Chapter 7

Structure and architecture

7.1 Introduction

Two related but distinct issues are discussed in this chapter. These are the relationship between structure and architecture and the relationship between structural engineers and architects. Each of these may take more than one form, and the type which is in play at any time influences the effect which structure has on architecture. These are issues which shed an interesting sidelight on the history of architecture.

Structure and architecture may be related in a wide variety of ways 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 infinite number of possibilities is discussed here under six broad headings:

- *ornamentation of structure*
- *structure as ornament*
- *structure as architecture*
- *structure as form generator*
- *structure accepted*
- *structure ignored*.

As in the case of the relationship between structure and architecture, the relationship between architects and structural engineers may take a number of forms. This may range from, at one extreme, a situation in which the form of a building is determined solely by the architect with the engineer being concerned only with making it stand up, to, at the other extreme, the engineer acting as architect and determining 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. As will be seen, the type of relationship which is adopted has a significant effect on the nature of the resulting architecture.

7.2 The types of relationship between structure and architecture

7.2.1 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 form of the buildings into which the age has poured its architectural creativity. In the periods in which this mood has prevailed, the forms that have been 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 in which structure dictated form was the Parthenon in Athens (Fig. 7.1). The architecture of the Parthenon is tectonic: structural requirements dictated the form and, although the purpose of the building was not to celebrate structural technology, its formal logic was celebrated as part of the visual expression. The Doric Order, which reached its greatest degree of

Fig. 7.1 The Parthenon, Athens, 5th century BC. Structure and architecture perfectly united.

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 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 which could be fashioned in a logical and straightforward manner from the available materials. In these buildings the structure and the architectural expression co-exist in perfect harmony.

The same may be said of the major buildings of the mediaeval Gothic period (see Fig. 3.1), 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, but unlike the Greek temples they had spacious interiors which 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

1 For example, Scully, V., *The Earth, the Temple and the Gods*, Yale University Press, New Haven, 1979.

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. Virtually everything which is visible is structural and entirely justified on technical grounds. All elements were adjusted so as to be visually satisfactory: the 'cabling' of columns, the provision of capitals on columns and of string courses in walls and several other types of ornament were not 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 (see Section 7.3), one of which was that the structural armatures of buildings were increasingly concealed behind forms of ornamentation which were not directly related to structural function. For example, the pilasters and half columns of Palladio's Palazzo Valmarana (Fig. 7.2) and many other buildings of the period were not positioned at locations which were 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 which developed between architects and those who were responsible for the technical aspects of the design of buildings (see Section 7.3).

It was not until the twentieth century, when architects once again became interested in tectonics (i.e. the making of architecture out of those fundamental parts of a building responsible for holding it up) and in the aesthetic possibilities of the new structural technologies of steel and reinforced concrete, that the ornamental use of exposed structure re-appeared in the architectural mainstream of Western architecture. It made its tentative first appearance in the works of early Modernists such as Auguste Perret and Peter Behrens (Fig. 7.3) and was also seen in the architecture of Ludwig Mies van der Rohe. The structure of the Farnsworth House, for example, 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

Fig. 7.2 The Palazzo Valmarana, Vicenza, by Andrea Palladio. The pilasters on this façade 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.

Fig. 7.3 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 forms a significant component of the visual vocabulary. Unlike in many later buildings of the Modern Movement the structure was used 'honestly'; it was not modified significantly for purely visual effect. With the exception of the hinges at the bases of the columns it was also protected within the external weathertight skin of the building. (Photo: A. Macdonald)

Reliance Controls building at Swindon, UK (Fig. 7.4), for example, by Team 4 and Tony 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] which was selected for its 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 (Fig. 7.17) is another example. The overall configuration of the steel structure, which forms the principal architectural element of this building, was determined from technical considerations. The visual aspects of the design were carefully controlled, however, and the design evolved through very close collaboration between the teams of architects and engineers from the offices of Nicholas

2 See Macdonald, Angus J., *Anthony Hunt*, Thomas Telford, London, 2000.

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.

Fig. 7.4 Reliance Controls building, Swindon, UK, 1966; Team 4, architects; Tony Hunt, structural engineer. The exposed structure of the Reliance Controls building formed an important part of the visual vocabulary. It was modified in minor ways to improve its appearance. (Photo: Anthony Hunt Associates)

Grimshaw and Partners and Anthony Hunt Associates 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 well-resolved buildings which perform well when judged by either technical or non-technical criteria.

7.2.2 Structure as ornament

> 'The *engineer's aesthetic*[4] and architecture – two things that march together and follow one from the other.'[5]

The relationship between structure and architecture categorised here as *structure as ornament* involves the manipulation of structural elements by criteria which are

4 Author's italics.
5 Le Corbusier, *Towards a New Architecture*, Architectural Press, London, 1927.

principally visual and it is a relationship which has been largely a 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 these structures is often less than ideal when judged by technical criteria. This is the feature which 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 which 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 which is intended to convey the idea of progress and of a future dominated by technology. The images associated with advanced technology are manipulated freely to produce an architecture which celebrates 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 which 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 which 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, etc. (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 Lloyds headquarters building in London is an example (Fig. 7.5). The curved steel elements which 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 (Fig. 4.14). 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 Lloyds merely increases the probability that it will be blown away by the wind. Its use here is entirely symbolic.

The Renault Headquarters building in Swindon, UK, by Foster Associates and Ove Arup and Partners is another example of this approach (see Figs 3.19 and 6.8). 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'[6] and an established position at the cutting edge of technology. The building is undoubtedly elegant 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.'[7].

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: the

6 Lambot, I. (Ed.), *Norman Foster: Foster Associates: Buildings and Projects*, Vol. 2, Watermark, Hong Kong, 1989.
7 *Ibid*.

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 Associates at Thamesmead, London (see Fig. 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[8]. The decision to use the more expensive, more spectacular structure was therefore taken on stylistic grounds.

The structure possesses a number of other features which 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[9] 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 which 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

Fig. 7.5 Entrance canopy, Lloyds headquarters building, London, UK, 1986; Richard Rogers and Partners, architects; Ove Arup & Partners, structural engineers. The curved steel ribs with circular ‘lightening’ holes are reminiscent of structures found in the aerospace industry. (Photo: Colin McWilliam)

8 *Ibid*.
9 See Lambot, *ibid*.

earliest days of iron and steel frame design in the nineteenth century.

The sources of the visual vocabulary of structural technology used in the symbolic version of *structure as ornament* are various and, for the most part, not architectural. In some cases the source has been science fiction. More usually, images were employed which were perceived to represent very advanced technology, the most fruitful source for the latter being aeronautical engineering where the saving of weight is of paramount importance, and particularly the element with complex 'improved' cross-section and circular 'lightening' holes. Forms and element types which are associated with high structural efficiency – see Chapter 4 – are therefore employed.

One of the problems facing the designers of aircraft or vehicle structures is that the overall form is dictated by non-structural considerations. The adoption of structurally efficient form-active shapes is not possible and high efficiency has to be achieved by employing the techniques of 'improvement'. The whole vocabulary of techniques of 'improvement' – stressed-skin monocoque and semi-monocoque 'improved' beams, internal triangulation, sub-elements with I-shaped cross-sections, tapered profiles and circular 'lightening' holes – is exploited in these fields to achieve acceptable levels of efficiency (see Figs 4.13 to 4.15). It is principally this vocabulary which has been adopted by architects seeking to make a symbolic use of structure and which has often been applied in situations where the span or loading would not justify the use of complicated structures of this type on technical grounds alone.

The dichotomy between the appearance and the reality of technical excellence is nowhere more apparent than in the works of the architects of the 'Future Systems' group (Fig. 7.6):

> 'Future Systems believes that borrowing technology developed from structures designed to travel across land (automotive), or through water (marine), air (aviation) or vacuum (space) can help to give energy to the spirit of architecture by introducing a new generation of buildings which are efficient, elegant, versatile and exciting. This approach to shaping the future of architecture is based on the celebration of technology, not the concealment of it.'[10]

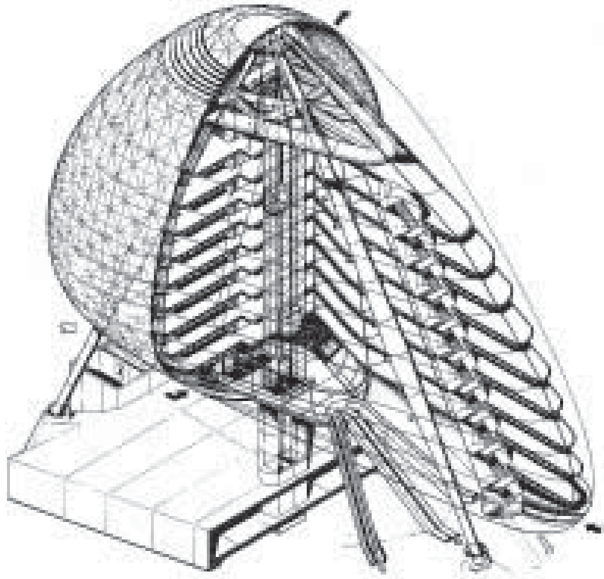


Fig. 7.6 Green Building (project), 1990: Future Systems, architects. Technology transfer or technical image-making? Many technical criticisms could be made of this design. The elevation of the building above ground level is perhaps the most obvious as this requires that an elaborate structural system be adopted including floor structures of steel-plate box-girders similar to those which are used in long-span bridge construction. There is no technical justification for their use here where a more environmentally friendly structural system, such as reinforced concrete slabs supported on a conventional column grid, would have been a more convincing choice. This would not have been so exciting visually, but it would have been more convincing in the context of the idea of a sustainable architecture.

10 Jan Kaplicky and David Nixon of Future Systems quoted in the final chapter of Wilkinson, C., *Supersheds*, Butterworth Architecture, Oxford, 1991. Later in the same statement Kaplicky and Nixon declare, of the technology of vehicle and aerospace engineering, 'It is technology which is capable of yielding an architecture of sleek surfaces and slender forms – an architecture of efficiency and elegance, and even excitement.' It is clear from this quotation that it is the appearance rather than the technical reality which is attractive to Kaplicky and Nixon.

The quotation reveals a degree of naivety concerning the nature of technology. It contains the assumption that dissimilar technologies have basic similarities which produce similar solutions to quite different types of problem.

The 'borrowing of technology' referred to in the quotation above from Future Systems is problematic. Another name for this is 'technology transfer', a phenomenon in which advanced technology which has been developed in one field is adapted and modified for another. Technology transfer is a concept which is of very limited validity because components and systems which are developed for advanced technical applications, such as occur in the aerospace industry, are designed to meet very specific combinations of requirements. Unless very similar combinations occur in the field to which the technology is transferred it is unlikely that the results will be satisfactory from a technological point of view. Such transfer is therefore also misleading symbolically on any level but the most simplistic.

The claims which are made for technology transfer are largely spurious if judged by technical criteria concerned with function and efficiency. The reality of technology transfer to architecture is normally that it is the image and appearance which is the attractive element rather than the technology as such.

It is frequently stated by the protagonists of this kind of architecture[11] 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 shortages of materials and energy 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 which 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[12]. This is a high-energy-consumption scenario which is not ecologically sound.

The benefits of new technological solutions would have to be much greater than at present for this approach to be useful. The forms of a future sustainable architecture are more likely to be evolved from the combination of innovative environmental technology with traditional building forms, which are environmentally friendly because they are adapted to local climatic conditions and are constructed in durable, locally available materials, than by transferring technology from the extremely environmentally unfriendly aerospace industry.

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 and concerns the way in which the floor girders are connected to the columns (Figs 7.7 and 6.7).

The rectangular cross-section of this building has three zones at every level (Fig. 7.8). There is a central main space which is flanked by two peripheral zones: on one side of the building the peripheral zone is used for a circulation system of corridors and escalators; on the other it contains services. The architects chose to use the glass wall which formed the building's envelope to delineate these zones

11 Chief amongst these is Richard Rogers and the arguments are set out in Rogers, *Architecture, A Modern View*, Thames and Hudson, London, 1991.

12 This is very well articulated by Charles Jencks in 'The New Moderns', AD Profile – *New Architecture: The New Moderns and The Super Moderns*, 1990.

Fig. 7.7 Gerberette brackets, Centre Pompidou, Paris, France, 1978; Piano and Rogers, architects; Ove Arup & Partners, 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 occur if the floor beams were attached to them directly. (Photo: A. Macdonald)

and placed the services and circulation zones outside the envelope. The distinction is mirrored in the structural arrangement: the main structural frames, which consist of triangulated girders spanning the central space, are linked to the perimeter columns through cantilever brackets, named 'gerberettes' after the nineteenth-century bridge engineer Heinrich Gerber, which are associated with the peripheral zones. The joints between the brackets and the main frames coincide with the building's glass wall and the spatial and structural zonings are therefore identical.

The elaborate gerberette brackets, which are major visual elements on the exterior of the building, pivot around the hinges connecting

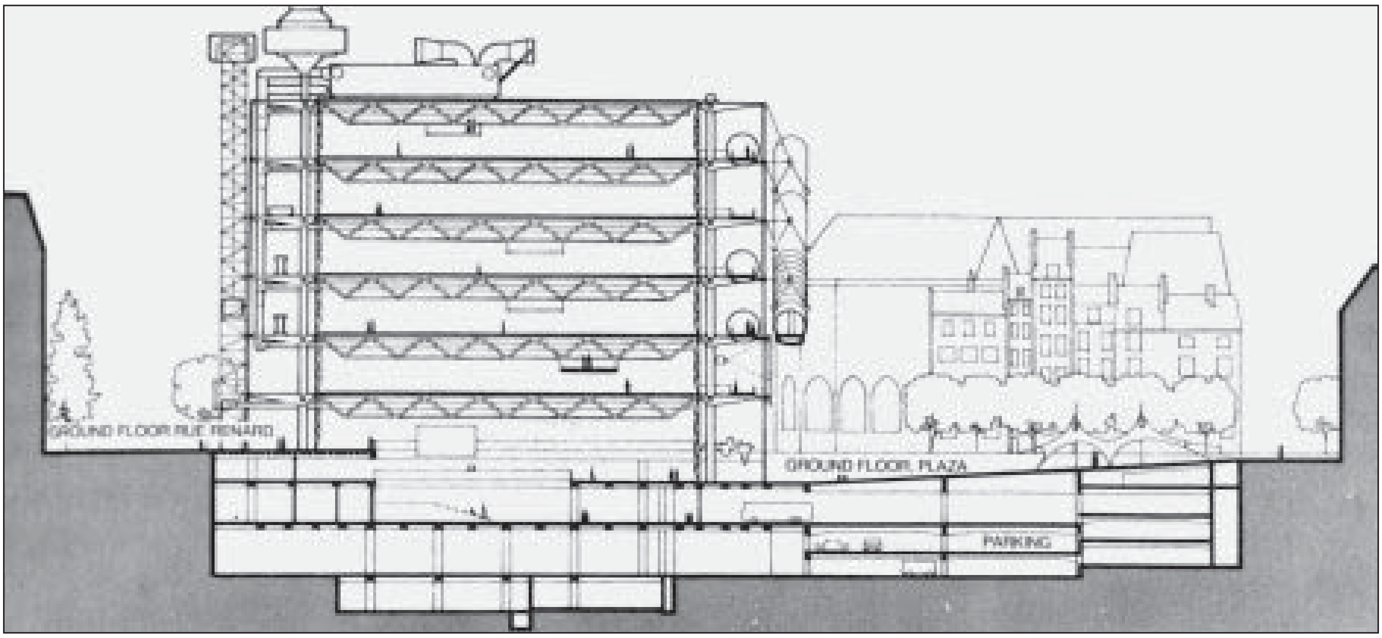


Fig. 7.8 Cross-section, Centre Pompidou, Paris, France, 1978; Piano and Rogers, architects; Ove Arup & Partners, structural engineers. The building is subdivided into three principal zones at every level and the spatial and structural arrangements correspond. The main interior spaces occupy a central zone associated with the main floor girders. The gerberette brackets define peripheral zones on either side of the building which are associated with circulation and services.

them to the columns (Fig. 7.7). The weights of the floors, which are supported on the inner ends of the brackets, are counterbalanced by downward-acting reactions at the outer ends provided by vertical tie rods linking them with the foundations. This arrangement sends 25% more force into the columns at each level than is required to support the floors. The idea of connecting the floor girders to the columns through these cantilevered brackets does not therefore make a great deal of engineering sense.

