrava's design does involve the use of twin arches but, in the case of his design, the second arch is concealed under the deck. This results in the over-sailing arch having to carry the full weight of the bridge, including that of the second arch. The inclined geometry of the upper arch also results in its being subjected to a greater force than if it were in the vertical plane, given that the principal load carried is gravitational. The eccentricity also imposes significant torsional load on the combined deck structure and requires that elaborate supporting structures be provided at the ends of the bridge to absorb this torsional load. The spectacular, dramatic effect is therefore obtained at the price of lower efficiency than could be achieved with a conventional design.

Calatrava's Chords Bridge, Jerusalem (2008 – Figure 9.19) is based on a similar device. In this case, in the context of a cable-stayed arrangement, the bridge deck itself acts as a horizontal arch to displace itself laterally from the supporting mast. This, together with the curved plan-form, creates a highly spectacular and exciting visual effect of splaying cable stays, when viewed against the sky.

The Margaret Hunt Hill Bridge in Dallas (2012) (Figure 9.20) is perhaps even more ingenious because the arrangement of suspending ties is in fact fairly simple but nevertheless gives an impression of high complexity. The effect is created by the device of configuring the single tall mast of the cable-stayed bridge as a transverse arch. The hanger cables emerge from either side of the tightly curved upper section of the arch and are twisted in four sets to form a single-plane of cables by the time they reach the deck, where they are attached in a single line to a central spine beam. When viewed obliquely, the twisting sets of cables produce an interesting pattern of intersecting lines whose apparent complexity is increased by a three-dimensional layering effect.

These are only three examples from Calatrava's prodigious output, much of which has excited considerable controversy due to its departure from the conventions of bridge design and, in the case of the forms that he has devised for buildings, their apparent extravagance. There have also, inevitably with such novel forms, been many instances in which the function of a bridge or other structure has been compromised by unforeseen contingencies. It is nevertheless the case that Calatrava's has been a unique and highly innovative voice in the field of both architecture and engineering, which has added a new set of images to the visual vocabulary of Modern architecture and civil engineering. As with the shell architecture of the mid-twentieth century, there have inevitably been many imitations, often involving misunderstanding of the structural principles on which the originals were based. This does not, however, detract from Calatrava's considerable and innovative achievement.





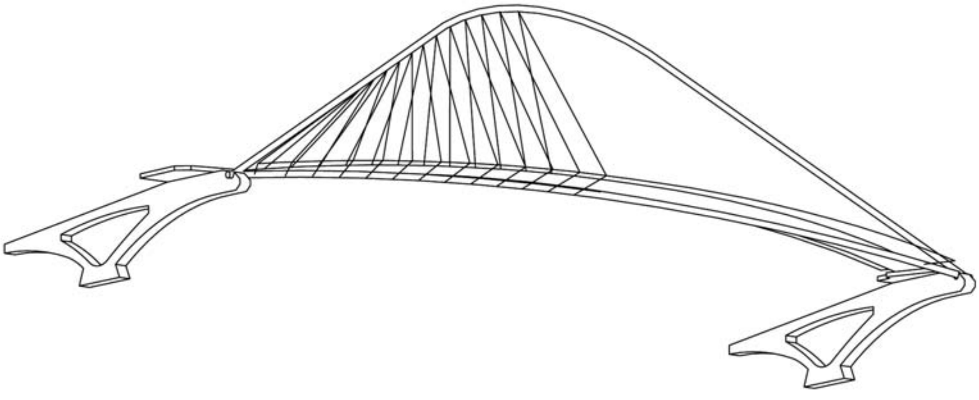
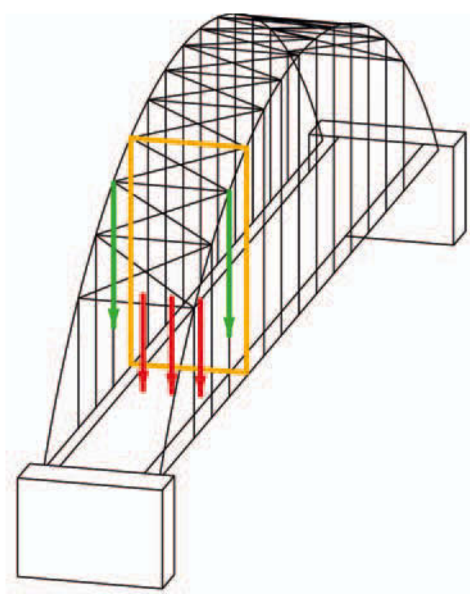
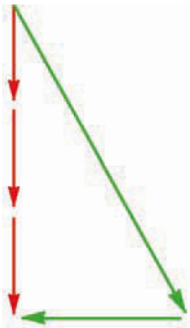


Figure 9.17 (*this page and facing page*) Campo Volantin (Zubizuri) bridge, Bilbao, 1997; Santiago Calatrava, architect/engineer. The skewing of the over-sailing arch is made possible by the presence of a second arch, concealed under the deck, that acts compositely with the deck itself to restore equilibrium.

Photos: Andreas Praefcke and Daniel Lobo/Wikimedia Commons; Diagrams: Andrew Sidddall after originals by Angus J. Macdonald.





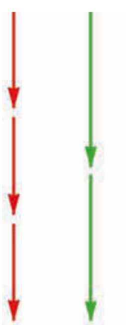


Figure 9.18 (*this page and facing page*) Campo Volantin (Zubizuri) bridge, Bilbao, 1997; Santiago Calatrava, architect/engineer. The superimposed force diagram indicates the forces that act on a typical single cross-section of the Zubizuri bridge: the red arrows represent the load on the deck; the green arrows give the forces transmitted to the two arches (shown in cross-section as orange discs). The horizontal green arrow shows the reaction provided by the horizontal arch under the deck, which is required to displace the deck horizontally. The upper, inclined, green arrow shows the load transmitted to the oversailing arch that carries the weight of the bridge. Only the vertical component of this would be required if the arch were to be in the vertical plane. The conventional arrangement in the lower diagrams shows that the complex two-arch arrangement of the Calatrava design produces a less efficient structure because the entire weight of the structure, including that of the second, horizontal arch, is carried by the oversailing arch, whose efficiency is further compromised, in the context of the resistance of gravitational load, by its being inclined from the vertical.

Photo: Andreas Praefcke/Wikimedia Commons; Diagrams: Andrew Sidddall after originals by Angus J. Macdonald.

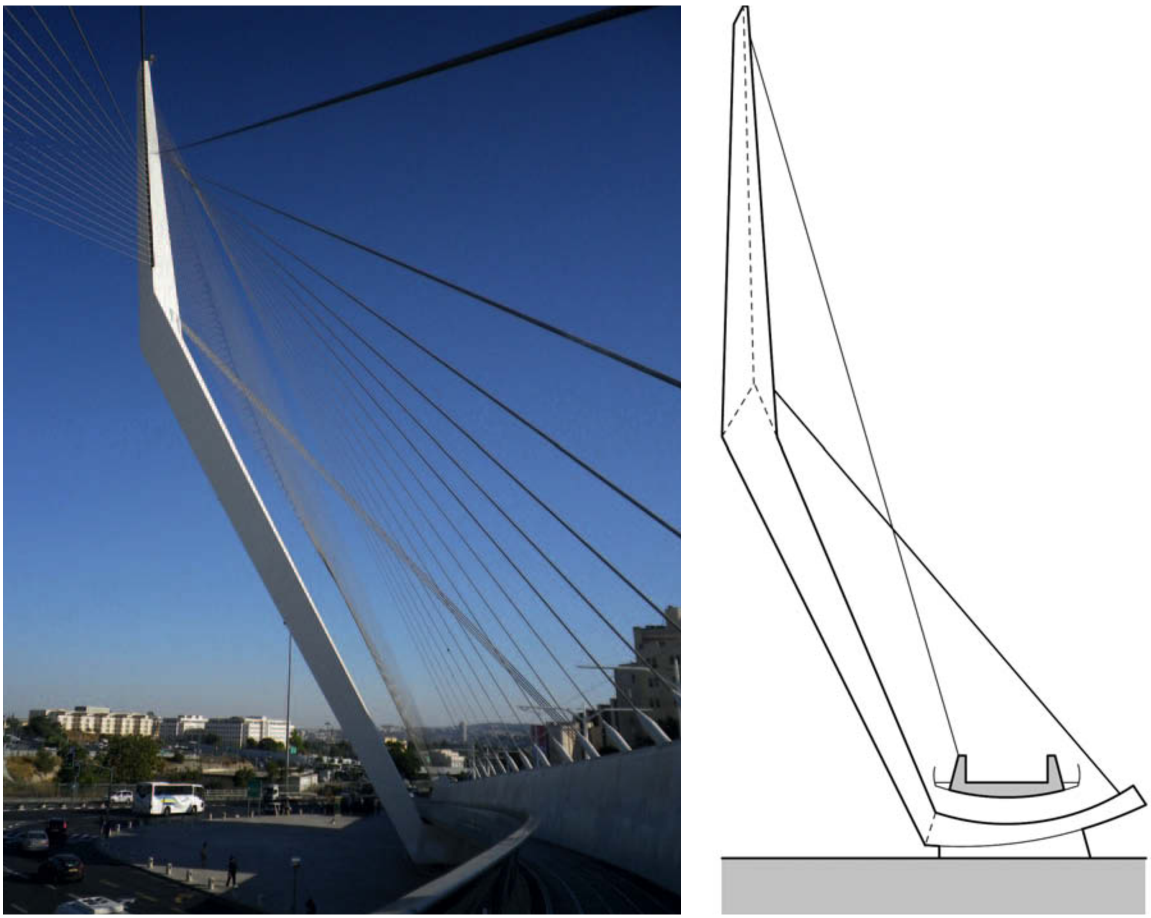


Figure 9.19 Chords bridge, Jerusalem, 2008; Santiago Calatrava, engineer. The out-of-balance forces caused by the eccentric position of the supporting mast of this cable-stayed bridge are compensated for by the horizontal-arch effect of the deck. The complex geometry produces a spectacular network of support cables, some of which are used directly to stabilise the mast.

Photo: Leinad/Wikimedia Commons; Diagram: Andrew Siddall after original by Angus J. Macdonald.

Figure 9.20 Margaret Hunt Hill bridge, Dallas, 2012; Santiago Calatrava, engineer. The device that produced the spectacular network of cables in this bridge was the use of a transverse arch rather than a mast as the vertical structural element. The cables are splayed from the crown of the arch to a single, central spine beam in the deck. The avoidance of eccentricity, as the creator of visual interest, resulted in a more satisfactory structural performance than was achieved with either of the other two examples of bridges by Calatrava shown here.

Photo: D. M. Hinlrving/Wikimedia Commons.

9.3 The engineers who worked with architects in design teams

The significance of the introduction to architecture of the 'new' structural materials of steel and reinforced concrete was not only that they made possible new architectural forms and types of building. This also brought about a revolution in the way in which buildings were designed and, in particular, in the relationship between the aesthetic and technical aspects of design. This, in turn, led ultimately to the creation of a profession that was new in the context of architecture, that of the consulting structural engineer, but the evolution of these new design practices was slow and occupied most of the first half of the twentieth century.

In the period immediately preceding the introduction of the new materials, and indeed since the time of the Italian renaissance, the aesthetic and technical aspects of architecture had become largely separated in the design process. This was principally due to the fact that the structural technology in use, that of masonry and timber, was well understood. The span capabilities of the materials had become reliably established and, from long experience, the dimensions required for timber joists and trusses and the minimum thicknesses and maximum feasible heights of masonry walls had become known through centuries of custom and practice. This had the consequence that gentleman practitioners such as Sir John Vanbrugh and Lord Burlington, who had no technical background or knowledge, could become successful architects, concerning themselves only with aspects of style, because the decisions relating to the structures and construction of buildings could safely be left to builders, who understood well the nature of the materials, their properties and their capabilities.

This comfortable arrangement was disturbed by the introduction of the new materials for a number of reasons, one of which was a developing desire that building materials should be used efficiently. Most traditional building methods involved a considerable degree of over-specification with the result that the structural elements were significantly stronger than required to carry the loads to which they were normally subjected. The new structural materials were used in structural configurations that were considerably more refined than their traditional predecessors. The delicate wrought-iron trusses of the nineteenth-century train sheds bear only a passing resemblance to the massive semi-trussed timber arrangements that had spanned over the grand interiors of Italianate palaces, and the slender steelwork of the early skyscrapers was in stark contrast to the massive pillars of the Gothic cathedrals.

This enormous change in structural practice brought about the need for a new type of individual to be added to the group that evolved the design of a building. This was a person who understood from first principles, and from a scientific perspective, the physics of building structures and the properties of materials; someone who was educated in mathematics and who could devise and carry out the calculations required for structural analysis and the evaluation of stresses and deformations; someone, in other words, who had theoretical knowledge and who had undergone some form of university education, rather than a craft apprenticeship. Such individuals were initially employed by the contractors responsible for actually building the structures in the new materials, but as the twentieth century progressed a profession emerged that was new in the context of architecture – that of the consulting structural engineer – a professional who was independent of architects and builders and who was appointed separately by the client.

An individual whose career spanned the entire transition period of the professional structural engineer, from contractor's employee to independent consultant, and who was responsible for establishing one of the new structural engineering consultancies, was Ove Arup (1895–1988). Arup was a highly competent design engineer and expert in early reinforced concrete design. Crucially, he was also a broad thinker who saw beyond the immediate concerns of particular design problems to the whole process involved in the creation of a building, both at the design stage and during construction. This led him to develop strong ideas concerning the nature of the working relationships which should exist between architects, engineers and other design professionals, and he was instrumental in determining the ethos of the highly successful firm of consulting engineers that he founded – Ove Arup & Partners – which became one of the world's largest transnational design organisations.

Arup studied engineering at the Polytechnic Institute in Copenhagen (the Polyteknisk Læreanstalt) from which he graduated with specialism in reinforced concrete, in 1922. He found immediate employment as a designer with the civil engineering contractors Christiani and Nielsen, then leading exponents in Europe of the still relatively new material of reinforced concrete. He was posted first to Hamburg and then to London where he became chief designer in 1925.

Christiani and Nielsen specialised in dock and harbour works as well as industrial structures such as grain silos. During his period working with them, Arup became an expert in reinforced concrete design, but also acquired an appreciation of the need, during the design of a structure, to produce forms that could be built in a straightforward manner – this, of course, being necessary so that his contractor employers could make a profit. The perception that buildability was as important as final performance exerted a lasting influence on his approach to design.

Arup was a highly cultured individual and was inevitably concerned with the aesthetic qualities of structures and also with the role of structure in architecture. In the context of architectural design he held the view that all aspects of the design of a building should be considered together from the beginning of a project in order that all could be satisfied in equal measure – a concept that he termed **'total design'**. A corollary to this was a belief that the conceptual design of buildings should be carried out by teams of professionals rather than by individual architects, an approach to design that he promoted through the firm that he founded.

Following his move to London, and during what John Allan has described as his 'crucial decade (the 1930s)' (in Allan, J., *Ove Arup*, 1995, Institution of Civil Engineers, pp. 38–44), Arup became increasingly interested in architecture and became part of a lively Modern architecture scene that developed in London during that period. He became a member of the MARS (Modern Architectural Research) group, and this led to a collaboration with Berthold Lubetkin that resulted in the creation of several of the most important works of early Modern architecture to be built in Britain, and that secured Arup's reputation as a structural engineer who could work with architects [with good understanding of their concerns]. Only two of the buildings that Arup designed with Lubetkin are discussed here, the Penguin Pool complex at London Zoo (1934) and the block of flats, Highpoint I (1935), also in London.

The Penguin Pool complex (Figure 9.21) was one of a number of buildings that Lubetkin and Arup designed for London Zoo and was the commission that produced one of the most striking and memorable images of 1930s Modernism in Britain, that of the gravity-defying reinforced concrete ramps. It is interesting to note, however, that, although the design of the Penguin Pool ramps may have been the result of a genuine collaboration between architect and engineer, the visual agenda was totally dominant and led to engineering that, though brilliant in its execution, was flawed when considered from the point of view of efficient use of material and the effort involved in design and construction. It did not, therefore, fulfil the requirements of Arup's concept of 'total design'.

At the time of the design of the Penguin Pool ramps Arup was employing Felix Samuely (1902–1959) as his assistant. Samuely had a strong interest in architecture and had worked with Erich Mendelsohn in Germany and with Mendelsohn and Serge Chermayeff at the De La Warr Pavilion, Bexhill-on-Sea (1935), which was one of the earliest examples of Modern architecture in Britain and also notable for its minimalist all-welded steel framework – the first of its kind in Britain. He was a brilliant engineer who was skilled in mathematical analysis and who had something of an obsession with minimalist structures.

The structural configuration of the famous ramps at the Penguin Pool was far from ideal. The internal forces are a combination of bending and torsion, which is one of the least efficient scenarios for resisting load. The fact that such a slender structure was created was due to a combination of knowledge, through calculation, of precisely the level of internal force that was present, and confidence that the quality of the concrete would be high – consequences of the particular combination of skills that Samuely and Arup brought to the project. The shortness of the spans and the very light loads involved also made thin sections possible by lessening the levels of strength and rigidity

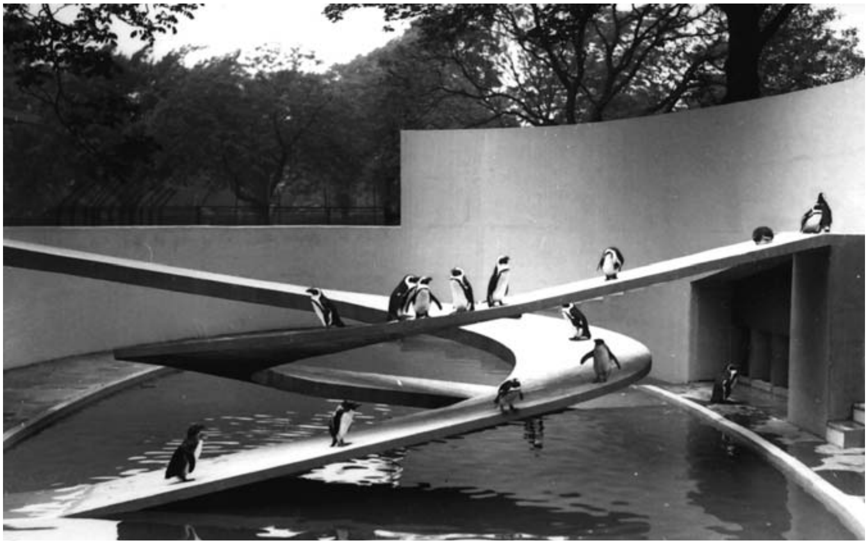


Figure 9.21 Penguin Pool, London Zoo, 1934; Berthold Lubetkin (Tecton), architects; Ove Arup and Felix Samuely, engineers. The aesthetically engaging reinforced concrete ramps were highly problematic structurally, being subjected to a combination of bending and torsion. Their successful execution required a considerable degree of knowledge and expertise from the structural designers. The idea, which is often suggested, that this structure demonstrated the capabilities of reinforced concrete to the world may be questioned because much larger spans, using similar thicknesses of concrete, had already been constructed (e.g. the domes at the Leipzig Market or hangars at Orly airport – see Figures 9.3 and 9.4). Engineering skill was used here in the service of the aesthetic ambitions of Modern architecture and in the context of a structural scheme of questionable technical worth.

Photo: RIBA Library Photographs Collection/Wikimedia Commons.

required. The Penguin Pool ramps in fact provide a striking contrast in design approach with the structures of Nervi and Torroja, in which much larger spans were achieved with similar thicknesses of concrete because structural function was not compromised and conflict between the visual and the functional was avoided. At the Penguin Pool, architectural considerations were allowed to dominate and engineering expertise was used in the service of visual effect. It is interesting that a precedent was being set here: there would be many subsequent examples in the history of Arup's organisation, the Sydney Opera House being perhaps the supreme case, in which high-quality engineering was used in the service of an architectural idea that was flawed technically.

The views of Nervi and Torroja on the Penguin Pool ramps are not recorded. It is possible that they would have considered the structural scheme of questionable value other than as an exercise in constructional bravura. It has often been suggested that the ramps demonstrated to the world the capability of the 'new' material, but this had already been done by the engineers Freyssinet, Maillart, Nervi and Torroja and, of course, the relatively unknown Dischinger, Finsterwalder and Rüsch, with structures that achieved much greater spans with much greater efficiency due to the structural appropriateness of their forms.

The penguins themselves ultimately voted with their feet – which had perhaps found bare concrete to be a less congenial surface than ice:

> During a refurbishment in 2004, the penguin colony was temporarily relocated to one of the zoo's duck ponds and took such a strong liking to their new habitat that it was decided that they would remain there.[1]
>
> [The penguins'] . . . original Modern Movement home remains in place, now used as a fountain in summer.[2]

The Penguin Pool therefore suffered the fate of many of the icons of Modern architecture and is no longer used for its intended purpose.

The other very significant work of architecture that resulted from the Arup/Lubetkin collaboration was the block of flats known as Highpoint I in London (1935) (Figures 9.22 and 9.23). Like the ramps at the Penguin Pool, this building became something of an icon that has featured in most accounts of the history of Modern architecture in Britain. Unlike the earlier collaboration, however, Highpoint I is remarkable for the degree of successful integration that was achieved between the architecture and the engineering.

The structural scheme was that of loadbearing walls carrying one-way spanning rib-less slabs, all executed in thin sheets of in-situ reinforced concrete. The plan-form of the building, which is a spine-wall configuration, was worked out by Arup and Lubetkin so as to integrate the space-planning and structural requirements. The ability of the reinforced concrete walls to act also as beams, if appropriately reinforced, was exploited to provide long horizontal windows at every level and to substitute rows of columns for walls at ground-floor level so as to create an open foyer at the entrance.

The degree of integration between the architectural and technical agendas was high, as comparison with its near contemporary, the Villa Savoye by Le Corbusier (1931) (Figure 9.24) demonstrates. The two buildings share an almost identical visual vocabulary of straight-edged, plane-walled rectilinearity rendered in pure white. The Highpoint flats are, however, what they appear to be – a multi-storey building supported by its walls with a structural scheme that is unadorned apart from a coating of paint. The Villa Savoye has a reinforced concrete beam/column framework supporting non-loadbearing walls of blockwork and coated with cement-based render to give the appearance of a simple unified building armature; its structural arrangement was compromised by the adoption of different column grids at different levels, so as to accommodate space-planning requirements, in contrast to the well-integrated scheme at Highpoint.

Figure 9.22 Highpoint I, London, UK, 1935; Berthold Lubetkin, architect; Ove Arup, structural engineer. The structure of this building is of reinforced concrete slabs in both vertical and horizontal planes. The non-form-active structural arrangement with solid slab cross-sections is entirely appropriate for the spans involved. The integration of architectural and engineering design considerations is remarkable and the result of close collaboration between architect and engineer through all stages of the design and construction.

Photo: Alchetron/Wikimedia Commons.

One feature that the buildings did share, however, was their unsuitability as living accommodation. The Villa Savoye was used as a dwelling house for only 18 months of the 80+ years of its existence to date, having been declared uninhabitable by the client who commissioned it. The main problem was the poor performance of the building envelope as an effective environmental barrier – the interior became unacceptably hot in summer and cold in winter – and there were the common problems of water penetration often associated with modern methods of construction. Compared to a traditional house, with masonry walls and a pitched roof, the building was simply unsound. Similar problems arose at Highpoint, principally as a consequence of the poor thermal and acoustic performance of the very thin walls. Unlike at the Villa Savoye, most of the inhabitants at Highpoint have been prepared to accommodate its

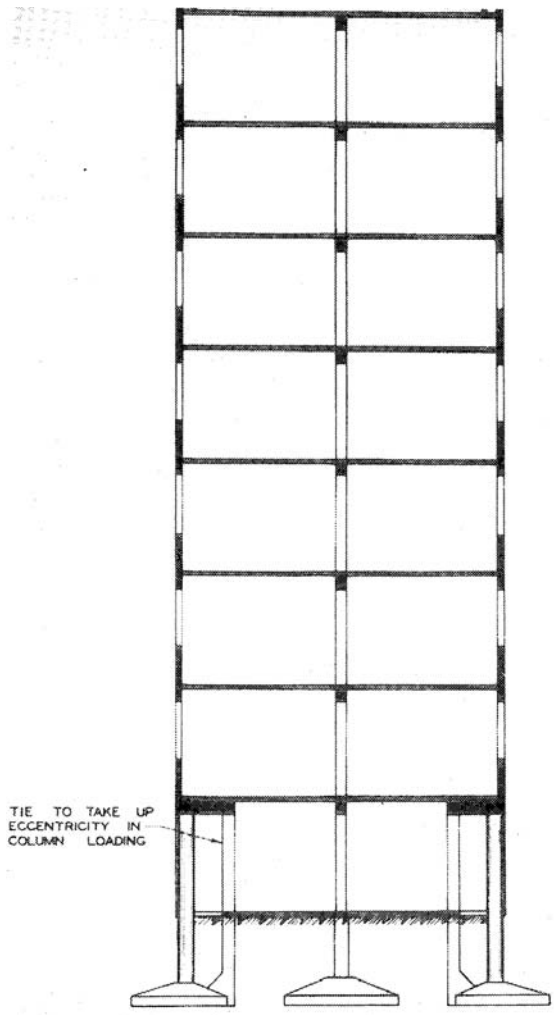


Figure 9.23 Cross-section, Highpoint I, London, UK, 1938; Berthold Lubetkin, architect; Ove Arup, structural engineer. The structural arrangement at Highpoint involved one-way-spanning floor slabs carried by the external walls and a central spine wall. Structure and architecture are seamlessly combined.

Image: Black Dog Publishing/RIBA/St James's House.

various practical shortcomings which have been regarded as a small price to pay for the privilege of living in an architectural icon.

The striking and highly graphic images that both the Penguin Pool ramps and the Highpoint building generated were perhaps their strongest feature. As has been observed here, their performance in service was less successful and both had technical shortcomings. They do, however, serve as early examples of the two types of collaboration between architects and engineers

Figure 9.24 Villa Savoye, Poissy, France, 1929; Le Corbusier, architect. Although visually similar to the Highpoint building, the Villa Savoye lacks its constructional integrity. The wall planes here are of non-structural masonry carried on a reinforced concrete frame. Artifice is used to disguise the lack of integration of the architecture and engineering.

Photo: Inexhibit/© FLC/ADAGP, Paris and DACS, London 2018.

that would develop as the Modern period progressed. The first of these – exemplified by the approach adopted at the Penguin Pool – involves the engineer acting primarily as a technical facilitator, devising structural schemes that enable forms to be constructed that originate from ideas unconnected to technical performance. The second – as pursued at Highpoint – involves a close collaboration between architects and engineers through all stages of the design to evolve forms in which aesthetic and structural criteria are satisfied in equal measure.

At the time of his collaborations with Lubetkin, Arup was being increasingly drawn into the world of architecture and found himself acting, in his own time, as a structural consultant on various architectural projects. The potential conflict of interest between the dual roles of contractor's employee and architect's consultant caused Arup to leave his contractor employer in 1938 and set up his own contracting concern. There was in fact a succession of these, all short lived, before Arup concluded that the roles of contractor and design engineer were incompatible in the context of architecture, and this realisation caused him to set up the firm of Ove Arup & Partners, which was purely a design consultancy and independent of contracting responsibility.

Ove Arup & Partners flourished from the beginning and, as with most highly successful enterprises, this was for a number of reasons. Chief among these were, of course, the abilities and personality of Arup himself, which manifested themselves in a variety of ways, and included an ability to surround himself with very high-quality staff – some of the best engineering talent then available. Arup's connections with the world of architecture, established in the 1930s through his involvement with MARS, were also important. These, together with his reputation as an engineer who was sympathetic to the concerns of architects, resulted in his being appointed as engineer to some of the most progressive architecture then being designed. The fact that the foundation of the firm coincided with the post-war building boom of the 1950s and 60s was also important. Due to the particular circumstances that came together around Arup, the finest engineers of the day found themselves working with the most progressive architects, and in an atmosphere of collaboration that was particularly fostered by Arup himself and that has continued into the present day. As the architectural critic and historian Charles Jencks observed in 2002,[3] '(Arups) is an extended organisational framework of collaboration, of teams of engineers with a certain flexible autonomy and democracy. [It] is one of the first examples of that type which has become prevalent today, the network organisation.'

The results have been some of the most significant buildings of recent decades. In the early days these included the Hunstanton School (Alison and Peter Smithson, 1954) (Figure 8.13), the Brynmawr Rubber Factory (Architects Co-partnership, 1951) and the Sydney Opera House (Jørn Utzon (1959–1973) – the building that established the firm's reputation internationally (Figures 9.25 to 9.27). This was consolidated in the 1970s and 80s by buildings such as the Centre Pompidou, Paris (Piano and Rogers, 1971–1977) (Figures 9.28 to 9.31), the Hong Kong and Shanghai Bank Headquarters (Foster & Partners, 1985), and the Lloyd's Headquarters Building, London (Richard Rogers, 1986) (Figures 10.6 to 10.10); more recent prominent buildings engineered by Arups have included the CCTV Headquarters building, Beijing (East China Architectural Design and Research Institute/ Rem Koolhaas, 2012) (Figures 9.35 and 9.36) and the terminal at Chek Lap Kok Airport, Hong Kong (1998, with Foster & Partners), these being a very small selection of many thousands of buildings worldwide.

Traceable through all of this was an ideology concerned with a preferred method of working, that of full collaboration between architect and engineer from the very beginning of a design, so as to realise Arup's ideal of 'total design'. It was a methodology that was rarely achieved in practice, however, mainly due to the preference of architects for evolving forms for buildings from considerations of aesthetics and style only, rather than from an integrated approach to design. This was the methodology that had produced the Penguin Pool by Lubetkin and Arup and that has been by far the most common relationship between architects and engineers in the Modern period, and increasingly so in the present day.

The Sydney Opera House (Figure 9.25), by the architect Jørn Utzon (1918–2008), was perhaps the most extreme example of this 'enabling' type of relationship, as opposed to the full collaboration of the 'total design' approach. It was also one of the most controversial buildings of twentieth-century Modernism that attracted superlatives of praise of the most extreme kind: it

Figure 9.25 Sydney Opera House, Sydney, 1958–1972; Jørn Utzon, architect; Ove Arup & Partners, engineers. Although often referred to as 'shells' (which, in structural terms, they are not), the distinctive forms of this building were constructed as a series of linked semi-form-active portal frameworks clad in non-structural pre-cast concrete panels faced with ceramic tiles.

Photo: Roybb95/Wikimedia Commons.

was said to be a masterpiece, a work of genius, and it has certainly achieved iconic status. It has also been widely condemned as an elephantine, if not exactly 'heroic', failure due to a number of causes including: the facile nature of the architectural concept; the sheer impracticability of the building as evidenced by its failure adequately to fulfil its primary function as an opera house and also most of the other requirements of the brief; the near impossibility of construction of the original design concept; and its enormous overrun in costs (approximately 30 times the original estimate as detailed below).

Such conflicting opinions of the success or otherwise of the building are perhaps simply a reflection of the very different views that are taken by different commentators on architecture concerning the criteria for judging the quality of a building. Many of the difficulties associated with both its impracticality in use and the difficulty of its construction were connected to the incompatibility of its external form and its internal arrangements – the reconciliation of which conflict is normally considered to be fundamental to architecture. The Sydney Opera House is certainly a very striking visual object but it could be argued that this was due largely to its location, its sheer size and its undoubtedly novel form, rather than to any intrinsic architectural merit. It is questionable, especially when the form was so problematic in so many respects, whether these sculptural attributes should be sufficient to warrant the accolade of a work of architectural genius.

The various aspects of the design and construction processes of the building have been well described by Peter Jones (2006) who has provided one of the best accounts of the Sydney Opera House saga. Jones is an academic with no professional background in either architecture or engineering and therefore no axe to grind. His account is refreshingly balanced, impartial, factual and free from the kind of polemic that is common in architectural discourse. Jones has provided a straightforward account of the role that Ove Arup's firm played in the realisation of the project, and of its importance for the growing international reputation of the firm. His book also gives insights into the types of relationship that were developing between architects and the profession of the consulting structural engineer in relation to architecture.

