3

Relationships between architectural and structural form

Introduction

This chapter is the first of seven that imagine visiting a building and progressively exploring in greater detail the roles structure plays in various areas and aspects of its architecture. As such it observes and reflects on architectural issues arising essentially *outside* the building. From a location some distance away, the form or massing of the building, rather than any exterior detail, dominates visually and invites an exploration of the relationships between architectural and structural form. But before considering the diversity of relationships between these forms that designers can exploit for the sake of architectural enrichment, the meaning of several terms require clarification.

Architectural form is often used but less frequently defined. Ching breaks from the tradition of using the term loosely. Yet, although he defines it explicitly, his definition still remains imprecise. He suggests that architectural form is an inclusive term that refers primarily to a building's external outline or shape, and to a lesser degree references its internal organization and unifying principles. He also notes that *shape* encompasses various visual and relational properties; namely size, colour and texture, position, orientation and visual inertia.[1] Form, in his view, is therefore generally and primarily understood as the shape or three-dimensional massing, but also encompasses additional architectural aspects including structural configuration and form, in so far as they may organize and unify an architectural design.

For the purpose of this discussion, architectural form is essentially understood as and limited to enveloping form, or shape. This deliberate simplification and clarification conceptually excludes from architectural form any consideration of interior and exterior structural organization. It acknowledges the fact that three-dimensional massing may be completely unrelated to structural form. By decoupling structure from the rather nebulous but conventional usage of architectural form, opportunities are provided to examine structure's relationships to specific aspects of architecture included previously within more general definitions of architectural form. These aspects include issues such as texture, order and spatial organization. This limited definition of architectural form, exclusive of structural considerations, also reflects observations of both the reality of architectural design approaches and the built architecture discussed in this chapter. In the design process, within architectural practice and buildings themselves, separation between architectural and structural forms is commonplace. The two distinctive structural forms in the Baumschulenweg Crematorium have already been observed. Walls that relate closely to the architectural form, and columns that do not, both coexist within the building envelope and contribute richly to its exterior and interior architecture respectively.

Structural form also requires elaboration. In the context of architectural writing its traditional usage usually conveys the structural essence of a building. For example, the structural form of a post-and-beam structure might be described as skeletal, even though the posts and beams might support planar floor structure and are stabilized by shear walls. In this case the observer perceives the structural framework as the dominant structural system in the building. Perhaps the framework is a more visually pronounced element than the shear walls. Visibility of the framework's elements, its beams and columns, is in all likelihood enhanced by an absence of interior partitions, while the shear walls recede into the background.

This book generally understands structural form as a building's primary or most visually dominant structural system. While most buildings have several primary structural systems, some have only one. Library Square, Vancouver is one such example (Fig. 3.1). Moment-resisting frames running at regular intervals across the plan resist gravity and longitudinal lateral loads, and two perimeter frames resist transverse lateral loads.

Most buildings contain two or three structural systems – either a gravity-load resisting system and one or two systems that resist lateral loads in both orthogonal directions, or a combined gravity and uni-directional lateral load system complimented by another system for lateral loads in the orthogonal direction. The Mont-Cenis Academy, Herne, exemplifies the first configuration (see Figs 3.26 and 3.27). Continuous roof trusses on pole columns resist gravity loads while steel rod cross-bracing in the roof plane and along each of the four exterior walls withstands lateral loads. Exchange House, London, typifies the second situation, comprising two different lateral load resisting systems. Arches, stiffened by diagonal ties,

▲ **3.1** Library Square, Vancouver, Canada, Moshe Safdie and Associates Inc., 1995. A typical longitudinal frame and the end of a perimeter transverse frame.

resist gravity and longitudinal loads, and exposed cross-bracing resists transverse loads (see Figs 3.40 and 3.41).

In buildings with more than one structural system and where it is unclear which system is primary from a visual perspective, the concept of *structural form* is too simplistic. The term *structural systems* is more appropriate in these cases.