Apart from the unnecessary overloading of the columns, the brackets themselves are subjected to high levels of bending-type internal force and their design presented an interesting, if unnecessary, challenge to the engineers. The required solution to this was to give the brackets a highly complex geometry which reflected their structural function. The level of complexity could only be achieved by casting of the metal, and the idea of fabricating the brackets from cast steel, a technique which was virtually unknown in architecture at the time, was both courageous and innovative. It allowed forms to be used which were both expressive of the structural function of the brackets and which made a more efficient use of material than would have occurred had they been made from standard I-sections. According to Richard Rogers: 'We were repeating the gerberette brackets over 200 times and it was cheaper to use less steel than it was to use an I-beam. That's the argument on that I would have thought'[13].

Another advantage of casting was that it introduced an element of hand crafting into the steelwork. This was something of a preoccupation of Peter Rice, the principal structural engineer on the project who, in something of the tradition of the much earlier British Arts and Crafts Movement, believed that much of the inhumanity of Modern architecture stemmed from the fact that it was composed entirely of machine-made components.

There were therefore several agendas involved, most of them concerned with visual rather than structural considerations, and there is no doubt that the presence of these unusual components on the exterior of the building contributes greatly to its aesthetic success. Thus, the ingenious solution of an unnecessarily-created technical problem found architectural expression. This is the essence of this version of *structure as ornament*. Its greatest exponent has perhaps been the Spanish architect/engineer Santiago Calatrava.

A third kind of architecture which involves structure of questionable technical validity occurs in the context of a visual agenda that is incompatible with structural requirements. The Lloyds headquarters building (Fig. 7.9) in

Fig. 7.9 Lloyds headquarters building, London, UK, 1986; Richard Rogers and Partners, architects; Ove Arup & Partners, structural engineers. The building has a rectangular plan and six projecting service towers.

13 Interview with the author, February 2000.

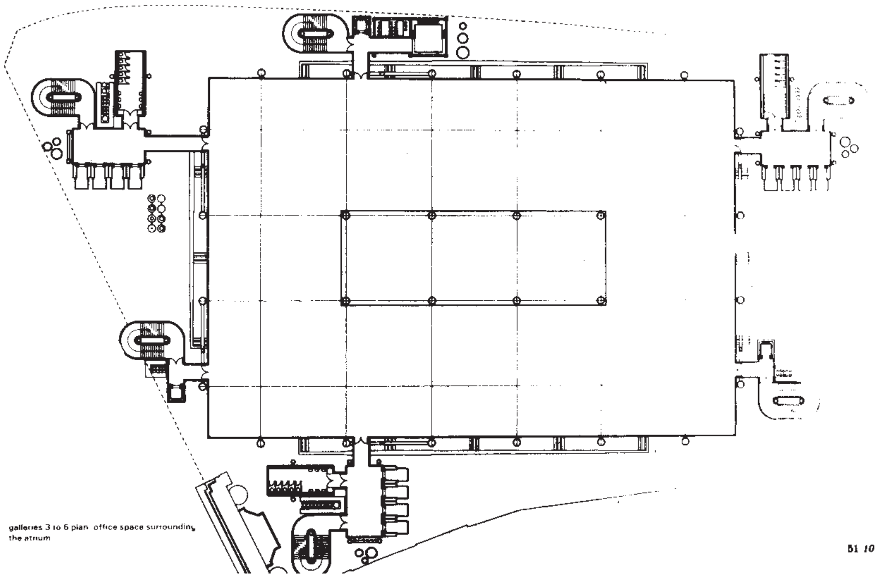


Fig. 7.10 Plan, Lloyds headquarters building, London, UK, 1986; Richard Rogers and Partners, architects; Ove Arup & Partners, structural engineers. The building has a rectangular plan with a central atrium. The structure is a reinforced concrete beam-column frame carrying a one-way-spanning floor.

Fig. 7.11 Lloyds headquarters building, London, UK, 1986; Richard Rogers and Partners, architects; Ove Arup & Partners, structural engineers. The service towers which project from the rectangular plan are one of the most distinctive features of the building.

London, by the same designers who produced the Centre Pompidou (Richard Rogers and Partners as architects and Ove Arup and Partners as structural engineers), is a good example of this.

Lloyds is a multi-storey office building with a rectangular plan (Fig. 7.10). The building has a central atrium through most levels, which converts the floor plan into a rectangular doughnut, and, as at the Centre Pompidou, services which are external to the building's envelope. At Lloyds these are placed in a series of towers which disguise the rectilinearity of the building. There are also external ducts which grip the building like the tentacles of an octopus (Fig. 7.11). The structural armature is a reinforced concrete beam-and-column framework which supports the rectangular core of the building. This forms a prominent element of the visual vocabulary but is problematic technically.

The columns are located outside the perimeter of the floor structures which they support and this has the effect of increasing the eccentricity with which load is applied to the columns – a highly undesirable consequence structurally. This solution was adopted to make the structure 'readable' (a continuing concern of Richard Rogers) by articulating the different parts as separate identifiable elements. It resulted in the floors being connected to the columns through elaborate pre-cast concrete brackets (Fig. 7.12). In this respect the Lloyds building is similar to the Centre Pompidou. An architectural idea, 'readability', created a problem which required a structural response. The pre-cast column junctions were less spectacular than the gerberettes of the Centre Pompidou, but had an equivalent function, both technically and visually.

There are, however, important differences between Pompidou and Lloyds which place them in slightly different categories so far as the relationship between structure and architecture is concerned. At Lloyds, the logic of readability was abandoned in the treatment of the underside of the exposed reinforced concrete floors. These take the shape of a rectangular doughnut in plan due to the presence of the central atrium. Structurally, they consist of primary beams, spanning between columns at the perimeter and within the atrium, which support 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 which had a satisfactory technical performance while at the same time appearing to be that which it was not.

This task was not made easier 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 which eliminated the possibility of continuity between the ribs and the floor slab which they support. The benefits of composite action between the ribs and the floor slab, which normally greatly increases the efficiency of reinforced concrete floors, were thus foregone. The design of this structure was therefore driven almost entirely by visual considerations and a heavy penalty was paid in terms of structural efficiency.

Fig. 7.12 Atrium, Lloyds headquarters building, London, UK, 1986; Richard Rogers and Partners, architects; Ove Arup & Partners, structural 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, which causes high concentrations of stress at the junctions.

The conclusion which may be drawn from the above examples of *structure as ornament* is that in many buildings with exposed structures the structure is technically flawed despite appearing visually interesting. This does not mean that the architects and engineers who designed these buildings were incompetent or that the buildings themselves are examples of bad architecture. It does mean, however, that in much architecture 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 which have been employed are not themselves examples of technology which is appropriate to the function involved. It will remain to be seen whether these buildings stand the test of time, either physically or intellectually: the ultimate fate of many of them, despite their enjoyable qualities, may be that of the discarded toy.

7.2.3 Structure as architecture

7.2.3.1 *Introduction*

There have always been buildings which consisted of structure and only structure. The igloo and the tepee (see Figs 1.2 and 1.3) are examples and such buildings have, of course, existed throughout history and much of human pre-history. In the world of architectural history and criticism they are 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 the very large scale of the particular example. Examples are the Crystal Palace (Fig. 7.25) in the nineteenth century and the CNIT building (see Fig. 1.4) in the twentieth. These were buildings in which the limits of what was technically feasible were approached and in which no compromise with structural requirements was possible. This is a third type of relationship between structure and architecture which 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 tall buildings. Other cases are those in which extreme lightness is desirable, for example because the building is required to be portable, or where some other technical issue is so important that it dictates the design programme.

7.2.3.2 *The very long span*

It is necessary to begin a discussion on long-span structures by asking the question: when is a span a long span? The answer offered here will be: when, as a consequence of the size of the span, technical considerations are 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 and the tensile membrane, and the non- or semi-form-active types into which significant 'improvements' have been incorporated.

In the pre-industrial age the structural form which was used for the widest spans was the masonry vault or the dome. The only other structural material available in the pre-industrial age was timber. Due to the small size of individual timbers, any large wooden structure involved the joining together of many elements, and making joints in timber which had satisfactory structural performance was difficult. In the absence of a satisfactory jointing technology, large-scale structures in timber were not feasible in the pre-Modern world. Also, the understanding of how to produce efficient fully-triangulated trusses did not occur until the nineteenth century.

The development of reinforced concrete in the late nineteenth century allowed the extension of the maximum span which was possible with the compressive form-active type of structure. Reinforced concrete has a number of advantages over masonry, the principal one being its capability to resist tension as well as compression and its consequent ability to resist bending. The vault and the dome are, of course, compressive form-active structures, but this does not mean that they are never subjected to bending moment because the form-active shape is only valid for a specific load pattern. Structures which 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 structural material has little tensile strength, as is the case with masonry, its cross-section must be sufficiently thick to prevent the tensile bending stress from exceeding the compressive axial stress which is also present. Masonry vaults and domes must therefore be fairly thick and this compromises their efficiency. An additional complication with the use of the dome is that tensile stresses can develop in the circumferential direction near the base of the structure with the result that cracks develop. Most masonry domes are in fact reinforced to a limited extent with metal – usually in the form of iron bars – to counteract this tendency.

Because reinforced concrete can resist both tensile and bending stress, compressive form-active structures in this material can be made very much thinner than those in masonry. This allows greater efficiency, and therefore greater spans, to be achieved because the principal load on a dome or vault is the weight of the structure itself.

Another advantage of reinforced concrete is that it makes easier the adoption of 'improved' cross-sections. This technique has been used with masonry domes, however, the twin skins of Brunelleschi's dome for Florence Cathedral (Fig. 7.13)[14] being an example, but the

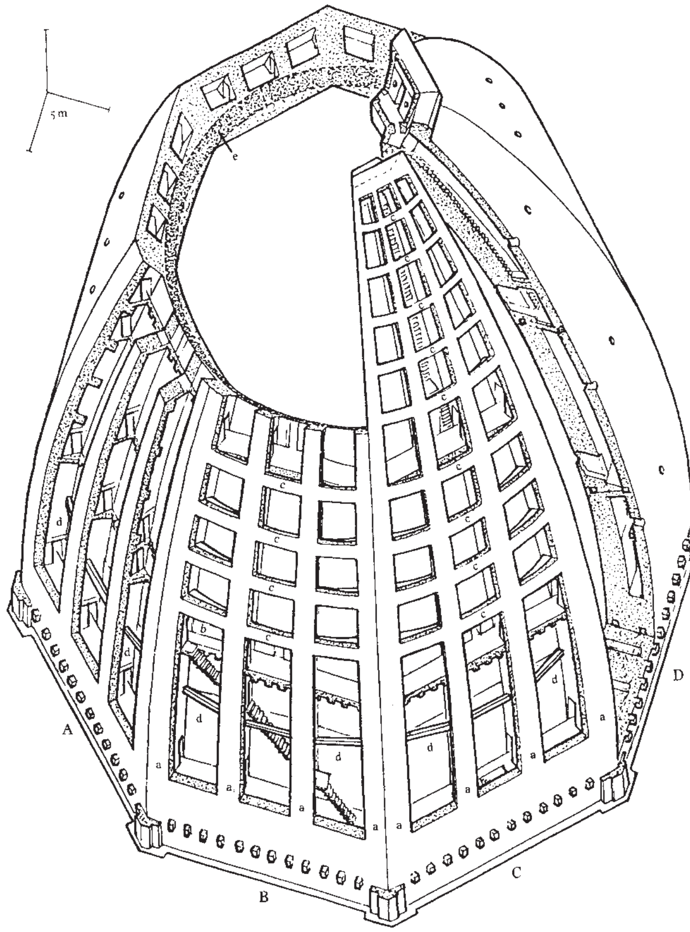


Fig. 7.13 Dome of the cathedral, Florence, Italy, 1420–36; Brunelleschi. The dome of the cathedral at Florence is a semi-form-active structure. The brickwork masonry envelope has an 'improved' cross-section and consists of inner and outer skins linked by diaphragms. An ingenious pattern of brickwork bonding was adopted to ensure satisfactory composite action. Given the span involved, and certain other constraints such as that the dome had to sit on an octagonal drum, it is difficult to imagine any other form which would have been feasible structurally. This memorable work of architecture is therefore an example of genuine 'high tech'. The overall form was determined from structural considerations and not compromised for visual effect. (Drawing: R. J. Mainstone)

mouldability of reinforced concrete greatly extended this potential for increasing the efficiency with which a dome or vault can resist bending moment caused by semi-form-active load patterns.

Among the earliest examples of the use of reinforced concrete for vaulting on a large scale are the airship hangars for Orly Airport in

14 The twin skin arrangement may not have been adopted for structural reasons. An interesting speculation is whether Brunelleschi, who was a brilliant technologist, may have had an intuitive understanding of the improved structural performance which results from a two-skin arrangement.

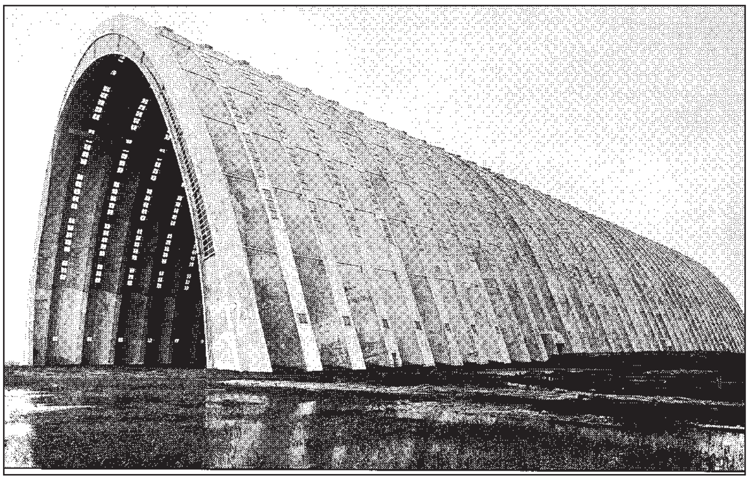


Fig. 7.14 Airship Hangars, Orly Airport, France, 1921; Eugène Freyssinet, structural engineer. The skin of this compressive form-active vault has a corrugated cross-section which allows efficient resistance to secondary bending moment. The form adopted was fully justified given the span involved and was almost entirely determined from structural considerations.