Arup's firm's principal involvement was in the design of the external envelope that gave the building its distinctive shape. Utzon's intention was that this should be constructed of lightweight thin shells similar to those of Nervi and Candela, which were then attracting considerable attention in the architectural media, but the shapes that he insisted upon (as in his original sketch (Figure 9.26a)) precluded this. These were not form-active and required

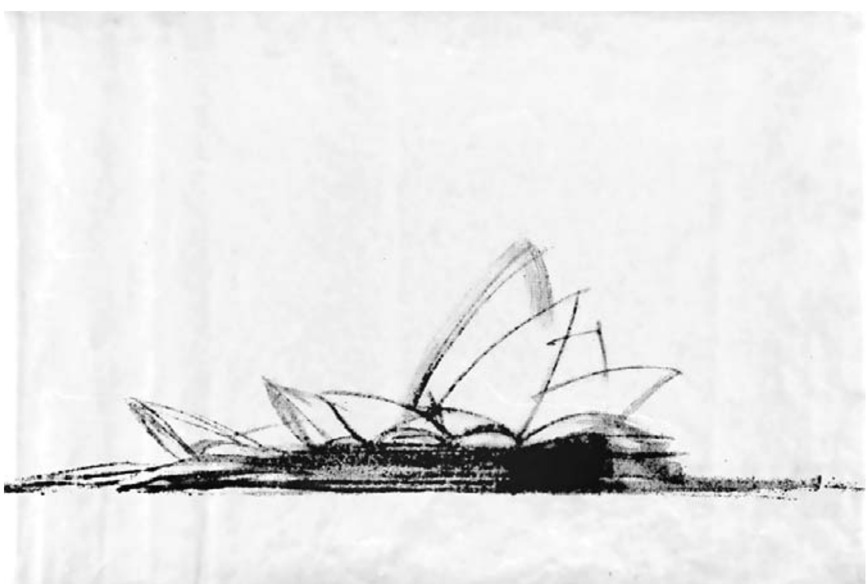


Figure 9.26a Sydney Opera House, Sydney, 1958–1972; Jørn Utzon, architect; Ove Arup & Partners, engineers. Utzon's competition-winning sketch, which proved to be unbuildable.

Image: State Archives and Records, New South Wales Government, Australia.

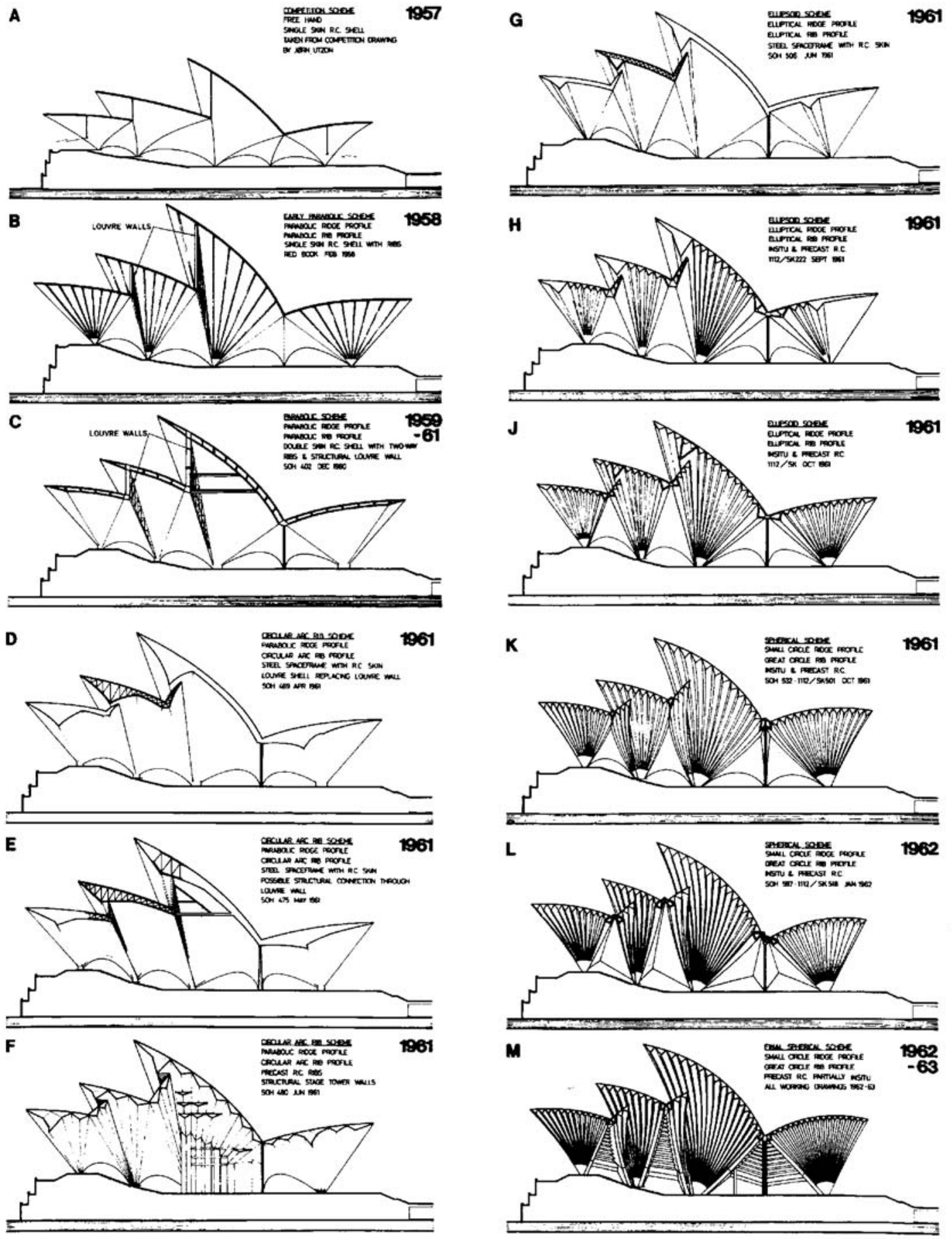


Figure 9.26b Sydney Opera House, Sydney, 1958–1972; Jørn Utzon, architect; Ove Arup & Partners, engineers. A selection of trial structural schemes. Many alternatives were explored by Arups in their quest for a feasible constructional solution.

Image: Ove Arup & Partners.

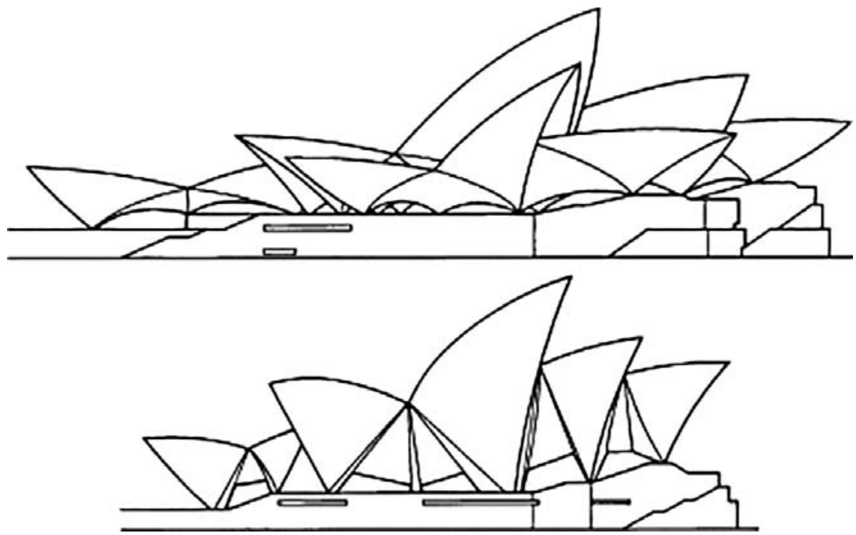


Figure 9.26c Sydney Opera House, Sydney, 1958–1972; Jørn Utzon, architect; Ove Arup & Partners, engineers. Comparison of the initial competition-winning and final schemes.
Line drawing by Steve Gibson after original by Angus J. Macdonald.

significant bending strength and therefore thickness. The experts in shell design had pointed this out: 'the shells are not self supporting' (Felix Candela, quoted in Jones, 2006, p. 180), 'all three engineers [Nervi, Candela and Torroja] severely criticised Utzon's published sketches' (Jones, 2006, p. 201, commenting on the results of conversations between these individuals and Arup).

Utzon, however, was a self-styled lone genius and was impervious to such comments or advice. It was Arup's firm, working almost independently of Utzon, that devised not only the final scheme that would provide the building with the necessary structural integrity but also the methodology by which it was constructed. Many alternative schemes were considered (Figure 9.26b), including one based on a steel skeleton – a logical proposition that would have exploited the very high strength of steel but one that was rejected by Utzon, who insisted that the structure had to be of reinforced concrete to preserve the integrity of the design (*sic*). The scheme finally adopted (Figure 9.26c) was based on a series of reinforced concrete semi-arches shaped as circular arcs to give a constant radius of curvature that would facilitate both the structural calculations and the construction. The massive frameworks (Figure 9.27) were pre-cast on site into sections that were sufficiently small to be handled by the largest cranes then available, and were pre-stressed by post-tensioning. The contrast with the shells of Nervi and Candela could hardly have been greater. Whereas at Sydney the use of the most sophisticated high-quality pre-stressed concrete in copious volumes achieved the necessary end by brute force, the shells of Candela, in particular, were achieved with minimal use of

Figure 9.27 Sydney Opera House, Sydney, 1958–1972; Jørn Utzon, architect; Ove Arup & Partners, engineers. The frameworks at Sydney were constructed in pre-cast sections that were sufficiently small to be lifted by the largest cranes then available. The massive volumes of concrete required to provide sufficient strength contrast with the thin shells designed by engineers such as Torroja and Candela, which achieved much greater spans with concrete thicknesses of around 100 mm.

material. The difference was in the overall form adopted: whereas Utzon's shapes were structurally meaningless, those by Candela conformed to the appropriate use of the laws of physics.

As is well known, Utzon resigned from the project in February 1966 in a welter of publicity and self-justification, and the building was finished under the direction of a different architect (Peter Hall (1931–1995)), whose team did their best to satisfy its programmatic requirements and to marry the interior that was required for that purpose with the incompatible enclosing envelope. The final cost was \$AU 102,000,000 compared to an estimate made following Utzon's appointment of \$AU 7,000,000 and an original projected cost of \$AU 3,600,000.

Whatever the merits or otherwise of the building itself there can be no question that the Sydney Opera House was a very important project both for the city of Sydney, and for the Arup organisation – the one that established the firm at an international level. It is probably also true to say that without the involvement of the Arup organisation the building would never have been built. Utzon, and his small group of assistants, were certainly incapable of realising it and few other engineering consultancies had the combination of engineering knowledge and experience, together with organisational ability of the group that Arup had assembled around himself. It was nevertheless a project over which Arups took considerable risks – both reputational and financial – which ultimately paid off as a demonstration of the enormous capabilities of the organisation that Arup had created.

In addition to its importance for the establishment of the reputation of Ove Arup & Partners as world-leading engineering consultants, the Sydney Opera House had a wider significance for the engineering profession as a whole because, due to the enormous media attention that it attracted and the controversial nature of the project, it drew attention to the role of consulting engineers, and the type of organisations that they developed, in the creation of major works of architecture.

Against the background of the flim-flam of the architectural media, with its need for geniuses and masterpieces, and the much-reported intrigues of Australian politics in which the press revelled, Arup's firm, and the contractors M. R. Hornibrook, quietly got on with the job of designing and constructing the highly problematic building enclosure and bringing it to a successful conclusion. This process set a pattern that would be followed in most major buildings of the second half of the twentieth century. The engineering consultants of the Modern period became the equivalents of the builders of pre-modern architecture in the days of masonry and timber by relieving architects of the need to have concerns about the buildability of their creations. The engineers demonstrated at Sydney that 'firmness' could be provided in almost any circumstances, and independently of 'commodity'. In the age of steel and reinforced concrete virtually any form is buildable, given an appropriate input of skilled engineering, and many architects, particularly those who have produced the type of iconic buildings that have pleased clients and critics alike, have exploited this by insisting on forms that have frequently made little technical sense. The Sydney Opera House paved the way for the spectacular forms that characterised the extremes of architectural fashion which developed towards the end of the twentieth century in the vogue for free forms of expression and which have since continued to be 'in vogue'.

Arup's ideal of 'total design' and the idea that architects and engineers should work together as full collaborative partners nevertheless survived and was continued in the next generation of engineers, many of whose talents were fostered through association with the Arup organisation. Two of these, who acquired public profiles in their own right and became recognised due to their engineering significance, were Peter Rice (1935–1992) and Anthony Hunt (1932–). Each of these had a connection with Arup: Rice was employed by Ove Arup & Partners; Hunt was mentored by Felix Samuely, who had worked with Arup in the 1930s.

Both Rice and Hunt formed close associations with prominent architects of the second half of the twentieth century and were involved with some of its most significant buildings. Their respective distinctive 'styles' of engineering make for very interesting comparisons and shed further light on the types of working relationships that developed in the Modern period between the prominent architects and engineers.

Peter Rice was employed by Ove Arup & Partners from his graduation from university in 1956 until his untimely death in 1992. He joined Arups with the reputation of having been a brilliant student with a particular facility for mathematics. He was also, however, a well-rounded and cultured individual with a strong interest also in the arts and therefore in architecture. He was fascinated by the possibilities offered for the visual expression of the properties of materials, especially in the context of innovative materials technology. The re-humanising of Modern architecture, through the re-introduction of a degree of hand crafting, was another of his concerns.

On joining Arups, Rice was immediately assigned to the Sydney Opera House project. He worked on the design in the London office and was subsequently transferred to Australia where he gained intimacy with the relationship between an engineering material – in this case reinforced concrete – and its expressive possibilities through the use of what were, in effect, hand crafting techniques on a gargantuan scale. It also introduced him to the idea of the expert technocrat – the engineer who could build the unbuildable – a role that he clearly found attractive and that would become one of his signatures.

It was the next project, the Centre Pompidou in Paris (Figures 9.28 to 9.31), that allowed Rice to establish his reputation as someone sympathetic to the concerns of architects, and who could work with them in a truly creative partnership. The project was the brainchild of the French Minister of Cultural Affairs, André Malraux and, as at the Sydney Opera House, the winning design was selected in a high-profile international competition by a jury consisting of architectural megastars – in this case Oscar Niemeyer, Jean Prouvé and Philip Johnson. There were 681 entries and the winner was announced in 1971.

The Centre Pompidou (Figure 9.28) is a building that expressed in a very overt way the established norms of Modernism. It symbolised a highly optimistic belief in a utopian technological future based on the benefits of industry and the machine, and the visual celebration of this in architecture. It rendered these ideas in a novel form and was the first major project in which the new sub-style of Modern architecture that became known as High-Tech was established internationally. It also launched the international careers of the architects, Richard Rogers and Renzo Piano, and secured the reputation of Peter Rice as a leading architectural engineer.

This was a building that drew very public attention to a type of collaborative design methodology of architects and engineers that was an important, even

Figure 9.28 Centre Pompidou, Paris, 1978; Piano and Rogers, architects; Ove Arup & Partners (Peter Rice), structural engineers. The Centre Pompidou is perhaps the ultimate expression of 'techno-optimism', a celebration of the Modernist belief that the solution to the world's problems will lie in ever more sophisticated technology.

Photo: Mister No/Wikimedia Commons.

essential, aspect of the evolution of the High-Tech style, and significant for the relationship between the architectural and engineering professions. It required an engineer who cared about the appearance of structure but who was prepared to sacrifice structural integrity for visual effect.

The design was dominated by two somewhat simplistic architectural ideas; '**flexibility**' and '**readability**'. 'Flexibility' in architecture is an idea that became something of an obsession for Rogers following his experiences in partnership with Norman Foster, during which they collaborated in the design of several buildings for clients whose requirements changed in ways that made the buildings partially obsolete even as they were being constructed. The idea of 'readability' stemmed from the rather dubious architectural notion of 'honesty' but also allowed the roles of the various essential components of a building to be 'celebrated'. This required that functions be separated so that they could be obviously visible. The structural components had to be purely structural; the transparent skin of the building had to be purely a delineator of the boundary between inside and outside, with no structural and minimal environmental control functions. It was a strategy that Rogers often justified on the grounds of practicability, arguing that because different elements deteriorated at different time scales, their maintenance and replacement would be facilitated by their being entirely separate components. This was, in fact, a post-rationalisation of a feature that was adopted for stylistic reasons. It is, for example, more practical, and certainly more efficient, to combine the functions of enclosure, structure and environmental barrier in a single element, such as a traditional masonry wall, and services elements, such as pipes, fans and air-handling units, are much more accessible for maintenance and replacement if they are located in internal ducts and plant rooms rather than hanging from the exterior of a building.

The combination of these fairly simplistic architectural ideas resulted in a building that, though complex in its external appearance, is very straightforward in its general arrangement. Each of its storeys consists of a single unobstructed interior space flanked by two much narrower services zones, one for the circulation of people and the other providing space for air-handling ducts and other services (Figure 9.29). The structure, which consists of a series of identical plane frameworks spaced 12.8 m apart in a rectangular plan, is configured to delineate these zones. Single columns are placed at the boundaries between the zones, on the outer faces of the skin, and carry the triangulated floor girders that span the internal space. The beam-to-column connections are made through cantilevered 'gerberette'[4] brackets that pivot about the columns and that are anchored by vertical ties that define the outer edges of the narrow service zones.

The structural layout is determined almost entirely from architectural considerations and contains a number of features that are less than ideal for the efficient use of material. The most easy to justify is the long span of the floors. Internal columns to reduce these would have greatly lessened the quantity of steel required but their inclusion would undoubtedly have decreased the planning freedom of the interior. A less justifiable feature was the idea of removable floors, which were intended to allow the possibility of double-height internal spaces (never actually used). This prevented the adoption of a primary/secondary beam system and resulted in the main frames having to be

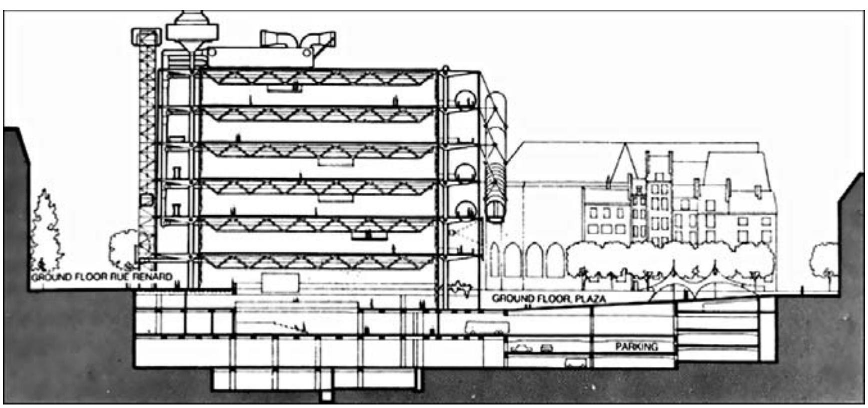


Figure 9.29 Cross-section, Centre Pompidou, Paris, 1978; Piano and Rogers, architects; Ove Arup & Partners (Peter Rice), structural engineers. The building is subdivided into three principal zones at every level and the spatial and structural arrangements correspond. The main interior spaces occupy a central zone associated with the main floor girders. The gerberette brackets define peripheral zones on either side of the building that are associated with circulation and services.

Image: Piano and Rogers/Architecture Week.

Figure 9.30 Gerberette brackets, Centre Pompidou, Paris, 1978; Piano and Rogers, architects; Ove Arup & Partners (Peter Rice), structural engineers. The floor girders are attached to the inner ends of these brackets, which pivot on hinge pins through the columns. The weights of the floors are counterbalanced by tie forces applied at the outer ends of the brackets. The arrangement sends 25% more force into the columns than would have occurred if the floor beams had been attached to them directly. Fabrication by casting allowed a very neat appearance and reintroduced the technique to architecture for the shaping of major components.

Photo: Patricia Macdonald.

more closely spaced than would have been ideal – another feature that increased the quantity of steel required. The use of the unconventional gerberette rocking brackets (Figure 9.30) to connect the floor girders to the columns was the structural feature that was least justified technically because it greatly increased the load on the columns. A mitigating factor was that, by converting the vertical elements at the perimeter of the building to tension members, it allowed them to be very slender, greatly to the benefit of the external appearance of the building. It was, however, another example of a technical compromise being driven by a visual concern.

One of the most interesting technical features of the structure of the Centre Pompidou was its contribution to the re-introduction of cast metal into the vocabulary of architectural engineering. The use of casting for major components in structural engineering had been discontinued in the late nineteenth century due to its perceived unreliability following a series of catastrophic failures, most notably that of the Tay Railway bridge in Scotland in 1879. The principal problem with casting was the difficulty in proving that the component was sound and free from voids, impurities and other

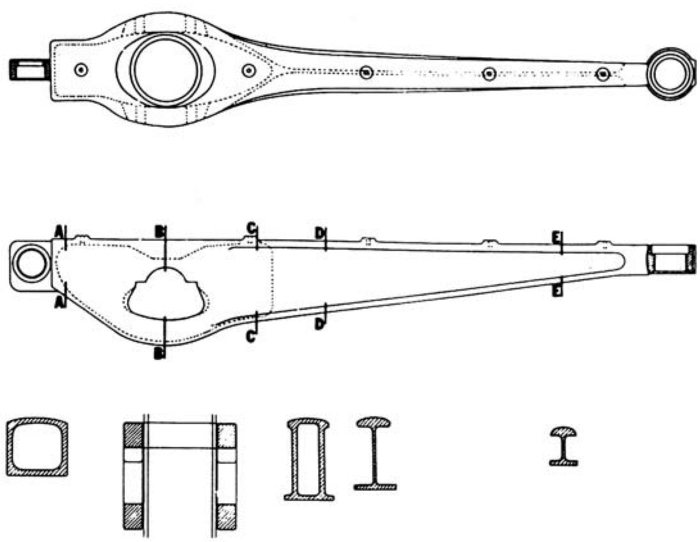


Figure 9.31 Gerberette bracket, Centre Pompidou, Paris, 1978; Piano and Rogers, architects; Ove Arup & Partners (Peter Rice), structural engineers. The longitudinal profile and variations in cross-section are matched to the internal forces carried (see Section 4.3).

defects. In the case of ferrous metals, there was an additional difficulty because relatively high carbon levels were required to give the molten metal adequate liquidity, and this made the finished castings susceptible to brittle fracture at stress concentrations, such as occurred around fixings, and to fatigue failure.

By the 1970s the problems associated with the structural use of cast metal had been solved through research and proving techniques that had been developed largely in connection with other engineering applications. Its re-introduction to architecture was slow due mainly to the extreme conservatism of the building industry. The gerberette brackets at the Centre Pompidou were an overt demonstration that casting was once again a viable technology for shaping major structural components.

Its use at the Centre Pompidou was due to Peter Rice, who had seen casting being used in novel ways while on a visit to Japan. It was a significant development in the architectural engineering of the twentieth century because it solved the problem of making a complex three-dimensional joint visually acceptable. The use of existing jointing techniques such as riveting, bolting or even welding produced steelwork junctions that were notoriously cumbersome. The re-introduction of casting was an important innovation in the aestheticisation of the steel framework, which was essential for the development of the High-Tech style, and which was employed in some of its most significant structures – such as the Waterloo Terminal in London by Anthony Hunt (Figures 10.4 and 10.5).

The evolution of the design for the gerberette brackets provides an insight into the conflicting priorities of architecture and structural engineering. The need for the brackets originated in the decision to subdivide the cross-section of the building into a wide central zone flanked by two much narrower service zones – a space-planning concept derived from the conventional architectural idea of delineating 'served' and 'servant' spaces. This produced the undesirable structural combination of adjacent spans of widely varying length. The need for readability, another purely architectural concept, meant that the structural solution had to be visible and therefore of acceptable appearance. The idea of using cantilever brackets to connect the floor girders to the columns solved this brilliantly because it gave the major and minor horizontal structural components of each frame different functions, which allowed them to be treated differently visually, and also allowed the vertical elements on the perimeter of the building to be very slender – as described above.

The brackets themselves could have been fabricated by welding from rolled-steel components. The use of casting allowed a very elegant shape to be adopted with a continuously varying profile and cross-section. The form of the brackets is precisely related to their structural function (Figure 9.31). The profile is matched to the distribution of internal forces, as would be seen in a bending moment diagram, and the variation in the cross-section from solid rectangle at the tip, through an increasing I-section to a hollow rectangle where the bracket wraps around the supporting column, is virtually a diagram of the manner in which the stresses can be most efficiently accommodated. The shape of the brackets, if not the idea of using them to connect the floor girders to the columns, is probably the only aspect of the design that would have met with the approval of structural purists such as Nervi and Torroja. The cast brackets also allowed Rice to incorporate a humanising element into the steelwork which resulted in it not being entirely a machine-made product. The brackets were cast in sand moulds by pouring the liquid metal into voids created by timber patterns that had been crafted by hand.

The Centre Pompidou has been undoubtedly one of the most significant works of architecture of the late twentieth century. It is unashamedly Modernist and in consequence deeply flawed functionally. Its interior environment has proved to be highly unsuitable for the conservation of museum collections and as a venue for staging exhibitions of artwork (its primary purposes), and the ongoing energy and maintenance requirements caused by its fabric are increasingly problematic in relation to wider environmental concerns.

The compromising of technical performance in order to accommodate a purely visual agenda was even more evident in Rice's next major project, the Lloyd's Headquarters building in London (1986), also with the architect Richard Rogers. The building is described here in Chapter 10 and is another supreme example of structural form being determined by visual rather than technical criteria. In this case the dominating architectural ideas were once again 'readability' and 'flexibility', and, as at the Centre Pompidou, several aspects of the structure were less than ideal technically, and were adopted for purely visual reasons which severely compromised the efficiency of the structure.

As with the Sydney Opera House and the Centre Pompidou, Rice's role at Lloyd's was as the technologist who delivered a structure with a form that had been determined mainly by ideas that were purely architectural in origin. It represented a relationship between architect and engineer that was not a partnership of equals. At the Centre Pompidou and at Lloyd's, almost no compromises to enhance technical performance were made with the visual agenda. Visual compromises were made at Sydney but only because the sheer scale of the building made any other course impossible. The design scenario that operated in all of these cases did not conform to Arup's idea of a collaboration of equals, despite their occurring under his aegis, and, not surprisingly, the results did not represent his ideal of *total design*.

Anthony Hunt (1932–), an almost exact contemporary of Rice and another significant engineer of the High-Tech movement, adopted an approach to design that was significantly different from that of Rice and closer to what Arup would have considered to be ideal.

At the beginning of his career, Hunt spent eight formative years working for Felix Samuely before setting up his own practice (Anthony Hunt Associates) in 1962, and it was largely due to his experiences with Samuely that he favoured properly functioning design teams as a methodology and 'total design' as an appropriate objective for the creation of a work of architecture. He was also influenced by the structural purist ideas of Nervi and Torroja and the ideal of the achievement of economy of means as a criterion of good engineering design. Added to this was a genuine interest in the purely aesthetic qualities of structure – something that he also shared with Samuely.

Hunt's combination of abilities, knowledge and experience ideally fitted him to be the engineer who played the key role in the creation of the High-Tech style. In collaboration with Norman Foster and Richard Rogers, whose careers he helped to launch, Hunt was responsible for the creation of the particular amalgamation of aesthetics and technology that became one of the major components of the fragmented architectural Modernism of the last quarter of the twentieth century.

The crucial building with which the High-Tech movement was initiated was the Reliance Controls factory at Swindon in England (1967) (Figure 9.32) by the architects Team 4 (a partnership formed by Foster and Rogers in 1963) with structural engineering by Hunt. The evolution of the design of this building has been described elsewhere (see Macdonald, *Anthony Hunt*, 2000, Thomas Telford, London), but its significance here is in the methodology that was used.

The building resulted from a genuinely collaborative partnership between architects and engineer that was sufficiently close to make difficult the

Figure 9.32 Reliance Controls factory, Swindon, 1967; Team 4, architects; Anthony Hunt Associates, engineers. Considered to be the building that defined the High-Tech style, this building resulted from a close collaboration between architects and engineer at every stage in the design process, which resulted in the harmonisation of the aesthetic and technical agendas.

Photo: Anthony Hunt Associates.

attribution of any aspect of the design to a particular individual. As with later buildings, such as the Centre Pompidou, the aesthetics were largely dependent on the visual qualities of the structure but, unlike at Pompidou, the structure of the Reliance Controls building performed well when judged by purely technical criteria. The post-and-beam frame, primary/secondary beam configuration, and minor bending-element 'improvement' in the form of the I-section, were entirely appropriate for the spans and loads involved. Crucial to the aesthetics were the site-welded steelwork joints (an unusual technique in Britain at the time) and it is significant, given their stylistic importance, that the final drawings for these were hand-drafted by Hunt rather than by the architects.

The single departure from structural 'purity' was the inclusion of cross-bracing in all of the bays on two faces of the building. One braced bay would have been sufficient for the purposes of stability. Two might have been justified on the grounds of balancing the wind resistance through the building, but the insertion of cross-bracing in every bay was technically unnecessary. It was insisted upon by Foster for aesthetic reasons and his sensibilities proved to be appropriate, because it is notable that the mostly redundant cross-bracing always featured prominently in the photographs of the building that appeared in the architectural media.

The Reliance Controls building is generally considered as the work that began the High-Tech movement. As with most of the iconic buildings of twentieth-century Modernism its appeal was almost entirely aesthetic because, other than structurally, it was a failure as a practical building. Unloved by its owners and users, it was demolished unceremoniously in 1990. Once again visual delight, at least in the eyes of the cognoscenti, triumphed over commodity. Firmness was, of course, a necessity.

The Reliance Controls building brought a novel aesthetic across the Atlantic to Europe. It represented a new architectural voice that spoke a different language from the then current architectural fashion for massive, brutalist buildings executed in exposed reinforced concrete, such as the British National Theatre in London or even the Hunstanton School, with its combination of steel and exposed brickwork masonry. The vocabulary at Reliance Controls was much slicker: one of glass, profiled cladding and exquisitely detailed

Figure 9.33 Sainsbury Centre for the Visual Arts, Norwich, 1978; Foster Associates, architects; Anthony Hunt Associates, engineers. With its clean-cut lines and simplicity of form this building exemplifies Foster's approach to architecture. The cross-sectional shape is far from ideal structurally, considering the relatively long span of 35 m, and many compromises with structural performance were required to provide adequate support for the bespoke cladding system. The internal environment of the thinly-clad single-volume enclosure proved to be highly problematic in respect of conservation of the art objects which it was intended to house and display. Appearance, rather than function, was the principal driver of the design.

Photo: Anthony Hunt Associates.

structural steelwork, which would come to typify the new version of Modernism known as High-Tech.

Following the completion of the Reliance Controls building, Team 4 was disbanded and Foster and Rogers set up independent practices. Foster continued his collaborations with Hunt in the early years of his practice. Initially, they worked on the basis of the very close teamwork that had produced the Reliance Controls building and one of the most praised results, which many consider to be one of Foster's finest buildings, was the Willis, Faber & Dumas (WFD) building of 1976 (Figures 1.6, 5.15 and 5.16). The integration of structure and architecture that was achieved with this building was perhaps the closest that Foster and Hunt ever came to the realisation of the ideal of 'total design'. The aesthetics and technical aspects of the design are perfectly harmonised and no compromises were made with the structure to produce specifically architectural effects.

As his fame and reputation grew, Foster fairly rapidly began to allow visual considerations to dominate his designs and, against his inclination, Hunt found himself in the role of technical facilitator rather than true collaborator. This was particularly evident in the design of the Sainsbury Centre for the Visual Arts in Norwich, England (Figure 9.33), a near contemporary of the WFD building and the Centre Pompidou. It had more in common with the latter so far as the design methodology was concerned.