Suckle's study of ten leading architects suggests that architects determine building form after considering a wide range of factors that usually, in the first instance, do not include structure.[2] Design issues such as integrating the programme or brief within the allowable site coverage and budget all within an overriding architectural concept tend to be dealt with first. She finds that while the intensity and importance of an initial design concept varies greatly from designer to designer, structural considerations are never paramount during the initial design stage to determine building massing. Many architects probably identify with Erickson when he states:

> *Structure is the strongest and most powerful element of form, so much so that if it is not the last consideration in the long series of decisions determining form, it distorts or modifies all other determinants of a building. One finds in fact, that the structure has dictated all the other aspects of the design. The inhabitants should not behave as the columns dictate – the contrary should surely be the case . . . As with all my buildings the structure was not even considered until the main premises of the design – the shape of the spaces and the form of the building had been determined. Thus, the structure did not preclude but followed the design intent.*[3]

It is worth noting that although Erickson postpones structural decisions in the early design stages, his architecture is notable for its rational and clearly expressed structure. His buildings lack any evidence of conceptual structural design decisions being left too late in the design process, resulting in structure poorly integrated with building function and aesthetics. One just needs to recall his Vancouver Law Courts building and the Museum of Anthropology, University of British Columbia, Vancouver, to appreciate the clarity with which structure 'speaks' in his architecture.

Such an attitude towards structure as 'form-follower' rather than 'form-giver' contrasts starkly with opposing views that have been articulated in various periods of architectural history. For example, Viollet-le-Duc expressed the views of eighteenth-century Structural Rationalists: 'Impose on me a structural system, and I will naturally find you the forms which should result from it. But if you change the structure, I shall be obliged to change the forms.'[4] He spoke with Gothic architecture in mind, where masonry load-bearing walls and buttresses comprise the building envelope. By virtue of its large plan area and its exterior and interior spatial impact, structure so dominates Gothic construction that a close relationship exists between structural and architectural form. However, since the eighteenth century and the advent of high-strength tension-capable materials like iron and then steel, the previously limited structural vocabulary of walls, vaults and buttresses has been extended greatly and often been relieved of the task of enveloping buildings. Newer systems like moment frames and cantilever columns are common, and these are used in conjunction with modern non-structural enveloping systems such as precast concrete and light-weight panels. Building enclosure is now frequently separated from the structure to the extent that the structural form may be quite unexpected given the architectural form.

Viollet-le-Duc's beliefs in structure as 'form-giver' were reaffirmed just as forcefully in the 1950s by Pier Luigi Nervi:

> *Moreover, I am deeply convinced – and this conviction is strengthened by a critical appraisal of the most significant architectural works of the past as well as of the present – that the outward appearance of a good building cannot, and must not, be anything but the visible expression of an efficient structural or constructional reality. In other words, form must be the necessary result, and not the initial basis of structure.*[5]

Nervi's view, persuasive only in the context of high-rise and long-span construction, is supported by Glasser: 'as in the case of arenas, auditoriums, and stadiums – it is equally clear that a conceptual design without a rigorous and well-integrated structural framework would be specious.'[6]

The following sections of this chapter illustrate the diversity of relationships between architectural and structural forms. Works of architecture where architectural and structural forms synthesize are first examined. Then, after considering the most commonly encountered situation where the relationships between the forms can be considered consonant, the chapter finally moves to examples of buildings where, for various reasons, architectural and structural forms contrast.

The order in which the three relationships are discussed is not intended to imply a preference towards any one of them in particular. No relationship between architectural and structural form, be it synthesis, consonant or contrast, is inherently better than another. What *is* of utmost importance, however, is the degree to which structure, whatever its relationship to architectural form, contributes to a successful realization of architectural design aspirations.

Synthesis of architectural and structural form

This section considers seven structural systems that typically exemplify a synthesis between architectural and structural form. In these cases structure defines architectural form and often functions, at least partially, as the building envelope. The order in which the structural systems are discussed begins with shell structures that of all structural systems most closely integrate the two forms. The remaining systems then generally follow a progression from curved to more linear and planar forms.