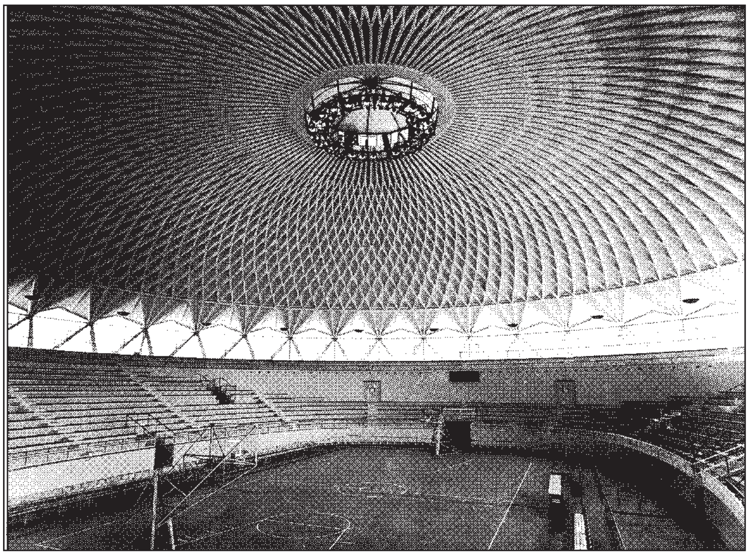


Fig. 7.15 Palazzetto dello Sport, Rome, Italy, 1960; Pier Luigi Nervi, architect/engineer. This is another example of a building with a form determined solely from structural requirements. The compressive form-active dome is a composite of *in situ* and pre-cast reinforced concrete and has an 'improved' corrugated cross-section. (Photo: British Cement Association)

Paris by Eugène Freyssinet (Fig. 7.14). A corrugated cross-section was used in these buildings to improve the bending resistance of the vaults. Other masters of this type of structure in the twentieth century were Pier Luigi Nervi, Eduardo Torroja and Félix Candela. Nervi's structures (Fig. 7.15) are especially interesting because he developed a system of construction which involved the use of pre-cast permanent formwork in ferro-cement, a type of concrete made from very fine aggregate and which could be moulded into extremely slender and delicate shapes. The elimination of much of the temporary formwork and the ease with which the ferro-cement could be moulded into 'improved' cross-sections of complex geometry, allowed long-span structures of great sophistication to be built relatively economically. The final dome or vault consisted of a composite structure of *in-situ* concrete and ferro-cement formwork.

Other notable examples of twentieth-century compressive form-active structures are the CNIT building in Paris by Nicolas Esquillan (see Fig. 1.4) and the roof of the Smithfield Poultry Market in London by R. S. Jenkins of Ove Arup and Partners (Fig. 7.16).

Compressive form-active structures are also produced in metal, usually in the form of lattice arches or vaults, to achieve very long spans. 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) (Fig. 7.51) and the structure of the Galerie des Machines for the Paris Exhibition of 1889, by Contamin and Dutert (span 114 m) being notable examples. The subject has been well reviewed by Wilkinson[15]. This tradition continues in the present day and notable recent examples are the International Rail Terminal at Waterloo Station, London, by Nicholas Grimshaw & Partners with YRM Anthony Hunt Associates (Fig. 7.17) and the design for the Kansai Airport building for Osaka, Japan by Renzo Piano with Ove Arup and Partners.

Cable-network structures are another group whose appearance is distinctive because

15 *Op. cit.*

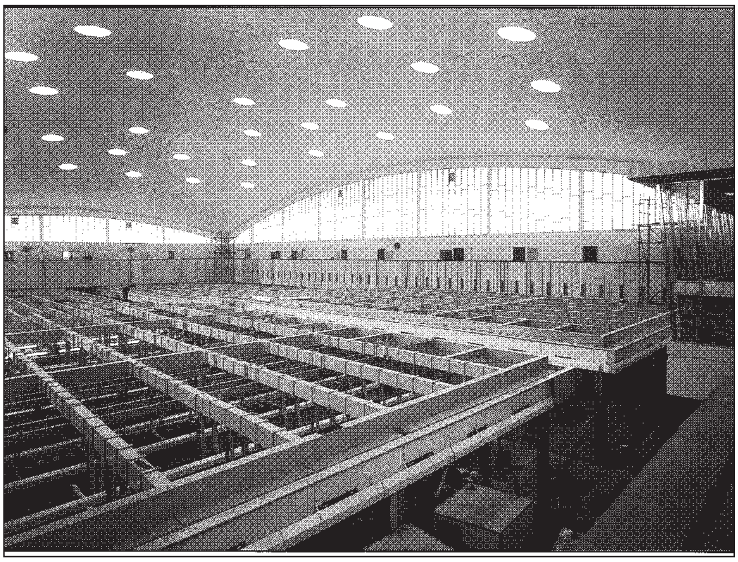


Fig. 7.16 Smithfield Poultry Market, London, UK; Ove Arup & Partners, structural engineers. The architecture here is dominated by the semi-form-active shell structure which forms the roof of the building. Its adoption was justified by the span of around 60 m. The elliptical paraboloid shape was selected rather than a fully form-active geometry because it could be easily described mathematically, which simplified both the design and the construction. (Photo: John Maltby Ltd)

Fig. 7.17 International Rail Terminal, Waterloo Station, London, UK, 1992; Nicholas Grimshaw & Partners, architects; YRM Anthony Hunt Associates, structural engineers. This building is part of a continuing tradition of long-span structures for railway stations. The design contains a number of innovatory features, most notably the use of tapering steel sub-elements. (Photo: J. Reid and J. Peck)

Fig. 7.18 David S. Ingalls ice hockey rink, Yale, USA, 1959; Eero Saarinen, architect; Fred Severud, structural 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.

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 (Fig. 7.18) and the cable-network structures of Frei Otto (see Fig. i) are typical examples.

In these buildings the roof envelope is an anticlastic double-curved surface[16]: 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 which 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 principal advantage of these over the earlier anticlastic forms was that, due to the greater simplicity of the form, the manufacture of the cladding was made easier.

The Millennium Dome in London (Fig. 7.19), 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 which 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 which 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 cladding fabric of the Millennium Dome is PTFE-coated glass fibre.

The few examples of cable networks illustrated here demonstrate that, although this type of structure is truly form-active with a shape which is dependent on the pattern of applied load, the designer can exert

16 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 at Munich (Fig. i) is an example. Synclastic surfaces are also doubly curved but with the describing curves acting in the same direction. The shell roof of the Smithfield Poultry market (Fig. 7.16) is an example of this type.

Fig. 7.19 Millennium Dome, London, UK, 1999; Richard Rogers and Partners, architects; Buro Happold, structural engineers. This is mast-supported, dome-shaped cable network with a diameter of 358 m. The use of a tensile form-active structure is fully justified for structures of this size.

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 which are adopted for these influence the overall appearance of the building.

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 is justified, however, in the interests of achieving the high levels of structural efficiency required to produce large spans. In the cases described here the compromise which has been reached is satisfactory, given the spans involved and the uses for which the buildings were designed.

All of the long-span buildings considered here may therefore be regarded as true 'high-tech' architecture. They 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.

7.2.3.3 *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 worthy of careful 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 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. The problem was solved by the introduction of steel framing. Columns are loaded axially, and so long as the storey height is low enough to maintain the slenderness ratio[17] at a reasonably low level and thus inhibit buckling, the strength of the material is such that excessive volume of structure does 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. There have, of course, been many technical innovations in connection with aspects of the support of gravitational load in high buildings. In particular, as was pointed out by Billington[18], changes in the relationship between the vertical and horizontal structural elements have led to the creation of larger column-free spaces in the interiors. These innovations have, however, found very limited architectural expression.

The need to accommodate wind loading as opposed to gravitational loads has had a greater effect on the aesthetics of very tall buildings. As with vertical support elements, in the majority of skyscrapers the architect has been able to choose not to express the

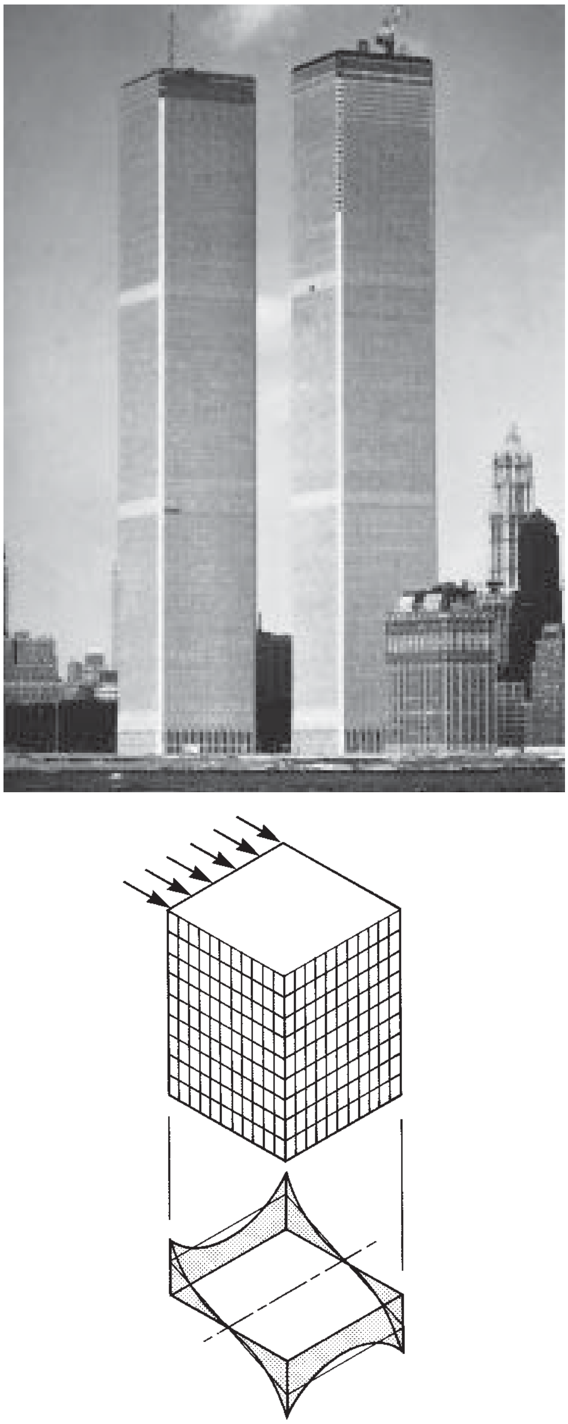
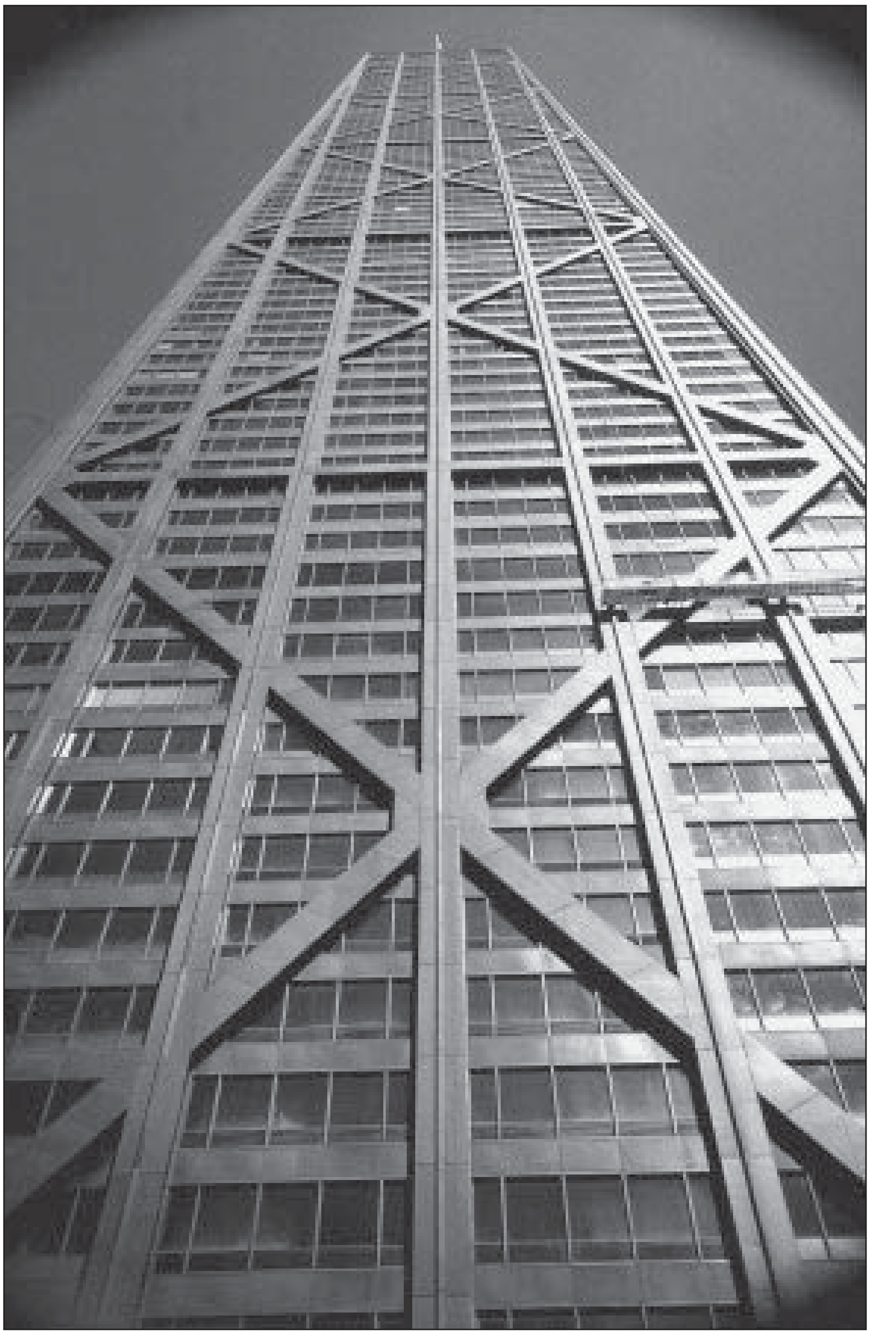


Fig. 7.20 World Trade Centre, New York, USA, 1973; Minoru Yamasaki, architect; Skilling, Helle, Christiansen & Robertson, structural engineers. The closely-spaced columns on the exteriors of these buildings are structural and form a 'framed-tube' which provides efficient resistance to lateral load. In response to lateral load the building acts as a vertical cantilever with a hollow box cross-section. This is an example of a structural system, not compromised for visual reasons, exerting a major influence on the appearance of the building. (Photo: R. J. Mainstone)

17 See Macdonald, Angus J., *Structural Design for Architecture*, Architectural Press, Oxford, 1997, Appendix 2, for an explanation of slenderness ratio.
18 Billington, D. P., *The Tower and the Bridge*, Basic Books, New York, 1983.