At the Sainsbury Centre the structural layout was greatly influenced by purely visual concerns. The building is essentially a large single-volume enclosure, which is rectangular in both plan and cross-section, with an interior that is uninterrupted by structural elements. The structure is simply of a series of rectangular main frames, each consisting of a horizontal beam spanning 35 m and supported on two column units, one in each of the side walls. The beam and column units are identically configured, fully triangulated space frameworks. The cladding is attached directly to these main frameworks, there being no secondary structure (Figure 9.34).

Several features of the structure are less than ideal technically. The elongated rectangle of the building's cross-section, which determines the overall form of the frameworks, is non-form-active and results in large internal forces. A parabolic profile, such as at Barlow's St Pancras Station (Figure 9.1) or Nervi's aircraft hangars (Figure 9.5), would have allowed much greater structural efficiency to have been achieved. The adoption of a constant depth for the framework, rather than a profile that matched the bending moment diagram, greatly increased the strength required, and therefore the weight, of the frame's sub-elements. The absence of a secondary structure of purlins and cladding rails – the normal configuration for a single-storey steel framework, and which would have allowed the main frameworks to be more widely spaced and significantly reduced in number – was necessary due to the extreme sensitivity to movement of the bespoke cladding system. Only by stacking the main frameworks alongside each other could the necessary rigidity be provided.

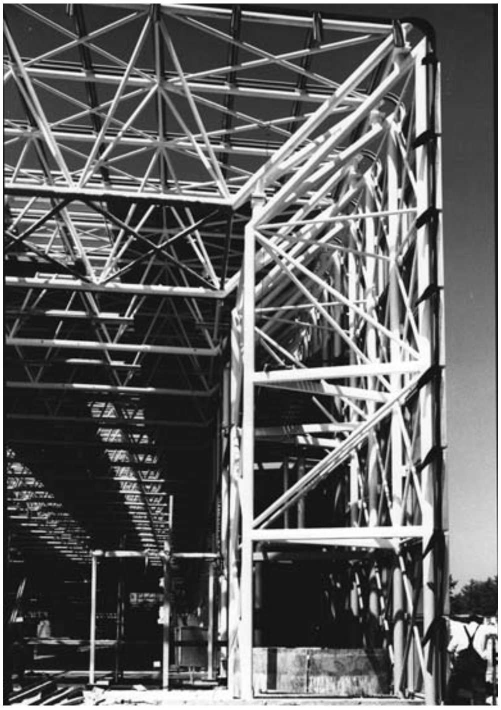


Figure 9.34 Sainsbury Centre for the Visual Arts, Norwich, 1978; Foster Associates, architects; Anthony Hunt Associates, engineers. This progress shot shows the bespoke cladding attached directly to the primary structural elements. A secondary structure of purlins and cladding rails, which would have allowed the primary elements to be more widely spaced with significant saving in material, was not possible due to the sensitivity of the cladding to movement. The cladding system failed and had to be replaced soon after the completion of the building for reasons unconnected to structural action.

Photo: P. Hunt.

The small radius of curvature of the cladding at the junction between the walls and the roof required that the structural connection between the horizontal and vertical elements be made with a considerable degree of eccentricity. All of these features, which were detrimental to the efficiency of the structure, were adopted to satisfy purely visual requirements.

The building was also deficient technically in other respects, many of them associated with the cladding that, again to satisfy visual requirements, was designed in house by the Foster office rather than by a cladding specialist. It failed, and had to be entirely replaced within a few years due to corrosive interaction between its layers, which were incompatible chemically. Even without this defect, the cladding was unsatisfactory because its subdivision into small panels that were interchangeable to provide flexibility (a feature that was not requested and never used), and that produced a network of junctions that were crossed only by a thin sheet of neoprene, caused it to be a very ineffective barrier between the internal and external environments. The network of junctions in effect turned the envelope into a thermal sieve that allowed significant variations of temperature and relative humidity to occur in the interior – the worst possible scenario for a space in which the conservation of artworks was a major consideration.

Despite its many technical shortcomings the building was well received critically in the architectural media as an important addition to the developing High-Tech movement. On being invited to comment on it by Foster, Richard

Buckminster Fuller (1895–1983), that great self-styled guru of progressive technology, asked Foster what the building weighed, and on being told, and citing the comparison of it to a cargo ship of similar overall dimensions, famously replied: 'You have got a whole lot for 5,000 tons.' The comparison was, of course, completely inappropriate. The structural problems posed by the design of ships to enable them to withstand the bending and torsional loads associated with an oceanic crossing are entirely different from those that are presented by a building enclosure. Buckminster Fuller's catchy reply was equally meaningless. Foster (or rather his client) could have got the same for much less. The structure in fact contains at least 30% more steel than would have been required if a conventional arrangement had been adopted. The exchange with Fuller, which was quoted in Volume 1 of the series of books on the Foster practice that was sponsored by the firm, was fairly typical of the

Figure 9.35 China Central Television Headquarters, Beijing (CCTV) (2008); OMA (East China) and Rem Koolhaas, architects; Arups (Cecil Balmond), engineers. The distinctive form of this building was supported on a steel skeleton framework, of modified but relatively conventional design.

Photo: Jakob Montrasio/Wikimedia Commons.

kind of gimmicky, pseudo-technical discourse with which the technically illiterate architectural media surrounded the High-Tech movement. The teams of designers who created the High-Tech buildings may have gone some way to achieving the kind of collaboration of equals that Arup promoted but the majority of the buildings that resulted did not match up to the idea of 'total design'.

Similar methodology has continued into the present day with engineers such as Cecil Balmond (1943–). Balmond has been responsible for some of the most visually striking images of recent times including the Imperial War Museum North, Salford (2001), with Daniel Libeskind (1943–) (Figures 10.23 and 10.24), the China Central Television (CCTV) Headquarters, Beijing (2008), with architects OMA (East China) and Rem Koolhaas (1944–) (Figures 9.35 and 9.36), the Pedro e Inês Bridge at Coimbra (2006) with Antonio Adao da Fonseca and the Centre Pompidou-Metz (2009) with Shigeru Ban (1957–) (Figure 11.6). Balmond worked for Ove

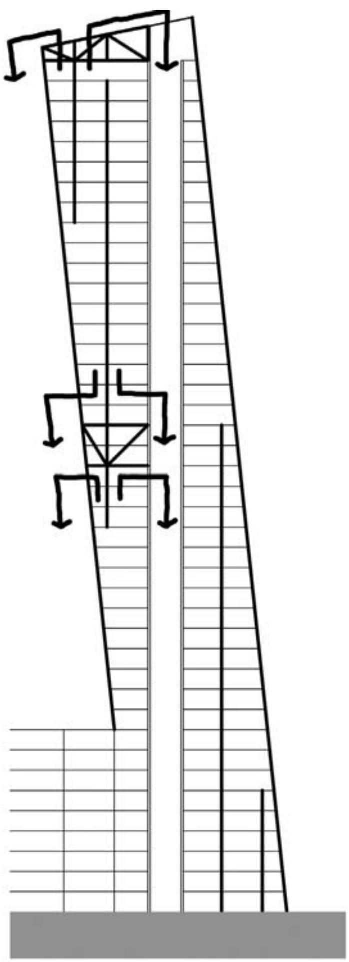


Figure 9.36 China Central Television Headquarters, Beijing (CCTV) (2008); OMA (East China) and Rem Koolhaas, architects; Arups (Cecil Balmond), engineers. Internal columns are vertical and act in conjunction with a structural diagrid in the inclined external walls to provide vertical support. Internal triangulated trusses are used to transfer loads from columns that do not reach the ground to those that do. The volume of steelwork required to provide support for the building is significantly greater than would be required for a conventional vertical building with the same floor area.

Line drawing: Andrew Siddall after original by Balmond.

Arup & Partners before setting up his own studio and consultancy in 2010. He is the author of several books on structural design philosophy and innovative structural design.

One of Balmond's most visually interesting projects is the Maison de Floirac, Bordeaux, France (1998) with Rem Koolhaas OMA (Figure 9.37). The evolution of the design, which involved close collaboration between architect, engineer and client, is well described in Balmond's book *Informal* (2002). As Balmond explains, the 'principal tectonic . . . is a box, up in the air' containing bedrooms, with living spaces below that are surrounded by glass walls 'which may open out onto the landscape and vanish'. Balmond also states that 'The aim was to declare, "look no hands"' and that, in this context, 'Structure . . . becomes the enemy of promise', 'Gravity is a tyrant'.

Balmond's structural solution was to make the upper level from an arrangement of storey-high reinforced concrete beams and cross-walls (the 'box') and to create the illusion of weightlessness by supporting this on two steel frames, one under the 'box' at one end and one above it at the other. The latter is displaced laterally and supported on an eccentrically positioned drum of concrete that houses the building's stair. Equilibrium is restored to this out-of-balance arrangement by projecting the high-level steel girder beyond the perimeter of the building and anchoring it to the ground through an

Figure 9.37 Maison de Floirac, Bordeaux, France, 1998; Rem Koolhaas OMA, architects; Arups (Cecil Balmond), engineers. The architectural concept was of a box up in the air (containing bedrooms) floating on a glass-walled living space which could open out to the landscape and vanish. Considerable ingenuity was required to realise the structure. The box was formed by a chequerboard of intersecting reinforced concrete walls and was supported on two offset steel frameworks (both partially visible). The degree of collaboration between architect and engineer was significant.

Photo: Ila Bêka & Louise Lemoine (from film: *Koolhaas Houselife*).

external slender steel tie. The structural solution is ingenious and produces the required disorientating effect of mass levitating above transparent walls and apparently visually inadequate support.

Many of the major works with which Balmond has been involved, such as the Maison de Floirac and the CCTV Headquarters in Beijing (see also Section 10.2.5), do not, however, perform well against the criteria associated with economy of means in the consumption of energy, materials and other resources. They are, rather, examples of engineering being used primarily to create interesting visual effects. In this respect Balmond's built work invites comparison with that of both Peter Rice and Santiago Calatrava, and also Arup's Penguin Pool, both for its visual excitement but also for the tendency to set up seemingly impossible problems of equilibrium and stability that are then 'solved' using highly innovative engineering (e.g. Figures 9.35 and 9.37).

9.4 Conclusion

This chapter has been concerned with the role of structural engineers in the creation of the architecture of the Modern period which, from the perspective of structural engineering, began with the introduction of the 'new' structural materials of steel and reinforced concrete. This brought about a great expansion in the possibilities available for architectural form, and also created the need for the addition of a new profession to the architectural design team, that of the consulting structural engineer. Space limitations here have meant that the coverage of the topic has been restricted to the work of a very small number of the many individuals who have contributed to these processes, but several generally applicable conclusions may nevertheless be drawn.

The collaborations that emerged between architects and engineers in the Modern period have taken a number of forms. At one extreme, architects determined the forms of buildings from purely architectural considerations and engineers were called upon simply to devise a structure that would provide the necessary support. This process has frequently resulted in the creation of structures that made an inefficient use of material but, such is the strength of steel and reinforced concrete, that it has normally been possible for an adequate structure to be provided, so long as the spans were not too great. Some of the best-known buildings of Modern architecture fall into this category – such as the Centre Pompidou in Paris and the Sainsbury Centre for the Visual Arts in Norwich. Occasionally, and usually due to a problem of scale, an architect has suggested a form that was simply unbuildable. The original design for the Sydney Opera House is perhaps the most famous example of this situation.

At the other extreme of the possible spectrum of collaboration between architects and engineers was the 'design-team' methodology, as advocated by engineers such as Ove Arup and Anthony Hunt, in which engineers and architects evolved a design in a partnership of equals. The ideal has been the achievement of 'total design' – a concept promoted by Arup in particular – in which technical and aesthetic issues were resolved in equal measure. There have been relatively few buildings that have truly fallen into this category. The collaboration between Arup and Lubetkin in the 1930s, which produced the Highpoint flats in London, was an example; that between Hunt and the young Norman Foster and Richard Rogers, which created the Reliance Controls factory and the Willis, Faber & Dumas building was perhaps another. The methodology adopted for the vast majority of buildings has fallen between the two extremes described above but usually with the visual requirements of the architectural agenda dominating the design decisions and compromises, if required, being made in relation to the engineering.

Throughout the Modern period a truly rational approach to the design of buildings was pursued by the structural fundamentalists such as Nervi, Torroja and Candela. In their case the aesthetic followed from a process of form determination driven by a concern to use material efficiently and minimise constructional complexity. In the process, a new aesthetic for domes and vaults came into being that was distinctly different from that which had been adopted by traditional builders in masonry. This new visual vocabulary, detoxified as it was of association with historic architecture, was quickly absorbed into the world of Modern architecture but often with only a limited understanding of its underlying technical significance.

Of the engineers in the generations that followed that of Nervi and Torroja, including Hunt, Rice, Balmond and Calatrava, who have mostly worked closely with architects and have been concerned with the aesthetic qualities of structure, different 'styles' of engineering can be discerned. The engineer who most closely adhered to the methodology described by Nervi and Torroja was Hunt, the majority of whose structures are good examples of 'building correctly' (see Chapter 8); he studiously avoided the use of complexity for its own sake. At the Waterloo Terminal, for example (see Section 10.2.1 and Figures 10.4 and 10.5), where he was faced with site and programmatic conditions of great complexity, the simplicity of the final engineering solution was remarkable and in stark contrast to structures by Calatrava, such as the Campo Volantin Bridge in Bilbao (Figure 9.16), in which significant complexity was introduced into what was a relatively simple engineering problem, purely for aesthetic effect. Rice, on the other hand, was content to employ his considerable engineering ability in the service of complexity introduced, not from necessity, but as a result of an aesthetic agenda imposed by the architect.

Both of these 'styles' of engineering practice – as might be expected – continue into the present day, and both ways of working clearly have their uses in different types of projects. A recent positive trend has been the increasing discussion of the various approaches to collaboration and the working in teams of professionals with complementary inputs to the design and construction process.[5]

The tendency for architects to be concerned only with the visual qualities of form, and to neglect its technical significance, has been a prominent aspect of the age of Modern architecture. This tendency has been encouraged by the extremely versatile structural properties of steel and reinforced concrete. These properties have produced for architects an almost complete freedom in the possible forms of buildings. Following the swing to the complete irrationality of Deconstruction and other versions of Late-Modern architecture, it has become increasingly obvious that the visual and technical aspects of Modern architecture have become almost entirely separate aspects of the design process. This feature of much of current architecture – the ability to create form in the absence of any significant consideration of its technical consequences – and the approach to design that it implies, is further discussed in Section 10.2.5; it gives considerable cause for concern in relation to the role of architects, and to the relation of this to the role of engineers, in the development of environmentally sustainable forms of building.

Notes

1 http://architectuul.com/architecture/penguin-pool-london-zoo (2015).
2 www.engineering-timelines.com/scripts/engineeringItem.asp?id=795 (2016).
3 In his preface to C. Balmond, 2002, *Informal*, Prestel.
4 Gerberettes are named after the nineteenth-century German engineer Heinrich Gerber, who pioneered a design method involving the insertion into structures of hinge-joints, so as to modify the distribution of internal forces.
5 See, for example: https://www.istructe.org/blog/2016/women-structural-engineers-inspire-tomorrows-engi for a range of approaches, in the context of outstanding recent projects: Jackie Heath of Ramboll (on the re-development of the Lighthouse Building in London); Leslie Paine of AECOM (on Medina Airport, Saudi Arabia); Katalin Andrasi of Mott Macdonald (on the Harlech Castle Footbridge); Juliet Handy of Atkins Global (on Birmingham New Street Station); and Catherine Poirrez of Passage Projects (on The Future of Us Gridshell in Singapore) (2018).

CHAPTER 10

Structure and architecture

10.1 Introduction

This chapter is concerned with the relationship between structure and architecture and with the various forms that this can take depending on the aspirations and intentions of the designers involved. The varieties of relationship can be very wide, ranging between the extremes of complete domination of the architecture by the structure to total disregard of structural requirements in the determination of both the form of a building and of its aesthetic treatment. This large number of possibilities is discussed here under five broad headings:

- ornamentation of structure
- structure as ornament
- structure as architecture
- structure accepted
- structure ignored.

As discussed in Chapter 9, the relationship between architects and structural engineers can vary from one in which the form of a building is determined solely by the architect, having little regard to structural performance and with the engineer acting mainly as a technical facilitator, to one in which the engineer acts as architect and determines the form of the building and all other architectural aspects of the design. Mid-way between these extremes is the situation in which architect and engineer collaborate fully over the form of a building and evolve the design jointly to satisfy aesthetic and technical requirements in equal measure. As will be seen, the type of relationship that is adopted has a significant effect on the nature of the resulting architecture.

Facing page: Riverside Museum, Glasgow, Hadid/Happold. Photo: Eoin.

10.2 The types of relationship between structure and architecture

10.2.1 Ornamentation of structure

There have been a number of periods in the history of Western architecture in which the formal logic of a favoured structural system has been allowed to influence, if not totally determine, the overall forms of buildings. In such periods, the forms that were adopted have been logical consequences of the structural armatures of buildings. The category *ornamentation of structure*, in which the building consists of little more than a visible structural armature adjusted in fairly minor ways for visual reasons, has been one version of this.

Perhaps the most celebrated building in the Western architectural tradition was the Parthenon in Athens (Figure 10.1). Structural requirements dictated the form and, although the purpose of the building was not to celebrate structural technology, the formal logic of the structure was celebrated as part of the visual expression. The Doric Order, which reached its greatest degree of refinement in this building, was a system of ornamentation evolved from the post-and-beam structural arrangement.

There was, of course, much more to the architecture of the Greek temple than ornamentation of a constructional system. The archetypal form of the

Figure 10.1
The Parthenon, Athens, C5 BCE. Structure and architecture perfectly united.

Photo: Barcex/Wikimedia Commons.

buildings and the vocabulary and grammar of the ornamentation have had a host of symbolic meanings attributed to them by later commentators.[1] No attempt was made, however, by the builders of the Greek temples, either to disguise the structure or to adopt forms other than those that could be fashioned in a logical and straightforward manner from the available materials. In these buildings the structure and the architectural expression coexist in perfect harmony.

The same may be said of the major buildings of the medieval Gothic period (Figures 3.1 and 7.5), which are also examples of the relationship between structure and architecture that may be described as 'ornamentation of structure'. Like the Greek temples the largest of the Gothic buildings were constructed almost entirely in masonry. Unlike the Greek temples they had spacious interiors that involved large horizontal roof spans. These could only be achieved in masonry by the use of compressive form-active vaults. The interiors were also lofty, which meant that the vaulted ceilings imposed horizontal thrust on the tops of high flanking walls and subjected them to bending moment as well as to axial internal force. The walls of these Gothic structures were therefore semi-form-active elements (see Section 4.2) carrying a combination of compressive-axial and bending-type internal force. The archetypical Gothic arrangement of buttresses, flying buttresses and finials is a spectacular example of a semi-form-active structure with 'improved' cross-section and profile (Figure 7.5). Virtually everything that is visible is structural and entirely justified on technical grounds. All elements were also adjusted so as to be satisfactory visually: the 'cabling' of columns, the provision of capitals on columns and of string courses in walls and several other types of ornament were not strictly essential structurally.

The strategy of 'ornamentation of structure', which was so successfully used in Greek Antiquity and in the Gothic period, virtually disappeared from Western architecture at the time of the Italian Renaissance. There were several causes of this, one of which was that the structural armatures of buildings were increasingly concealed behind forms of ornamentation that were not directly related to structural function. For example, the pilasters and half columns of Palladio's Palazzo Valmarana (Figure 10.2) and many other buildings of the period were not particularly significant structurally. They formed part of a loadbearing wall in which all parts contributed equally to the load carrying function. Such disconnection of ornament from structural function led to the structural and aesthetic agendas drifting apart and had a profound effect on the type of relationship that developed in Western architecture between architects and those who were responsible for the technical aspects of the design of buildings.

It was not until the twentieth century, when architects once again became interested in the aesthetic possibilities of the expression of structural function, that the ornamental use of exposed structure reappeared in the mainstream of Western architecture. The early Modern period was, however, an age in

Figure 10.2 The Palazzo Valmarana, Vicenza, 1565; Andrea Palladio, architect. The pilasters on this facade have their origins in a structural function but here form the outer skin of a structural wall. The architectural interest of the building does not lie in its structural make-up, however.

Photo: Hans A. Rosbac/Wikimedia Commons.

Figure 10.3 AEG Turbine Hall, Berlin, 1908; Peter Behrens, architect. Glass and structure alternate on the side walls of this building and the rhythm of the steel structure, which is exposed on the exterior, forms a significant component of the visual vocabulary. Unlike in many later buildings of the Modern Movement the structure was used 'honestly'; it was modified slightly for purely visual effect, but not to the detriment of its function.

Photo: Doris Antony/Wikimedia Commons.

which the idea of ornamentation was positively rejected, so the forms that it took were subtle, amounting mostly to very minor adjustments that were made to structural arrangements for purely aesthetic purposes. It made its tentative first appearance in the works of early Modernists such as Auguste Perret and Peter Behrens (Figure 10.3) and was also seen in the architecture of Ludwig Mies van der Rohe. The structure of the Farnsworth House, for example (Figure 0.4), is exposed and forms a significant visual element. It was also adjusted slightly for visual reasons and in that sense is an example of 'ornamentation of structure'. Other more recent examples of such visual adjustments occurred in British High-Tech. The exposed-steel structure of the Reliance Controls building at Swindon, England (Figure 9.32), for example, by Team 4 and Anthony Hunt, is a fairly straightforward technical response to the problems posed by the programmatic requirements of the building and stands up well to technical criticism.[2] It is nevertheless an example of 'ornamentation of structure' rather than a work of pure engineering because it was adjusted in minor ways to improve its appearance. The H-section Universal Column[3] that was selected for the very slender purlins, for example, was less efficient as a bending element than the I-section Universal Beam would have been. It was used because it was considered that the tapered flanges of the Universal Beam were less satisfactory visually than the parallel-sided flanges of the Universal Column in this strictly rectilinear building.

The train shed of the International Rail Terminal at Waterloo Station in London (Figure 10.4) is another example. The overall configuration of the steel structure that forms the principal architectural element of this building was determined from technical considerations. The visual aspects of the design, such as the tapering of the scantlings and the detailing of the complex joints in the steelwork (Figure 10.5), were carefully controlled, however, and the design evolved through very close collaboration between the teams of

Figure 10.4 International Terminal, Waterloo Station, London, 1992; Nicolas Grimshaw, architect; Anthony Hunt Associates, engineers. The form of the exposed structure of this building was determined entirely from technical requirements. It nevertheless formed an important part of the visual vocabulary and was modified in minor ways to improve its appearance.

Photo: Anthony Hunt Associates.

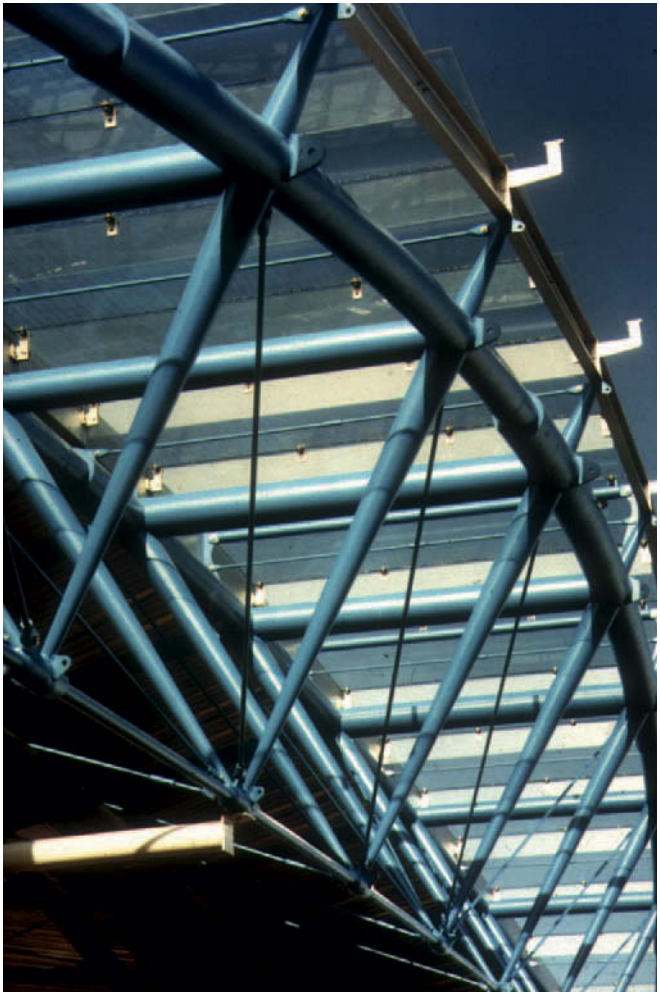


Figure 10.5 International Terminal, Waterloo Station, London, 1992; Nicolas Grimshaw, architect; Anthony Hunt Associates, engineers. The general arrangement of the principal trusses was determined from structural considerations. The compressive upper elements are larger than the single tensile tie rod so as to be capable of resisting buckling. The scantlings that connect the two sets of elements are tapered mainly for visual reasons.

Photo: Anthony Hunt Associates.

architects and engineers involved, so that it performed well aesthetically as well as technically.

These few examples serve to illustrate that throughout the entire span of the history of Western architecture, from the temples of Greek Antiquity to late-twentieth-century structures such as the Waterloo Terminal, buildings have been created in which architecture has been made from exposed structure. The architects of such buildings have paid due regard to the requirements of the structural technology and have reflected this in the basic forms of the buildings. The architecture has therefore been affected in a quite fundamental way by the structural technology involved. At the same time the architects have not allowed technological considerations to inhibit their architectural imagination. The results have been carefully resolved buildings that perform well when judged by either technical or non-technical criteria.

10.2.2 Structure as ornament

The relationship between structure and architecture categorised here as 'structure as ornament' involves the manipulation of structural elements according to criteria that are principally visual and is a largely twentieth-century phenomenon. As in the category 'ornamentation of structure' the structure is given visual prominence but unlike in ornamentation of structure, the design process is driven by visual rather than by technical considerations. As a consequence, the performance of the structures is often less than ideal when judged by technical criteria. This is the feature that distinguishes 'structure as ornament' from 'ornamentation of structure'.

Three versions of 'structure as ornament' may be distinguished. In the first of these, structure is used *symbolically*. In this scenario the devices that are associated with structural efficiency (see Chapter 4), which are mostly borrowed from the aerospace industry and from science fiction, are used as a visual vocabulary that is intended to convey the idea of progress and of a future based on a benign and powerful technology. The images associated with advanced technology are manipulated freely to produce an architecture that is intended to celebrate technology. Often, the context is inappropriate and the resulting structures perform badly in a technical sense.

In the second version, spectacular exposed structure may be devised in response to *artificially created circumstances*. In this type of building, the forms of the exposed structure are justified technically but only as the solutions to unnecessary technical problems that have been created by the designers of the building.

A third category of 'structure as ornament' involves the adoption of an approach in which structure is expressed so as to produce a readable building in which technology is celebrated, but in which a *visual agenda is pursued that is incompatible with structural logic*. The lack of the overt use of images associated with advanced technology distinguishes this from the first category.

Where structure is used symbolically, a visual vocabulary that has its origins in the design of lightweight structural elements – for example the I-shaped cross-section, the triangulated girder, the circular hole cut in the web (see Chapter 4) – is used architecturally to symbolise technical excellence and to celebrate state-of-the-art technology. Much, though by no means all, of the architecture of British High-Tech falls into this category. The entrance canopy of the Lloyd's headquarters building in London is an example (Figure 10.6). The curved steel elements that form the structure of this canopy, with their circular 'lightening' holes (holes cut out to lighten the element – see Section 4.3) are reminiscent of the principal fuselage elements in aircraft structures (Figure 4.15). The complexity of the arrangement is fully justified in the aeronautical context where saving of weight is critical. The use of lightweight structures in the canopy at Lloyd's merely increases the probability that it will be blown away by the wind. Its use here is entirely symbolic.

Figure 10.6 Entrance canopy, Lloyd's headquarters building, London, 1986; Richard Rogers & Partners, architects; Ove Arup & Partners, engineers. The curved steel ribs with circular 'lightening' holes are reminiscent of structures found in the aerospace industry.

Photo: embarch.

The Renault (Spectrum) building in Swindon, England, by Foster Associates and Ove Arup & Partners is another example of this approach (Figure 3.19) (see also Section 6.4 and Figure 6.7). The structure of this building is spectacular and a key component of the building's image, which is intended to convey the idea of a company with a serious commitment to 'quality design'[4] and an established position at the cutting edge of technology. The building is undoubtedly elegant and enjoyable and it received much critical acclaim when it was completed; these design objectives were therefore achieved. Bernard Hanon, President-Directeur General, Régie Nationale des Usines Renault, on his first visit felt moved to declare: 'It's a cathedral.'[5]

The structure of the Renault building does not, however, stand up well to technical criticism. It consists of a steel-frame supporting a non-structural envelope. The basic form of the structure is of multi-bay portal frames running in two principal directions. These have many of the features associated with structural efficiency (Figure 6.7): the longitudinal profile of each frame is matched to the bending moment diagram for the principal load; the structure is trussed (i.e. separate compression and tensile elements are provided); the compressive elements, which must have some resistance to bending, have further improvements in the form of I-shaped cross-sections and circular holes cut into the webs. Although these features improve the efficiency of the structure, most of them are not justified, given the relatively short spans involved (see Chapter 6). The structure is unnecessarily complicated and there is no doubt that a conventional portal-frame arrangement (a primary/secondary structural system with the portals serving as the primary structure, as in the earlier building by Foster at Thamesmead, London (Figure 1.5)), would have provided a more economical structure for this building. Such a solution was rejected at the outset of the project by the client on the grounds that it would not have provided an appropriate image for the company.[6] The decision to use the more expensive, more spectacular structure was therefore taken on stylistic grounds.

The structure possesses a number of other features that may be criticised from a technical point of view. One of these is the placing of a significant part of it outside the weathertight envelope, which has serious implications for durability and maintenance. The configuration of the main structural elements is also far from ideal. The truss arrangement cannot tolerate reversal of load because this would place the very slender tension elements into compression. As designed, the structure is capable of resisting only downward-acting gravitational loads and not uplift. Reversal of load may tend to occur in flat-roofed buildings, however, due to the high suction forces which wind can generate. Thickening of the tensile elements to give them the capability to resist compression was considered by the architect to be unacceptable visually[7] and so this problem was solved by specifying heavier roof cladding than originally intended (or indeed required) so that no reversal of load would occur. Thus the whole structure was subjected, on a permanent basis, to a larger gravitational load than was strictly necessary. A further observation that might be made regarding the structure of this building is that the imagery employed is not particularly 'cutting edge', much of it having been evolved in the earliest days of iron and steel frame design in the nineteenth century.

It is frequently argued by the protagonists of this kind of architecture[8] that, because it appears to be advanced technically, it will provide the solutions to the architectural problems posed by the worsening global environmental situation. This is perhaps their most fallacious claim. The environmental problems caused by over-exploitation of materials and energy sources and by increasing levels of pollution are real technical problems which require genuine technical solutions. Both the practice and the ideology of the symbolic use of structure are fundamentally incompatible with the requirements of a sustainable architecture. The methodology of the symbolic use of structure, which is to a large extent a matter of borrowing images and forms from other technical areas without seriously appraising their technical suitability, is incapable of addressing real technical problems of the type that are posed by the need for sustainability. The ideology is that of Modernism which is committed to the belief in technical progress and the continual destruction and renewal of the built environment.[9] This is a high-energy-consumption scenario that is not environmentally sound.

The second category of *structure as ornament* involves an unnecessary structural problem, created either intentionally or unintentionally, which generates the need for a spectacular response. A good example of this is found in the structure of the Centre Pompidou in Paris and concerns the way in which the floor girders are connected to the columns through the prominent 'gerberette' brackets (See Chapter 9 and Figs 9.28 to 9.31). As is discussed in Chapter 9, there were several agendas involved in the configuration of the structure of the Centre Pompidou building, most of them concerned with visual rather than structural considerations. There is little doubt that the presence of the unusual gerberette brackets on the exterior of the building contributed greatly to its aesthetic success, but these were in reality an ingenious solution to an avoidable problem associated with the connection of the floor girders to the columns. The architectural expression of ingenious solutions to unnecessary problems is the essence of this version of 'structure as ornament'.