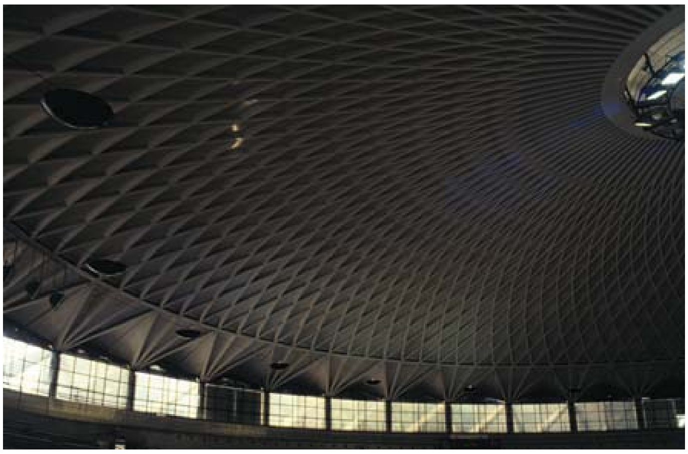
Shell structures

Shell structures achieve the most pure synthesis of architectural and structural forms. Also known as 'surface structures', shells resist and transfer loads within their minimal thicknesses. They rely upon their three-dimensional curved geometry and correct orientation and placement of supports for their adequate structural performance. When constructed from reinforced concrete, many shells, such as those designed by Isler, a leading European concrete shell designer, reveal smooth curved surfaces inside and out, much like those of a hen's egg.[7] Isler's shells unify architectural and structural form as they spring from their foundations and continuously curve over to envelop interior space (Fig. 3.2).

At the Palazzetto dello Sport, Rome, the shell surface does not meet the foundations directly but ends at the eaves level where inclined struts resist the outward thrusts (Fig. 3.3). This shell also defines the roof form, functioning simultaneously as structure and enclosure. Its interior surfaces are ribbed (Fig. 3.4). Interlacing ribs that evidence its precast concrete formwork segments both increase shell stability and achieve a much admired structural texture.

▲ **3.2** Interior of a concrete shell structure. (Courtesy J. Chilton)

▲ **3.3** Palazzetto dello Sport, Rome, Italy, Pier Luigi Nervi with A Vitellozzi, 1957. Inclined struts support the shell roof.



▲ **3.4** Interior ribbed surface of the shell.

▲ **3.5** Eden Project, Cornwall, England, Nicholas Grimshaw & Partners, 2001. A cluster of interlinked biomes.

Shell structures can also be constructed from linear steel or timber members, as in the cases of geodesic or other braced domes. Although in these cases the many short structural members shape a faceted structural surface which must then be clad, structure nonetheless defines architectural form. The huge greenhouses of the Eden Project, Cornwall, are such examples (Fig. 3.5). Hexagons, a geometrical pattern found in many naturally occurring structures, are the building blocks of these shells, or biomes as they are called. Due to the long spans of up to 124 m, the outer primary hexagonal steel structure is supplemented by a secondary inner layer of tension rods (Fig. 3.6). By increasing structural depths of the biomes like this, the diameters of the main hexagon tubes could be more than halved to less than 200 mm, considerably

▲ **3.6** Biome interior structure consisting of outer primary hexagons and an inner layer of braced rods.