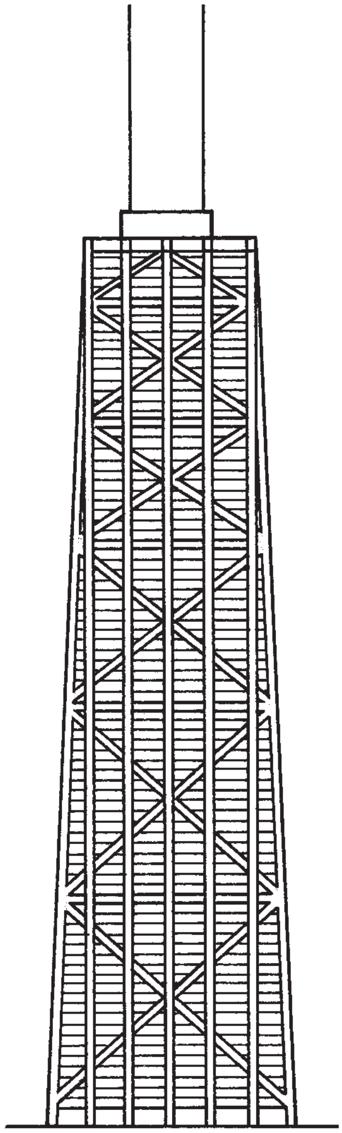


Fig. 7.21 John Hancock Building, Chicago, USA, 1969; Skidmore, Owings and Merrill, architects and structural engineers. The trussed-tube structure here forms a major component of the visual vocabulary. (Photo: Chris Smallwood)

bracing structure so that, although many of these buildings are innovative in a structural sense, this is not visually obvious. The very tallest buildings, however, have been designed to behave as single vertical cantilevers with the structure concentrated on the exterior; in these cases the expression of the structural action was unavoidable.

The framed- and trussed-tube configurations[19] (Figs 7.20 and 7.21) are examples of structural arrangements which allow tall buildings to behave as vertical

19 See Schueller, W., *High Rise Building Structures*, John Wiley, London, 1977, for an explanation of bracing systems for very tall buildings.

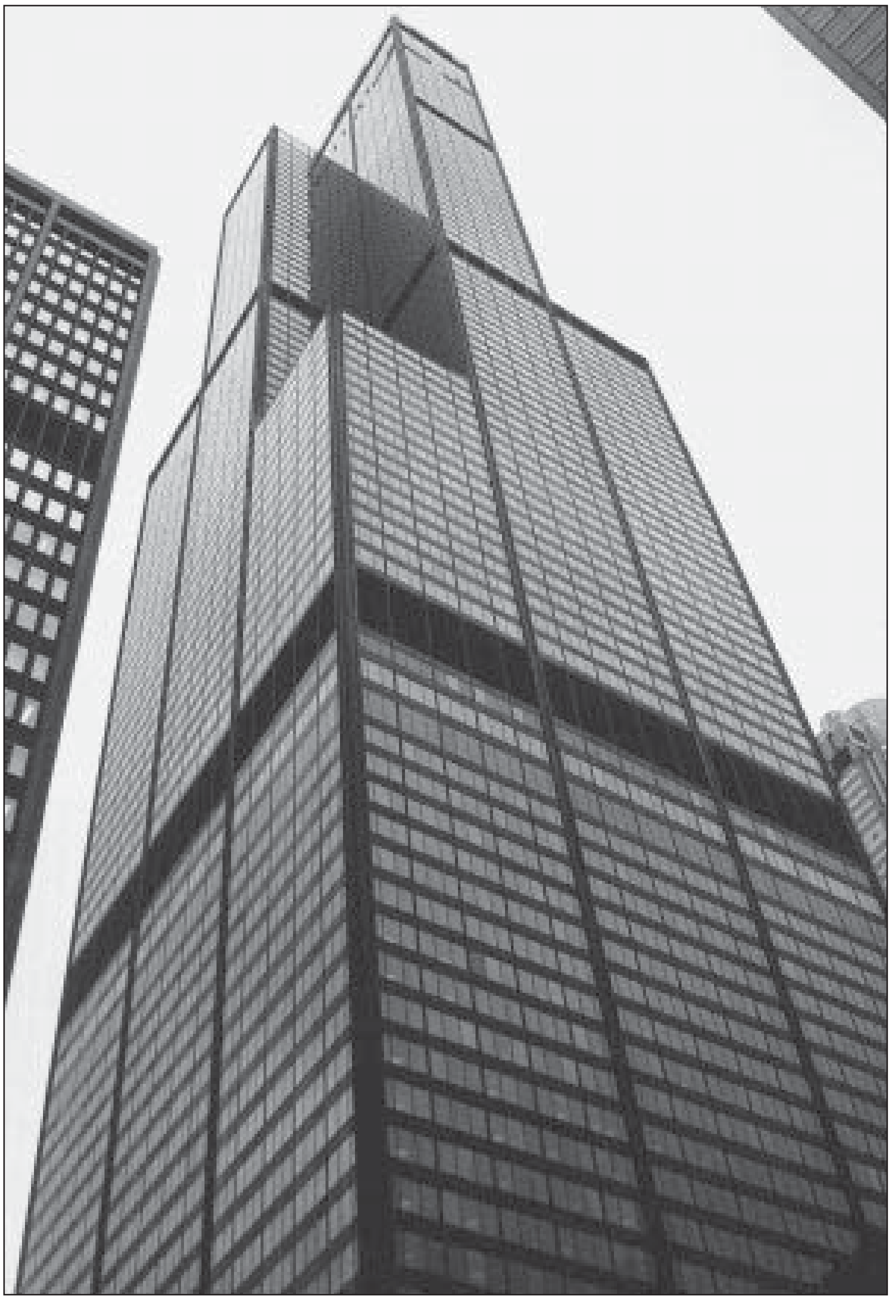


Fig. 7.22 Sears Tower, Chicago, USA, 1974; Skidmore, Owings and Merrill, architects and structural engineers. This building, which is currently the tallest in the world, is subdivided internally by a cruciform arrangement of 'walls' of closely spaced columns which enhance its resistance to wind loading. This structural layout is expressed in the exterior form.

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 which provides vertical support but does not normally contribute 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 the case of the framed tube, of which the World Trade Centre buildings in New York by Minoru Yamasaki (Fig. 7.20) are examples, the shear connection is provided by rigid frame action between the columns and the very short beams which link them. In trussed-tube structures, such as the John Hancock Building in Chicago by Skidmore, Owings and Merrill (Fig. 7.21), the shear connection is provided by diagonal bracing elements. Because in each of these cases the special structural configuration which 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 Skidmore, Owings and Merrill 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.'[20]

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 Sears Tower in Chicago, also by Skidmore, Owings and Merrill (Fig. 7.22), has this type of structure which is expressed architecturally, in this case by varying the heights of each of the compartments created by the structural grid. The structural system is therefore a significant contributor to the external appearance of this building.

Thus, among very high buildings some examples of *structure as architecture* may be found. These are truly high tech in the sense that, because the limits of technical possibility have been approached, structural considerations have been given a high priority in the design – to the extent that the appearance of the building has been significantly affected by them.

7.2.3.4 *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. 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.

As has been repeatedly emphasised, the most efficient type of structure is the form-active one and the traditional solution to the problem of portable buildings is, of course, the tent, which is a tensile form-active structure. The tent also has the advantage of being easy to demount and collapse into a small volume, which compressive form-active structures have not, due to the rigidity which 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 7.23 shows an example of state-of-the-art engineering used for a building to house a temporary exhibition – another example of truly high-tech architecture.

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 for the travelling exhibition of

20 Conversation with Janice Tuchman reported in Thornton, C., Tomasetti, R., Tuchman, J. and Joseph, L., *Exposed Structure in Building Design*, McGraw-Hill, New York, 1993.

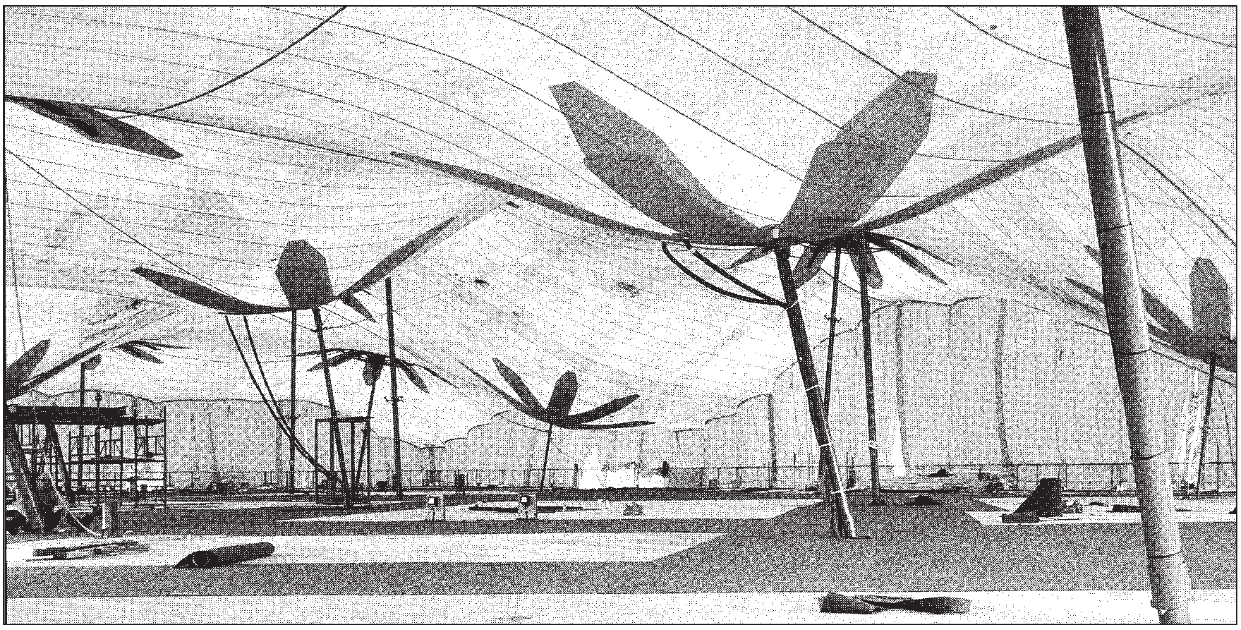


Fig. 7.23 Tent structure for temporary exhibition building, Hyde Park, London, UK; Ove Arup & Partners, structural engineers. Lightweight, portable buildings may be considered as examples of genuine 'high-tech' architecture in any age because the forms adopted are determined almost entirely from structural and constructional considerations.

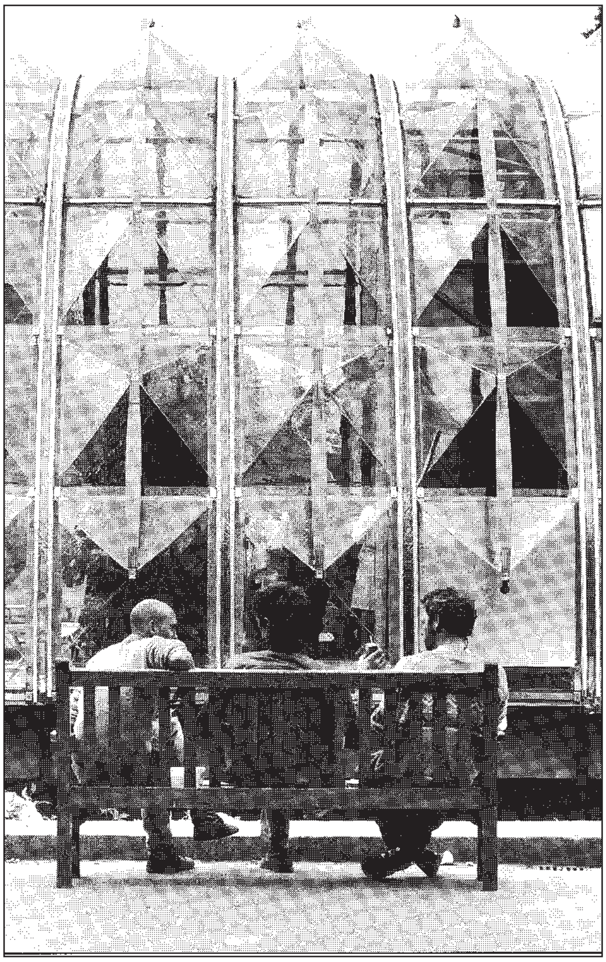


Fig. 7.24 Building for IBM Europe travelling exhibition; Renzo Piano, architect/engineer; Ove Arup & Partners, structural engineers. This building consists of a semi-form-active compressive vault. The 'improved' cross-section of the membrane is achieved with a highly sophisticated combination of laminated timber and plastic – each is a material which offers high strength for its weight. Technical considerations reign supreme here to produce a portable, lightweight building.

IBM Europe (Fig. 7.24). This consisted of a semi-form-active vault which 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.

7.2.3.5 *Special requirements*

Other forms of special requirement besides the need for a lightweight structure can result in structural issues being accorded the highest

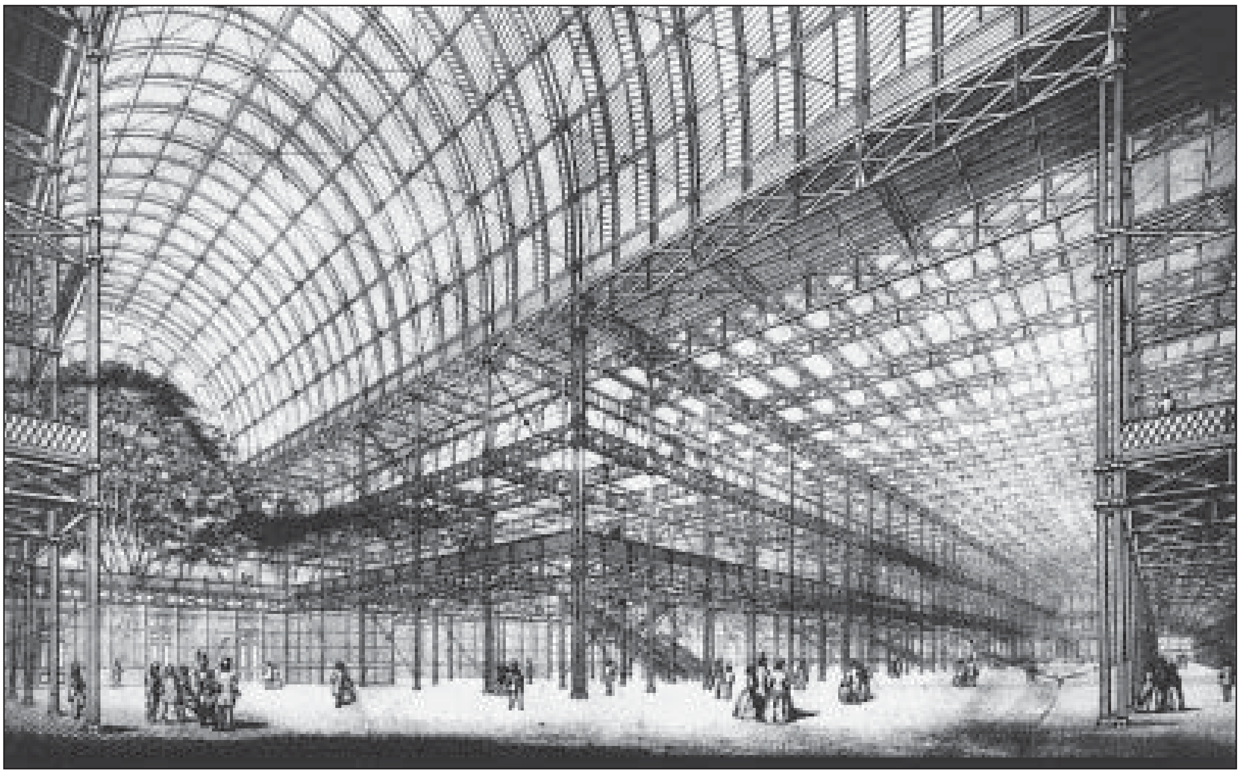


Fig. 7.25 Crystal Palace, London, UK, 1851; Joseph Paxton, architect/engineer. The Crystal Palace was a truly high-tech building and an inspiration to generations of modern architects. Unlike many twentieth-century buildings to which the label High Tech has been applied, it was at the forefront of what was technically possible at the time. The major decisions affecting the form of the building were taken for technical reasons and were not compromised for visual or stylistic effect. The building has technical shortcomings, such as the poor durability of the many joints in the external skin, but in the context of a temporary building it was appropriate that these were given a low priority.

priority in the design of a building to the point at which they exert a dominating influence on its form. A classic example of this from the nineteenth century was the Crystal Palace in London (Fig. 7.25) which was built to house the Great Exhibition of 1851.