A third kind of architecture that involves structure of questionable technical validity occurs in the context of a visual agenda that is incompatible with structural requirements. The Lloyd's headquarters building (Figures 10.7 to 10.10) in London, by the same designers as had produced the Centre Pompidou (Richard Rogers & Partners as architects and Ove Arup & Partners as structural engineers) is a good example of this.

Lloyd's is a multi-storey office building with a rectangular plan (Figures 10.7 and 10.8). The building has a central atrium through most levels, which gives the floor plan a rectangular-doughnut form. Services are located externally in a series of towers and external ducts which disguise the rectilinearity of the building (Figure 10.9). The structural armature is a reinforced concrete beam-and-column framework that forms a prominent element of the visual vocabulary but that is problematic technically in several respects.

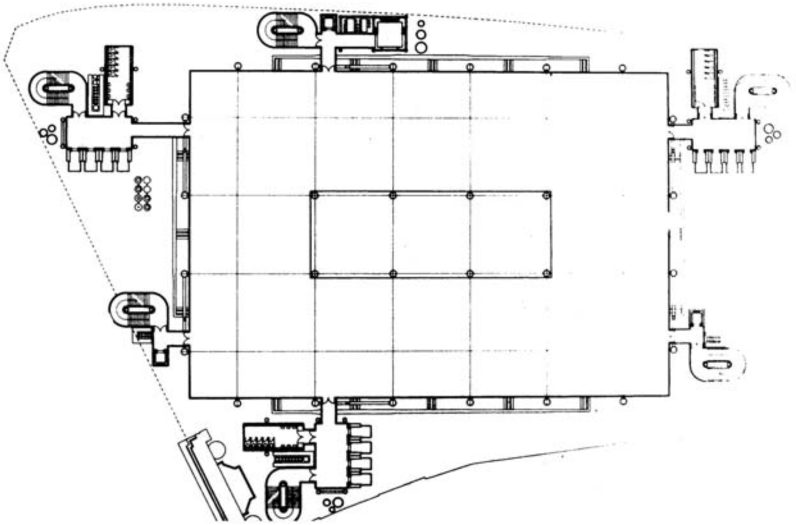
The columns are located outside the perimeter of the floor structures that they support and this has the effect of increasing the eccentricity with which load is applied to these – a highly undesirable consequence structurally that not only introduces unnecessary bending into the columns but also results in the floors having to be connected to the columns through elaborate pre-cast concrete brackets (Figure 10.10). This configuration was adopted to make the structure 'readable' (a continuing concern of Rogers) by articulating the different parts as separate identifiable elements. In this respect the Lloyd's building is similar to the Centre Pompidou. An architectural idea, 'readability', created a problem that required a structural response. The resulting pre-cast

Figure 10.7 Lloyd's headquarters building, London, 1986; Richard Rogers & Partners, architects; Ove Arup & Partners, engineers. The building is basically a rectangular-plan office block. Much of the visual interest depends on the six projecting service towers.

Lloyd's/Wikimedia Commons.

Figure 10.8 Floor plan, Lloyd's headquarters building, London, 1986; Richard Rogers & Partners, architects; Ove Arup & Partners, engineers. The building has a rectangular plan with a central atrium. The structure is a reinforced concrete beam-column frame carrying a one-way-spanning floor.

Image: Designing Buildings/Wikimedia Commons.



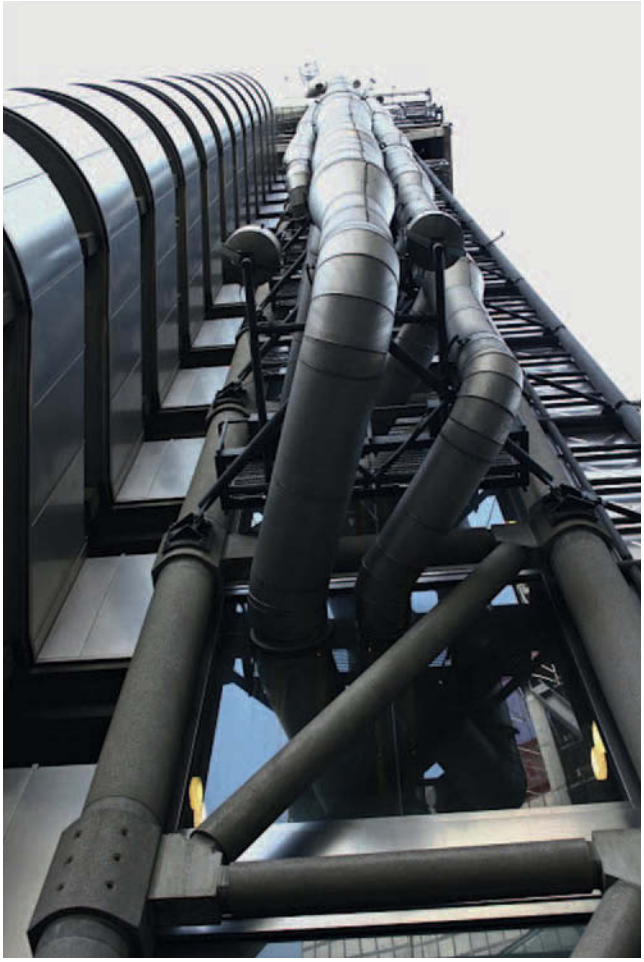


Figure 10.9 Lloyd's headquarters building, London, 1986; Richard Rogers & Partners, architects; Ove Arup & Partners, engineers. Ducts and other services hardware are exposed on the exterior of the building.

Photo: everheardoflondon.

column junctions were less spectacular than the gerberettes of the Centre Pompidou, but had an equivalent function, both technically and visually.

The visual treatment of the floors themselves was also highly detrimental to their structural performance. Structurally, they consist of primary beams, spanning between columns at the edges of the floor, and supporting a ribbed one-way-spanning floor system. For purely visual reasons the presence of the primary beams was suppressed and they were concealed by the square grid of the floor structure. The impression thus given is that the floors are a two-way spanning system supported directly on the columns without primary beams. Great ingenuity was required, on the part of the structural engineering team, to produce a structure that had a satisfactory technical performance while at the same time appearing to be that which it was not.

This task was made more difficult by another visual requirement, namely that the ribs of the floor structure should appear to be parallel-sided rather

than tapered. A small amount of taper was in fact essential to allow the formwork to be extracted, but, to make the ribs appear to be parallel-sided, the taper was upwards rather than downwards. This meant that the formwork had to be taken out from above, thus eliminating the possibility of composite action being achieved between the ribs and the floor slab, which normally greatly increases the efficiency of reinforced concrete floors. The design of this structure was therefore driven almost entirely by visual considerations and a heavy penalty was paid in terms of structural performance.

The conclusion that may be drawn from the above examples of *structure as ornament* is that, in many buildings in which exposed structure is used to convey the idea of technical excellence (most of High-Tech architecture falls into this category), the forms and visual devices that have been employed are not themselves examples of technology that is appropriate to the function involved. It will remain to be seen whether these buildings stand the test of time, either physically or intellectually.

10.2.3 Structure as architecture

10.2.3.1 Introduction

There have always been buildings that consisted of structure and only structure. The igloo (Figure 1.2) is an example and such buildings have, of course, existed throughout history. The buildings of the structural functionalists such as Nervi and Torroja (see Section 9.2) fall into this category. In the world of architectural history and criticism they are often considered to be 'vernacular' rather than 'architecture'. Occasionally, they have found their way into the architectural discourse and where this has occurred it has often been due to their very large scale. An example is the CNIT building (Figure 1.4) in Paris. This is a building in which the limits of what was feasible technically were approached and in which no compromise with structural requirements was possible. This is a third type of relationship between structure and architecture that might be referred to as 'structure without ornament', but perhaps even more accurately as 'structure as architecture'.

The limits of what is possible structurally are reached in the obvious cases of very long spans and very tall buildings. Other examples are those in which extreme lightness is desirable, for example because the building is required to

Figure 10.10 (*facing page*) Atrium, Lloyd's headquarters building, London, 1986; Richard Rogers & Partners, architects; Ove Arup & Partners, engineers. The columns are set outside the perimeter of the floor decks and connected to them through visually prominent pre-cast concrete brackets. The arrangement allows the structure to be easily 'read' but is far from ideal structurally. It introduces bending into the columns and causes high concentrations of stress at the junctions.

Photo: Steve Cadman/Wikimedia Commons.

be portable (Figures 5.20 and 10.17), or where some other technical issue is so overwhelmingly important that it determines the design programme.

10.2.3.2 The very long span

A long-span structure is defined here as one in which the size of the span forces technical considerations to be placed so high on the list of architectural priorities that they significantly affect the aesthetic treatment of the building. As has already been discussed in Chapter 6, the technical problem posed by the long span is that of maintaining a reasonable balance between the load carried and the self-weight of the structure. The forms of longest-span structures are therefore those of the most efficient structure types, namely the form-active types such as the compressive vault or tensile membrane, and non- or semi-form-active types into which significant 'improvements' have been incorporated.

In the pre-industrial age the structural form that was used for the widest spans was the masonry vault or the dome. These were compressive form-active structures but this did not mean that they are never subjected to bending moment because the form-active shape is only valid for a specific load pattern (see Section 4.2). Structures that support buildings are subjected to variations in the load pattern, with the result that compressive form-active structures will in some circumstances become semi-form-active and be required to resist bending. If the material has little tensile strength, as is the case with masonry, the structural cross-sections must be sufficiently thick to prevent the tensile bending stress from exceeding the compressive **axial stress** that is also present. Masonry vaults and domes had therefore to be fairly thick and this compromised their efficiency. Because reinforced concrete can resist both tensile and bending stress, compressive form-active structures in this material can be made very much thinner, and therefore more efficient, than those of masonry. The development of reinforced concrete in the late nineteenth century therefore allowed the maximum span that was possible with this type of structure to be greatly increased. Another advantage of reinforced concrete is that it makes easier the adoption of 'improved' cross sections by the introduction of folds and corrugations.

Among the earliest examples of the use of reinforced concrete for vaulting on a large scale are the airship hangars for Orly Airport in Paris by Eugene Freyssinet (Figure 9.4). A parabolic (form-active) cross-section was used in these buildings and corrugations were employed to improve the bending resistance of the vaults. Other exponents of this type of structure in the twentieth century were Pier Luigi Nervi, Eduardo Torroja, Felix Candella and Nicolas Esquillan as described here in Chapters 8 and 9. The timber lattice domes by Happold and Otto (Figure 11.5) and by Balmond, in the Centre Pompidou-Metz (Figure 11.6), are further examples of buildings whose overall form was determined from structural considerations.

Compressive form-active structures in iron and steel have usually relied on 'improvement' by triangulation to achieve very long spans with appropriate levels of efficiency. Some of the most spectacular of these are also among the earliest, the train shed at St Pancras Station in London (1868) by William Barlow and R. M. Ordish (span 73 m) (Figure 9.1) and the structure of the Galerie des Machines for the Paris Exhibition of 1889 by Victor Contamin and Charles L. F. Dutert (span 114 m) (Figure 8.7) being notable examples. Recent examples include the International Rail Terminal at Waterloo Station, London, by Nicholas Grimshaw & Partners with YRM Anthony Hunt Associates (Figure 10.4 and 5) and the design for the Kansai Airport building for Osaka, Japan by Renzo Piano with Ove Arup & Partners (1994).

Cable-network structures are another group whose appearance is distinctive because technical considerations have been allocated a very high priority due to the need to achieve a long span or a very lightweight structure. They are tensile form-active structures in which a very high level of efficiency is achieved. Their principal application has been as the roof structures for large single-volume buildings such as sports arenas. The Ice Hockey Arena at Yale by Eero Saarinen (Figure 10.11) and the cable-network structures of Frei Otto (Figure 10.12) are typical examples.

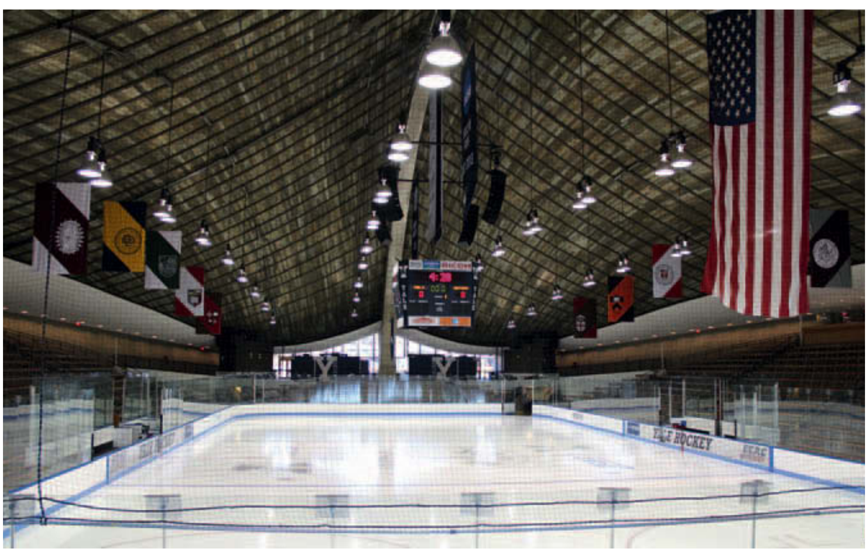


Figure 10.11 David S. Ingalls Hockey Rink, Yale, USA, 1959; Eero Saarinen, architect; Fred Severud, engineer. A combination of compressive form-active arches and a tensile form-active cable network was used in this long-span building. The architecture is totally dominated by the structural form.

Photo: Nick Allen/Wikimedia Commons.

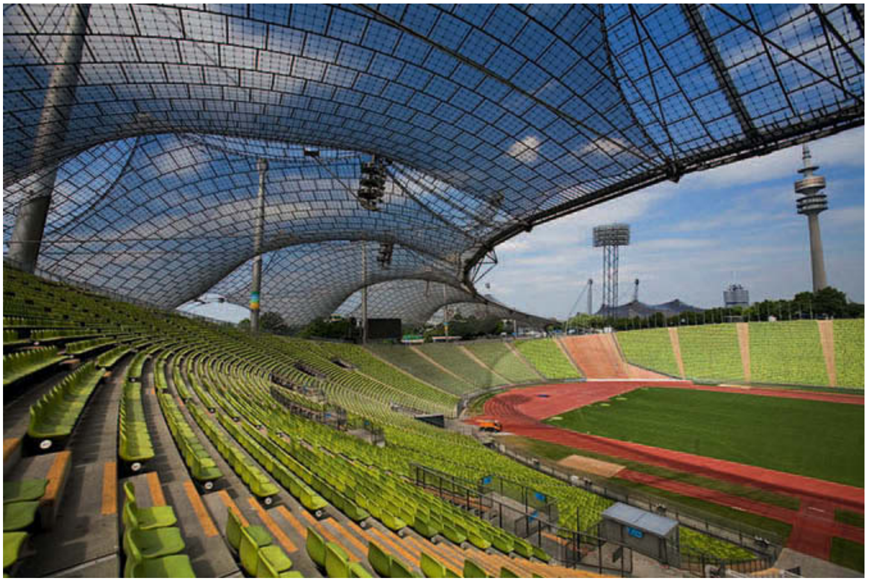


Figure 10.12 Olympiastadion (Olympic Stadium), Munich, 1972; Günther Behnisch, architect; Frei Otto, engineer. Long-span form-active cable networks allowed the use of few supporting steel masts, located to the rear of sightlines. The distinctive shape of the canopy is determined by the boundary conditions set by the supporting masts and perimeter cable. No formalist architectural input was possible.

Photo: Jorge Royan/Wikimedia Common.

In these buildings the roof envelope is an anticlastic double-curved surface:[10] two opposite curvatures exist at every location. The surface is formed by two sets of cables, one conforming to each of the constituent directions of curvature, an arrangement which allows the cables to be pre-stressed against each other. The opposing directions of curvature give the structure the ability to tolerate reversals of load (necessary to resist wind loading without gross distortion in shape) and the pre-stressing enables minimisation of the movement that occurs under variations in load (necessary to prevent damage to the roof cladding).

In the 1990s, a new generation of mast-supported synclastic cable networks was developed. The Millennium Dome in London (Figure 10.13), which is not of course a dome in the structural sense, is perhaps the best known of these. In this building a dome-shaped cable network is supported on a ring of 24 masts. The overall diameter of the building is 358 m but the maximum span is approximately 225 m, which is the diameter of the ring described by the 24 masts. The size of the span makes the use of a complex form-active structure entirely justified. The cable network to which the cladding is attached consists of a series of radial cables, in pairs, which span 25 m between nodes supported by hanger cables connecting them to the tops of the masts.

The nodes are also connected by circumferential cables that provide stability. The downward curving radial cables are pre-stressed against the hanger cables and this makes them almost straight and converts the surface of the dome into a series of facetted panels. It is this characteristic that simplifies the fabrication of the cladding. In fact, being tensile form-active elements, the radial cables are slightly curved, and this curvature had to be allowed for in the design of the cladding, but the overall geometry is nevertheless considerably less complex than an anticlastic surface.

The few examples of cable networks illustrated here demonstrate that, although this type of structure is truly form-active with a shape that is dependent on the pattern of applied load, the designer can exert considerable influence on the overall form through the choice of support conditions and surface type. The cable network can be supported either on a configuration of semi-form-active arches or on a series of masts; it can also be either synclastic or anticlastic and the configurations that are adopted for these influence the overall appearance of the building.

Figure 10.13 Millennium Dome, London, 1999; Richard Rogers & Partners, architects; Buro Happold Engineering, engineers. This is a mast-supported, dome-shaped cable network with a diameter of 358 m (span *c.* 225 m). The use of a tensile form-active structure is fully justified for spans of this size and determines the overall form of the building.

Photo: *mattbuck*/Wikimedia Commons.

Judged by the criteria outlined in Section 6.3, most of the form-active vaulted and cable structures are not without technical shortcomings. They are difficult to design and build and, due to their low mass, provide poor thermal barriers. In addition, the durability of these structures, especially the cable networks, is lower than that of most conventional building envelopes. Acceptance of these deficiencies may be justified, however, in the interests of achieving the high levels of structural efficiency required to produce large spans.

All of the long-span buildings considered here may therefore be regarded as true High-Tech architecture. They were and are state-of-the-art examples of structural technology employed to achieve some of the largest span enclosures in existence. The technology employed was necessary to achieve the spans involved and the resulting forms have been given minimal stylistic treatment.

10.2.3.3 Very tall buildings

In the search for the truly High-Tech building, which is another way of thinking of the category 'structure as architecture', the skyscraper is worth consideration. From a structural point of view two problems are posed by the very high building: one is the provision of adequate vertical support and the other is the difficulty of resisting high lateral loading, including the dynamic effect of wind. So far as vertical support is concerned, the strength required of the columns or walls is obviously greatest at the base of the building, where the need for an excessively large volume of structure is a potential problem. In the days before the introduction of iron and steel this was a genuine difficulty which placed a limit on the possible height of structures although the limiting factor was primarily the need to avoid buckling of piers or walls rather than excessive compressive stress (see Section 7.2.2). The problem was solved by the introduction of steel framing. The principal load on the columns was axial, and so long as the storey height was low enough to maintain the **slenderness ratio** at a reasonably low level and thus inhibit buckling (see Glossary for explanations of slenderness ratio and buckling), the strength of the material was such that excessive volume of structure did not occur within the maximum practical height limits imposed by other, non-structural constraints.

The need to increase the level of vertical support towards the base of a tall building has rarely been expressed architecturally. In many skyscrapers the *apparent* size of the vertical structure – the columns and walls – is identical throughout the entire height of the building. As with vertical support elements, in the majority of skyscrapers the architect has also been able to choose not to express the bracing structure so that, although many of these buildings were innovative in a structural sense, this was not visually obvious. As the desire for ever higher skyscrapers increased, from the 1960s, the expression of the structural action began to emerge.

The framed- and trussed-tube configurations[11] are examples of structural arrangements that allow tall buildings to behave as vertical cantilevers in response to wind loads. In both cases the building is treated as a hollow tube (a non-form-active element with an 'improved' cross-section) in its resistance to lateral loading. The tube is formed by concentrating the vertical structure at the perimeter of the plan. The floors span from this to a central services core that provides vertical support but only partially contributes to the resistance of wind load.

Such buildings are usually given a square plan. With the wind blowing parallel to one of the faces, the columns on the windward and leeward walls act as tensile and compression flanges respectively of the cantilever cross-section while the two remaining external walls form a shear link between these. In trussed-tube structures, such as the John Hancock Building in Chicago by Skidmore, Owings & Merrill (SOM) (Figure 10.14a), the shear connection is provided by diagonal bracing elements. Because in such cases the special structural configuration that was adopted to provide resistance to lateral load resulted in the structure being concentrated in the outer walls of the building, the structure contributed significantly to, and indeed determined, the visual expression of the architecture. Hal Iyengar, chief structural engineer in the Chicago office of SOM described the relationship thus: 'the characteristics of the project create a unique structure and then the architect capitalises on it. That's exactly what happened in the Hancock building.'[12]

The strategy of concentrating structure on the exterior of a tall building and expressing it visually has been widely adopted since, notable examples being the O-14 building in Dubai (2010, Figure 14b) and the Canton Tower in Guangzhou (2010).

A development of the cantilever tube idea is the so called 'bundled-tube' – a system in which the shear connection between the windward and leeward walls is made by internal walls as well as those on the sides of the building. This results in a square grid arrangement of closely spaced 'walls' of columns. The Willis Tower (formerly Sears Tower) in Chicago, also by Skidmore, Owings & Merrill (Figure 10.15), has this type of structure that is expressed architecturally, in this case, by varying the heights of each of the compartments created by the structural grid. The structural system was therefore a significant contributor to the external appearance of this building.

A further, and obvious, strategy for the efficient resistance of lateral load in very tall buildings and that has visual consequences, was the tapering of the profile to reflect the distribution of bending caused by lateral loads, prominent examples of this type being the Burj Khalifa building in Dubai (2010, Figure 10.16a), which is currently the world's tallest building (828 m / 2,717 ft), and the Shard in London (2012, Figure 10.16b). In the Shard, by the architects Renzo Piano Building Workshop with structural engineering by WSP Cantor Seinuk, the arrangements for resistance of lateral load are actually relatively conventional, being based on an in-situ reinforced concrete central core,

Figure 10.14a John Hancock Building, Chicago, USA, 1969; Skidmore, Owings & Merrill, architects and structural engineers. The trussed-tube structure here forms a major component of the visual vocabulary.

Photo: Joe Ravi/Wikimedia Commons.

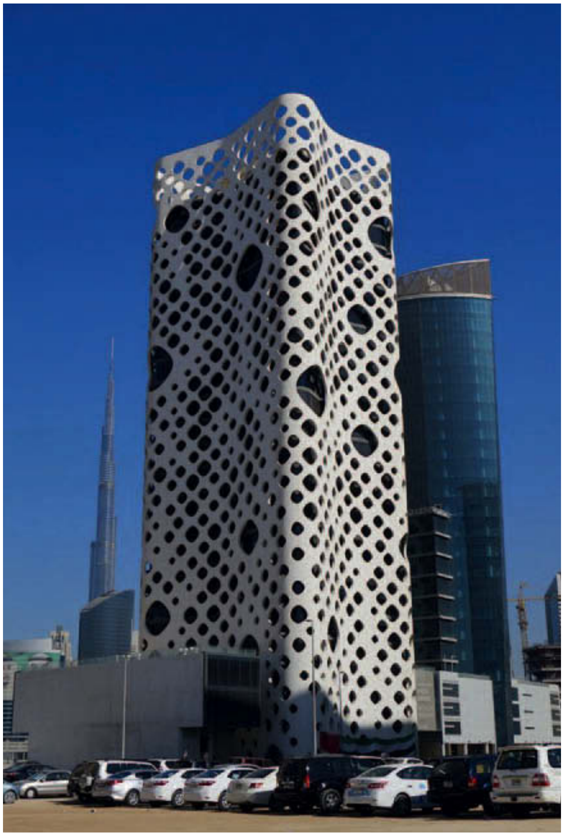


Figure 10.14b O-14 Building, Dubai, UAE, 2010; Reiser + Unemoto RUR, architects; Ysrael A. Seinuk, engineer. The perforated reinforced concrete outer shell of this building acts with its core to provide lateral and vertical support. The embedded clusters of reinforcing bars form a diagrid that is reminiscent of the steel structures in the CCTV building (Figure 9.35) and at 30 St Mary Axe (Figure 11.1).

Photo: Propsearch/Wikimedia Commons.

although additional stiffening is provided by the inclusion of a cross-girder formed by diagonal members linking the primary beam and column elements between the 66th and 68th floors. The building is structurally unconventional in other ways, however, as it consists of a steel frame up to level 40 which becomes a reinforced concrete flat-slab structure between floors 41 and 69 and then reverts to steel to the top of the building at level 95, the changes of structural system being adopted largely for space-planning reasons. The highly sophisticated structure of the Shard, based as it is on a combination of different frame types and materials, acting compositely, is typical of the approach that has tended to be adopted in recent decades for the design of tall buildings in which no single structural strategy is used in isolation.

Figure 10.15 Willis (Sears) Tower, Chicago, USA, 1974; Skidmore, Owings & Merrill, architects and structural engineers. This building is subdivided internally by a cruciform arrangement of 'walls' of closely spaced columns that enhance its resistance to wind loading, a structural layout that is expressed in the exterior form.

Photo: Rusewcrazy/Wikimedia Commons.

In the twenty-first century, as the desire to produce the world's tallest building has intensified in corporate circles, and in particular in the expanding cities of Arabia and Southeast Asia, the strategy adopted for the resistance of lateral load has been to use combinations of all the structural devices available and, in similar fashion to other forms of architecture, to suppress visually the structural action in favour of other aspects of style. Even with this type of building in which the limits of what is structurally possible are approached, the current trend in architecture, which is to manipulate form visually and without being inhibited by its technical consequences, can be seen to be operating. The resulting buildings are, of course, more costly in every sense, than would be the case if technical considerations were given a higher priority.

Figure 10.16a Burj Khalifa Building, Dubai, UAE, 2010; Skidmore, Owings & Merrill, architects and structural engineers. Multiple strategies were adopted in the structural design of this 'megatall' building, in which the principal structural material is reinforced concrete. The Y-shaped plan allowed the creation of shear walls in the wings to buttress the central hexagonal core. The tapering profile conformed to the intensity of bending produced by wind loading, which was minimised by aspects of the building's overall form. Technical consideration significantly influenced the appearance of the building.

Photo: Donaldytong/Wikimedia Commons.

Figure 10.16b The Shard, London, 2013; Renzo Piano Building Workshop, architects; WSP Cantor Seinuk, engineers. The building has a composite steel and reinforced concrete structure with the concrete core (seen exposed in this progress shot) providing the principal resistance to lateral load. In addition to the normal considerations that affect the design of very tall buildings, the implication of the collapse of the World Trade Centre in 2001 influenced the structural design. As with many of the world's most recently completed very tall buildings, it is doubtful if The Shard should be considered as an example of *structure as architecture* because, apart from the tapering profile, structural requirements had little effect on its appearance. The current state of structural technology would in fact have allowed a non-tapering profile to be adopted so the taper could be considered to be a stylistic device.

Photo: George Rex Photography/Wikimedia Commons.

10.2.3.4 The lightweight building

The situation in which saving in weight is an essential requirement is another scenario which causes technical considerations to be allocated a very high priority in the design of a building. This often comes about when the building is required to be portable. The backpacker's tent – an extreme example of the need to minimise weight in a portable building – has already been mentioned (Figure 5.20). Portability requires not only that the building be light but also that it be demountable – another purely technical consideration. In such a case the resulting building form is determined almost entirely by technical criteria.

The tent, which is a tensile form-active structure, has the advantage of being easy to demount and collapse into a small volume, which compressive form-active structures are not, due to the rigidity that they must possess in order to resist compression. This solution has therefore been widely used for temporary or portable buildings throughout history and is found in a very wide range of situations from the portable houses of nomadic peoples to the temporary buildings of industrialised societies, whether in the form of tents for recreation or temporary buildings for other purposes.

Figure 10.17 Building for IBM Europe travelling exhibition, 1982; Renzo Piano, architect/engineer; Ove Arup & Partners (Peter Rice), engineers. This building consists of a semi-form-active compressive vault. The 'improved' cross-section of the membrane is achieved with a highly sophisticated combination of laminated timber and plastic – each is a material that offers high strength for its weight. Technical considerations dominated to produce a portable, lightweight building.

Photo: Renzo Piano Building Workshop.

Although the field of temporary buildings remains dominated by the tent in all its forms, the compressive form-active structure has also been used for such purposes. A late-twentieth-century example was the building designed by Renzo Piano and Peter Rice for the travelling exhibition of IBM Europe (Figure 10.17). This consisted of a semi-form-active vault that was 'improved' by triangulation. The sub-elements were laminated beechwood struts and ties linked by polycarbonate pyramids. These elements were bolted together using aluminium connectors. The structure combined lightness of weight, which was achieved through the use of low-density materials and an efficient structural geometry, with ease of assembly – the two essential requirements of a portable building. No technical compromises were made for visual or stylistic reasons.

10.2.3.5 Special requirements

Other forms of special requirement besides the need for a lightweight structure can result in structural issues being accorded the highest priority in the design of a building to the point at which they exert a dominating influence on its form. A classical example of this from the nineteenth century was the Crystal Palace in London (Figures 8.4 and 8.5) which was built to house the Great Exhibition of 1851 (see Section 8.3).

10.2.3.6 *Conclusion*

In most of the cases described in this section the buildings have consisted of little other than a structure, the form of which was determined by purely technical criteria. The inherent architectural delight therefore consisted of an appreciation of 'pure' structural form. These truly High-Tech structure types, especially the long-span, form-active structures, are considered by many to be beautiful, highly satisfying built forms.

10.2.4 Structure accepted

The term 'structure accepted' is used here to describe a relationship between structure and architecture in which structural requirements are allowed to influence strongly the forms of buildings even though the structure itself is not necessarily exposed. In this type of relationship the configuration of elements that is most sensible structurally is accepted and the architecture accommodated to it.

The vaulted structures of Roman Antiquity are an historic example of this type of relationship. The large interior spaces of the basilicas and bath houses of Imperial Rome, which are one of the chief glories of the architecture of the period and are among the largest interiors in Western architecture, were roofed by vaults and domes of masonry or unreinforced concrete (Figure 7.4).

Figure 10.18 The Pantheon, Rome, C2 CE. The hemispherical concrete dome is supported on a cylindrical drum also of concrete. Both have thick cross-sections that have been 'improved' by the use of coffers or voids of various types and these technical devices have been incorporated into the visual scheme of the interior.

Painting: Giovanni Paolo Panini (1692–1765)/Wikimedia Commons.

The absence at the time of a strong structural material that could withstand tension dictated that compressive form-active structures be adopted to achieve the large spans involved. Lofty interiors of impressive grandeur were created by placing the vaults and domes on top of high walls which were given great thickness so as to accommodate the lateral thrusts produced at the wallheads.

The Roman architects and engineers quickly appreciated that the walls did not have to be solid and a system of voided walls was developed that allowed a large overall thickness to be achieved using a minimum volume of material. The coffering on the undersides of vaults and domes was a similar device for reducing the volume and therefore weight of material involved. The walls of the main spaces in these vaulted structures are semi-form-active elements with 'improved' cross-sections. They carry axial load due to the weights of the vaults that they support and bending moments caused by the lateral thrusts of the vaults.

Both the voiding of the walls and the coffering of the vaults were used brilliantly by the architects of Imperial Rome to create a distinctive architecture of the interior. The Pantheon in Rome (Figure 10.18) is one of the best

Figure 10.19 Reconstruction of interior of frigidarium, Baths of Diocletian, Rome, C4 CE. The vaulted roof of the principal internal volume is supported on very thick walls from which large voids with vaulted ceilings have been extracted to reduce the volume of structural material required. These have been used to create variety in the disposition of internal volumes. As at the Pantheon, the technical and visual programmes of the architecture have been brilliantly combined (see also Figure 7.4).