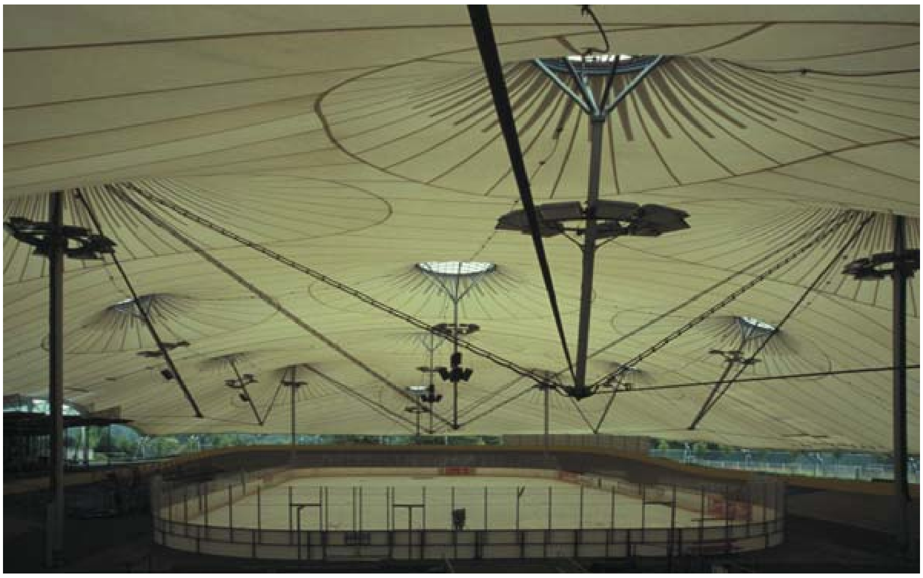
▲ **3.7** Stellingen Ice Skating Rink and Velodrome, Hamburg, Germany, Silcher, Werner + Partners, 1996. Overall form.

improving their overall transparency. The biomes demonstrate the degree of synthesis of forms possible with shell structures. Although in this project structure acts as building skin in a very minor way, it defines an organic architectural form whilst achieving rational, economic and transparent construction.

Fabric structures

Fabric or membrane structures represent another type of surface structure. These structures, where tensioned fabric initially resists self-weight and other loads, also rely upon their three-dimensional curvatures for structural adequacy. Fabric form, thickness and strength must match the expected loads, and all surfaces must be stretched taut to prevent the fabric flapping during high winds. Like shell structures, there is no distinction between the architectural and the structural forms. Fabric structures, however, require additional and separate compression members to create high-points over which the fabric can be stretched. Arches, with their curved forms, are well suited and aesthetically the most sympathetic to the curving fabric geometry, but masts, flying struts and cables which are more common, introduce dissimilar geometric forms and materiality. Their linearity, density and solidity contrast with the flowing double-curved, light-weight and translucent fabric surfaces, and can sometimes visually disturb the fabric's overall softness of form.

At the Stellingen Ice Skating Rink and Velodrome, Hamburg, four masts that project through the fabric and connect to it by tension cables provide the primary means of compression support (Fig. 3.7). Eight flying struts provide additional high points. From interior cables tensioned between the four outermost masts they thrust upward into the fabric



▲ **3.8** Contrasting architectural qualities of fabric surface and interior structural elements.

to increase its curvature and improve its structural performance. The building interior illustrates clearly the different architectural qualities of the fabric and its linear supporting structure – masts, flying struts and interior steel cables (Fig. 3.8).

Catenaries

Catenary structures, like fabric structures, transfer loads to their supports through tension. The simplest example of a catenary is a draped cable spanning between two high points. Catenaries that support roofs are usually designed so that the roof self-weight exceeds the wind suction or uplift pressures that would otherwise cause excessive vertical movement. Reinforced concrete is sometimes chosen as a catenary material for this reason. The concrete encases the tension steel protectively and provides the exterior and interior surfaces. Lighter catenary systems are possible provided that wind uplift is overcome with ballast or a separate tie-down system. Catenary tension members are usually distinct from the cladding and exposed within or outside the building envelope. The Portuguese Pavilion canopy, Lisbon, and Hall 26 of the Trade Fair, Hanover, illustrate these two approaches.