The problem which Joseph Paxton, the designer of the Crystal Palace, was required to solve was that of producing a building which could be manufactured and erected very quickly (nine months elapsed between the original sketch design and the completion of the building) and which could subsequently be dismantled and re-erected elsewhere. Given the immense size of the building, comparable with that of a Gothic cathedral, the technical problem was indeed formidable. Paxton's solution was to build a glasshouse – a glass envelope supported by an exposed structure of iron and timber. It is difficult to imagine any other contemporary structural solution which could have met the design requirements. Possibly a series of very large tents would have sufficed – there was in existence at the time a fairly large canvas- and rope-making capability associated with shipbuilding and a tradition of large tent manufacture. Tents would not, however, have provided the lofty interior which was desirable to display adequately the latest products of industry. The Crystal Palace not only solved the problem of the large and lofty enclosure; it was itself a demonstration of the capabilities of the latest industrial processes and techniques of mass production.

The technology used for the building was developed by the builders of glasshouses for horticulture, of whom Paxton was perhaps the most innovative. It contained much that the enthusiast of structural engineering and industrial technology could enjoy. The post-and-beam structure was appropriate for the spans and loads involved. Form-active arches were used as the horizontal elements in the post-and-beam format to span the large central 'nave' and 'transepts', and non-form-active, straight girders with triangulated 'improved' profiles formed the shorter spans of the flanking 'aisles'. The glazing conformed to a ridge-and-furrow arrangement, which was designed originally in connection with horticultural glasshouses to improve the daylight-penetration characteristics – it provided some shade during the hours around mid-day when the sun was high in the sky but admitted more light in the early morning and late evening. Although this characteristic was not particularly important in the case of the Crystal Palace, the arrangement enhanced the structural performance by giving the glass cladding a structurally 'improved', corrugated cross-section. Many other examples of good technology were features of the building – one of which was that the secondary beams supporting the glazing served also as rainwater guttering to conduct the run-off to the columns whose circular hollow cross-sections, as well as having ideal structural shapes for compression elements, allowed them to function as drain pipes. Another example was that much of the structure was discontinuous and this, through the elimination of the 'lack-of-fit' problem (see Appendix 3), together with the very large degree of component repetition, facilitated both the rapid manufacture of the elements by mass-production techniques and the very fast assembly of the building on site.

The building was therefore at the forefront of contemporary technology – a genuine example of a high-tech building – and was ideally suited to its purpose, which was to house a temporary exhibition. The technical shortcomings of the arrangement – the lack of thermal insulation, the susceptibility to leaks at the many joints in the cladding and the questionable long-term durability of the structure and of the cladding joints – were not significant in this context, as they would have been in a permanent building.

Many twentieth-century Modern architects have been inspired by the glass-clad framework of the Crystal Palace. As was the case with the later examples of 'technology transfer' already mentioned, although with some notable exceptions such as the Patera Building described below, it was the imagery rather than the technical reality which was attractive to them.

Fig. 7.26 Patera Building; Michael Hopkins, architect; Anthony Hunt Associates, structural engineers. The building consists of a lightweight steel framework which supports an insulated cladding system and fully glazed end walls. The principal structural elements are external and the purlins and cladding rails are located within the cladding zone to give a very clean interior. (Photo: Anthony Hunt Associates)

The Patera Building, by Michael Hopkins with Tony Hunt as structural engineer (Fig 7.26) has been directly compared to the Crystal Palace because its design was also based on the principle of pre-fabrication. The project was an attempt to address the problem of the poor architectural quality of most industrial estates by producing a building system which would be economic, flexible and stylish and linking this to a development company which would act as the co-ordinator of industrial estates. The development company would acquire land, design a layout of building plots and install infrastructure. Individual tenant clients would then have buildings tailor-made to their requirements within a consistent style offered by a building system. The buildings would, in effect, be industrial apartments capable of being adapted to different client requirements and offered for rent for varying lengths of tenure to suit clients' needs.

The principal hardware element in the concept was a basic building shell which could be erected and fitted out quickly to meet the needs of an individual tenant and then easily adapted to suit the requirements of subsequent tenants. It was envisaged that the scale of the operation would allow the building to be treated as an industrial product; it would be developed and tested in prototype form and subsequently manufactured in sufficient numbers to cover its development costs.

It was envisaged that the erection of the building would occur in three phases. The first of these was the laying of a rectangular foundation and ground-floor slab in which services would be incorporated. This was the interface between the superstructure and the site and rendered the building non-site-specific. The building could be built anywhere that this standard rectangular slab could be laid. The second stage was the erection of the superstructure, a shell of cladding, incorporating trunking for electrical and telephone services, supported on a steel framework. The third stage was the subdivision and fitting out of the interior to meet specific client requirements.

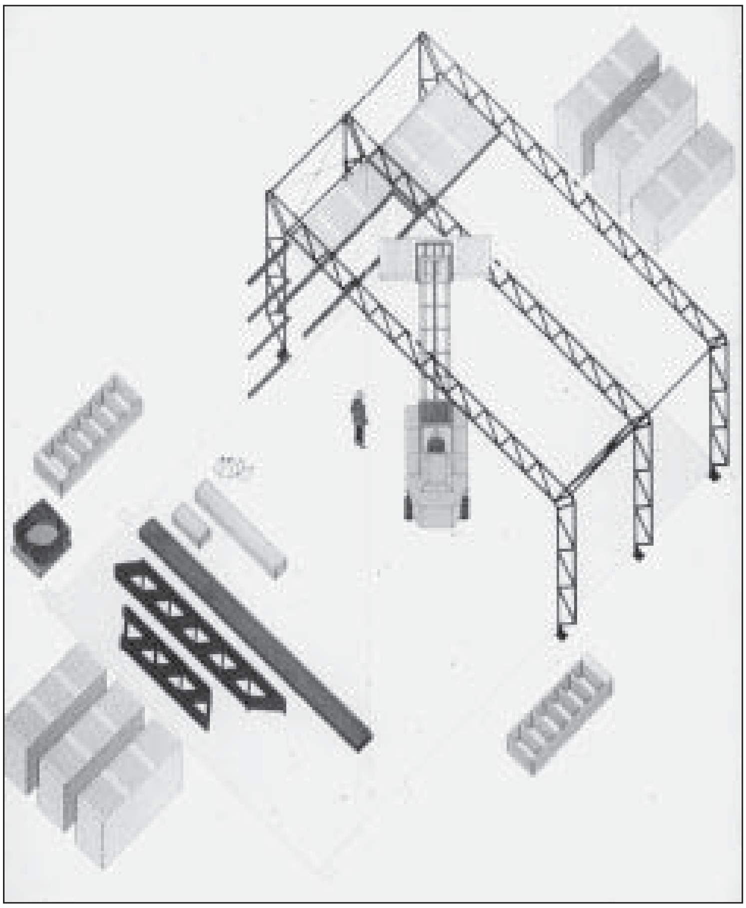


Fig. 7.27 Patera Building; Michael Hopkins, architect; Anthony Hunt Associates, structural engineers. Technical considerations, such as the need for containerisation and for simple assembly with a fork-lift truck exerted a major influence on the design. (Photo: Anthony Hunt Associates)

The structure of the building consisted of a series of triangulated portal frameworks which spanned 13.2 m across the building, linked by rectangular-hollow-section purlins and cladding rails spaced 1.2 m apart and spanning 3.6 m between the main frames. The main frameworks were ingeniously designed to meet exacting performance requirements which called for a structure that would be of stylish appearance with, for ease of containerisation, no element longer than 6.75 m and, for ease of construction, no element heavier than could be lifted by a fork-lift truck (Fig. 7.27). To meet

Fig. 7.28 Patera Building; Michael Hopkins, architect; Anthony Hunt Associates, structural engineers. The ingenious use of pin connections and cast nodes allowed a fully rigid joint to be made between the principal elements which could be easily assembled. (Photo: Anthony Hunt Associates)

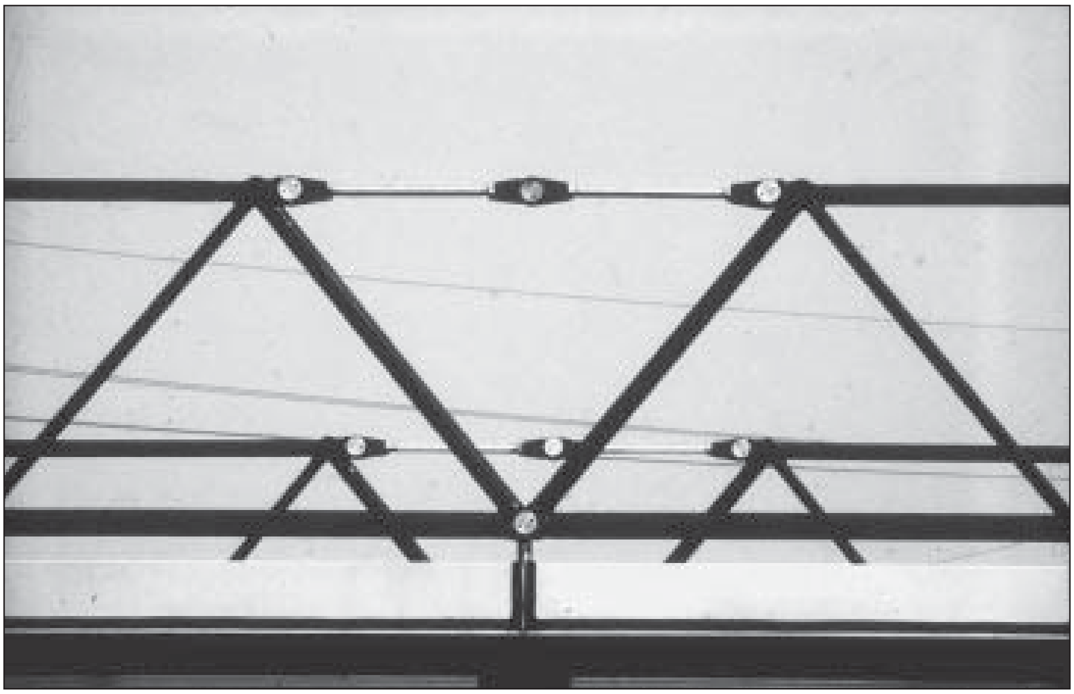


Fig. 7.29 Patera Building. The mid-span joint in the primary structure has a three-hinge tension-only link. Under gravitational load the latter collapses and the joint as a whole behaves as a hinge. Under wind uplift the tension-only link comes into play and the connection becomes rigid. The device maintains the laterally-restrained lower booms of the structure in compression under all conditions of load. (Photo: Anthony Hunt Associates)

these requirements a hybrid 2-hinge/3-hinge portal framework was chosen. The inherent efficiency of the semi-form-active arrangement, together with the full triangulation of the elements and the relatively small ratio of span to depth that was adopted, allowed very slender circular-hollow-section sub-elements to be used. Each portal consisted of two horizontal and two vertical sub-units which were pre-fabricated by welding. Cast-steel jointing components allowed the use of very precise pin-type site connections and these were cleverly arranged at the junction between the horizontal and vertical elements to provide a rigid connection there (Fig. 7.28).

The hybrid 2-hinge/3-hinge arrangement was adopted to eliminate the need for additional lateral bracing of the compression side of the structure by ensuring that the inner booms of the main elements, which were restrained laterally by the cladding, remained in compression under all conditions of loading. The key to this behaviour was an ingenious 3-pin tension-only link between the top elements of the portal at the central joint (Fig. 7.29). Under gravitational load, this was subjected to compression and collapsed to produce a hinge joint between the main elements at the mid-span position which ensured that compression was concentrated in the inner booms of the frame. If load reversal occurred due to wind uplift, reversal of stress within the structure did not occur because the tension-only link now became part of the structure and converted the main frame to a 2-hinge arrangement due to the mid-span joint between the horizontal elements becoming rigid. This meant that the laterally-restrained inner boom remained in compression and that most of the outer boom continued to be subjected only to tension. The need for lateral restraint for the outer booms was therefore eliminated under all conditions of load.

The Patera building is therefore an example of architecture resulting from a skilful technical solution to a set of very particular requirements. In this respect it is similar to the Crystal Palace.

7.2.3.6 *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. Billington[21] goes so far as to argue that they may be considered to be examples of an art form and this issue has been discussed more recently by Holgate[22]. It is questionable, however, although it may not be important, whether a shape which has been evolved from purely technical considerations can be considered to be a work of art, however beautiful it may appear to those with the technical knowledge to appreciate it.

7.2.4 Structure as form generator/structure accepted

The terms *structure as form generator* and *structure accepted* are 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 which is most sensible structurally is accepted and the architecture accommodated to it. The reason why two cases are distinguished is that the closeness of the link between the architectural and the structural agendas is subject to considerable variation. Sometimes it is very positive, with the form-generating possibilities of structure being used to contribute to an architectural style. Alternatively, even though the overall form of a building may have been determined largely to satisfy structural requirements, the architectural interest may lie elsewhere.

The vaulted structures of Roman antiquity are an example of the first of these possibilities. 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 which are among the largest interiors in Western architecture, were roofed by vaults and domes

21 Billington, D. P., *Robert Maillart*, MIT Press, Cambridge, MA, 1989.

22 See Holgate, A., *The Art in Structural Design*, Clarendon Press, Oxford, 1986 and Holgate, A., *Aesthetics of Built Form*, Oxford University Press, Oxford, 1992.