Painting: artist unknown/Eagles and Dragons Publishing.

examples. In this building the pattern of the coffering on the underside of the dome helps to increase the apparent size of the interior, and the voids and recesses in the walls of the drum that supports the dome create an illusion of the walls dissolving so that the dome appears to float above the ground.

Such techniques were further developed in the designs for bath houses and basilicas (Figure 10.19). Interiors were created in which the possibilities offered by the structural system were fully exploited to produce spaces of great interest and variety. The device of the transverse groined vault was also used in these buildings – again, principally for a technical, though not structural, reason. This was adopted in order to create flat areas of wall at high level that could be pierced by clerestory windows admitting light into what would otherwise have been dark interiors.

The vaulted structures of Imperial Rome are therefore buildings in which features that were necessary for structural reasons were incorporated into the aesthetic programme of the architecture. This was not celebration of technology but rather the imaginative exploitation of technical necessity.

Many twentieth-century architects attempted to produce a Modern architecture in which the same principles were followed. One of the most enthusiastic exponents of the acceptance of structure as a generator of form was Le Corbusier, and the structural technology that he favoured was that of the non-form-active reinforced concrete flat slab, capable of spanning simultaneously in two directions and of cantilevering beyond perimeter columns. The structural action was well expressed in his famous drawing (Figure 10.20) and the architectural opportunities that it made possible were summarised by Le Corbusier in his 'five points of a new architecture'.[13]

This approach was used by Le Corbusier in the design of most of his buildings. The archetype is perhaps the Villa Savoye (Figure 9.24), a building of prime importance in the development of the visual vocabulary of twentieth-century Modernism. As in Roman Antiquity, the structure here is not so much celebrated as accepted and its associated opportunities exploited although, as discussed here in Section 9.3, aspects of the structure of this building were compromised for visual reasons. Later buildings by Le Corbusier,

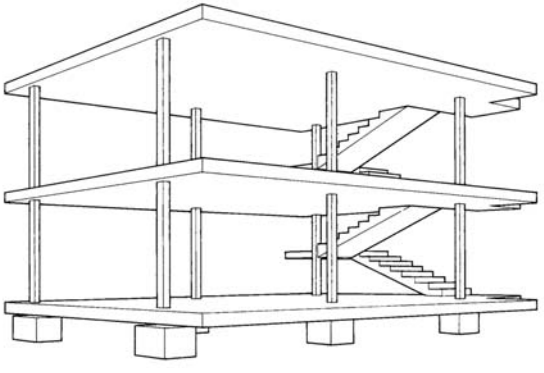


Figure 10.20 Drawing of the structural armature of the *Maison Dom-Ino* (Domino House), 1915; Le Corbusier, architect. The advantages of the structural continuity afforded by reinforced concrete are admirably summarised in the structural armature of Le Corbusier's Domino House. Thin, two-way spanning slabs are supported directly on a grid of columns. The stairs provide bracing in the two principal directions.

Image: Wikimedia Commons/© FLC/ADAGP, Paris and DACS, London 2018.

such as the Unité d'Habitation at Marseilles or the monastery of La Tourette near Lyon show similar combinations of structural and aesthetic programmes.

The 'Modernistic' (as opposed to Modern – see Huxtable[14]) skyscrapers that were constructed in the 1920s and 1930s in the USA, such as the Chrysler (Figure 10.21) and Empire State Buildings, are further examples of the adoption but not expression of a new structural technology – in this case that of the multi-storey steel frame. Although the architectural treatment of these buildings was more conventional than that in those by Le Corbusier, making use of a pre-existing architectural vocabulary, they were nevertheless novel forms that owed their originality to the structural technology upon which they depended. Another example of an early twentieth-century building in which an innovative structure was employed, although not expressed in an overt way, was the Highpoint I building in London by Berthold Lubetkin and Ove Arup (Figure 9.22), which is described here in Section 9.3.

Figure 10.21 Chrysler building, New York, 1930; William Van Alen, architect. Although the overall forms of modernistic skyscrapers such as the Chrysler Building are determined by the steel frame structure, the visual treatment is not.

Photo: Carol M. Highsmith's America, Library of Congress, Prints and Photographs Division/Wikimedia Commons.

A late-twentieth-century example of the positive acceptance rather than the expression of the structural technology is found in the Willis, Faber & Dumas (WFD) building in Ipswich, UK by Foster Associates (Figures 1.6, 5.15 and 5.16)) with the structural engineer Anthony Hunt. The structure is of the same basic type as that in Le Corbusier's drawing (Figure 10.20) and its capabilities were fully exploited in the creation of the curvilinear plan, the provision of large wall-free spaces in the interior and the cantilevering of the floor slabs beyond the perimeter columns. The building has a roof garden and free non-structural treatment of both elevation and plan and it therefore conforms to the requirements of Le Corbusier's 'five points'.

It is likely that the type of relationship between structure and architecture that is described in these examples will be adopted increasingly in future in the context of the need to develop building forms in which the wasteful use of material and energy is minimised. This will increasingly favour the adoption of structural typologies in which economy of means, in the widest sense, is a principal objective and in which the architectural and technical aspects of design are well integrated with neither being allowed to dominate. Given the dependence of structural performance on overall form, this is likely to lead to the raising of the priority of structural considerations in the early stages of architectural design. It will also increasingly favour the wider use of structural materials with low embodied energy, such as timber and masonry, which will in turn have an effect on the types of form that can be adopted. In the context of new technologies, such as the latest adhesives and jointing techniques, and computer-controlled fabrication processes such as 3-D printing, this will create significant opportunities for the development of new types of architectural form. It will be important, however, that visual aspects of design are not allowed to compromise technical performance, as for example occurred with so-called High-Tech architecture, and that the design process is genuinely collaborative, with the visual and technical performance aspects of design being accorded similar priorities and neither being allowed to dominate.

10.2.5 Structure ignored in the form-making process and not forming part of the aesthetic programme

Since the development of the structural technologies of steel and reinforced concrete it has been possible to design buildings, at least to a preliminary stage of the process, without considering how they will be supported or constructed. This has come about because the strength properties of steel and reinforced concrete are such that practically any form can be built, provided that it is not too large and that finance is not a limiting consideration. This freedom represents a significant and often unacknowledged contribution that structural technology has made to architecture, liberating architects from the constraints imposed by the need to support buildings with masonry and timber.

For most of the period following the introduction of steel and reinforced concrete into building in the late nineteenth century, the dominant architecture in the industrialised world was that of International Modernism. Most of the architects of this movement subscribed to the doctrine of rationalism and held the view that buildings should be tectonic: they believed that the visual vocabulary should emerge from, or at least be directly related to, the structural armature of the building, which should be determined by rational means. The consequence of this was that the forms of most buildings were relatively straightforward from a structural point of view – based on the geometry of the rectilinear post-and-beam framework.

An additional factor that favoured the use of simple forms was that, for most of the twentieth century, the design and construction of very complex forms was laborious and costly, thus inhibiting the full exploitation of the potential offered by the new materials. There were of course exceptions. Erich Mendelsohn's Einstein Tower in Potsdam, Gerrit Rietveld's Schroeder House in Utrecht (Figure 8.12) and Le Corbusier's chapel of Notre-Dame du Haut at Ronchamp (Figure 10.22) were successfully realised despite having complex forms unrelated to structural function. Their relatively small scale meant that it was not difficult in each case to produce a structural armature that would support the form, rather in the manner of the armature of a sculpture.

Great ingenuity was often required of the engineers who devised the structural solutions for buildings whose forms had been devised in a purely sculptural way. That of the chapel at Ronchamp (Figure 10.22) is remarkable due to the great simplicity of the structure that supports the free-form roof. The walls of the building are of self-supporting stone masonry, rendered white. There is a gap between the tops of these and the underside of the roof so as to admit a small amount of light into the interior in a gesture that is architecturally significant. The walls do not therefore carry the weight of the roof.

The upwardly curving, oversailing roof is formed by a thin shell of reinforced concrete that conceals an integral and conventional post-and-beam reinforced concrete framework. Reinforced concrete columns of small cross-section are embedded in the masonry walls in a regular grid, and carry beams that span across the building. These provide support for the roof shell from above and the shell sweeps up at the edges of the building to conceal them. Thus, although the overall form of the building bears no relation to the manner in which it functions structurally, a satisfactory and relatively simple structure was accommodated within it.

The introduction of the computer in the late twentieth century, first as a tool for structural analysis and subsequently as a design aid that allowed very complex forms to be described, and cutting and fabricating processes to be controlled, was a major factor in the evolution of the very complex geometries that appeared in architecture towards the end of the twentieth century. It made almost unlimited freedom available to architects in the matter of form.

Figure 10.22 Chapel of Notre-Dame du Haut, Ronchamp, France, 1954; Le Corbusier, architect. Structural considerations played very little part in the determination of the form of this building. Its small scale together with the excellent structural properties of reinforced concrete, which was used for the roof, meant that it could be constructed without difficulty.

Photo: A. Bourgeois/Wikimedia Commons/(c) ADAGP, Paris and DACS, London 2018.

Wolf Prix, of Coop Himmelblau, was one of several late twentieth-century architects who fully exploited this freedom: 'we want to keep the design moment free of all material constraints'[15] . . . 'In the initial stages structural planning is never an immediate priority.'[16]

The structural organisation of buildings such as the Daniel Libeskind's (1946–) Imperial War Museum North in Manchester (2001) (Figure 10.23) involved complex arrangements to realise the sculptural forms (intended to depict a shattered Earth) – in this case a steel space-framework (Figure 10.24).

Two important considerations must be taken into account when form is devised without having regard to structural requirements. First, because the form will almost certainly be non-form-active, bending-type internal force will have to be resisted. Second, the magnitudes of the internal forces that are generated are likely to be high in relation to the load carried. The implications of both of these considerations are that structural material will be inefficiently used and that the element sizes required to produce adequate strength will be high. This is a scenario that can result in structures that are clumsy and ungainly.

A scale effect also operates because the strength of structural material remains constant even though the size of the structure increases. As was discussed in Chapter 6, all structural forms, whatever their shape, tend to become less efficient as spans increase. The maximum span for a given form occurs when the strength of the material is fully occupied supporting only the self weight of the structure. If the form adopted is fundamentally inefficient, because it has been designed without reference to structural requirements, the maximum possible span may be quite small.

The neglect of structural issues in the determination of the form of a building can therefore be problematic if a large span is involved. The small

Figure 10.23 Imperial War Museum North, Manchester, 2001; Daniel Libeskind, architect; Arups, engineers. The predominant idea which informed the design was that the form should represent three interlocking shards of a globe shattered by conflict. Structural considerations were a lower priority.

Photo: Bitter Bredt/Studio Libeskind.

scale of the buildings already mentioned meant that the internal forces were nowhere so large that they could not be resisted without the use of excessively large cross-sections. Eero Saarinen's terminal for TWA at Idlewild (now Kennedy) Airport, New York (Figure 9.15) paid little regard to structural logic. Although the roof of this building was a reinforced concrete 'shell' it did not have a form-active shape. Because it was relatively large, difficulties occurred with the structure. These were overcome by modifying the original design to strengthen the shell in the locations of highest internal force. Very large volumes of reinforced concrete were involved and the envelope is far from being a 'delicate thin shell' as is sometimes claimed.

In the case of the Sydney Opera House (Figures 9.25 to 9.27), and as discussed in Section 9.3, the scale was such that it was impossible to overcome the consequences of the complete disregard of structural and constructional concerns in the determination of the original form. In the resulting saga, in which the form of the building had to be radically altered for constructional reasons, the architect resigned and the client was faced with a protracted construction period and with costs which were two orders of magnitude greater than had originally been envisaged. This building may serve as a warning to the architects who choose to disregard the inconveniences of

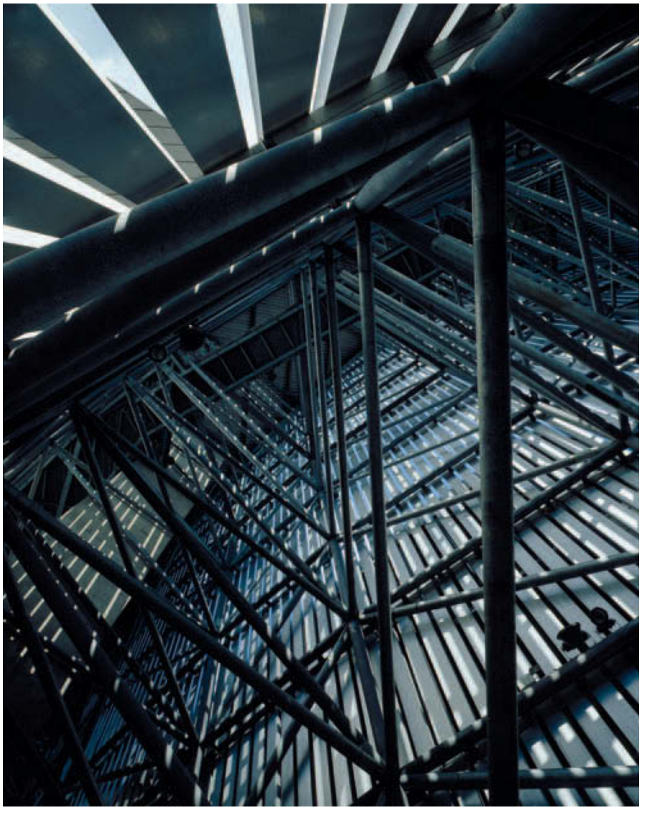


Figure 10.24
Imperial War Museum North, Manchester, 2001; Daniel Libeskind, architect; Arups, engineers. A structure of steel space frameworks, clad in aluminium alloy, was required to realise the geometry of the 'shards'.

Photo: Hélène Binet.

structural requirements when they determine form. The consequence may be that the final form will be different from their original vision in ways that they may be unable to control.

Two recent examples of this approach to the generation of architectural form without serious consideration of its structural implications, but that have in fact been largely successful, are the Riverside Museum in Glasgow (2012) by Zaha Hadid (1950–2016), with structural engineering by Buro Happold (Figures 10.25 and 10.26), and the CCTV Headquarters building in Beijing (2008) with architects OMA (East China) and Rem Koolhaas (1944–) in collaboration with Arups (Balmond) (Figures 9.35 and 9.36).

From its exterior the Riverside Museum (Figures 1.10 and 10.25) presents a striking and interesting visual image especially when viewed towards either of its fully glazed end walls with their irregularly serrated tops. The plan is S-shaped (Figure 10.25) and the tunnel-like configuration of the interior is intended to link the city and the river with a fluidity that engages with its context. The interior is studiedly visual due to the very clean lines of the folded ceiling of the single-volume gallery space that runs longitudinally through the entire length of the building and that has a tightly curved S configuration in its central section. No transverse horizontal elements, either

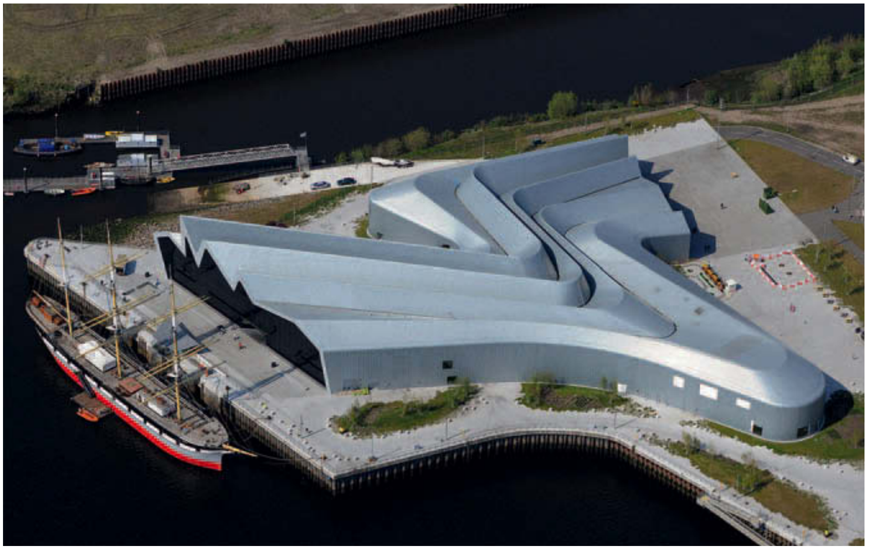


Figure 10.25 Riverside Museum, Glasgow, 2011; Zaha Hadid, architect, Buro Happold, Engineering, engineers. The Z-form plan of the building, together with the single-volume gallery space that runs its full length, are intended to allow the building to be a 'mediator between city and river'. The irregularly varying serrated cross-section can be seen as 'a cityscape and a responsive gesture to encapsulate waves on water'.

Photo: E. Z. Smith/Hawkeye.

externally or internally, are allowed to cross the deep V-forms of the roof whose ridges and valleys run continuously, but varying in height and width, and uninterrupted between the glazed ends.

According to the architect, 'the design combines complexity with structural ingenuity and material authenticity'. Structurally, however, the building is somewhat of a contradiction. It is supported on a steel skeleton framework, which is appropriate for a long-span single-storey enclosure, but logic required that the V-form roof should span longitudinally and be supported on transverse frameworks at its ends and at the junction between the straight portions and the S-curves of the plan. Visually, no such transverse frameworks were possible. The conflicting visual and structural requirements presented great difficulties to the structural engineers. Their solution was to provide a series of longitudinally spanning triangulated girders and carry these on transverse frames at key locations. At the ends of the building the transverse frames consist of closely spaced slender columns in the end walls that read as if they were actually vertically spanning mullions supporting only the glazing against wind loading. Adjacent to the S-curves sufficient extra steelwork, concealed within the ceiling finishes and roof cladding, is provided to allow transverse portal frame action to occur, with the horizontally spanning parts of these configured in a zig-zag that exactly matches the ridge-and-furrow form of the roof – an arrangement that makes no structural sense and that is consequently a very

Figure 10.26 Riverside Museum, Glasgow, 2011, Zaha Hadid, architect; Buro Happold Engineering, engineers. The continuous variation in width and depth of the ridges and furrows of the roof greatly complicated the detailing of the supporting steelwork (see also Figure 1.11).

Photo: Eoin/Wikimedia Commons.

inefficient way in which to provide the necessary support. Large quantities of steel were required to give the structure the necessary strength. The continuously changing shape of the cross-section of the building (Figures 10.25 and 10.26) greatly complicated the detailing of both the steelwork and most other aspects of the building's fabric. The use of material and energy, of all kinds, was wasteful.

The form of the CCTV building is similarly nonsensical from a structural point of view (Figure 9.35) and also required the specification of substantially more steelwork than would have been necessary with a conventionally designed tower of similar total floor area. The floor structures in this building are of conventional arrangement with systems of parallel, closely spaced secondary beams carrying a one-way-spanning floor slab and themselves carried on primary beams configured into plane frameworks that reach vertically upwards throughout the building. The internal columns are vertical and, due to the fact that the two towers that form the lower part of the building are inclined to the vertical, elaborate girders were used to transfer laterally the loads from the columns that do not reach the ground to those that do (Figure 9.36). Vertical support was also provided by the inclined perimeter walls which were configured as diagrids to provide lateral as well as vertical support. Significant quantities of steel were required to support the cranked horizontal part of the buildings that joins the tops of the two towers.

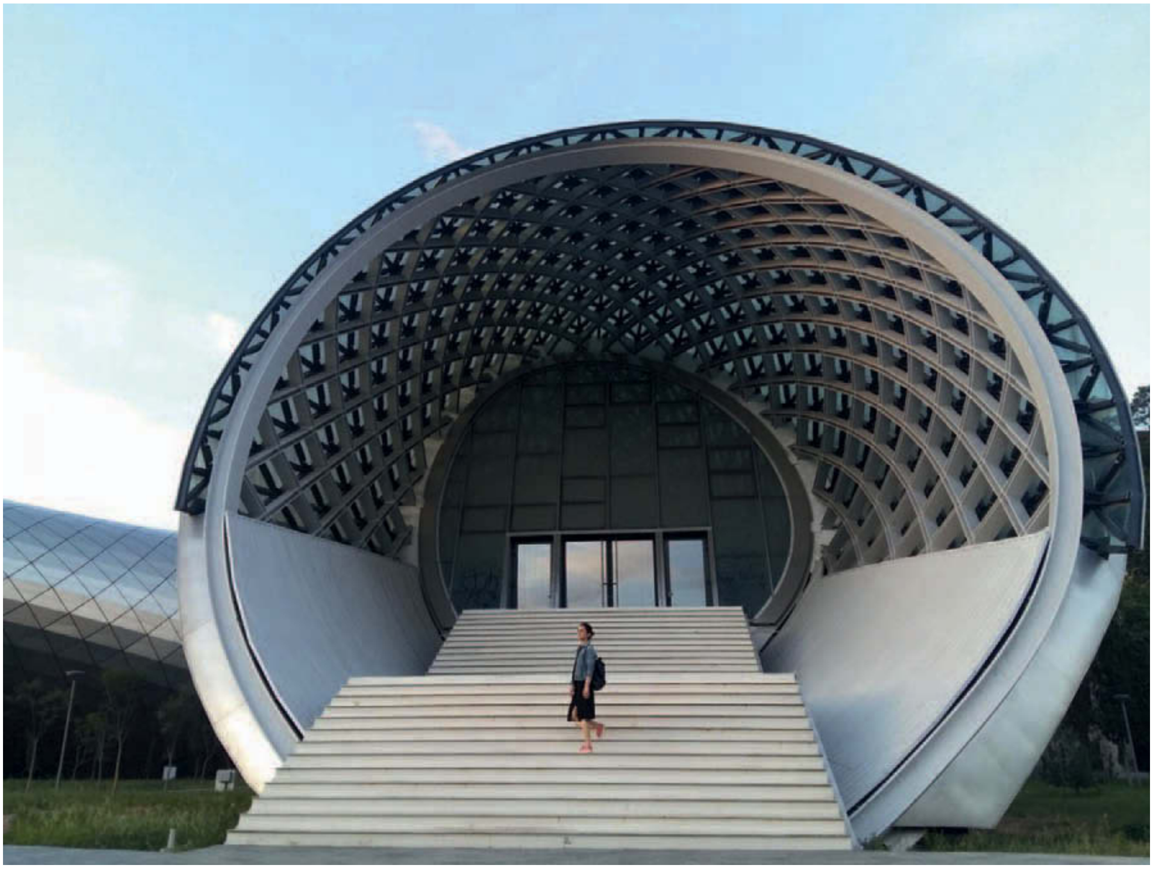


Figure 10.27 Entrance, Music Theatre and Exhibition Hall, Tbilisi, 2017; Massimiliano and Doriana Fuksas, architects. Although superficially similar to form-active grids (see Figure 10.5), forms like this are not directly related to structural function. The supporting steel frameworks are semi-form-active with relatively high levels of internal force requiring the use of substantial quantities of material to achieve adequate strength.

Photo: Fuksas/Sophia Arabidze.

The Music Theatre and Exhibition Hall, Tibilisi, 2017 (Figure 10.27), by the architects Massimiliano and Doriana Fuksas, and the ArtScience Museum building in Singapore by the architect Moshe Safdie (Figure 10.28), are further examples of free-form architecture for which extravagant forms of structure were required.

Given their overall size, none of these visually styled buildings could have been constructed in any material that did not have the great strength of steel or reinforced concrete. In all cases, the same amount of accommodation could have been provided at a much lower cost in material and construction effort had a more conventional arrangement been adopted. It is a matter of conjecture whether the novelty and excitement of the forms justified the additional cost in both environmental and monetary terms. It will remain to be seen whether

Figure 10.28 ArtScience Museum, Marina Bay Sands, Singapore, 2011; Moshe Safdie, architect; Arups, engineers. Complex forms such as this generate high internal forces, because they are unrelated to structural function, and are difficult to design and construct. In this case an elaborate steel lattice framework supports a skin of fibre-reinforced polymer. The fabric of the building performs poorly in respect of sustainability criteria.

Photo: Victor Pogadaev/Wikimedia Commons.

such extravagant and wasteful use of resources will remain acceptable as the environmental situation of the planet worsens.

In all of the buildings considered in this section the structure is present in order to fulfil its principal function of supporting the building envelope. In this kind of architecture structural engineers act as facilitators – the people who make the building stand up. It should not be thought, however, that the world of structures has played no part in the evolution of the free-form architecture that became fashionable in the late twentieth century. It was the structural techniques that were developed in the twentieth century that made such an architecture possible, and that gave architects the freedom to exploit geometries that in previous centuries would have been impossible to realise.

10.3 Conclusion

This chapter has reviewed the interaction between structure and architecture and has shown that this can operate in a variety of ways. It is hoped that the several categories that have been identified for this relationship, however artificial they may be, nevertheless contribute to the understanding of the processes and interactions that constitute architectural design.

Five broad categories were identified and these may be considered to be grouped in different ways – something that sheds further light on the design process. One grouping would be to subdivide the various types of relationship into two broad categories: '*structure exposed*' and '*structure hidden from view*'. There are three sub-categories of the structure exposed relationship: 'ornamentation of structure', 'structure as ornament' and 'structure as architecture'. Structure hidden contains the two sub-categories of 'structure accepted' and 'structure ignored'.

The original five categories may alternatively be considered as grouped into two other overarching categories namely '*structure respected*', in which forms are adopted which perform well when judged by technical criteria, and '*structure disrespected*', in which little account is taken of structural requirements when the form is determined. The first of these would include 'ornamentation of structure', 'structure as architecture' and 'structure accepted'. The second would include 'structure as ornament' and 'structure ignored'.

This second way of regarding the various possible relationships between structure and architecture focuses attention on the types of collaboration that can exist between architects and engineers, a fascinating aspect of the history of architecture. If structure is to be respected, engineers and architects must collaborate in a positive way over the design of a building with the engineer being an equal member of the team of designers that evolves the form of the building. Where the relationships fall into the category of 'structure disrespected' the engineer is simply a technician – the person who works out how to build a form that has been determined by someone else. The first of these methodologies is the one most likely to produce an architecture that is truly environmentally sustainable.

Notes

1 For example, V. Scully, *The Earth, the Temple, and the Gods*, Yale University Press, Yale, 1969.
2 See Angus J. Macdonald, 2000, *Anthony Hunt: the engineer's contribution to contemporary architecture,* Thomas Telford, London.
3 The Universal Column and Universal Beam are the names of standard ranges of cross-sections for hot-rolled steel elements which are produced by the British steel industry.
4 I. Lambot (ed.), *Norman Foster: Foster Associates: Buildings and Projects*, Vol. 2, Watermark, Hong Kong, 1989.
5 *ibid.*
6 *ibid.*

7 See Lambot, *ibid*.
8 Chief among these is Richard Rogers and the arguments are set out in Rogers, *Architecture: A Modern View*, Thames & Hudson, London, 1991.
9 This is very well articulated by Charles Jencks in 'The New Moderns', AD Profile – *New Architecture: The New Moderns and The Super Moderns*, 1990.
10 The terms *anticlastic* and *synclastic* describe different families of curved surface. An anticlastic surface is described by two sets of curves acting in opposite directions. The canopy of the Olympic stadium in Munich (Figure 10.12) is an example. Synclastic surfaces are also doubly curved but with the describing curves acting in the same direction. The surface of the Millennium Dome in London (Figure 10.13) is an example of this type.
11 See W. Schueller, *High Rise Building Structures*, Wiley, London, 1977, for an explanation of bracing systems for very tall buildings.
12 Conversation with Janice Tuchman reported in C. Thornton, R. Tomasetti, J. Tuchman and L. Joseph, *Exposed Structure in Building Design*, McGraw-Hill, New York, 1993.
13 Le Corbusier. Five points towards a new architecture, authored in *L'Esprit Nouveau* (1920–1925) and *Vers Une Architecture*, 1923.
14 A. L. Huxtable, *The Tall Building Reconsidered: The Search for a Skyscraper Style*, Pantheon Books, New York, 1984.
15 Quotations from *On the Edge*, the contribution of Wolf Prix of Coop Himmelblau to Noever (ed.), *Architecture in Transition: Between Deconstruction and New Modernism*, Prestel-Verlag, Munich, 1991.
16 *ibid*.

CHAPTER 11

Structure and sustainability

No challenge poses a greater threat to future generations than climate change.

(President Barack Obama, State of the Union Address, 20 January 2015)

The vital premise and the predominant issue in ecological design . . . is essentially one of effective integration of all our human-made systems with the natural systems and processes in the biosphere.

(Ken Yeang, 2006, Ecodesign: A Manual for Ecological Design, London)

11.1 Introduction

Before discussing the implications, for structural design, of the aspiration to create architecture that is environmentally sustainable it is necessary to consider the broad context for such activity. The single most important requirement, if an architecture is to be truly sustainable, is that it should be made in such a way that the Earth's systems are respected and not disrupted significantly; sustainable forms of building are those that achieve optimal use of material resources and energy at all stages of their life cycle, while minimising waste and ensuring that such waste as cannot be avoided is re-used, recycled or at least disposed of in an environmentally responsible way. This implies that the challenge of sustainability must be responded to in a comprehensive way and not merely by attaching 'green' features to building types that are otherwise damaging to the environment.

Significant problems that stand in the way of the design of buildings that meet the criteria for sustainability are firstly, that the World's political and economic systems, as they are currently configured, generate cost regimes that

Facing page: Spire Edge Building, Manesar, Yeang. Photo: Nyawara.

are unfavourable to environmentally benign practices, and secondly, that the current culture of mainstream architecture is preoccupied with design influences and built forms that are unrelated to environmental concerns. The designer who genuinely wishes to practice in a sustainable way is therefore currently working in a largely hostile economic and cultural climate.

The question of developing a scenario for the design of a sustainable built environment clearly has implications that reach far beyond considerations of the relationship between structure and architecture, which is the subject of this book. This short chapter is intended simply as an exploration of the principal issues that influence the role of structural engineering in the creation of sustainable buildings. It touches on topics – political, social and economic – that are not directly related to structural design but that form an essential background to it in the context of sustainability.

11.2 General background

The wider context in relation to current concerns with sustainability issues has been admirably summarised in *An Introduction to Environmental Sustainability* (Mulligan, 2015). As is argued there, and – although apparently unconvincing to the staunchest of climate-change deniers, growth-obsessed capitalist economists, and neoliberal politicians – the evidence for the seriousness of the global environmental situation is now overwhelming to most informed observers. The various challenges for humanity that these issues have posed – politically, socially and culturally, as well as environmentally – have provoked a wide variety of responses ranging from total denial, based on 'head-in-the-sand' naive optimism, through various scenarios, most of them also naive, for the development of possible sustainable futures by the use of technical fixes for environmental problems, to deep gloom and despair at the seeming inevitability of an eventual breakdown of global ecosystems, famine, disease, war and ultimately, multiple extinctions, including perhaps that of humankind. The failure, to date, of the dominant neoliberal world political system, based as it is on serving the requirements of global capitalism, to address successfully the principal environmental problems is obviously a cause for concern. The current situation has been well critiqued in such publications as *Capital in the Twenty-First Century* (Piketty, 2013) and *Anthropocene or Capitalocene?* (Moore, 2016), neither of which is optimistic about the future.

The search for a realistic assessment of how to develop a sustainable way of operating should begin with the well-known concept of 'spaceship Earth' – a system that is closed and finite so far as material is concerned but that is supplied continuously with energy from the Sun which, in terms of humankind's future, can probably be considered to be an indefinitely available source. Another essential – although not necessarily a future given – so far as human life on the planet is concerned, is the continued operation of the biosphere, itself dependent upon the continued functioning of the natural processes involved in the maintenance of atmospheric, soil and ocean systems. The idea of sustainable existence on a planetary scale is untenable in the absence of continually functioning ecosystems. The way in which these concerns impact on human activity is in the restrictions that they place on the environmentally acceptable levels of consumption and pollution of all kinds.

The contribution which the architecture and structural engineering professions can make to mitigating the situation is principally in helping to evolve a built environment that minimises the requirements for raw material and energy on a long-term basis, and that fully incorporates the principle of recycling in all its forms. Doing so will require that changes occur at a fundamental level to the design of built form, and, in particular, the abandonment of many currently conventional building typologies that are environmentally damaging. New typologies will be required rather than add-ons to existing types (such as improved standards of building insulation, passive systems for environmental control or the reduction of hydrocarbon pollution through the use of renewable energy systems), important though all of these may be. A much more radical approach will be necessary.