At the southern end of the Portuguese Pavilion, built for Expo '98, a ceremonial plaza 65 m long by 58 m wide is sheltered by a 200 mm thick reinforced concrete catenary slab. It has been variously described as a 'veil' or 'tent' on account of its remarkable slimness and draped form (Fig. 3.9). Two porticoes, one at each end, act as massive end-blocks to resist the catenary tension. Within each portico, nine parallel walls or

▲ **3.9** Portuguese Pavilion, Lisbon, Portugal, Alvaro Siza, 1998. The canopy drapes between two porticoes.

▲ **3.10** Dulles International Airport, Washington, DC, USA, Saarinen (Eero) and Associates, 1962. Inclined piers support the catenary slab.

buttresses resist the large inwards pull from the hanging slab. Its simplicity of detailing carries through to the design of the porticoes which are not at all expressive of their important structural roles. Their simple orthogonality would have been compromised if the common procedure of tapering buttress walls in acknowledgement of the reduction of their bending moments with height had been undertaken. The piers of the Dulles International Airport Terminal, Washington, DC, illustrate the usual approach. Their tapering as well as their inclination express the strain of supporting a heavy reinforced concrete roof (Fig. 3.10).

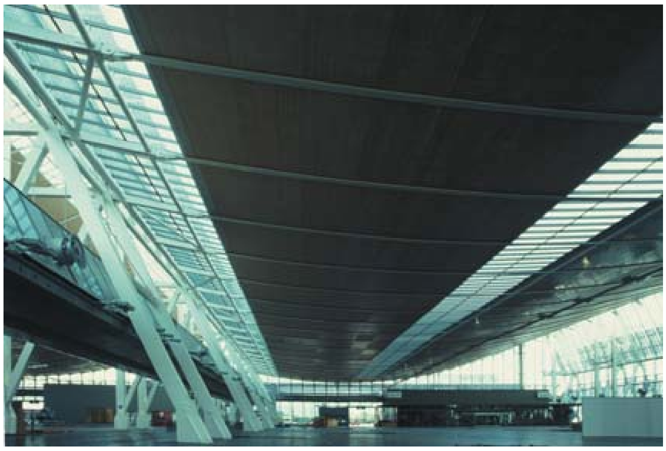
The Portuguese Pavilion plaza shelter therefore consists of two forms, the catenary and the porticoes. Both, simple and plain, exemplify synthesis of architectural and structural form. (Chapter 6 examines the novel detail of exposed catenary tendons at a portico-to-slab junction.)

Undulating waves formed by alternating masts and catenary roofs at Hall 26, Hanover, also demonstrate totally integrated architectural and structural forms (Fig. 3.11). In stark contrast to the solid concrete porticoes of the Portuguese Pavilion, the triangulated and trestle-like masts possess architectural qualities of lightness and transparency. Within the main interior spaces the structural steel catenary members that read as ‘tension bands’ support the roof and timber ceiling, or in selected areas, glazed roof panels (Fig. 3.12).

Ribbed structures

Ribbed structures can also become almost synonymous with enclosure where they generate and define architectural form, although their skeletal character often necessitates a separate enveloping system. Ribs usually cantilever from their foundations or are propped near their

▲ 3.11 Hall 26, Trade Fair, Hanover, Germany, Herzog + Partner, 1996. Three catenaries span between masts.



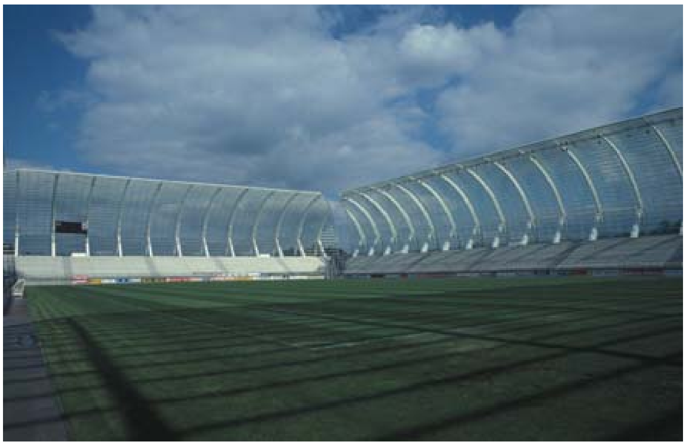
▲ 3.12 Exposed steel catenary members connect to an interior mast.