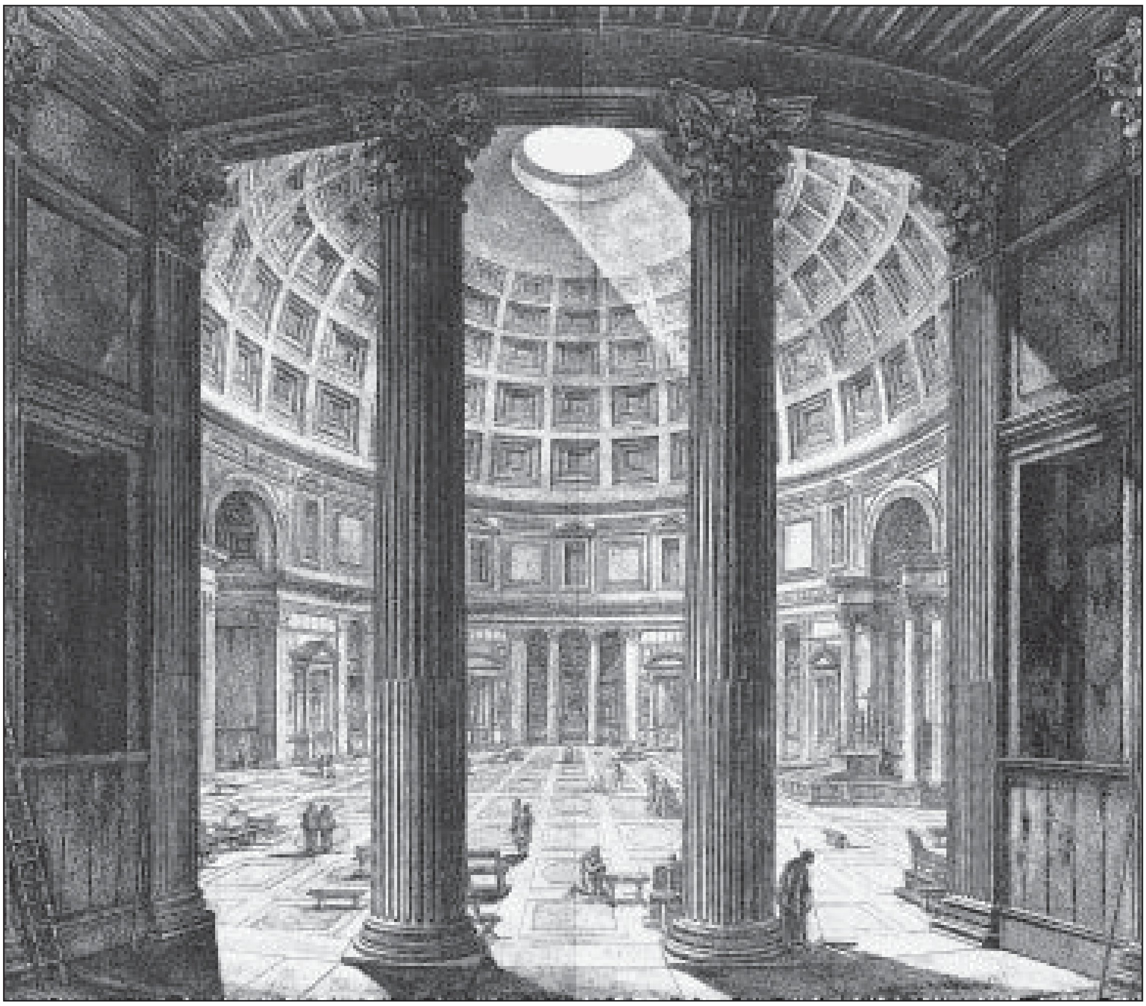


Fig. 7.30 The Pantheon, Rome, 2nd century AD. The hemispherical concrete dome is supported on a cylindrical drum also of concrete. Both have thick cross-sections which have been 'improved' by the use of coffers or voids of various types and these technical devices have been incorporated into the visual scheme of the interior.

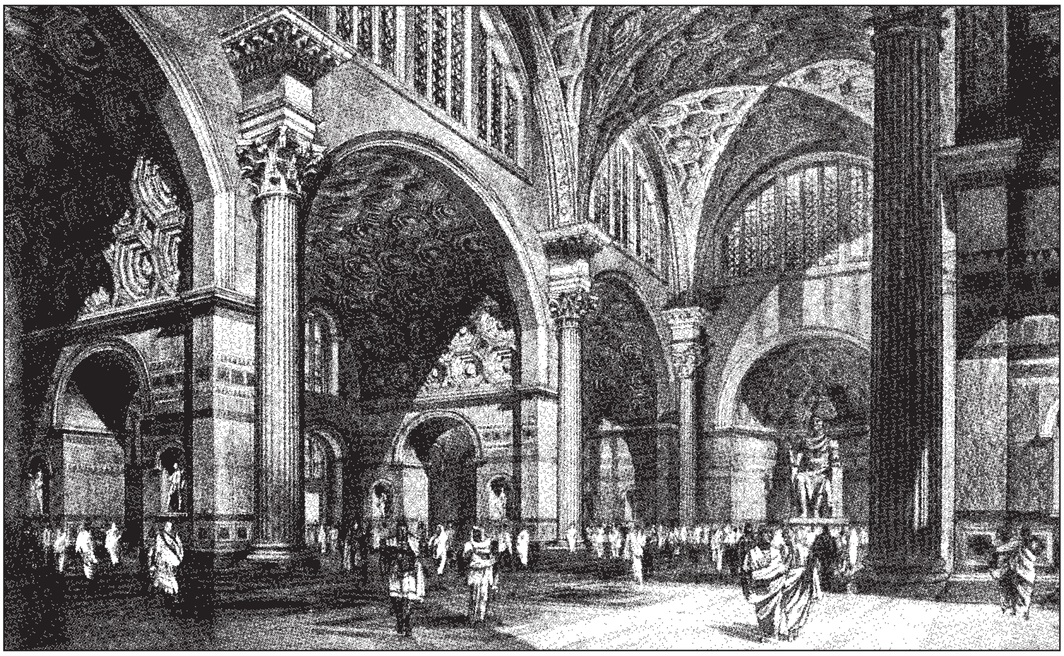
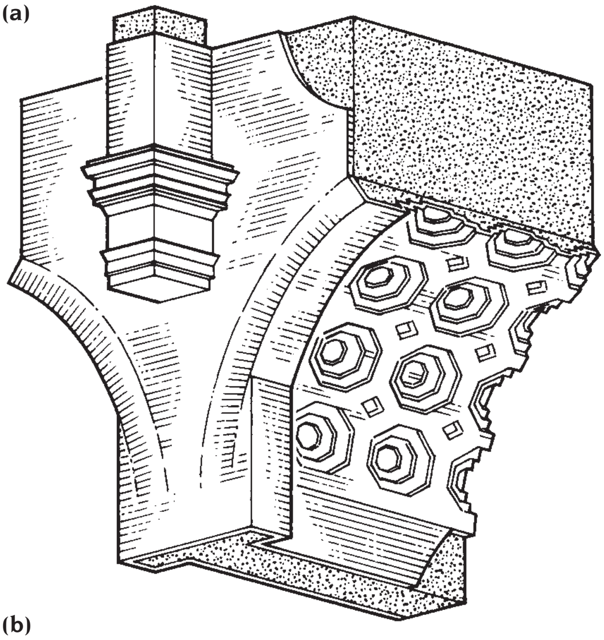


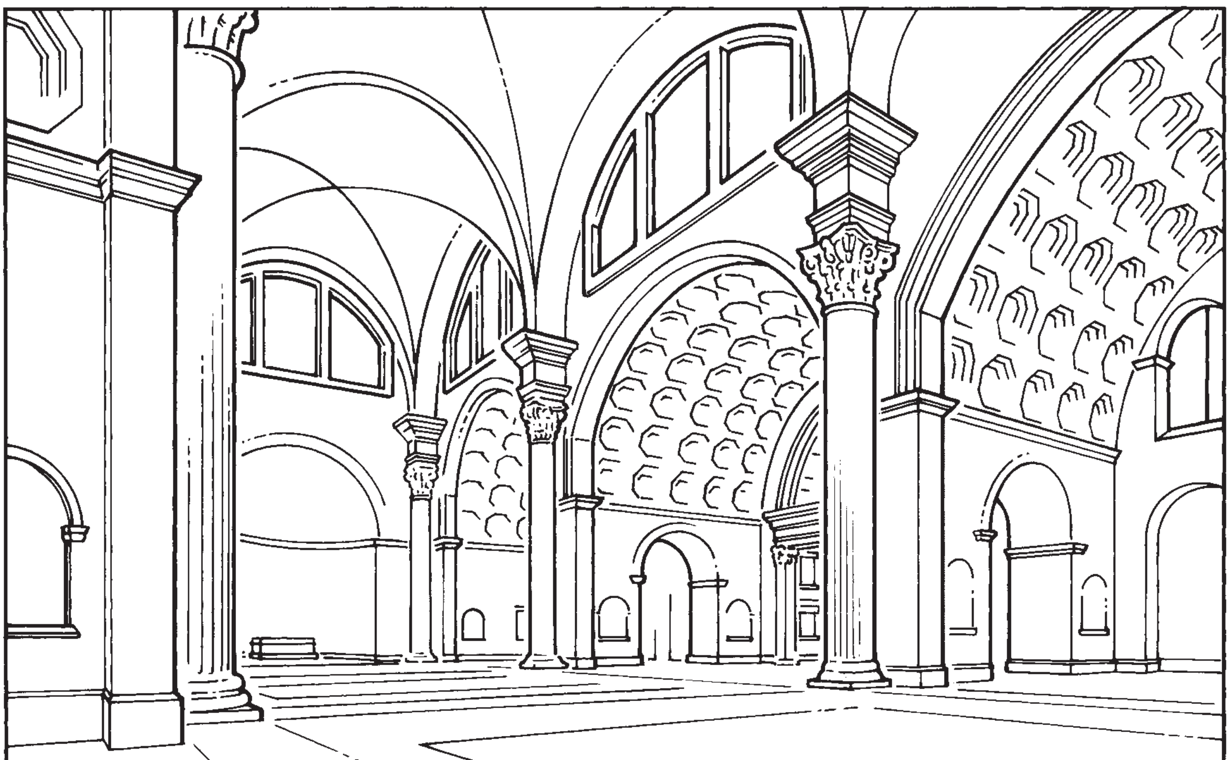
Fig. 7.31 The Basilica of Constantine, Rome, 4th century AD. The vaulted roof of the principal internal volume is supported on very thick walls from which large voids with vaulted ceilings have been extracted to reduce the volume of structural material required. These have been used to create variety in the disposition of internal volumes. As at the Pantheon the technical and visual programmes of the architecture have been brilliantly combined.

Fig. 7.32 Construction system of Roman vault. The largest interiors in Rome were constructed in unreinforced concrete which was placed in a thin skin of brickwork which acted as permanent formwork. The structural armature was then faced in marble to create a sumptuous interior. Although structural requirements dictated the overall form of the building, no part of the structure was visible.

(a)



(b)



of masonry or unreinforced concrete (Figs 7.30 to 7.32). The absence at the period of a strong structural material which 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 wall-heads.

The Roman architects and engineers quickly appreciated that the walls did not have to be solid and a system of voided walls was developed which 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 which 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 by the architects of Imperial Rome to create a distinctive architecture of the interior. The Pantheon in Rome (Fig. 7.30) is one of the best 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 which 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 (Fig. 7.31). 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 which 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 which 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 which 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 (Fig. 7.33) and the architectural opportunities which it made possible were summarised by Le Corbusier in his 'five points of a new architecture'[23].

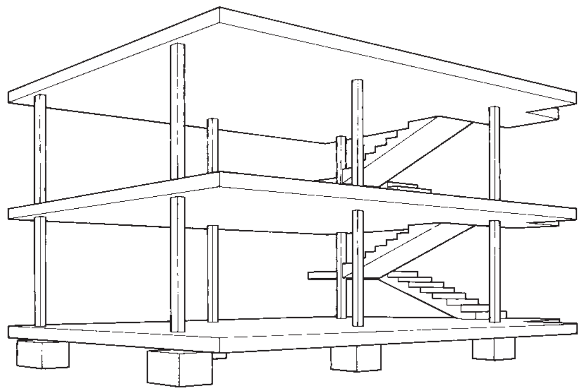


Fig. 7.33 The advantages of the structural continuity afforded by reinforced concrete are admirably summarised in the structural armature of Le Corbusier's Domino House of 1914. Thin two-way spanning slabs are supported directly on a grid of columns. The stairs provide bracing in the two principal directions.

This approach was used by Le Corbusier in the design of most of his buildings. The archetype is perhaps the Villa Savoye (Fig. 7.34), 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. Later buildings by Le Corbusier, such as the Unité d'Habitation at Marseilles or the monastery of La Tourette near Lyon, show a similar combination of structural and aesthetic programmes.

The 'Modernistic' (as opposed to Modern – see Huxtable[24]) skyscrapers which were constructed in the 1920s and 1930s in the USA, such as the Chrysler (Fig. 7.35) 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

23 Le Corbusier, *Five Points Towards a New Architecture*, Paris, 1926.

24 Huxtable, A. L., *The Tall Building Reconsidered: The Search for a Skyscraper Style*, Pantheon Books, New York, 1984.

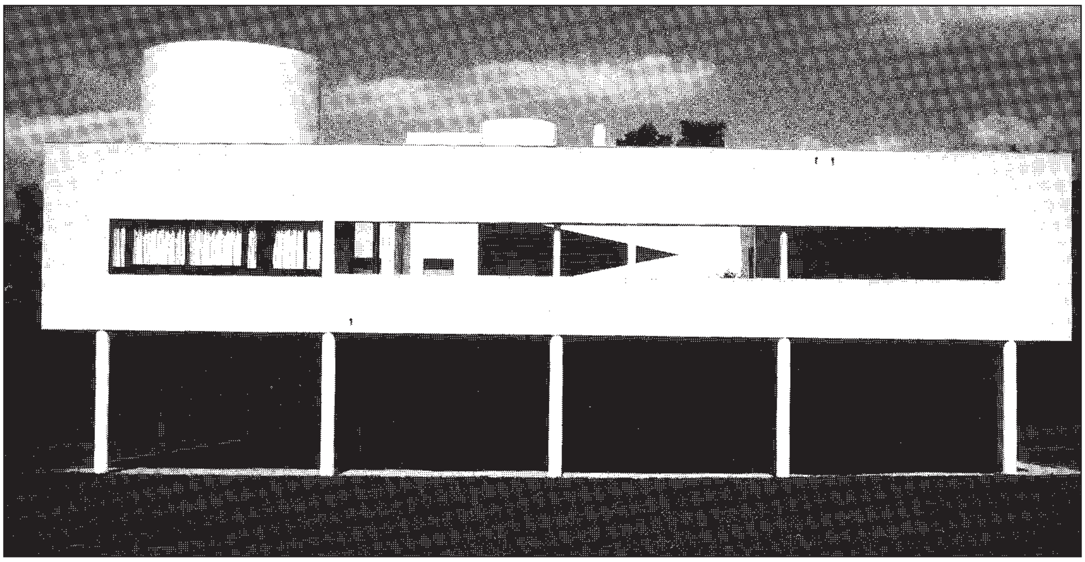


Fig. 7.34 Villa Savoye, Poissy, France, 1931; architect, Le Corbusier. The reinforced concrete structural armature of this building has, to a large extent, determined its overall form. Many other factors connected to Le Corbusier's search for a visual vocabulary appropriate to the 'machine age' contributed to the final appearance of the building, however. (Photo: Andrew Gilmour)

more conventional than those by Le Corbusier, making use of a pre-existing architectural vocabulary, they were nevertheless novel forms which 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 1 building in London by Berthold Lubetkin and Ove Arup (Fig. 7.36). Here the structure was a 'continuous', post-and-beam arrangement of reinforced concrete walls and slabs. There were no beams and few columns and therein lay one of its innovatory aspects. The system offered great planning freedom: where openings were required, the walls above acted as beams. The level of structural efficiency was modest but was entirely appropriate for the spans involved, and other aspects of the structure, such as its durability, were also highly satisfactory. The method of construction was also original. The structure was cast on site on a reusable, moveable system of wooden formwork – also designed by Arup – and the building represented, therefore, an harmonious fusion of new architectural ideas with structural and constructional innovations. The architectural language used was discreet, however, and made no grand statement of these innovative technical features.