Major non-technical considerations that inevitably influence the design of buildings are the cultural and artistic aspirations that operate in the world of architecture. As is discussed here in Sections 8.3, 10.2.5 and 11.3.3, it is these, rather than technical considerations, that have largely determined the mainstream of architectural form in the Modern period and that have been responsible for the absence of any meaningful consideration of sustainability in the planning of most Modern buildings.

An example of a prominent feature of most Modern buildings which is not environmentally sensible is the separation of support and enclosing functions in their perimeter walls. As is discussed in Section 8.3.2, this was legitimised by Semper and subsequently applauded in the many eulogies for the Crystal Palace building (Figures 8.4 and 8.5) which appear in Modernist architectural literature. It found its way into Modernist architectural theory where it was ultimately sanctified in Le Corbusier's 'five points', and it became ubiquitous in its application, such as, for example, in the service of 'readability' in the High-Tech architecture of the late twentieth century (see Section 9.3 – discussion of Centre Pompidou in Paris). The continued and seemingly inevitable perpetuation of such shibboleths of Modernism needs to be reassessed if a truly sustainable architecture is to be developed.

Perhaps the most comprehensive assessment of contemporary practice in relation to sustainable design is to be found in the book *Building for a Changing Culture and Climate: World Atlas of Sustainable Architecture* (Pfammatter, 2014). The many case studies described in this survey range from highly innovative 'deep green' approaches to design to prime examples of significant 'greenwashing' (see Section 11.3.15). In most cases the sustainability strategy is directed solely at the issue of environmental control (principally in relation to insulation, heating and air handling) rather than being concerned with the whole building throughout its life cycle. Such strategies may nevertheless gain a 'green' accolade for a building (see Section 11.3.16). The survey described in Pfammatter clearly demonstrates that an enormous range of strategies are currently being pursued in the quest for sustainable forms of building. It is an unfortunate fact, however, that most recently constructed buildings for which claims of sustainability are made do not actually address the issue at a fundamental level.

11.3 Relevant concepts

11.3.1 Introduction

As noted above, the problems posed by the need to evolve a sustainable way of life for humans on planet Earth are deeply rooted in current lifestyles and only soluble in the context of significant political will for change on a global scale. What follows in Sections 11.4 and 11.5 is a broad-brush discussion of general principles as they might apply to the fairly narrow concerns related to the role of structure in the evolution of a sustainable architecture. Some concepts relevant to this discussion are briefly reviewed in this section.

11.3.2 The terms 'sustainable' and 'green'

The terms 'sustainable' and 'green' are used in architectural discourse (and elsewhere) with meanings that are often ill defined. For clarity, the meanings that will be attributed to them here are given in the following brief descriptions.

The term '*sustainable*' will refer to forms of human activity that do not lead to environmental degradation in the short or long term (Robertson, 2014, p. 5). The key requirement for sustainability is that an activity should be capable of continuing into an indefinite future. It should not consume the resources on which it depends (materials, water, energy, air) at rates that are greater than their capacity to regenerate naturally and it should not produce waste at a rate that is greater than the capacity of the environment to reprocess it. Neither should it disrupt the living ecosystems (and the associated reciprocal eco-services) on which life depends to an extent that is greater than their resilience can accommodate. A requirement for sustainability is therefore that the consumption of water, energy and materials can continue into an indefinite future because the materials involved are renewable, recyclable or re-synthesisable and such waste as is generated can be broken down and recycled in the environment.

A system will be described as '*green*', in the context of this book, if the sources of materials, water and energy, the manufacturing processes, any resulting pollution and the required continuing maintenance are such as to minimise impact on the natural environment. 'Greenness' is therefore a relative epithet and a necessary but insufficient condition for sustainability.

11.3.3 The Anthropocene, the Cartesian duality, 'free Nature' and the problem of Modernism in architecture

Perhaps the most serious impediment to the development of a sustainable built environment is the Modernist mindset and the concept of lifestyle that it generates. It is an issue that closely relates to the current intense discussion surrounding the meaning and significance of the term '*Anthropocene*', and is concerned with the perceived relationship between humans and everything else that exists on planet Earth. The basis of the arguments has been well reviewed by the philosopher Timothy Morton in books such as *Humankind* (2017) and their political and social implications by Moore in *Anthropocene or Capitalocene?* (2016).

The arguments and controversies that constitute the 'Anthropocene debate' are relevant to every aspect of the built environment including the types of buildings that society considers it necessary to commission, the architectural theories that underpin the types of visual environment and the types of built form that are thought to be desirable, as well as the general attitude to 'Nature' and the wider environment.

As is well articulated by Morton, a fundamental aspect of the Modernist mindset is the *Cartesian duality*: the idea that mind and body are separate entities. As stated by Plumwood (1993), the Cartesian duality considers that, 'The body and Nature became the dualised other of the mind'. Though its roots were much deeper (traceable to prehistoric times, as discussed by Morton), the Cartesian duality became a dominant aspect of Western philosophy from the period of the Enlightenment onwards, and led to the Modernist idea that humans were separate from Nature and could, through technology, dominate and control the 'natural world'. These modes of thinking resulted in the concept of '*free Nature*', the idea that the resources of planet Earth – including materials and energy sources – were a free gift from 'Nature' that could be exploited for human use without any meaningful duty of care or serious concern for consequences. Some commentators argue that in capitalist thinking, which has been the dominant socio-economic system throughout the Modernist period, the majority of humanity has been included in 'free Nature' and exists to be exploited by the capital-owning minority.

The idea of humans being separate from 'Nature' was a fundamental aspect of Modernist thinking that had significant effects on the imagery of the associated architecture. Piet Mondrian (1872–1944), (a leading exponent of the Modernist aesthetic, although not an architect) clearly articulated this idea: 'The life of today's cultivated humanity is gradually turning away from natural conditions; it is becoming more and more an abstract life.'[1]

Theo van Doesburg (1883–1931), a fellow member of the De Stijl group to which Mondrian belonged, expressed succinctly one of the underlying credos of Modernism:

> Science has analysed and established the laws of nature: without the knowledge of these laws, man is doomed to impotence. Once in the possession of this knowledge, he owns the means to use these laws against nature itself and to deliver humanity from its dependence on nature. By this knowledge he commands the means to force nature to work for him.[2]

Many similar sentiments were expressed by the leaders of the first Modernist movements in the visual arts and architecture.

Unsurprisingly, the architecture that developed from this kind of early Modernist thinking was probably the least sustainable of any age, being based on abstract forms and transparent surfaces that demanded extravagant use of materials and energy, both during initial fabrication and subsequently, and that were deliberately unrelated in any way to the natural environment. They were, in other words, as Mondrian pointed out, intended to express the idea of the separation of humans from 'Nature'.

Architecture has always functioned largely through the innovative manipulation of images intended to be the physical expressions of ideas and concepts, and this has certainly been the case in the Modern period. From the viewpoint of sustainability, however, a significant problem with the imagery of Modernism is that much of it was intended to express the idea of separation and even alienation from 'Nature'. It is unlikely, therefore, that the images developed from Modernist thinking will be able to provide useful precedents for a sustainable architecture. The mainstream architecture movements that followed early Modernism (Postmodernism, Neo-Modernism, Deconstruction and their successors) have perpetuated the use of this imagery and none has addressed the issue of the development of a vocabulary that is sympathetic to Nature, which is fundamental to the achievement of sustainability. The current preoccupation, in the architecture field, with a purely formalist approach to design, based on forms that are unrelated to environmental concerns, is exemplified by the types of building that appear prominently in the literature that describes and discusses mainstream architecture (see Jodidio, 2013, for a typical survey). An illustrative selection of such buildings is discussed in Section 10.2.5.

A serious questioning and adjustment of the Modernist mindset derived from the Cartesian duality will be required if a genuinely sustainable architecture is to be evolved.

11.3.4 Fashion and 'making it new'

The cult of 'newness' – the idea that the visual environment must be continuously refreshed by new images and old models discarded – is a fundamental aspect of Modernism. The Modern aesthetic must always be fresh, in every sense, and therefore subject to continuous replacement and renewal. This type of thinking, the *raison d'être* of the fashion industry, has pervaded the culture of architecture. It is incompatible with the idea of sustainability, which requires that objects, be they items of furniture or whole buildings, should remain in use for as long as they are useful, and that useful forms should not be discarded as ideas for new buildings, simply because they have been used before. The desire for newness, and for remaining fashionable, has resulted in the complete separation of the image-making process in architecture from environmental concerns. It has even subverted the worthy intentions of the designers of 'eco-houses' by encouraging the development of an 'eco-style' in which features with origins in the desire to improve energy performance have been reduced to the status of motifs. Such a trend, which appears to be inevitable in the architecture world, can be observed in surveys of so-called 'eco-architecture', such as Benitez, Vidiella and Mola, 2010, *Small Eco Houses: Living Green in Style*. Universe, New York.

The re-appraisal of the practice of architectural design as principally the manipulation of visual images in a quest for originality is one of the most essential tasks facing the world of architecture.

11.3.5 Architecture as a fine art

The idea that architecture should be a fine art, concerned with the expression visually and spatially of the major philosophical preoccupations of the age in which it is created, is obviously a worthy aspiration. It is, however, a concept that positions the architect as a creative artist rather than simply the designer of useful buildings and this has tended, in the context of the recent and current Modernist climate described earlier, to produce building forms that are wasteful of resources and energy. The problem of reconciling forms that satisfy the aspirations of culturally derived design theory with those that are environmentally sustainable is a task that mainstream architecture, as currently practised, shows little sign of addressing.

11.3.6 The linear economy

The *linear economy* is a term first used by the economist Kenneth Boulding (1941); it may be summed up in the phrase 'make stuff, use stuff, throw stuff away'. The idea of recycling clearly forms no part of this approach. The linear economy, which is a key aspect of Modernist thinking and Modern living, is a further example of the gulf that has developed between humans and Nature.

Recycling and re-use, neither of which feature in the linear economy, are fundamental to sustainability. In the context of a planet that is a finite size the 'away' in 'throw stuff away' does not exist. In practical terms this means that consideration of the ultimate fate of an artefact, be it a building or a household item, should be an important aspect of its design, not only so that its life may be extended for as long as possible, but also in order that the whole object or its constituents may easily be recycled once its useful life is over.

One of the greatest challenges for the establishment of a culture of sustainability is the combating of the unrealistic thinking that underpins the 'concept' of the linear economy.

11.3.7 Bioregionalism

Bio-regionalist thinking considers that human actions and systems should be aligned with local and regional ecological realities. To be consistent with the idea, an architecture would have to be based on building forms that were well adapted to local climate conditions and constructed from locally available materials. Such an architecture would be more likely to meet the criteria for sustainability than one that favours forms that are not directly related to climate and other regional characteristics, as is the case with the Modernist approach, which tends to impose across the whole globe a uniform type of architecture, associated with a homogeneous economic and consumer culture.

11.3.8 Biomimicry

In the broadest sense, *biomimicry* is the idea of looking to Nature for design inspiration. Although largely incompatible with much that is fundamental to the Modernist belief system, it is an idea that has occasionally been fashionable in architectural discourse, usually as a purely superficial visual exercise in the form of an interest in intriguing natural forms such as the Fibonacci patterns of sectioned mollusc shells or sunflower seed-heads, the orthogonal networks of fibres in sectioned mammal bones and numerous other curvilinear forms found in natural organisms. Such beguiling images, which have re-appeared in recent discussions that seek to give them meaning in the field of architectural sustainability, are mostly discussed very superficially in relation to the technical performance of architectural form. The preoccupation with such images is a further example of the tendency in architectural circles to be concerned only with the visual qualities of form rather than with its intrinsic properties.

A more serious and useful form of biomimicry, so far as sustainable design is concerned, is likely to be based on the development of an understanding of the underlying processes of the natural world, including those associated with the recycling of materials, and of the ways in which natural organisms are organised. It is rare in Nature, for example, for parts of organisms to have a single function only, as is advocated in some highly simplistic Modernist architectural theory. A more fundamental approach to Nature is found in the concept of *ecodesign*, which has been described by Yeang (2006, quoted in Hart, 2011, p. 15) as

> benign bio-integration with the environment. . . . the seamless benign environmental integration of all our human-made environment and all our human activities with the natural environment, from source to production to operation to demolition and eventual assimilation into the ecosystems and biospheric processes.

11.3.9 Ecological footprint

The *ecological footprint* of an activity or enterprise is simply the surface area of planet Earth that is necessary to provide the energy and material resources required for the project and for the disposal of the waste that it produces. This concept can be applied at all scales from the construction of a simple building to the running of whole cities or even nations. It originated in the early 1990s and has effectively drawn attention to the urgency of global environmental problems. It has resulted in a prediction that, if levels of world human consumption continue to grow at present rates, the resources of between two and three planets Earth will be required, by 2050, to supply the desired energy and raw materials, highlighting the already acute crisis of over-consumption. The concept has been criticised for its limitations as a predictor, due to its inability to take account of possible future efficiencies due to technical developments; on the other hand, if damage to existing habitats and the world soil resource is considered, predicted surface areas required may 'rise as well as fall'.

Despite its obvious limitations, the idea that an enterprise inevitably possesses an ecological footprint focuses attention on the probable wider environmental consequences of any project. Such thinking is crucial to the development of sustainable ways of operating.

11.3.10 Embodied energy

The availability of cheap sources of fuel and therefore of energy has been an essential aspect of Modern capitalism and industrialisation. It has also been, from the beginning of the industrial era, the cause of significant environmental problems. For example, the forests of North America and Northern Europe were devastated in the sixteenth and seventeenth centuries as the source of fuel for the sugar industry, which involved the first large-scale industrial processes of the Modern era. In the present day, excessive carbon emissions are just one of the consequences of the widespread use of fossil hydrocarbon fuel as the principal energy source of the developed world. The need to reduce dependence on hydrocarbon fuels is currently one of the greatest difficulties posed by the agenda for sustainability.

The problems associated with excessive energy consumption will not, however, be entirely solved by a significant reduction in the use of hydrocarbon fuels. Even renewable sources such as wind or hydro-power cause significant disruption to the environment and the use of this power can have undesirable consequences for atmospheric temperature and climate. One of the goals for sustainability is an overall reduction in energy consumption; an acute awareness of the energy involved in any enterprise will be an essential aspect of this.

Embodied energy is simply the sum total of the amount of energy required to produce an artefact. This includes the energy involved in extracting the raw materials, in manufacturing them into the finished object, and in their transportation at all stages of the supply chain. In the case of a building it also includes the energy involved in its design and construction.

As with the size of an ecological footprint, the total embodied energy of any artefact is very difficult to quantify precisely. The most useful strategy is the so-called 'cradle-to-grave' approach, in which total embodied energy is broken down into:

- *initial embodied energy*: the energy required to construct the building initially, which includes energy consumed in extraction of the raw materials, manufacturing of products, transportation to site;
- *recurring embodied energy*: the energy required for maintenance and refurbishment over the lifetime of the building;
- *demolition energy*: the energy required for demolition and disposal.

Embodied energy does not include the energy required to actually *operate* the building during its life cycle – the energy consumed for heating, lighting, etc. – and it is not normally accounted for in green rating systems (see 11.3.16) that, together with building regulations intended to improve green performance, tend to be focused solely on the reduction of energy consumption in use.

Although embodied energy is not amenable to easy calculation in an energy audit, it is nevertheless a concept that is an essential requirement of sustainability thinking because contemplation of all the various types of energy that are likely to be involved in the production of an object, be it a component or a whole building, focuses attention on the wider context of the enterprise.

11.3.11 Carbon footprint

The *carbon footprint* of a building measures the total contribution, through its life cycle, which it makes to the emission of greenhouse gases and therefore to anthropogenic (human-induced) climate change. As with the concept of 'ecological footprint', it is problematic to quantify and is usually expressed not as a 'footprint' (i.e. an area) but in terms of the carbon dioxide equivalent (given as a weight) of total greenhouse gas emissions; and is quoted as tonnes of CO_2e (carbon dioxide equivalent) per year.

To achieve the objective of sustainable design, the net emissions of greenhouse gases must be eliminated or at least minimised. This can be done by the reduction of dependence on hydrocarbon fuels through the use of renewable energy sources for environmental control; the reduction in transport dependency by use of locally available materials; the reduction of emissions caused by processing through the use of materials of low embodied energy; and by the re-use of components or the recycling of materials. The emissions can also be 'offset' by such measures as carbon capture or by making provision for the replacement of renewable materials, for example by reforesting or restocking of woodland from which timber has been extracted.

Buildings and projects are said to be 'carbon neutral' if CO_2e production is entirely compensated for by offsetting of some kind. This is obviously a requirement for an architecture that involves zero long-term impact on the environment – an architecture that is truly sustainable, in other words.

11.3.12 Embodied water

The management of water resources is one of the major environmental issues of the present day and a significant factor in several of the world's conflict zones. *Embodied water* is the cumulative quantity of water used in the production of an artefact, whether it is a manufactured product or a whole building. As with embodied energy and carbon footprint it is extremely difficult to quantify accurately. Embodied water is a factor that must be considered by anyone who is attempting to design responsibly for a sustainable future. Specification of steelwork for a building, for example, is likely to have some implications for water management at more than one location in the world, and to involve significantly more embodied water than the use of an alternative material such as timber. Even with timber, however, the wider implications are considerable due to the effects of forest management on such issues as climate change and flood control. As with all aspects of sustainability, the full implications of an action should always be considered.

11.3.13 Re-use and/or recycle/upcycle

A component is *re-used* if it is incorporated, with minimal alteration, into a new structure following its removal from an existing structure that has become redundant and been demolished. A material is *recycled* if it becomes a raw material in the manufacture of a new product. Both processes are fundamental to sustainability but both are also currently dependent on the existence of an infrastructure of organisations concerned with the activity of recycling that, in the current global economy, can only exist if the processes are profitable or subsidised by public funding. The contribution of designers to increasing the possibility that the material and components that they specify for buildings and structures may be re-used or recycled is to produce designs that enable these processes – perhaps the most fundamental form of biomimicry (see Section 11.3.8 above).

The term *up-cycling* refers to the practice of creating a product of higher value from discarded objects or from the waste created as by-products. It has been applied mainly in the contexts of fine art and the creation of high-priced fashion objects from parts of cheap consumables. Although it is a version of re-use or recycling, its principal concern has been, to date, with raising monetary value and it is therefore perhaps unlikely to play a significant part in the evolution of a sustainable and eco-friendly built environment.

11.3.14 Waste and waste disposal

An aspect of building design related to the concept of recycling is that of the production of waste. A crucial and far-reaching aspect of design for sustainability will be the need to minimise the wasteful use of materials and energy at every level, both during initial construction of buildings and subsequently. This has enormous implications for design because it will require that environmental considerations be given a high priority at all stages from the initial selection of built forms – so as to make minimal and appropriate use of materials and energy – to the adoption of systems of construction that facilitate dismantling for the re-use or recycling of components and materials. It will require the abandonment, or at least the serious reappraisal, of a whole set of Modernist ideas concerned with the continuous 'renewal' of the built environment, which have become embedded in the culture of architecture.

11.3.15 'Greenwashing'

'*Greenwashing*' is a term applied to the phenomenon in which the rhetoric of sustainability is used to describe an activity or process whose claims to 'greenness' are in fact largely invalid. It is a strategy that has been adopted by some major corporations in a predominantly cynical attempt to increase the market share of their products, and by politicians and capitalist economists wishing to undermine the political influence of the environmental movement. It is also a strategy that has been used by architects and developers to disguise the poor environmental performance of many Modern buildings, particularly high-rise office and residential complexes in inner-city areas; in such buildings large returns on capital are possible through a combination of the perpetuation of architecturally fashionable building forms and building techniques that are wasteful of energy and materials. Such strategies are, in part, encouraged by the lack of serious critical appraisal of such building forms from the largely sycophantic architectural media.

In the quest for sustainability, it is important to distinguish between building designs that have been influenced by genuine concern for environmental issues and those that are merely examples of greenwashing.

11.3.16 Green rating systems

A *'green' building* has been described (Robertson, *Sustainability Principles and Practice*, 2014, p. 184) as one that has been created 'using processes that are environmentally responsible and resource efficient throughout the building's life cycle'. A number of rating systems have been devised that enable the extent of the 'greenness' of a building to be assessed. The first of these was the UK system called BREEAM (Building Research Establishment Environmental Assessment Method, 1990) and this was quickly followed by the US LEED system (Leadership in Energy and Environmental Design, 1993), which was developed by the US Green Building Council (USGBC). There have been others, most notably Living Building Challenge (LBC, 2006), also developed in the USA.

These rating systems operate by the allocation to buildings of points for green features, most of which are concerned with energy use in the operational phase of the building's life, and are accumulated to gain a green rating. The number of criteria for which points may be gained is very large and some of these have only a tenuous connection with long-term sustainability. The BREEAM system, for example, includes the assessment of a wide range of aspects of design and construction practice and, although the demonstration of good practice is obviously a worthy objective in these fields, it is not necessarily directly relevant to environmental impact. In addition, only limited penalties can be imposed for the incorporation of features that are not green. The green rating systems have been criticised on the grounds that it is possible, by the incorporation of a large number of features that are only mildly green, to accumulate for a building sufficient points to qualify it for a green award, despite the fact that it may contain major features that are undesirable environmentally. This feature allows the very good intentions of the building accreditation systems to be subverted by unscrupulous architects and developers to greenwash developments that are far from environmentally responsible. The possession of a BREEAM or LEED award is not therefore necessarily a guarantee that the environmental performance of a building meets the criteria for sustainability.

11.3.17 Eco-economic decoupling

Eco-economic decoupling is a term used to describe the ability of an economy to grow without a corresponding increase in environmental pressure. In the context of the sustainability debate, an economy that maintains economic growth without it having a negative impact on environmental conditions is said to be decoupled and this may be possible if the increased efficiencies produced by technological development compensate for the rise in economic output. Decoupling is said to be *absolute* if resource efficiencies increase as fast as economic output. *Relative* decoupling occurs if ecological intensity per unit of economic output simply declines even though both may still be growing. The Organisation for Economic Co-operation and Development (OECD), which is an intergovernmental organisation of countries with high-income economies, has made decoupling a major focus of the activities of its International Resources Panel.

In the context of a planet of finite size, the validity of the concept as a permanent solution to the problems of environmental impact has been seriously questioned (e.g. Jackson, 2009). It may in fact be simply a necessary strategy for mitigating the worst effects of increasing global consumption caused by the continuation of policies for economic growth. It should not be regarded as the ultimate 'technical fix', as is sometimes suggested by technical optimists, or used as a justification for the postponement of more fundamental measures to deal with the problems of environmental degradation.

11.4 Recent practice in relation to 'sustainable' architecture

Most practising architects and structural engineers, including the transnational firms that are responsible for the design and construction of the largest building complexes of the world's expanding cities, profess a serious engagement with the agenda for sustainability and a recognition of the need to develop an architecture that respects environmental concerns. Additionally, almost all professional associations connected with the built environment, such as I.C.E., R.I.B.A. and A.S.C.E., actively promote the adoption of good design practice in relation to sustainability. There is therefore considerable evidence that the professions responsible for the design of the built environment recognise the need to evolve sustainable forms of building. It is also evident, however, that largely as a result of social, cultural and economic pressures, progress in this direction has so far been very slow.

For example, although a significant proportion of prominent recently completed buildings receive green accreditation in the form of an award under the BREEAM, LEED or similar systems, in virtually all cases it is the characteristics of the strategies that were adopted for environmental control that were responsible for the green award rather than the ecological footprint over the entire life cycle of the building. The validity of the claims for 'greenness' of the large-scale urban buildings that feature predominantly on the websites of virtually all of the principal architecture and structural engineering design organisations are therefore open to question. While most of these buildings do contain green features, very few meet the criteria of a genuinely sustainable architecture.

Such a lack of truly sustainable credentials applies particularly to high-rise buildings, which represent a significant proportion of the world's expanding building stock and therefore of the workload of large parts of the building design professions. This is a fact freely acknowledged by many practitioners:

'Skyscrapers are the least ecological of all building types. They use up about 30% more energy and materials to create and operate compared with low-rise buildings' (Ken Yeang, quoted in Sarah Hart, 2011, p. 221). Yeang has also described tall buildings as 'an energy-hungry symbol of power and machismo' and 'the least environmentally sustainable building [type] civilisation has yet devised . . . energy and resource hungry to build, maintain and demolish. However, until we find an economic alternative, I am afraid they will continue to be built ubiquitously.' In these circumstances it is not realistic to expect building professionals to bring about the substantial change required. It is society as a whole that will have to initiate the process by altering its priorities, and in the meantime the professionals can hope only to mitigate the situation.

Many instances may be found in which serious attempts have been made to deal with the environmental impact of the high-rise building. One such example is the office tower at 30 St Mary Axe in London (Figure 11.1), also

Figure 11.1 30 St Mary Axe ('The Gherkin'), London, 2004; Foster & Partners, architects; Arups, engineers. 'London's first ecological tall building', was the claim made by the architects; this may well be legitimate in view of the 'green' features that were incorporated.

Photo: Ian Muttoo/Wikimedia Commons.

known as 'the Gherkin', which was completed in 2004. Its designers, Foster & Partners, with Arups as engineers, have claimed that it was 'London's first ecological tall building' and there is some justification for this as the building goes some way to realising what Yeang describes as '"ecomimesis" – the mimicking of the attributes and properties of ecosystems' – (Hart, p. 262), by employing a number of the attributes of a natural organism.

The Gherkin building is a 41-storey office tower situated on a high-value site in the City district of London, and it provides 76,400 sq m of accommodation. Its distinctive shape is intended to enhance its environmental performance by reducing wind loading and improving the effectiveness of passive systems of environmental control. The structure is a post-and-beam steel framework that is in many respects conventional but that has unique characteristics in order to facilitate the unusual overall form of the building. The vertical structure consists of a ring of columns surrounding a central core, and a highly innovative steel diagrid at the perimeter wall, which provides both vertical and lateral support and accommodates the unique external form of the building. Conventional floor beams, carrying a standard one-way-spanning composite concrete-and-steel floor deck, span radially from the central ring of columns and the perimeter diagrid. At each level six segments of the radial plan are left clear and the locations of these are staggered between floors so as to create upwardly spiralling voids within the building (Figure 11.2). It is these voids, together with other passive systems, such as a regulated ability of occupants to open windows, that were intended to contribute to energy savings in respect of environmental control. It was claimed by its designers that the energy requirements of the building should be 50% lower than those of equivalent towers, and subsequent monitoring has confirmed that this claim is largely justified. It is a fact, however, that tenant resistance to the idea of natural ventilation, which involves greater temperature variation than full mechanical control, has meant that the energy-saving potential of the building has never been fully realised. This example illustrates in a small way the fact that, to achieve the objective of eco-friendliness, all participants in the building project, including its users, have to co-operate with the strategy, and also to realise that operating closer to Nature will involve the acceptance of an environment that has some natural characteristics.

The spiralling system for natural air handling in the Gherkin building is expressed by the treatment of the cladding on the diagonal steel perimeter structure and the building achieves a remarkable degree of integration of structural, environmental and architectural design. In this respect it has an organic quality that goes some way towards the achievement of the objective of an eco-architecture, as claimed by its designers. The building does, however, perhaps inevitably, contain many features that are not 'green' such as, for example, its circular plan, which is not adapted to local climatic conditions and therefore compromises its efficiency with respect to solar radiation, among other things.

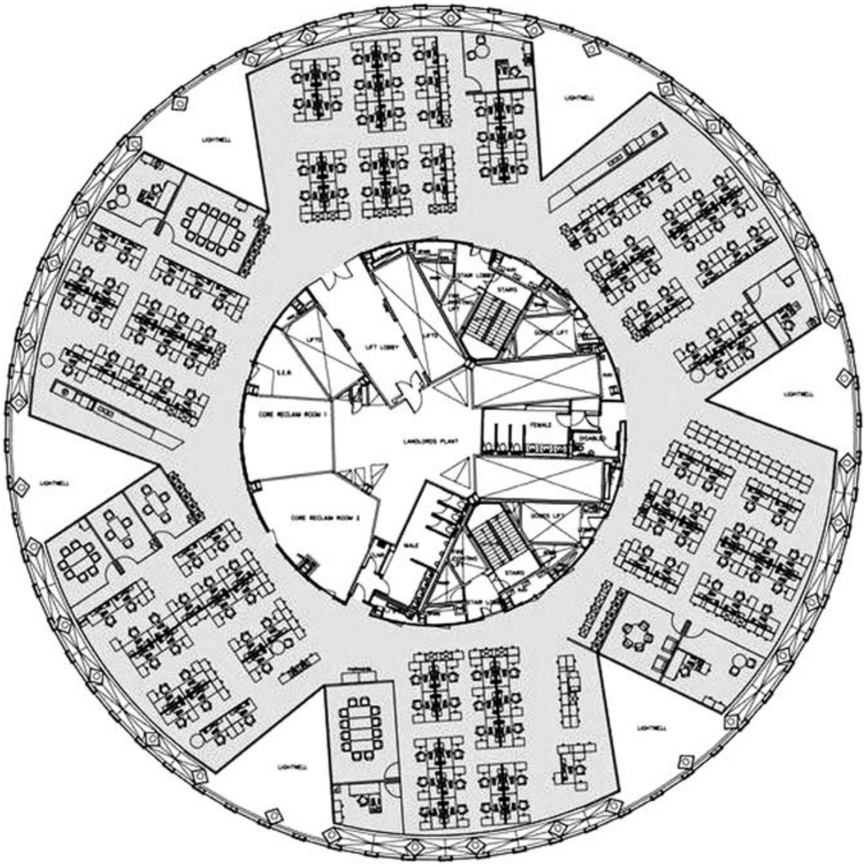


Figure 11.2 Plan, 30 St Mary Axe ('The Gherkin'), London, 2004; Foster & Partners, architects; Arups, engineers. The vertical structure consists of a ring of columns surrounding the central services core and a diagrid at the perimeter of the plan. Six triangular voids in each floor are staggered between levels to create voids that spiral upwards through the building to facilitate non-mechanical air circulation.

Image: Foster & Partners.

The architect who has perhaps done most in recent years to produce buildings that are truly sustainable is Ken Yeang (of T. R. Hamzah & Yeang), who regards the essential objectives of ecodesign as: 'the seamless and benign integration of the synthetic and the artificial (the human-made) with the natural environment' (Hart, 2011, p. 261). He believes that this can only be achieved by 'the systematic integration of our built forms and their operational systems and internal processes with the ecosystems in nature' which involves 'the conservation of both renewable and non-renewable resources to ensure that these are sustainable for future generations'. He sees as fundamental to sustainable design that 'imitating the attributes and properties of ecosystems is one of the fundamental premises behind ecodesign. Our built environment must imitate ecosystems in all respects.' Yeang is, however, quite realistic concerning the difficulty of realising these objectives in the context of present-day economic and social priorities and believes that 'Successfully achieving this is easier said than done, but herein lies the challenge'.

Most of Yeang's proposals for large-scale buildings intended to meet the challenge for sustainability remain unbuilt, but several of his built structures represent the most serious attempt to date to realise the ideal of an eco-architecture in the context of large building complexes.

One example is the Solaris building in Singapore which was completed in 2010 (Figures 1.7 and 1.8). This is a fifteen-storey complex that houses public spaces, offices and laboratories for businesses involved in R & D for the IT industry. The building has a naturally ventilated central atrium but the principal eco-design feature is a 'linear park' – a ribbon or corridor of vegetation that begins at basement level and is wrapped around the building's perimeter as a continuous strip, 1.5 km in total length, that spirals upwards to roof level and provides shading, insulation and cooling as well as amenity space to all parts of the building. Numerous other strategies were adopted to enhance the environmental responsiveness and performance of the building.

Other examples of Yeang's work that are based on similar principles to the Solaris building are the Spire Edge building in Manesar, India (2013, Figure 11.3), and the DiGi Technical Operations Centre in Selangor, Malaysia (2010). All of Yeang's buildings are based on conventional post-and-beam reinforced concrete structures.