bases. If ribs are inclined from the vertical or curved in elevation they may be propped by other ribs to achieve equilibrium, as in the case of a ribbed dome. Ribbed structures generally enclose single volumes rather than multi-storey construction. By restricting the height of these structures effectively to a single storey, albeit very high, designers avoid potentially compromising a pure architectural language of ribs with additional interior load-bearing structure.

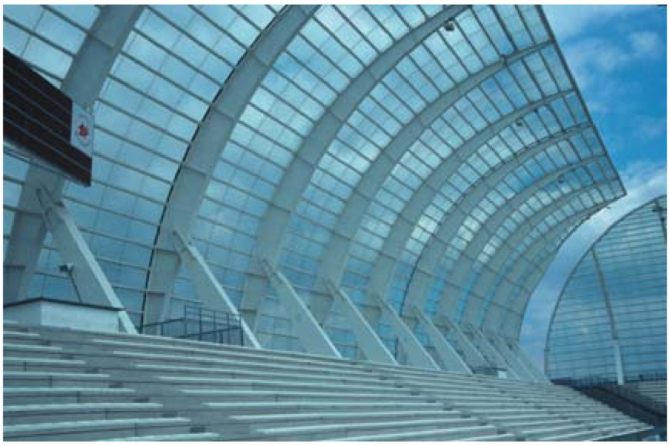
Ribs visually dominate each of the four structurally independent Licorne football stadium perimeter walls at Amiens (Fig. 3.13). Elegantly curved and tapered, the ribs shelter the spectators and accentuate a sense of enclosure. The combination of widely spaced ribs and glazing provides an unusually high degree of transparency and openness – daylight is maximized, spectators are more acutely aware than usual that the game is being played outside, and they can enjoy the surrounding townscape.

A prop near to the base of each rib provides its base-fixity and stability in the transverse direction. Unusually configured moment-resisting frames within the ribbed surface resist longitudinal loads. In these frames the ribs function as columns, and the horizontal tubes or girts, rigidly connected at 1 m spacing up the ribs, as beams (Fig. 3.14). The integration of girts with ribs to form these multi-bay frames avoids the need for a more common and economical form of resistance, such as diagonal bracing whose geometry would clash with an otherwise regular orthogonal pattern of ribs and girts.

A similar combination of primary structural ribs and secondary horizontal tubes defines the architectural form of the Reichstag Cupola, Berlin (Fig. 3.15). In this case, ribs lean against each other via a crowning compression ring. An internal double-helical ramp structure supported off



▲ **3.13** Licorne Soccer Stadium, Amiens, France, Chaix & Morel et Associés, 1999. Curved ribbed walls enclose the pitch and spectators.



▲ **3.14** Wall ribs, props and longitudinal girts.

▲ **3.15** The Reichstag Cupola, Berlin, Germany, Foster and Partners, 1999. Radial ribs and circumferential tubes.

▲ **3.16** Ludwig Erhard House, Berlin, Germany, Nicholas Grimshaw & Partners, 1998. Arched end of building as seen from the rear.

the ribs provides them with additional horizontal stiffness through its in-plan ring-beam action. A circumferential moment-resisting frame similar to that of the Licorne Stadium lies within the dome surface to resist lateral loads.