Fig. 7.35 Chrysler Building, New York, USA, 1930; William Van Allen, 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: Petra Hodgson)

(a)

(b)

Fig. 7.36 Highpoint 1, London, UK, 1938; Berthold Lubetkin, architect; Ove Arup, structural engineer. The structure of this building is of reinforced concrete which lends itself to a rectilinear form. The visual treatment was as much influenced by stylistic ideas of what was visually appropriate for a modern architecture as it was by technical factors connected with the structure. (Photo: A. F. Kersting)

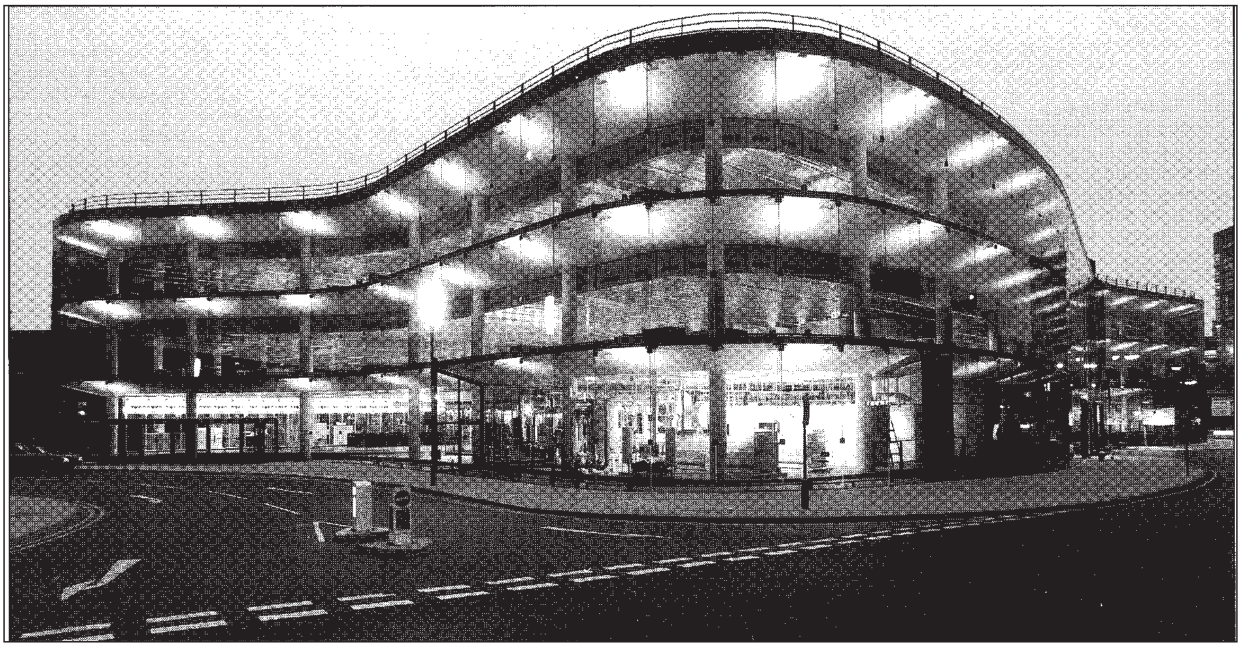


Fig. 7.37 Willis, Faber and Dumas Office, Ipswich, UK, 1974; Foster Associates, architects; Anthony Hunt Associates, structural engineers. This building may be considered to be a late Modern equivalent of the Villa Savoye (Fig. 7.34). The relationship between structure, space planning and visual treatment is similar in both buildings. (Photo: John Donat)

A late-twentieth-century example of the positive acceptance rather than the expression of structural technology is found in the Willis, Faber and Dumas building in Ipswich, UK by Foster Associates (Fig. 7.37) with the structural engineer Tony Hunt. The structure is of the same basic type as that in Le Corbusier's drawing (Fig. 7.33) 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'.

Another example by Foster and Hunt is the pilot head office for IBM UK at Cosham (Fig. 7.38). This was intended to serve as a temporary UK main office for the IBM company and was located on a site adjacent to one on which a permanent headquarters building for IBM UK was already under construction. When the design was commissioned, IBM, in common with many rapidly-expanding companies at the time, was making significant use of clusters of timber-framed portable buildings and envisaged that this type of accommodation would be the most suitable for the temporary head office. Foster Associates were instructed to report on the most suitable of the proprietary systems then available and to advise on the disposition of the buildings on the site. This possibility was indeed considered, but the solution which Foster recommended was that of a custom-designed building based on lightweight industrialised components, and it was this scheme that was finally executed.

Due to the need to compete with the portable building alternative on cost and speed of erection, and due to the fact that the ground conditions were poor because the site was a former land-fill rubbish tip, technical considerations exerted a major influence on the design. The design of the structure was particularly crucial to the success of the project. Tony Hunt considered using long piles (40 ft) to reach firm strata, but this would have meant reducing the number of separate

Fig. 7.38 IBM pilot head office, Cosham, UK, 1973; Foster Associates, architects; Anthony Hunt Associates, structural engineers. Intended as temporary accommodation, Foster and Hunt provided a stylish building for the same cost and within the same time-scale as those of a cluster of temporary buildings, which is what the client originally envisaged. The form adopted was to a large extent dictated by structural requirements. (Photo: Anthony Hunt Associates)

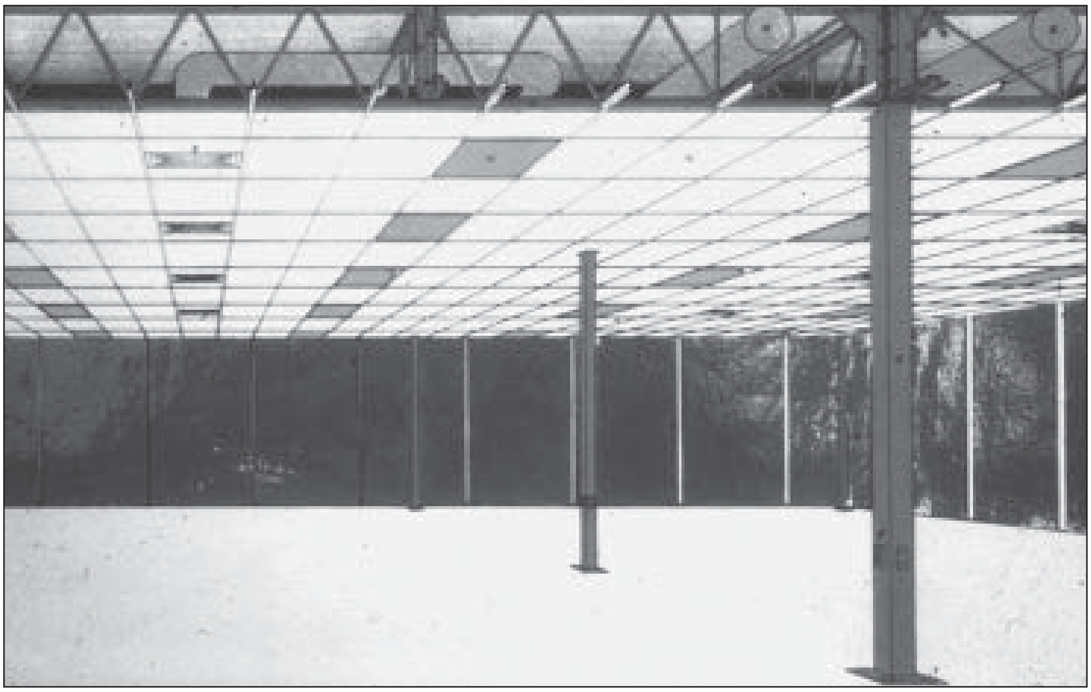


Fig. 7.39 IBM pilot head office, Cosham, UK, 1973; Foster Associates, architects; Anthony Hunt Associates, structural engineers. The structure was a steel framework with lightweight triangulated beam elements. These created a combined structural and services zone, at roof level which was essential to achieve the required flexibility in the use of the interior. (Photo: Anthony Hunt Associates)

foundations to a minimum and the resulting long-span structure would have been slow to erect and expensive to produce. The alternative was to use a short-span structure in conjunction with a rigid raft foundation that would 'float' on the low-bearing-capacity substrata. A number of such systems were considered. The favoured system was configured with lightweight triangulated girders which created a combined structure and services zone at roof level which was crucial to the provision of the required flexibility in the use of space (Fig. 7.39).

The IBM pilot head office was remarkably successful in almost every respect. It provided the client with a distinctive, stylish building which was enjoyable in use for all grades of employee, and which was undoubtedly a preferable solution to the client's requirements than the assemblage of proprietary portable buildings that they had originally envisaged. A measure of the success of the building was that, although it had been intended as temporary accommodation to last for a period of three to four years, it was retained by the company, following the completion of the permanent head office, and converted for use as an independent research unit.

The choice of the lightweight steelwork system was crucial to the success of the IBM building. It was a straightforward assemblage of proprietary Metsec components. This was both inexpensive and allowed the structure to be rapidly erected on site using no plant larger than a fork-lift truck. The resulting speed and economy was what made the building competitive with the alternatives. The structure does not form a significant visual element as most of it is concealed behind finishing elements. It did, however, exert a major influence on the final form of the building. This is therefore *structure as form generator* rather than *structure as architecture*.

The architectural interest in the IBM building lies in the stylish way in which the various components, particularly the finishing components such as the glass external wall, were detailed. Thus, although the need to produce a light and economical structure which could be erected very quickly played a significant role in determining the overall form of the building, the relationship between structure and architecture is here much less deterministic than was the case with the vaulted buildings of Roman antiquity or the Willis, Faber and Dumas building, where the final form was expressive of the behaviour of the constituent structural materials.

In the IBM pilot head office building, the relationship between structure and architecture is less direct than in the other buildings described in this section and is perhaps significantly different to warrant a different terminology, namely *structure accepted*. In this kind of relationship, a form is adopted which is sensible structurally but the architectural interest is not closely related to structural function. This is a relationship between structure and architecture which is commonly found in contemporary architecture and innumerable other examples could be cited. It has, in fact, been the dominant relationship between structure and architecture since the time of the Italian Renaissance (see Section 7.3).

7.2.5 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 is possible 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 which 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, i.e. 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 post-and-beam framework.

An additional factor which favoured the use of simple forms was that the design and construction of very complex forms was laborious and costly, thus inhibiting the full exploitation of the potential offered by these new materials. There were of course exceptions. Erich Mendelsohn's Einstein Tower in Potsdam (see Fig. iii), Gerrit Rietveld's Schroeder House in Utrecht and Le Corbusier's chapel at Ronchamp (Fig. 7.40) 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 which would support the form, rather in the manner of the armature of a sculpture.

Fig. 7.40 Notre-Dame-du-Haut, Ronchamp, France, 1954; Le Corbusier, architect. Structural considerations have 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: P. Macdonald)

The introduction of the computer in the late twentieth century, firstly as a tool for structural analysis and subsequently as a design aid, which allowed very complex forms to be described and cutting and fabricating processes to be controlled, gave architects almost unlimited freedom in the matter of form. This was a major factor in the introduction of the very complex geometries which appeared in architecture towards the end of the twentieth century. A good example is Frank Gehry's highly complex and spectacular Guggenheim Museum in Bilbao, Spain.

Wolf Prix, of Coop Himmelblau, was another late-twentieth-century architects who fully exploited this freedom:

> '... we want to keep the design moment free of all material constraints ...'[25]
> 'In the initial stages structural planning is never an immediate priority ...'[26]

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 is remarkable due to the great simplicity of the structure which 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 which 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 which 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 which span across the building. These provide support from above for the roof shell, which 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.

In more recent times a similar approach to that adopted by Le Corbusier at Ronchamp, at least so far as the relationship of structure to architecture is concerned, is to be found in the works of the architects of the Deconstruction school. The structural organisation of buildings such as the rooftop office in Vienna by Coop Himmelblau (see Fig. 1.11) or the Vitra Design Museum in Basel by Frank Gehry (Fig. 7.41) were relatively straightforward. The same may be said of Daniel Libeskind's Jewish Museum in Berlin (Fig. 7.42). More complex arrangements were required to realise the complicated geometries of Libeskind's extension to the Victoria and Albert Museum in London (Figs 7.43 and 7.44) and the new Imperial War Museum in Manchester.

Two important considerations must be taken into account when form is devised without recourse to structural requirements. Firstly, because the form will almost certainly be non-form-active, bending-type internal force will have to be resisted. Secondly, the magnitudes of the internal forces which 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 which can result in structures which 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 the self-weight of the structure. If

25 Quotations from *On the Edge*, the contribution of Wolf Prix of Coop Himmelblau to Noever, P. (Ed.), *Architecture in Transition: Between Deconstruction and New Modernism*, Prestel-Verlag, Munich, 1991.
26 *Ibid*.

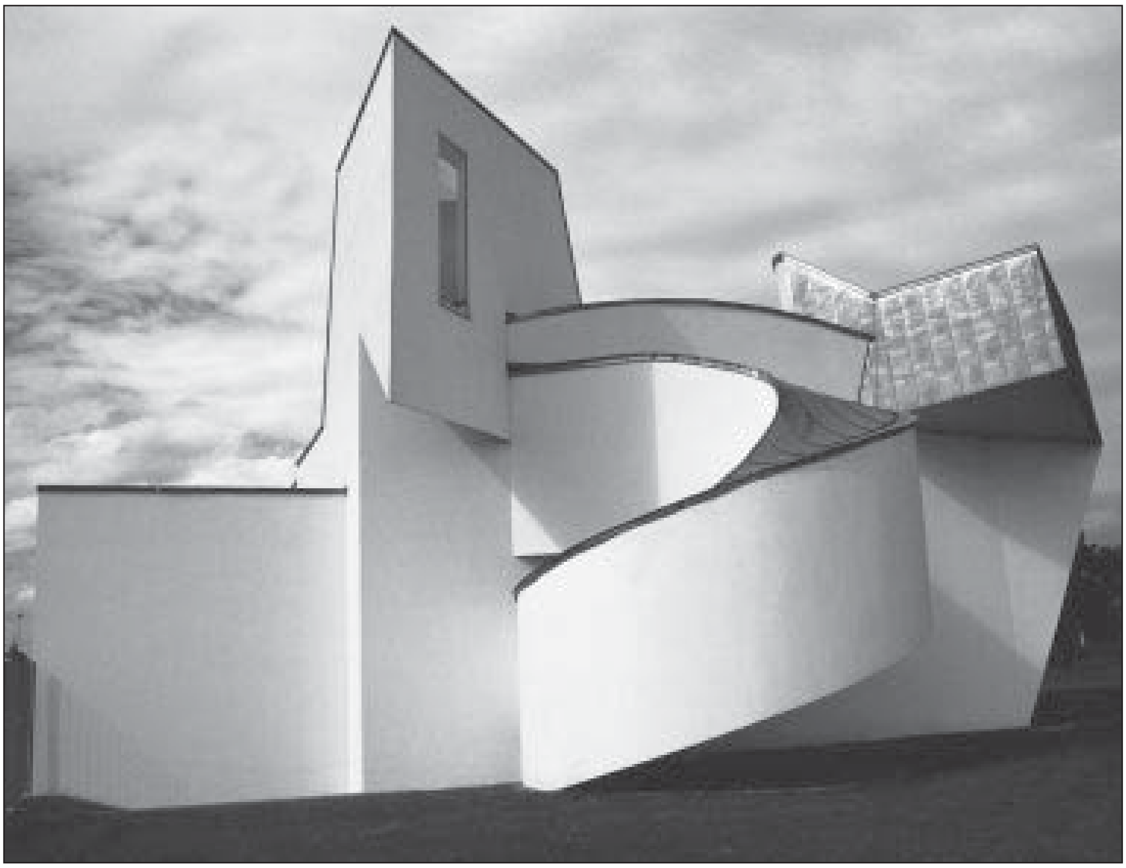


Fig. 7.41 Vitra Design Museum, Basel, Switzerland, 1989; Frank Gehry, architect. From a technical point of view forms such as this present a challenge. Their construction is made possible by the excellent structural properties of present-day materials such as reinforced concrete and steel. The scale of such a project must be small however. (Photo: E. & F. Mclachlan)