The role of structure in the context of large urban buildings that have been designed to meet sustainability criteria, such as those described above, is to provide a supporting armature that allows the various so-called 'green' strategies to be adopted and to function appropriately. The structures themselves are simply adaptations and extensions of the conventional frameworks in steel and reinforced concrete which, even when competently designed, do not perform particularly well against sustainability criteria concerned with embodied energy, or potential for recycling. This may be justified, however, on the grounds that the structure represents only a proportion of the total fabric of the building. The use of steel and reinforced concrete frameworks is in fact defensible for large building complexes, particularly where large numbers of storeys are involved, due to the versatility of the structural systems that results from the excellent structural properties of the materials, in particular their high bending strengths. This characteristic, together with exploitation of the benefits of structural continuity, allows great flexibility of form to be achieved in the context of non-form-active post-and-beam arrangements and this is often exploited for both architectural expression and to facilitate the environmental agenda. It allows the use of columns and walls that are inclined to the vertical; it can be used to make whole sections of buildings into bridges that span between other buildings; it facilitates the creation of volumes of

Figure 11.3 Spire Edge building, Manesar, India, 2013; T. R. Hamzah & Yeang Sdn Bhd, architects. Many 'sustainable' features were incorporated into this building, including a ramp-based 'green' corridor that ascends through every floor, a water harvesting, re-use and recycling system, and passive systems for lighting and ventilation. The green credentials of the building have inevitably been questioned, but it is nevertheless a rare example of a comprehensive approach being taken to address the problems that are posed by the design of large urban buildings that meet the criteria for sustainability. It is one of several examples by the architect Ken Yeang, a leading practitioner in the sustainability field.

Image: Brenda Nyawara/Archute.

complex shape within the buildings that encourage passive convection for air circulation; and it also allows the creation of variable-plan-form floor plates in multi-storey buildings to further enhance the possibilities for sculptural form-making and the inclusion of environmentally friendly features such as external overhangs to facilitate shading.

A building with a steel or reinforced concrete structure can never fully meet the requirements of 'ecomimesis', as described by Yeang, however, and therefore the conditions for a fully sustainable architecture. It is difficult to see how this ideal could ever be achieved while society has a requirement for high-rise buildings, although some of the systems described below here in Section 11.5 may go some way towards this.

The use of steel and reinforced concrete for small-scale buildings, for which high-strength structures are not a necessity, such as dwelling houses, is less easy to justify than for the large complexes described above. It is therefore surprising to find that much use is nevertheless made of these materials in buildings of this type for which claims of eco-friendliness are made. A recent survey of such buildings is Benitez, Vidiella and Mola, 2010, *Small Eco Houses: Living Green in Style*, Universe, New York. The buildings featured there owe their green credentials principally to the systems and methods that have been adopted for services and environmental control, such as off-grid capability and the use of passive systems for heating, cooling and ventilation.

The common features of this emerging eco-style for small buildings are rectilinear geometry, minimal contact with the underlying ground, cantilevering roof and floor plates and large areas of wall glazing. The building shown in Figure 11.4 is an example. Many of these stylistic features required that structural frameworks of steel or reinforced concrete be used and this greatly diminished the true ecological credentials of the buildings. Justifications for these features on the grounds that they are 'green' are often spurious, such as the naive notion that a building that only touches the ground at a few locations causes minimal disruption to the environment. (Plants do not grow under buildings.) Also, statements such as 'The structure and shape of the house reduce its carbon footprint on the land' (Benitez, Vidiella and Mola, 2010, p. 190) indicate only a very slight or even non-existent understanding of the true nature of sustainability questions. As described here in Section 11.3.11, carbon footprint, unlike ecological footprint – an entirely distinct concept – is expressed as mass rather than area and neither relates to the ground of the building's site. Although there is some ecological justification for reducing the contact area between a building and the underlying strata, in most of the cases described by Benitez, Vidiella and Mola this strategy was adopted for stylistic reasons.

In much of the so-called 'eco-architecture' of the late twentieth century and present day, stylistic considerations were allowed to override the ecological desirability of using locally available materials of low embodied energy, which were either biodegradable or easily recycled. The use of such low-tech materials would, of course, have had serious implications for the forms of buildings and other aspects of their appearance, and would have required that a fully integrated approach to design, as advocated by Yeang, be adopted. The buildings featured in many books on eco-architecture, such as that of Benitez, Vidiella and Mola, have instead simply promoted the idea of an 'eco style' rather than of a truly 'eco' approach to architecture.

In summary, the few examples described above illustrate that the provision of an armature that is sufficiently strong to facilitate the 'green' agenda, often in a structural form that is inherently inefficient, has been the role of structure in the vast majority of buildings that satisfy currently perceived criteria for environmental awards. The structures themselves, however, and therefore the buildings taken as a whole, rarely perform well against sustainability criteria, usually because large volumes of a very strong material, such as reinforced concrete or steel, are required to provide the necessary strength, in the context

Figure 11.4 Taliesin Mod.Fab House; Taliesin-West-Studio, architects. The cantilevering of the roof and floor planes and the extensively glazed external walls required the use of a structural steel framework for this modest-scale building. The building contains green features, such as off-grid capability and insulated wall panels, but its ecological footprint is considerably greater than required for a building of this size. Stylistic considerations have been given priority over sustainability.

Photo: Timmerman Photography/The Design Home.

of an inefficient, non-form-active structural geometry. The 'green' features that give the buildings eco-credentials often simply place them in the category of 'the wrong thing being done more efficiently' rather than that of a comprehensive attempt to address the fundamental challenges of sustainability.

It is probably unrealistic to expect this situation to improve until society as a whole is prepared to make serious adjustments to its lifestyle priorities. So far as the architectural profession is concerned, the challenge of producing a visual style that is capable of both satisfying architectural aspirations and the requirements for a truly sustainable architecture remains largely unfulfilled.

11.5 Structural design for sustainability

11.5.1 Introduction

What follows here is a discussion of the general principles that should be considered in relation to the design of structures that satisfy the criteria for sustainability and that could form the armatures of buildings in which environmental concerns were genuinely addressed. It is therefore concerned principally with sustainability in relation to building *fabric* rather than other design considerations.

As Pfammatter (2014) has identified, the crucial aspects of the structural choices that are related to sustainability lie in the fields of materials technology, the processes by which components are produced, and construction typology. Structural design is therefore considered here in relation to these aspects of building, and, as with other considerations in relation to sustainability thinking, only general principles are considered. It must be also appreciated, that, as the performance of a structure is highly dependent on all aspects of its form, these matters cannot be separated from consideration of the visual and stylistic treatment of a building throughout all stages of its design.

11.5.2 Selection of materials

The material that is used for the structure of a building forms a significant proportion of its total fabric and is therefore an important consideration so far as its impact on the environment is concerned. A recent study by the Arup organisation, for example, found that, in the case of office buildings, the structure contributed around 20–30% of the total greenhouse gas emissions. Given that most structures are relatively dormant parts of a building during its useful life, it is the initial construction phase and subsequent potential for re-use or recycling that are the principal concerns in relation to sustainability.

From a conventional structural-design point of view, the primary considerations in the selection of structural material are the mechanical properties of strength and elasticity. Other technical considerations are durability in service and the restrictions on geometry imposed by manufacturing techniques such as the rolling of steelwork or the sawmill-conversion of timber. Monetary cost, which in the Modern period was only marginally related to environmental realities, is also a factor.

In the context of environmental impact and sustainability, the consideration of other properties in addition to those concerned with mechanical performance have to be given a raised priority, the most obvious of which, as discussed above, being embodied energy, carbon footprint and embodied water – aspects of their ecological footprint, in other words – and the ease with which a component could be re-used or a material recycled. Included in the ecological footprint would be the likely environmental costs involved in the extraction of the raw material, for example in the mining and quarrying of metal ore or the rock involved in cement production or the forestry implications of timber extraction. The role of structure in the strategy for control of the internal environment of a building might also be a consideration, in which case such properties as thermal capacity – the ability to act as a heat store – and thermal conductivity might influence the choice of structural material.

Each of the conventional structural materials presents its own problems so far as sustainability is concerned. Steel is perhaps the least environmentally friendly with an embodied energy of around 32 MJ per kg and carbon footprint of 2,000 kg CO_2e per ton, which compare very unfavourably with traditional materials. It is also highly susceptible to corrosion to the extent that corrosion protection measures are essential and include processes such as painting or galvanising that are themselves not particularly environmentally friendly. On the other hand steel is the strongest of the commonly used structural materials, employed for the longest spans and the tallest structures. However, very tall structures and long-span enclosures were a feature of the Roman Imperial and Gothic periods, long before steel was used as a structural material, and these can be achieved with masonry and timber if appropriate structural forms are used.

What the unique properties of steel have allowed, in the Modern period, have been the creation of long spans and tall structures in forms that involved significant bending under load – forms, in other words, that ignored the physical realities of the situation in favour of a purely formalist approach to design in which visual aspects were allowed to take precedence over any consideration of the efficient use of material. In Modern architecture this has been applied at every scale, from the ability of steel to allow slender elements in the context of highly inefficient rectilinear post-and-beam frameworks to its use to achieve long spans in buildings with forms that were not form-active (see Section 4.2). The very slender elements that steel has made possible, together with the neatness and precision of their appearance, has been much exploited as an aspect of the visual vocabulary of Modern architecture.

In relation to the agenda for sustainability, advantages of steel are its potential for re-use and recycling, although these are energy intensive, and also its portability and suitability for pre-fabrication. The latter can, for example, give steel structures smaller ecological and carbon footprints, compared to bulkier materials such as concrete or masonry, in projects where significant transport distances are involved. As ever, all of the particular circumstances of an individual building must be considered in relation to sustainability.

For the foreseeable future, steel will remain an important structural material and essential for major infrastructure such as long-span bridges but, from a sustainability point of view, its use in architecture should be minimised. Its great strength is certainly not required for the majority of buildings that involve neither great height nor long spans.

With basic environmental costs of 1.5 MJ per kg for embodied energy and 150 kg CO_2e per ton for carbon footprint, reinforced concrete performs significantly better than steel but considerably worse than timber or masonry. In the broader context of installation in a building, and depending on the building type, however, the environmental costs of steel and reinforced concrete can be, overall, fairly similar. A recent study by the Arup Organisation (2013) found that for office buildings, and considering only the structural framework, with operational and other CO_2e excluded, the emissions for reinforced concrete were around 60% of those of steel, and other studies have found little difference between the two materials. As ever, it is the complete picture that must be taken into account if valid comparisons are to be made.

In the context of large building complexes with post-and-beam structural typologies, in situ reinforced concrete is capable of producing a very convenient and durable structural armature, as is demonstrated in the buildings of Yeang discussed above.

Some of the greatest disadvantages of reinforced concrete are the difficulties associated with disposal. This situation does not apply if a building that has become redundant can be stripped back to its structure and rebuilt around the original armature. In these circumstances the good durability of reinforced concrete is a considerable advantage. If the building has to be completely removed, however, the ecological costs are high due to the difficulty of demolition, the near impossibility of re-use of in situ components, and the difficulty associated with the separation, for recycling purposes, of concrete from steel reinforcement.

The traditional structural materials of masonry and timber perform much better than steel or reinforced concrete in respect of most environmental criteria. There are, however, environmental issues even with these, such as the quarrying and transport of the raw materials for masonry, and the extraction of timber from forests. The durability of both of these classes of material is generally good although there can be problems with rot and insect infestation of timber. The former can be dealt with by suitable detailing of structures to inhibit exposure to long-term damp. Infestation is more problematic in some parts of the world but can be dealt with by ensuring that structures are detailed such that affected components can be easily replaced. As with all traditional materials, there is a considerable knowledge base, accumulated through centuries of practice, concerning how problems of durability can be overcome. It is the recent considerations concerned with environmental impact for which innovative thinking is now required.

Given their preferable environmental properties in relation to steel or reinforced concrete, it is likely that the use of masonry of all types and timber will increase in future. From the point of view of structural use, the greatest shortcoming of both materials is their low strength and, in the case of masonry, almost complete absence of tensile and therefore of bending strength. This is not problematic for buildings of modest size with short spans and no great height, as has been demonstrated in numerous traditional construction typologies. The extension of the use of these materials to buildings of large scale, which is a possible strategy for the evolution of an architecture that is truly sustainable, is, however, likely to present major challenges, although impressive traditional examples exist. As is discussed in 11.5.3, considerable progress is already being made in this direction but the reintroduction of traditional structural materials to large-scale buildings in mainstream architecture will require that the limitations imposed by their mechanical properties be understood and respected, and the implications of these for the overall forms of buildings be accepted. This may be a major challenge for architects but could lead to exciting new forms being developed.

Two materials that have had limited structural applications in the Modern period are aluminium and the plastics group. Aluminium has similar structural properties to steel, with two additional very significant advantages, which are its much higher strength-to-weight ratio and its resistance to corrosion. It has been the lightweight ‘wonder material’ of the Modern age, used structurally to produce the most High-Tech machines such as high-performance aircraft. Its use structurally for buildings has been restricted, mainly due to its high cost which was itself a consequence of its very high embodied energy. Aluminium has in fact been described as ‘liquid energy’. For this reason, and despite being one of the most plentiful elements on the planet and relatively easy to recycle, it is unlikely that aluminium will find a significant structural application in a sustainable architecture.

The plastics group of materials caused a revolution in product design in the twentieth century, principally by displacing non-ferrous metals for small components. Despite numerous attempts, plastics have never achieved widespread use as structural materials other than in very specialised applications such as pneumatic structures and fabric tents, due principally to problems with mechanical properties, such as creep, and poor performance in fire. In addition, the disposal and recycling of plastic components are currently the cause of major environmental problems. These drawbacks, which are to a large extent fundamental because they are related to the internal structure of the materials at a molecular level, together with their origins in fossil hydrocarbons, will mean that plastics are unlikely to be developed as structural materials in future.

The need to evolve systems of building that are truly sustainable is likely to result in the introduction of materials that have not previously had a structural role. An example is paper, which, due to its organic origins, its ease of manufacture by low-energy methods and its potential for re-use and recycling, is compatible with an ecological approach to design. Its chemical constituents and organic origins also give it a high ratio of strength to weight. Paper is already being given serious consideration as a structural material, and its further development for this purpose is an example of the kind of innovative thinking that will be required to produce an architecture that is truly sustainable.

11.5.3 Structural typologies that could meet the criteria for sustainability

11.5.3.1 Introduction

As was discussed in Section 8.2, the principal traditional technical objectives of structural design are to achieve an efficient use of material, while minimising the effort and therefore energy required in design and construction, and to make the structure durable so as to minimise long-term expenditure of materials and energy on maintenance. Coincidentally, these are also the qualities that are most likely to make it meet the criteria for sustainability. Additional factors that have an important influence on the satisfaction of environmental criteria are the overall embodied energy involved, the ecological footprint of the structure, and its potential for the recycling or re-use of materials and components. All of these are compatible with the traditional objectives of structural design that have prevailed down the centuries, and have been discussed here in Chapters 4 and 6, namely the achievement of maximum overall economy of means.

Given that the avoidance of the wasteful use of materials and energy are crucial aspects of sustainability, the production of structures that provide the required support while minimising the use of material – that achieve high levels of structural efficiency, in other words – should clearly be given a high priority. The various factors on which this depends are well understood and have been described here in Chapter 4, where it was seen that the efficient use of structural material can only be achieved through complexity of form, either by the adoption of an overall geometry that is form-active or by the incorporation of as many of the suite of 'improvements' as can be used, and preferably both.

As was discussed in Chapter 6, the achievement of maximum economy of means, as opposed to the achievement of maximum efficiency in the use of material, depends on a balance being struck between the complexity required for the efficient use of material and the simplicity that would facilitate ease of construction. It was seen that the most significant factor that determined the nature of the best compromise is span: the longer the span the greater is the degree of complexity that is justified in the interests of achieving overall economy of means.

At the height of the Modern period, when the concept of 'free nature' made raw material and energy, and therefore structural materials such as steel and concrete, relatively cheap in relation to labour, inefficient forms that made an extravagant use of material but saved labour costs tended to be used for all but the largest of spans and this favoured the use of non-form-active post-and-beam structures in the short and medium span ranges. This situation produced building shapes that were compatible with the rectilinear forms favoured for quite different reasons by Modern architects.

For the development of a sustainable architecture, the emphasis will have to change in the direction of making more efficient use of material and this is likely to reduce the span levels at which complex forms will be justified. As the world economic system inevitably changes in response to deepening environmental problems, it seems likely that more complex, more materially efficient forms will become more viable economically for ever shorter spans.

If the efficient use of material is to be given a higher priority in the development of a sustainable architecture, this will have significant implications for the form of architectural structures and therefore of whole buildings. The most efficient structures are those that have overall shapes that are form-active and, in the context of horizontally spanning enclosures carrying mainly distributed gravitational loading, these are curvilinear. It is likely, therefore, that curvilinear form-active and semi-form-active shapes, which have hitherto been used principally for long-span enclosures, will become more economically viable, and will tend to displace post-and-beam forms, for much shorter spans.

In circumstances where the adoption of form-active and semi-form-active shapes are impractical, such as for multi-storey arrangements, the strategy for minimising the use of structural material is likely to be based on the use of the techniques of 'improvement' on overall shapes that are non-form-active or only mildly semi-form-active. This in turn will have a bearing on the selection of structural material. Both of these developments will have impacts on architectural form. The evolution of a truly sustainable architecture, based on sustainable structural armatures, will therefore require a complete re-examination of the manner in which the forms of buildings are derived, with technical considerations, such as structural performance, being given a much higher priority than has generally occurred in the Modern period. Useful precedents are likely to be found, not by the use of solely visual criteria, as occurred in the early Modern period, but in the methodologies that have been used to derive built form which performs well technically.

The design methods used by twentieth-century engineers such as Pier Luigi Nervi and Eduardo Torroja, and described here in Section 8.2, offer a useful precedent for a methodology by which sustainable architecture might be developed. The buildings of both of these eminent practitioners were designed to make a highly efficient use of material, while being relatively simple to construct. In citing Nevi and Torroja as exemplars, it is important to understand that it is the methodology – that of working from first principles, based on a sound knowledge of structural behaviour, material properties and constructional techniques – rather than the structures themselves, that are the useful precedent. Simply to imitate the visual aspects of the structures would not be appropriate. It is the integrative thinking based on a foundation of knowledge that is important.

Precedents for a sustainable architecture are more likely to be found in the vernacular than in the buildings of mainstream twentieth-century Modernism. Innovative designers who are seeking to create sustainable forms of architecture are currently turning to traditional forms, not from a romantic desire to re-create a lost and probably mythical 'ideal' past, but because most vernacular designs were created from low-energy, locally available materials and were used in constructional typologies that were well adapted to local climatic conditions. It is by the application of recent technology to low-energy traditional materials, such as timber or various forms of masonry, that an architecture appropriate to a sustainable future is most likely to be created. Useful precedents are more likely to be found in the architectures of parts of the world with long-standing traditions in timber or masonry, such as Japan, Scandinavia and Canada in the case of timber, and Africa and Asia in the case of brickwork, than in Modern Western architecture, which, in recent centuries, has been largely preoccupied with matters of style unrelated to environmental function.

11.5.3.2 Examples of possible sustainable typologies

In the case of timber, the development of sustainable typologies is already occurring across the full range of span possibilities and structure types. In the long-span range, significant developments have occurred with curvilinear form-active structures. Early versions were designed in the 1970s under the direction of Edmund (Ted) Happold, in collaboration with Frei Otto, the prime example being the canopy for the Multihalle at the Bundesgartenschau in Mannheim (1975) (Figure 11.5). The structural element of this building consisted of a timber lattice grid that was assembled as a square mesh laid flat on the ground and subsequently pushed up and locked into a form-active shape by diagonal steel tie elements. A very complex form was thus erected with comparative simplicity. The form-active shape was determined

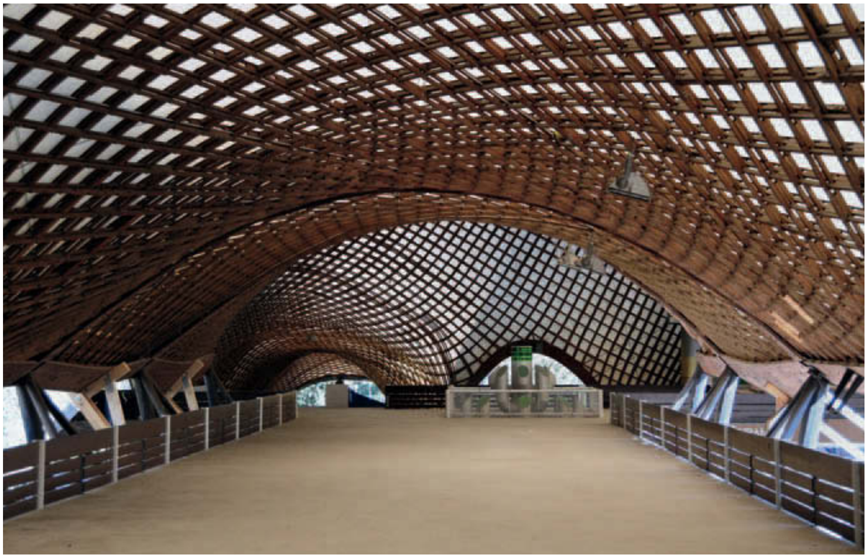


Figure 11.5 Multihalle, Bundesgartenschau, Mannheim, 1975; Carlfried Mutschler and Partners, architects; Ove Arup & Partners (Edmund (Ted) Happold), with Frei Otto, engineers. The 85 m principal span of this multi-space enclosure was achieved with a lightweight, form-active, timber grid-shell. An ingenious construction system was devised to allow the complex form to be built using straightforward techniques. The combination of sophistication and simplicity was similar to that found in the works of Nervi and Torroja.

Photo: Hubert Berberich/Wikimedia Commons.

Figure 11.6 Centre Pompidou-Metz, France, 2010; Shigeru Ban, architect; Arups (Cecil Balmond), engineers. The 90 m-span roof canopy of this building is a timber lattice grid-shell of similar configuration to that at the Multihalle at Mannheim, designed with the aid of recent form-determining software. The building demonstrates the continuing feasibility of using timber for large-scale public buildings.

Photo: Taiyo Europe/Wikimedia Commons.

empirically at the design stage using a scale model consisting of interlinking chains that simulated the tensile version. This was then inverted to give the shape of the compressive grid of the final structure. The internal forces were also assessed from the scale model and confirmed by computer analysis – an early example of computer-aided design. Thus, a highly sophisticated structural form was evolved using relatively simple techniques, especially with regard to construction.

The methodology used for the structure at Mannheim has been greatly extended subsequently, and the design of this type of structure is now almost totally dependent on computer-generated rather than physical models. A recent example is the grid-shell roof of the Centre Pompidou, Metz, France (2010) by the engineer Cecil Balmond (of the Arup organisation) in collaboration with the architect Shigeru Ban (Figure 11.6). The roof structures of the Weald and Downland Open Air Museum building (2002) by Buro

Happold and architects Cullinan, and of the Playhouse for Children at Fukushima (2015) by Arups with the architects Toyo Ito and Klein Dytham are further examples of this technique.

Another example of innovative timber construction is the roof structure of the Aspen Art Museum in Colorado, USA (2014) by the award-winning Japanese architect Shigeru Ban with engineers KL&A Inc. (Figure 11.7) which, with the Centre Pompidou at Metz, was cited in connection with the award of the Pritzker Prize for architecture to Shigeru Ban in 2014. The principal structural element in the Aspen building is in fact a reinforced concrete framework. The innovative timber roof structure covers half of the total 30 m × 30 m square plan in a triangular arrangement with a maximum span of 15 m and depth of 0.9 m and is supported on steel struts from the main structure. The two-way spanning capability of the triangulated timber roof deck, which allowed the use of support from a small number of perimeter columns, was fabricated from Kerto-S and birch plywood and is notable for

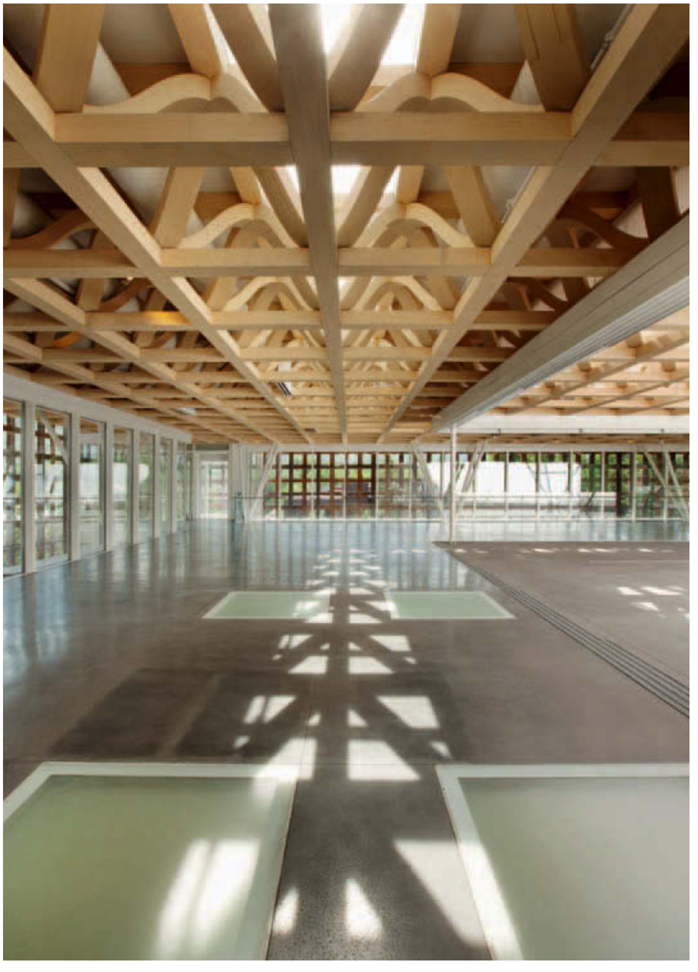


Figure 11.7 Roof structure, Aspen Art Museum, Colorado, USA, 2014; Shigeru Ban, architect; KL&A, structural engineers. The efficiency of this two-way spanning slab-type structure was improved by internal triangulation. The horizontal chord elements were of Kerto-S, a form of laminated timber, and the curved web elements of birch plywood. Both of these materials combined high strength with dimensional stability. The potentially complex 3-D joints were detailed for simple assembly with screws. The finished structure constitutes a highly sophisticated use of a traditional material.

Photo: Derek Skalko.

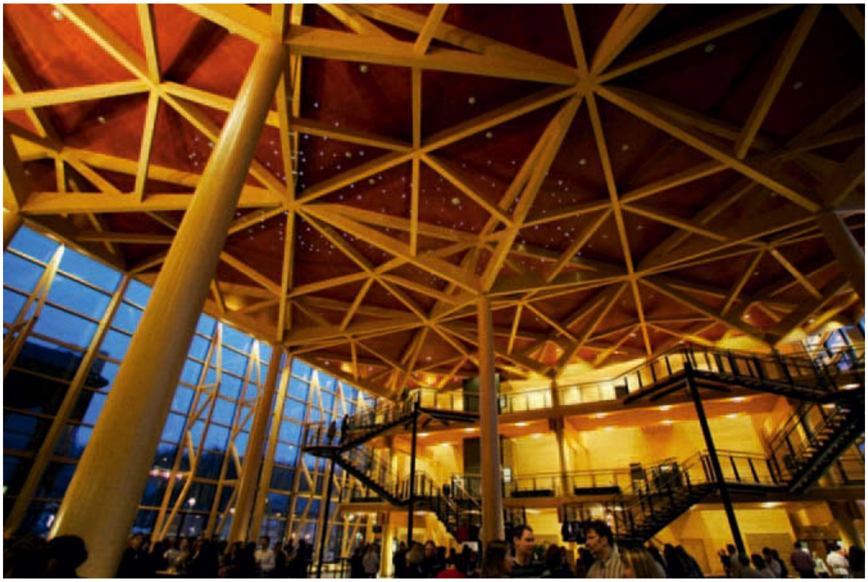


Figure 11.8 Sibelius Hall, Lahti, 2000; Kimmo Lintula and Hannu Tikka, architects; Turun Juva Oy, engineers. The structure of this large building, which includes a 1,100-seat concert hall and an extensive foyer, is entirely of timber and includes laminated timber beams, triangulated trusses and composite, solid-timber and plywood stressed-skin elements. The building demonstrates the continuing feasibility of timber structures for large-scale projects.

Photo: The Free Dictionary.

the simplicity with which potentially complex 3-D connections were made using only screws as fixings. The design is an example of highly innovative design thinking in the context of elements based on a traditional material.

The Sibelius Hall, Lahti, Finland (2000) (Figure 11.8; Kimmo Lintula and Hannu Tikka, architects, Turun Juva Oy, engineers), is a large-scale enclosure with a timber structure of more conventional type. The building forms part of a congress centre, and is supported by post-and-beam structural frameworks that are entirely made from timber. Triangulated space- and plane-frames are used to improve the efficiency of the horizontally spanning elements and laminated elements are used where large cross-sections are required. Timber cavity walls, filled with dried graded sand, are used to provide sound insulation. The concert hall, which is the home of the Lahti Symphony Orchestra, is regarded as one of the world's finest in acoustic terms. The Sibelius Hall building demonstrates that it is possible to build a large public building, with large interior spaces, that is entirely supported by a timber structure.

Timber has also been used for multi-storey buildings where it has supplanted the modern materials of steel and reinforced concrete for post-and-beam structures. A recent example is the LifeCycle Tower One (LCT ONE)

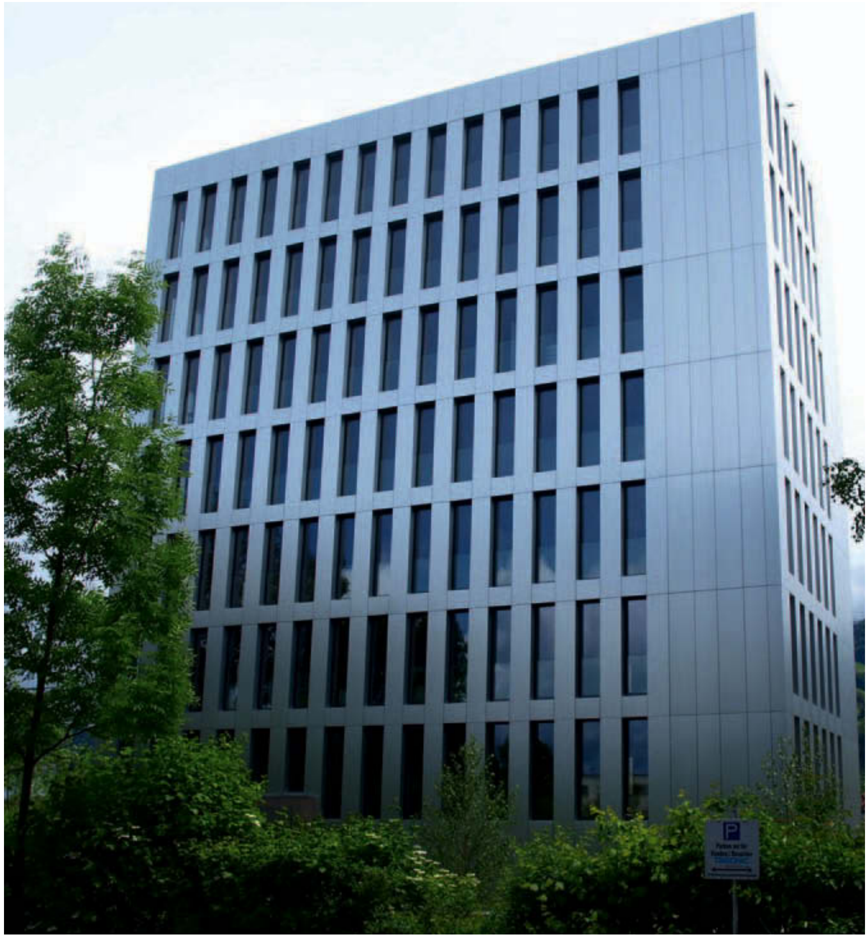


Figure 11.9 LifeCycle Tower One (LCT ONE), Dornbirn, 2013; Hermann Kaufmann, architect. This eight-storey prototype building, which was built as part of a research project for Cree GmbH, contains many features that are designed to reduce energy and material consumption and enhance sustainability performance. It is based on a timber framework structure with composite timber/pre-cast concrete floor slabs, stiffened by a reinforced concrete core containing stairs, ducts and lifts. It demonstrates the feasibility of structural timber for a building typology that is normally associated solely with steel or reinforced concrete frameworks.

Photo: Asumipal/Wikimedia Commons.

Building in Dornbirn, Austria (2013), by architect Hermann Kaufmann (Figures 11.9 and 11.10). This is a medium-rise (8-storey) tower block that houses open-plan offices. The structure consists of a self-supporting reinforced concrete core enclosing lifts and stairs, with a main framework consisting of exposed solid-timber beams and columns. The beams act compositely with a one-way-spanning reinforced concrete floor slab and are configured as prefabricated floor panels capable of spanning up to 9.45 m.

Figure 11.10 LifeCycle Tower One (LCT ONE), Dornbirn, 2013; Hermann Kaufmann, architect. Composite timber/pre-cast concrete floor slab units are supported on closely spaced timber columns. Most of the major components may be easily recycled.

Photo: Darko Todorovic/Build Up.

The building for the Wood Innovation and Design Centre (2014) (Figures 11.11 and 11.12) in Prince George, British Columbia, Canada, by Michael Green, architects, and Equilibrium Consulting, engineers, which is an eight-storey academic and laboratory complex supported entirely by a timber structure, is another recent example of the use of timber in a context that would more normally have been considered to be the province of steel or reinforced concrete. A further example is the 18-storey Brock Commons Tallwood House building (2017, when it was the world's tallest mass timber building), in Vancouver, Canada, by Acton Ostry Architects in collaboration with a number of leading companies and consulting firms, which is a hybrid of timber frame and reinforced concrete core.

The use of timber, rather than either steel or reinforced concrete, for the principal structural elements greatly reduces the embodied energy and carbon footprint of these buildings and makes provision for straightforward re-use or recycling. It also significantly reduces the overall weight of the structure, thus saving on foundation costs, and the prefabrication of the principal structural elements allows a considerable reduction of construction time.

Another example of innovative thinking in relation to timber is so-called bare-pole technology in which timber structural elements are used in

Figure 11.11 Wood Innovation and Design Centre building, Prince George, British Columbia, Canada, 2014; Michael Green Architecture, architects; Equilibrium Consulting, engineers. The structure of this multi-storey academic and laboratory building is entirely of timber.

Photo: WIDC.

Figure 11.12 Wood Innovation and Design Centre building, Prince George, British Columbia, Canada, 2014; Michael Green Architecture, architects; Equilibrium Consulting, engineers. The beams and columns of the building are of laminated timber. The floor decks are also constructed entirely of timber.

Photo: WIDC.

more-or-less their natural state with minimal processing. It avoids the lengthy and energy consuming procedures that have been developed in the Modern period to deal with the variability associated with a material the origins of which are as part of a living organism. These include sawmill conversion, seasoning and grading, which are designed to ensure that the mechanical properties of any timber incorporated into a structure are known within precise limits, as are the dimensions of the constituent elements. All of these processes increase embodied energy and, in this scenario, timber acquires the qualities of an industrial product similar to those of a steel beam. The building design professions and construction industry networks have evolved to deal with the material in this form. It is, however, an example of the kind of reductionist thinking that, though it has undoubtedly allowed a methodology to be developed for the safe and reliable use of timber structurally and for its applications to be extended economically beyond those that were possible with the traditional methods that developed historically, should not now be regarded as the sole possible approach to the design of timber structures. Sustainable design will require breaking into this cycle, so as to reduce the embodied energy by finding ways in which to use timber safely in a more raw state. Bare-pole timber engineering, one of the most 'primitive' versions of the vernacular, is an attempt, in the present day, to evolve structures that are safe and reliable, but which are not dependent on industrial processes that are wasteful of energy and material.

The extension of the structural timber typology to other low-energy materials is also a potentially fruitful development. Examples of this are the use of paper hollow tubes and bamboo in the work of the architect Shigeru Ban.

The potential for the rediscovery and reintroduction of masonry building techniques is also considerable. The Central Market complex in Koudougou, Burkina Faso (1999–2005) (Figures 11.13 and 11.14), which was constructed in bricks of tamped earth and in which traditional arch and vaulted forms were used to achieve the necessary large horizontal spans, further demonstrates that sustainable forms of construction can be applied in the making of large-scale public buildings.

The traditional masonry buildings of northern Europe also offer useful precedents for a sustainable architecture. Examples of the typology, from central Edinburgh in Scotland, are shown in Figure 11.15. These are buildings that have been in continuous use for more than 200 years, during which time their slate roofs and stone masonry walls have received very little maintenance (in comparison to that required for Modern buildings in steel, glass and metal cladding), and that, with minimal adaptation, still form useful elements of the building stock. Their components are also easily recycled or re-used. The typology is no longer considered feasible for new-build houses, due mainly to the labour-intensive nature of the construction process, but, with suitable

Figure 11.13 Central Market complex, Koudougou, Burkina Faso, 1999–2005; Swiss Agency for Development and Cooperation, architects and project directors. This complex, which involves 85 domes, 658 vaults and 1,425 arches covering a total area of 29,000 sq m (312,000 sq ft) provides shops, commercial accommodation and social spaces in the third largest city in Burkina Faso. It was constructed entirely from locally available materials (principally bricks and blocks in hand-pressed soil) and was designed to minimise solar exposure and enhance air circulation within its large and densely occupied interior. It is remarkable for its combination of low-tech materials and construction methods with a sophisticated approach to design.

Photo: Amir-Massoud Anoushfar/Aga Kahn Development Network.

Figure 11.14 Central Market complex, Koudougou, Burkina Faso, 1999–2005; Swiss Agency for Development and Cooperation, architects and project directors. Design for low environmental impact involves the adoption of forms that are structurally efficient, so as to minimise the use of material, and that are appropriate for their constituent materials. This is a context in which a purely formalist approach to architectural design is unlikely to be successful.

Photo: Laurent Séchaud/Swiss Agency for Development and Cooperation.

Figure 11.15 Town houses, New Town of Edinburgh, Scotland, *c.*1800 CE. Buildings such as this, with stone masonry walls and slate-clad roofs, were common throughout Scotland in the pre-Modern period and are examples of a building tradition, based on the use of locally available materials, that was well adapted to the climate of the region. After more than 200 years of continuous use, and with minimal maintenance or adaptation, they still form an important part of the building stock. This truly sustainable architecture, which also performs well in relation to the criteria of good structural design articulated by Nervi and Torroja (see Section 8.2), with suitable incorporation of contemporary technology, could provide one type of precedent for the sustainable built environment of the future.

Photo: Patricia & Angus J. Macdonald/Aerographica.

adaptation of techniques and masonry materials, it is possible that new developments of such stone-and-timber technology could be introduced, alongside some of the other innovative developments discussed above, to provide one of the components of a future sustainable architecture.

An example of innovative technology applied to the reintroduction to structures of a traditional material is the use of machined masonry blocks in the wall of the Pavilion of the Future at Expo 92 in Seville by the engineer Peter Rice (Figure 11.16). Machine cutting of stone is an industrial process that was developed in connection with the manufacture of stone cladding elements for building. It allows the production of stone blocks with perfectly flat surfaces and, although this was not the purpose of the process, it allows

Figure 11.16 Pavilion of the Future, Expo 92, Seville, Spain, 1992; Martorell Bohigas Mackay, architects; Arups (Peter Rice) engineers. One of the structural walls of this building consisted of a composite of slender steel elements and stone masonry blocks. The perfectly plane surfaces of the machine-cut stone blocks allowed smooth transfer of load without bedding in mortar. The filigree steelwork was arranged to apply the load to the masonry arches such that they were subjected to pure axial compression (form-action). The structure was intended as a demonstration that, with the use of contemporary shaping techniques, stone masonry might be reconsidered in the future as a structural material.

stone blocks to be configured as structural walls without the need for bedding in mortar. It was largely a desire to demonstrate this possibility (new in the context of Modern architecture) that led Rice to devise the highly unusual support wall for one side of a building that is otherwise configured as a steel framework. The filigree steelwork that was used to distribute the concentrated loads from the steel roof girders so that the supporting stone arches became form-active was a *tour-de-force* of structural virtuosity that was typical of this most innovative engineer. Rice's intention was, however, to demonstrate that, with the use of modern technology, it is possible to consider stone to be a structural material in the modern age. In view of its other environmental qualities, most particularly its high durability, high thermal mass and low embodied energy, stone offers considerable potential for sustainable design – so far unrealised.

An aspect of structural design for sustainability that must always be considered is that the minimisation of the use of structural material is not in all cases necessarily the most sensible option technically. Structural mass, provided by materials with low embodied energy, such as masonry or mud, can enhance the environmental performance of a building by providing thermal mass and insulation and an enclosure with good durability characteristics. As always in sustainable thinking, however, the wider picture must be a prime consideration, and concentration on one aspect of design avoided. The need for continuous feedback loops is always necessary. For example, the adoption of masonry or mud as a structural material for the non-structural reason that it had large thermal mass, would favour the adoption of forms that eliminate or significantly reduce tensile stress, such as vaults, domes or arches.

The development of sustainable forms is in every case facilitated by an intimate knowledge of structural behaviour – of the archetypes of structure (see Chapter 4). For example, the introduction of even a slight upwards curvature to a horizontally spanning slab or beam, which would convert it from non-form-action to semi-form-action, would make possible a considerable saving in material. Equally, the slight upward curvature in the transverse direction of a horizontally spanning floor slab, which would introduce a small degree of 'improvement' to its cross-section, would considerably increase the efficiency of the form and allow a significant reduction in the thickness required. At every stage of design, the intelligent use of a knowledge of the factors that affect structural efficiency could bring about savings in the amount of material required. Such thinking will be required at both the level of building design and that of component manufacture.

Holistic thinking in the interaction of structural design with other aspects of building design, especially those of increased environmental control and long-term durability – and always with regard to first principles and based on a knowledge of archetypes – is likely to be the way forward. As already emphasised above, useful precedents are most likely to come from traditional forms rather than from the majority of those commonly used in the Modern period.

11.6 Conclusion

As discussed throughout this chapter, the technical problems concerned with the evolution of a sustainable society tend currently to be overshadowed by those associated with cultural and social aspirations connected to lifestyle. In the context of the built environment, a major issue for the future will be the balance to be struck between the potential conflict between private and public interests, including such questions as whether or not it is in the interests of society as a whole that a particular building should actually be built at all – and who should decide this question. Does humanity really need a self-inflicted competition to build the highest skyscraper, or for individuals or consortia to make vast wealth from the development of inner-city complexes and corporate offices, clad mainly in glass? Questions such as these are beyond the competence or ability of the building design professions to resolve but are nevertheless among the most fundamental for the creation of a sustainable built environment.

So far as the question of architectural style is concerned, what can be done to bring about a re-examination of the drivers of the visual imagery of architecture in order to release it from the Modernist preoccupation with formalism and a visual vocabulary based on shapes and textures that have no meaning in the context of the physical realities of the natural environment? How is the discourse in the architectural media, which feeds the desire for the continued use of this imagery, to be deflected from its obsessions with 'originality', 'newness', fashion, and its embedded position in the linear economy? Is it possible to satisfy a natural desire for novelty with a visual agenda that is compatible with wider environmental concerns, and in particular, that does not make an unnecessarily profligate, and therefore unsustainable, use of energy and materials?

Efficiency in the use of structural material is almost entirely dependent on all aspects of form, from the overall form of the entire structure to the detailed shapes of the individual elements. Consideration of structural efficiency cannot, therefore, in the context of the desire for environmental sustainability, be separated from the determination of the form and massing of a building and thus from matters of style. This is one of the most serious considerations affecting the development of environmentally responsible building forms. Altering the current situation – in which sustainability is not given as high a priority as purely visual considerations – will require that architects (or, more realistically, teams of architects and other building professionals) pay much more attention to the environmental agenda when determining the forms of buildings, and further, that they take meaningful account of the relationship between form and technical performance in a way that has been conspicuously lacking in the design of most Modern architecture.

Truly creative thinking – genuine innovation based on knowledge of fundamental principles rather than on precedent – is above all what will be required. It is to be hoped that architects and engineers will energetically engage with and surmount this increasingly imminent challenge, to the benefit of the environment, both ecological and visual.

As Cecil Balmond states in his book *Informal* (2002, p. 14), discussing his own methodology:

> [T]he intervention that influences the design is a local forcing move, or a juxtaposition that stresses rhythm, or two or more events mixing to yield hybrid natures. As the effects are multiplied by extension or overlapping, surprising and ambiguous answers arise . . . there is no hierarchy, only interdependence.

Notes

1 *De Stijl*, Vol. 2, 1918, quoted in Jaffé, 1986.
2 *De Stijl*, Vol. 1, 1917, quoted in Jaffé, 1986.

Glossary of structural terms

Archetypes of structural form: Concepts that relate structural form to structural behaviour. Examples are the ideas of form-active or non-form-active shapes, which are concerned with the relationship between structural form and internal force type and therefore with structural efficiency. Another example is the concept of 'improved' shape of cross-section, such as occurs when a slab-type structure is folded to increase the second moment of area of its cross-section, and therefore the efficiency with which it resists bending.

Axial force: Force applied parallel to and coincident with the principal axis of a structural element.

Axial stress: Stress that is caused by axial force and that acts at right angles to the cross-sections of a structural element – normally of constant magnitude across the cross-section.

Bending moment: Moment (one of the internal 'forces') that acts on the cross-section of a structural element, caused by the components of external forces that act at right angles to its principal axis. Evaluated by considering the extent to which the moments of forces on one side of a cross-section are out of balance. Normally, bending moment is the internal 'force' that determines the size of cross-section required for elements subjected to loads that cause them to bend (non-form-active and semi-form-active elements).

Bending stress: Stress caused by bending moment, which acts at right angles to a cross-section and normally varies across the cross-section from a maximum tensile stress at one extreme fibre to a maximum compressive stress at the other.

Bracing: Structural elements provided to make an arrangement stable.

Buckling: A complex instability phenomenon in which elements loaded in compression fail by bending at levels of average stress that are significantly less than the failure/yield stress of the material. Investigated mathematically by Leonhard Euler who identified slenderness (see slenderness ratio) as the critical factor in buckling failure, and who devised a method for determining the average stress level at which buckling would be initiated (which was later evolved into a trial-and-error procedure for safe design of compressive elements). Most present-day design methods are based on, or are similar to, Euler's procedure.

Buckling failure can occur to any element or part-element that is subjected to compression. It can be inhibited by provision of lateral restraint (bracing).

Collapse load: The load required to cause a structure to collapse due to strength failure.

Continuous structure: See statically indeterminate structure.

Dead load: Weight of the structure itself and of anything that is permanently attached to it.

Deflection: Displacement caused by the application of load to a structure.

Derivative: In calculus, the result of the process of differentiation. Physically, the derivative of a mathematical function gives the rate at which the quantity shown by the function is changing, as shown by the gradient of the graph of the function.

Design load: **Working load** multiplied by a factor of safety. In load-factor and plastic design, the sizes specified for structural elements should be such that the collapse load is not less than the design load.

Design stress: In load-factor and plastic design, stress level used to evaluate the collapse load. Normally taken to be the yield stress of the material.

Differentiation: In calculus, an operation performed on a mathematical function (of x) which gives a new function (its derivative) that is related to the gradient of the graph of the original function, for all values of x. The gradient gives the rate at which the original function is changing for all values of x.

Discontinuous structure: See statically determinate structure.

Elastic behaviour: A condition of loading in which the deformation (strain) that occurs to material as a consequence of the application of load is directly proportional to the magnitude of the load and in which no permanent deformation remains following removal of the load.

The graph of load against deformation is a straight line and the material is said to be behaving 'linearly'. The concept can be applied to whole structures as well as to specimens of material. Most materials and structures behave elastically at low and moderate levels of load.

Elastic Bending Equation (also known as **Euler-Bernoulli Beam Theory**, **Engineer's Beam Theory** and **Classical Beam Theory**): The Elastic Bending Equation relates the load on an element that is subjected to bending to the deflection that results from the load. The most general form of the equation is:

$$d^4w/dx^4 = q(x)/\ E(x)\ I(x)$$

where:

w	=	deflection
x	=	distance along element
q	=	load function
E	=	modulus of elasticity of the material (Young's Modulus)
I	=	second moment of area of the element's cross-section about the axis through its centroid

In this form of the equation, provision is made for the load, the cross-section of the element, and the properties of the constituent material to vary along its length (that is, to be functions of x).

Derivatives of this equation are used extensively in structural analysis and for element sizing.

Elastic design: A method for sizing structural elements which is based on equations relating load to stress and deformation which assume elastic (linear) behaviour. The objective is to produce structures in which a maximum permissible stress (normally the yield stress of the material divided by a factor of safety) is not exceeded under working load conditions. The advantage of the method is that it is simple to apply and simulates the actual behaviour of the structure under working load conditions. Its disadvantage is that the collapse load of the structure (and therefore the true factor of safety against collapse) is not known. The level of risk that the structure may fail is therefore also unknown.

Elastic limit: The level of stress required to cause structural material to yield (that is pass from elastic to plastic behaviour – see also **yield stress** and **yield point**).

Elastic modulus (**Young's Modulus – E**): The ratio of axial stress to strain in a material when the applied load is within the elastic range. This is normally constant within the elastic range and the graph of stress against strain is a straight line ('linear' behaviour). Young's Modulus is a fundamental property of a material.

Elastic modulus of section (Z): A geometric property of the cross-section of a structural element found by dividing the second moment of area (I) by the distance from the neutral axis to the extreme fibre (y_{max}). The modulus of section allows the maximum (extreme fibre) bending stress to be calculated directly from the applied bending moment in the formula $\sigma_{max} = M/Z$, where:

σ_{max}	=	extreme fibre stress
M	=	applied bending moment
Z	=	modulus of section of cross-section.

Section Modulus is directly proportional to the square of the depth of the cross-section. It is also directly proportional to the bending strength of the element, which therefore also depends on the square of its depth.

If the cross-section is not symmetrical, the neutral axis is not mid-way between extreme fibres and there will be two values of Z, one for each extreme fibre. In this case the maximum values of compressive and tensile bending stress are not equal and the bending strength of the element is given by the lower value of Z.

Equations of equilibrium: See **equilibrium**.

Equilibrium: A condition in which the forces acting on a body cause it to remain at rest. The condition is satisfied if the forces have no resultant and exert no net turning effect on the body. The conditions for equilibrium can be used to set up equations which link the forces in a system under equilibrium. For a 2-D system these are,

The sum of the horizontal forces (ΣH)	=	0
The sum of the vertical forces (ΣV)	=	0
The sum of the moments of the forces (ΣH)	=	0

The equations of equilibrium can be used to solve for any of the forces that are unknown – for example, to calculate the reactions at the foundations of a structure from the applied loads.

Equilibrium analysis: Evaluation of all the forces acting on and within a structure solely from consideration of its equilibrium (and therefore from the equations of equilibrium).

Extreme fibre (of a **cross-section**): The parts of a cross-section (normally the top and bottom) that are furthest from the neutral axis and where the maximum bending stresses occur. If the cross-section is not symmetrical about the neutral axis, the distances to the extreme fibres will be different on the compressive and tensile sides of the cross-section and the maximum tensile and compressive bending stresses will also be different.

Form-active structure: A structure in which the internal force is purely axial (either tensile or compressive) due to the relationship between the shape of its longitudinal axis and the pattern of applied load.

Hinge-joint: A joint between two or more structural elements that allows relative rotation. A hinge-joint is incapable of transmitting bending moment. The bending moment at a hinge-joint is zero.

Imposed load (also called **variable load**): Load on a structure that is not permanent, for example due to people occupying a room, weights of non-permanent 'fixtures' and fittings, or climatic effects such as wind or snow. In structural analysis the maximum values and the most unfavourable combinations of imposed load must be evaluated. The latter are not necessarily the same for different elements in the same structure.

'Improved' cross-section: In the context of bending, a cross-section that reduces the amount of under-stressed material that is present – for example an I-shaped or hollow-box cross-section for a beam or a corrugated cross-section for a slab. More generally, a cross-section in which the ratio of second moment of area to cross-sectional area is high.

Integration: In calculus, an operation performed on a mathematical function (of x) that is the opposite of differentiation. The integral of the function is a new function which gives the accumulated magnitude of the quantity shown by the original function at the value of x (which is the same as the area under the graph of the original function up to that value of x).

Internal force: A force (or other phenomenon such as bending moment) which acts within a structural element and causes stress. Internal forces are evaluated during structural analysis and determine the sizes required for structural elements.

Linear behaviour: In the context of structures, this concept is used almost exclusively with respect to the relationship between load and deflection and refers to the load range in which deflection is directly proportional to the magnitude of load, and in which the graph of load against deflection is a straight line. This is one of two essential features of elastic behaviour, the other being the absence of permanent deformation once load is removed.

Live load: The same as **imposed load**.

Load: External forces acting on a structure. These may be caused by weight (gravitational load) of the structure itself (**dead load**) or items that it is designed to carry (gravitational imposed load) or by other agencies such as wind, snow or seismic phenomena (earthquakes). Evaluation of load is the essential initiating operation of structural analysis.

Load factor: Multiple by which the estimated working load on a structure is multiplied to give a factored design load.

Load factor design: A design methodology for structural elements by which sizes are allocated to achieve a condition in which the calculated collapse load of the structure is the same as the factored design load. The objective is to ensure that the true factor of safety against the possibility of collapse (and therefore the risk of collapse) is known. The method requires that the non-linear behaviour of the structure, as the collapse load is approached, be simulated. In practice the method, which usually involves the prediction of the locations of plastic hinges, is more complex to apply than the **elastic design** method.

Moment of a force: The turning effect of a force about a point that is not on its line of action.

Moment of resistance: The maximum bending moment that can be sustained by a beam – proportional to its elastic modulus of section (Z) and therefore to the square of its depth.

Monocoque structure: In a monocoque structure the enclosing skin (surface) is the only structural element and carries all of the load. A bird's egg is an example of a monocoque structure. See also **Semi-monocoque structure**.

Neutral axis: In elastic bending theory, the axis through the cross-section of a beam at which the bending stress changes from tensile to compressive. It is co-incident with the axis through the centroid of the cross-section that is perpendicular to the plane of bending. The values of second moment of area (I) and section modulus (Z) of cross-section that are used in elastic theory for the calculation of deflection and bending stress in an element must apply to the neutral (centroidal) axis of its cross-section.

Non-form-active structure: A structure in which the internal force is purely bending moment (and shear force) due to the relationship between the shape of its longitudinal axis and the pattern of applied load.

Permissible stress: In the elastic design method, the stress which must not be exceeded and which determines the sizes of elements required to provide adequate strength – normally the yield stress of the material divided by a factor of safety.

Plastic behaviour: A condition of loading in which the deformation (strain) that occurs to material as a consequence of the application of load is not directly proportional to the magnitude of the load and in which permanent deformation remains following removal of the load. In most materials, plastic behaviour occurs, under increasing levels of load, once the yield stress (yield point) has been exceeded. In the plastic load range, the graph of stress against strain is a curve.

Plastic design: A method for sizing structural elements based on the principle that the calculated collapse load of a structure should not be less than a factored design load. The method is intended to provide a more accurate assessment of the true factor of safety against collapse than is possible with elastic design. The theoretical basis of the method is complex, due to the difficulty of simulating the behaviour of a structure as the collapse state is approached and the material is behaving non-linearly at stress levels greater than the yield stress. In practice, design formulae relating element sizes to strength are normally empirically derived, which limits their usefulness to specific materials and element types.

Plastic hinge: A concept used to simulate the collapse of an element loaded in bending and that assumes hinge-like behaviour, due to the yielding of material in the vicinity of the maximum bending moment. Once a plastic hinge has formed, it offers continuing resistance to a particular level of bending and requires the application of sustained load for the collapse mechanism to proceed. If a structure is statically indeterminate, more than one plastic hinge will be necessary to bring about the collapse of the whole structure. The simulation of plastic hinges and the prediction of the sequence of their formation, as a structure proceeds to collapse under increasing load, is an essential aspect of the plastic (load factor) design method.

Portal framework: A framework that consists of a horizontally spanning element supported on two vertical elements. Its essential characteristic is that it is semi-form-active so that any load applied to it generates bending in all of the elements irrespective of the one to which it is applied. This normally requires that the joints between the horizontally spanning element and the supports be rigid joints. In the most commonly used form the horizontal element is pitched with a central peak. The frame is statically determinate if it contains three hinge joints but these must not be located at the ends of the horizontally spanning element otherwise semi-form-active behaviour will not occur. Portal frames should not be confused with post-and-beam arrangements in which hinge connections do occur between horizontal and vertical elements that prevent transmission of bending between them. Because they are semi-form-active, portal frameworks are more efficient than post-and-beam arrangements.

Reaction: Force required to balance a load to achieve equilibrium. Reactions occur at the foundations of structures and, if elements are considered in isolation, at the points where they derive support from adjacent elements. The conditions at foundations and at joints between elements must be such as to provide sufficient reactions to balance all possible configurations of load.

Resultant (of a set of forces): The resultant is the single force that produces the same effect as a group of forces. It may be found by vector addition in a triangle or polygon of forces.

Rigid joint: A joint between elements that prevents rotational movement between the elements and that can transmit bending moment between elements. Full rigidity is almost impossible to achieve in practice but is normally assumed to occur for the purposes of structural analysis, especially of statically indeterminate structures. The assumption introduces errors that degrade the accuracy of the analysis and that are difficult to quantify because even small amounts of slippage can significantly affect the distribution of internal forces in a structure.

Second moment of area (I): A geometric property of the cross section of a structural element that defines its response to bending and that is used in the calculation of bending stress and deflection. It takes account of the extent to which the material in the cross-section is dispersed from its neutral axis.

Second moment of area is defined by the relationship:

$$I_{xx} = \int y^2 b_y dy$$

where:

I_{xx} = second moment of area about the x–x axis (neutral axis)
y = distance from the neutral axis
b_y = breadth of cross-section at y

The x–x (neutral) axis is coincident with the centroidal axis of the cross-section.

In practice, second moment of area is normally calculated from a formula. For example, the second moment of area of a rectangle about its centroidal axis is given by:

$$I_{xx} = bd^3/12$$

where b and d are the breadth and depth of the cross-section respectively.

Second moment of area appears in many of the formulae that are derived from the Elastic Bending Equation. For example,

$$\sigma_y = My/I$$

where:

σ_y = bending stress at location y
M = applied bending moment
y = distance from neutral axis
I_{xx} = second moment of area of cross-section about its neural axis.

Second moment of area is sometimes referred to as moment of inertia. This is an incorrect usage. Moment of inertia is second moment of area multiplied by material density and is a concept used in the field of dynamics in connection with the behaviour of rotating systems such as gyroscopes.

Semi-form-active structure: A structure in which the internal force is a combination of axial thrust and bending moment (and shear force) due to the relationship between the shape of its longitudinal axis and the pattern of applied load.

Semi-monocoque structure: In a semi-monocoque structure a structural skin acts compositely with supporting ribs and stringers. The fuselages of most metal aircraft have semi-monocoque structures.

Shear force: Internal force in a structural element caused by the components of external forces that act at right angles to its principal axis, evaluated by considering the extent to which these forces are out of balance to one side of the location of the cross-section.

Shear force is linked to bending moment and at any location is directly proportional to the rate at which bending moment is changing.

Shear force causes opposing pairs of shearing effects in bending elements that act simultaneously on planes parallel and perpendicular to cross-sections.

Shear stress: The stress that results from shear force. Shear stress acts both parallel and perpendicular to the axes of structural elements that are loaded in bending, and varies in magnitude within cross-sections. In design calculations it is common for only the average value of shear stress (shear force divided by the area of cross-section) to be evaluated and compared to a permissible average shear stress for the material concerned. The need to limit shear stress is rarely the critical factor that determines the sizes required for structural elements.

Slenderness ratio: A measure of the slenderness of an element and therefore of its susceptibility to buckling failure. The most basic version is simply the length of the element divided by the least width of its cross-section. A more sophisticated version (as defined by Euler) is the length divided by the smallest radius of gyration of the cross-section, where radius of gyration is the square root of the second moment of area divided by the area of cross-section. In most practical design procedures the permissible average value of compressive stress is determined by slenderness ratio.

Slope: The change in orientation of part of a structural element that results from the deflection caused by bending.

Stability: The ability of a system to return automatically to its original state following minor disturbance. Structures must be stable, which is a separate property from strength. Tension is fundamentally stable and compression fundamentally unstable. Instability is therefore an important consideration in the design of columns, walls, the compression parts of beams and girders and in compressive form-active structures. Bracing systems can be used to prevent instability by providing lateral support for the compressive parts of structures.

Statically determinate structure (also called **discontinuous structure**): A structure in which all internal and external forces can be calculated from consideration of equilibrium alone, because sufficient equations can be generated from the conditions for equilibrium to solve for all unknown forces.

A statically determinate structure contains only the minimum constraint required to enable it to resist load and this gives it particular properties: movement due to thermal expansion or contraction, or to foundation subsidence, does not generate internal forces that are additional to those caused by load. Statically determinate structures are simpler to construct than indeterminate equivalents but are less efficient because internal forces are higher for a given level of load.

Statically indeterminate structure (also called **continuous structure**): A structure in which all internal and external forces cannot be calculated from consideration of equilibrium alone, because sufficient equations cannot be generated from the conditions for equilibrium to solve for all unknown forces. Normally, the deformation characteristics of the structure, determined from elastic theory, are used to generate the extra equations required for complete solution of the structure. Because deformation in response to load is dependent on element size, the design of a statically indeterminate structure is a cyclic process. Trial sizes must be allocated initially, to allow the analysis to proceed, and an iterative process used to determine satisfactory final sizes.

A statically indeterminate structure contains more than the minimum constraint required to make it a structure, rather than a mechanism, and this gives it particular properties: movement due to thermal expansion or contraction, or to foundation subsidence, generates internal forces that are additional to those caused by load and therefore affects the sizes of elements which must be selected for adequate strength. Statically indeterminate structures are more difficult to construct than determinate equivalents but are more efficient because internal forces are lower for a given level of load.

Strain: Deformation that results from the application of load, normally expressed as a dimensionless quantity by dividing the change that occurs to a dimension, as a result of the application of load, by the original value of that dimension. For example, axial strain is defined as change in length divided by original length.

Stress: Internal force per unit area. Strain and stress are inevitable consequences of load.

Structural analysis: A process, normally based on numerical calculations but possible by other methods such as graphic statics, in which all the forces that act on and within a structure are evaluated.

Structural archetype: See **archetypes of form**

Temperature stress: Stress in a structure caused by thermal expansion or contraction. This normally only occurs in statically indeterminate structures.

Wind bracing: A grouping of structural elements that conducts wind loading through a structure, often co-incident with bracing which would in any case be required to provide stability.

Working load: The maximum load to which a structure will actually be subjected, normally based on a statistical probability, and compiled from analysis of historical load data, and made available to designers in building standards. In practice, composed of several components (such as gravitational loads on floors and roofs, wind pressure loads, etc.). In structural design, the maximum and most unfavourable combinations of loads must be evaluated at the beginning of the structural analysis process. The worst combinations are frequently different for different elements in a particular structure.

Yield point: The point in a graph of stress against strain at which a material begins to behave in a non-linear way, with increasing amounts of strain being required to produce a given increase in stress. It is the point in the stress–strain graph that defines the transition from elastic to plastic behaviour, and at which the graph changes from a straight line to a curve.

Yield stress: Stress level at the yield point. In elastic design the structure is considered to have failed if the yield stress is exceeded. In plastic design, the yield stress is normally taken to be the **design stress**.

Young's Modulus: See **elastic modulus**.

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