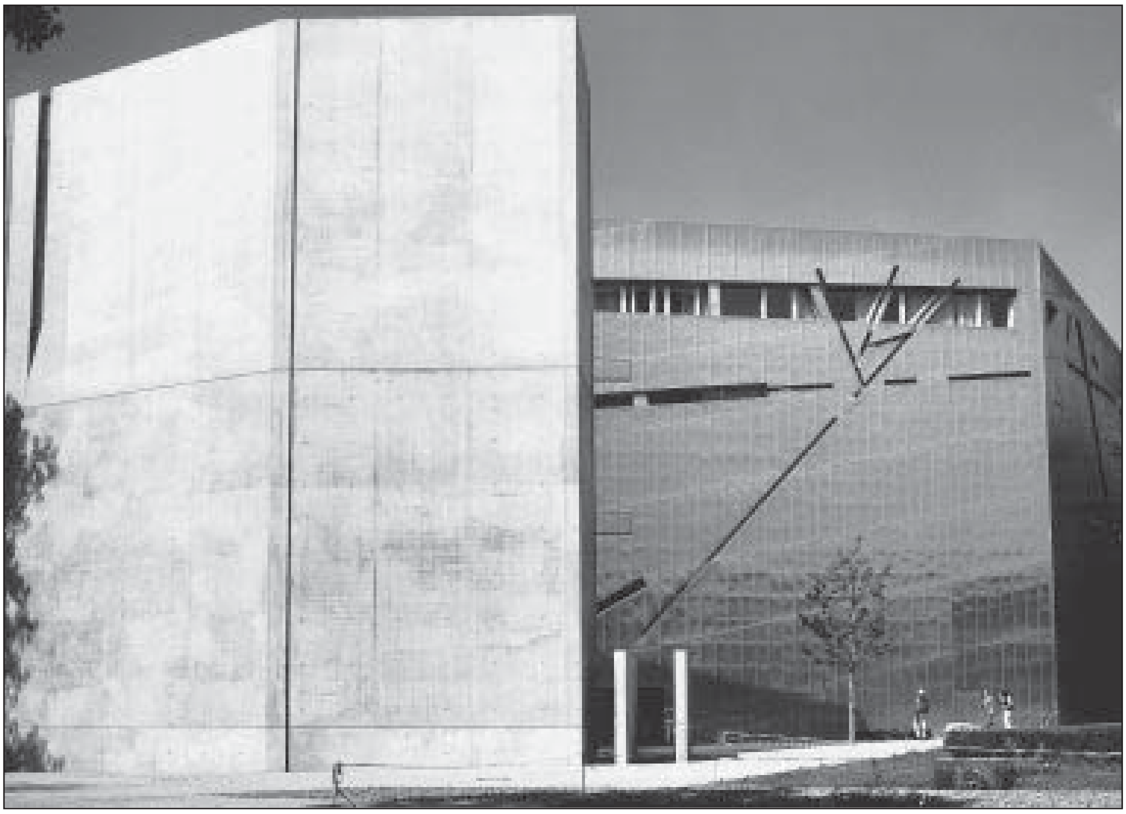


Fig. 7.42 Jewish Museum, Berlin, 1999; Daniel Libeskind Architekturburo, architects. The use of a reinforced concrete structural framework has allowed both a highly sculptured overall form to be created and a high degree of freedom to be achieved in the treatment of the non-structural cladding of the exterior.

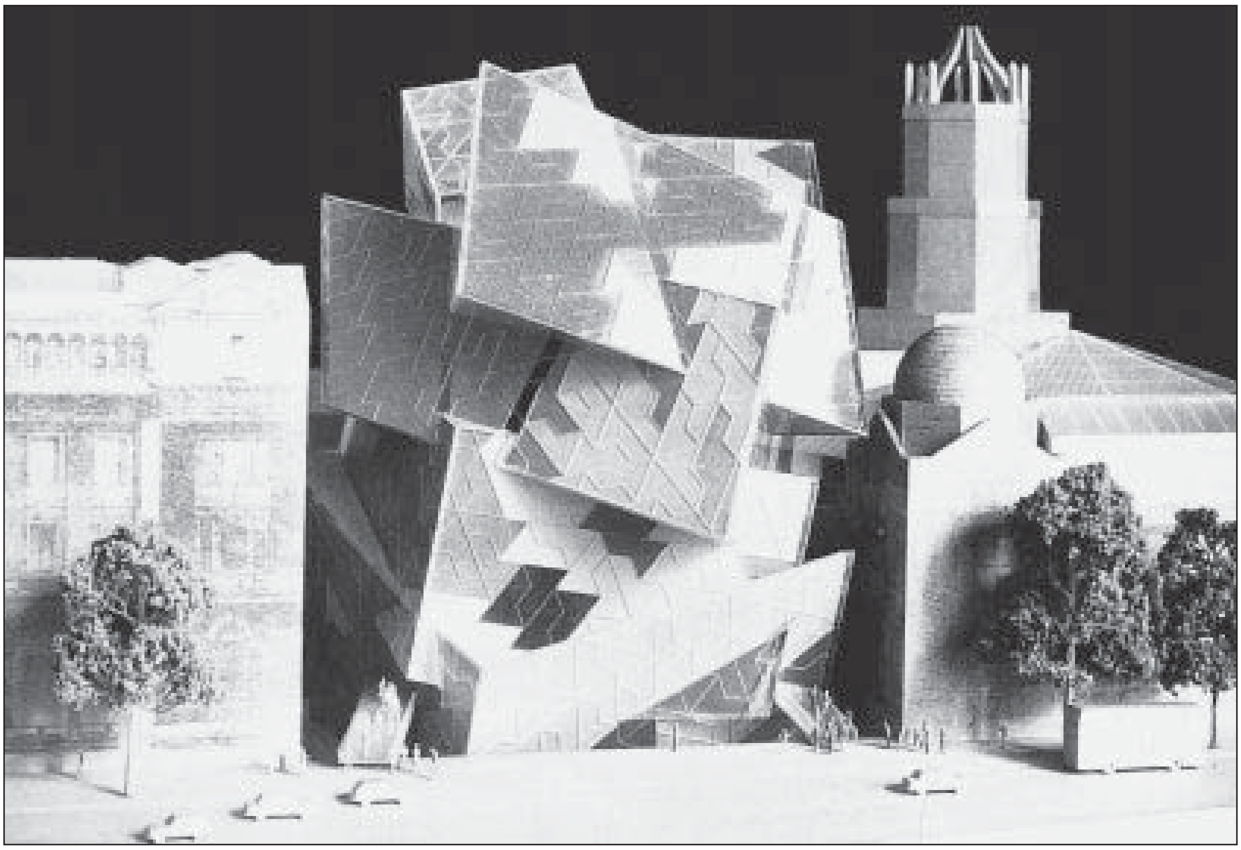


Fig. 7.43 Design for an extension to the Victoria and Albert Museum, London, UK, 1995–; Daniel Libeskind Architekturburo, architects; Ove Arup & Partners, structural engineers. Structural considerations had little influence on the original design for this building.

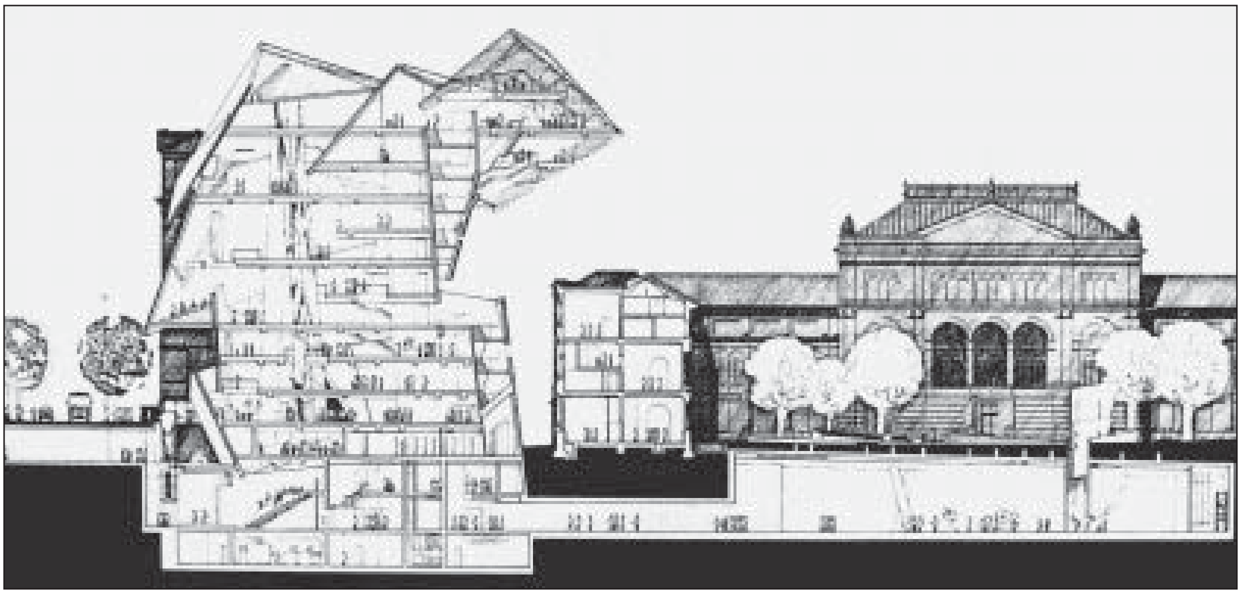


Fig. 7.44 Design for an extension to the Victoria and Albert Museum, London, UK, 1995–; Daniel Libeskind Architekturburo, architects; Ove Arup & Partners, structural engineers. The cross-section reveals that the structure is a fairly conventional post-and-beam framework. The relatively small scale of the project, the excellent properties of modern structural materials and the judicious use of structural continuity allowed this complex form to be realised.

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 scale of the buildings already mentioned meant that the internal forces were not 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 (Fig. 7.45) paid similar disregard to structural logic. Although the roof of this building was a reinforced concrete shell it did not have a form-active shape. The form was determined from visual rather than from structural considerations and, because it was larger than Ronchamp, difficulties occurred with the structure. These were overcome by modifying the original design to strengthen the shell in the locations of highest internal force.

Jorn Utzon's Sydney Opera House is another example of this type of building (Fig. 7.46). In this case, 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 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 an order of magnitude greater than had originally been envisaged. Amid great political controversy, the building was nevertheless completed and has become a distinctive image which is synonymous with Sydney, if not with Australia, rather as the Eiffel Tower, Big Ben or the Statue of Liberty have come to represent other famous cities and their respective countries. Although the expertise of Ove Arup and Partners in solving the structural and constructional problems brought about by Utzon's inspired, if technically flawed, original design are undisputed, the question of whether the final form of the Sydney Opera House is good

Fig. 7.45 TWA Terminal, Idlewild (now Kennedy) Airport, New York, USA, 1962; Eero Saarinen, architect; Amman and Whitney, structural engineers. The form here was far from ideal structurally and strengthening ribs of great thickness were required at locations of high internal force. The structure was therefore inefficient but construction was possible due to the relatively modest spans involved. (Photo: R. J. Mainstone)

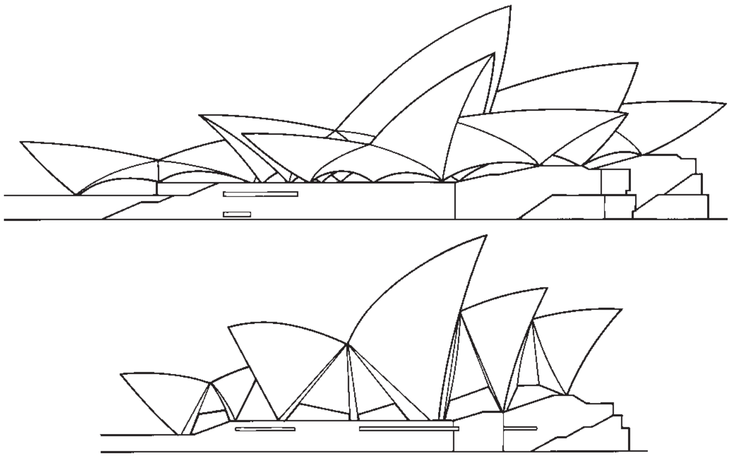


Fig. 7.46 Opera House, Sydney, Australia, 1957–65; Jorn Utzon, architect; Ove Arup & Partners, structural engineers. The upper drawing here shows the original competition-winning proposal for the building which proved impossible to build. The final scheme, though technically ingenious, is considered by many to be much less satisfactory visually. The significant difference between this and the buildings in Figs 7.41 to 7.45 is one of scale.

architecture remains open. This building may serve as a warning to architects who choose to disregard the inconveniences of structural requirements when determining form. The consequence may be that the final form will be different from their original vision in ways which they may be unable to control. The ignoring of structural logic in the creation of form is indeed possible but only in the context of short spans. The success of the recent buildings by Coop Himmelblau, Gehry and Libeskind has depended on this situation.

In all of the buildings considered in this section the structure is present in order to do its mundane job 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 which became fashionable in the late twentieth century. It was the structural techniques which were developed in the twentieth century which made such an architecture possible, and which gave architects the freedom to exploit geometries which in previous centuries would have been impossible to realise.

7.2.6 Conclusion

This section 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 which have been identified for this relationship, however artificial they may be, nevertheless contribute to the understanding of the processes and interactions which constitute architectural design.

Six broad categories were identified and these may be considered to be grouped in different ways – something which 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* also contains two sub-categories: *structure as form generator/structure accepted* and *structure ignored*.

The original six 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*, *structure as form generator* 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 which 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. The engineer is then a member of the team of designers which evolves the form of the building. Where the relationships fall into the category of *structure disrespected* the engineer can be simply a technician – the person who works out how to build a form which has been determined by someone else.

7.3 The relationship between architects and engineers

Collaboration has always been required between architects and those who have the technical expertise to realise buildings. The nature of the relationship has taken many forms, and the form in play at any time has always influenced the nature of the interface between structure and architecture.

In Greek and Roman antiquity, the relationship between the equivalents of architects and engineers must have been very close in order to achieve the creation of buildings in which the requirements of structure and architecture were reconciled in a very positive way. In this period the architect and engineer would, in many cases, have been the same individual – the master builder. This