Arches

Arches also offer a potential synthesis of architectural and structural form. At Ludwig Erhard House, Berlin (Fig. 3.16) repeated arches

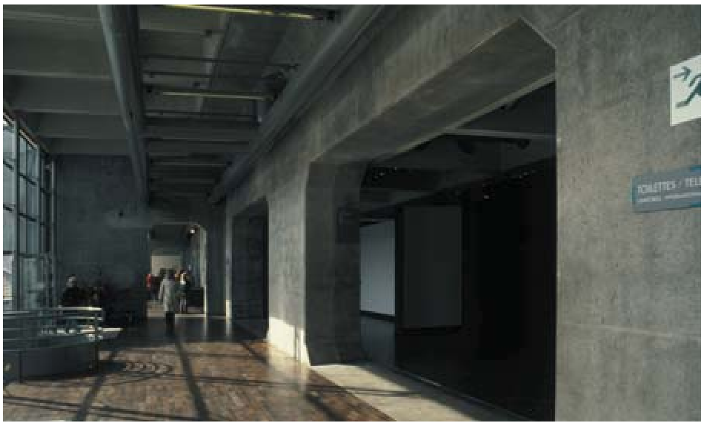
▲ 3.17 The Great Glasshouse, Carmarthenshire, Wales, Foster and Partners, 1998. Arched roof.

structure a vault-like building form. Varying arch spans respond to an irregularly shaped site. Suspended floors either hang from tension hangers under the arches, or as on the street frontage, are propped off them. This is an example of reasonably conventional arch usage where arches are regularly spaced and aligned vertically. But at the Great Glasshouse, Carmarthenshire, arches form a toroidal dome (Fig. 3.17). The dome's two constant orthogonal radii of curvature require that the arches distant from the building's centreline lean over in response to the three-dimensional surface curvature. Clarity of the arched structural form is undiminished by the small diameter tubes that run longitudinally to tie the arches back at regular intervals to a perimeter ring beam. Apart from supporting the roof glazing they also prevent the arches from buckling laterally and deflecting from their inclined planes.

Framed structures

Synthesis of architectural and structural form extends beyond curved forms. Consider the intimate relationship between orthogonal skeletal structural frameworks and rectilinear forms. In his discussion of the formative 1891 Sears Roebuck Store in Chicago, Condit asserts: 'for the first time the steel and wrought-iron skeleton became fully and unambiguously the means of architectonic expression . . . The long west elevation is developed directly out of the structural system behind it, much as the isolated buttresses of the Gothic Cathedral serve as primary visual elements in its indissoluble unity of structure and form.'[8]

▲ **3.18** La Grande Arche, Paris, France, Johan Otto van Spreckelsen, 1989. Frames within a frame.



▲ **3.19** An interior vierendeel truss to the right.

Most orthogonal beam-column frameworks integrate well within prismatic architectural forms. The ubiquitous medium- to high-rise office building is a typical example, but even though exemplifying integrated architectural and structural forms the ensuing architecture may not be meritorious. The following three rather unusual but well-regarded buildings illustrate the realization of and the potential for synthesizing frames and architectural form.

La Grande Arche, Paris, itself a huge open frame when viewed in frontal elevation, comprises a hierarchy of frames (Fig. 3.18). Along each leg of the frame four equally spaced five-storey internal mega-frames rise to support the roof. Each mega-frame storey is subdivided into seven intermediate floor levels. The long-span roof and the plinth structure that spans over numerous subterranean tunnels are also framed – in the form of three-storey deep vierendeel trusses. Similar secondary roof frames at right-angles to the primary trusses form a grillage in plan from which to cantilever the chamfered roof and plinth edges. Vierendeel truss elements are exposed within the roof exhibition areas. Although their chamfered top-chord sections and their chord-to-web haunches depart from the orthogonality of most of the structure they do resonate with the overall chamfered building form (Fig. 3.19).

Uncompromising orthogonal rigour characterizes the cubic form and perimeter frames of the San Cataldo Cemetery columbarium, or chamber for remains at Modena (Fig. 3.20). From both architectural and structural engineering perspectives, the exterior surfaces that are penetrated by unglazed openings can also be considered as highly pierced walls, given their plastered smoothness and an absence of any articulation of individual beam or column members. The frame thickness, exaggerated by the depth of the integral ossuary compartments, reinforces ideas of hollowness and

▲ **3.20** San Cataldo Cemetery columbarium, Modena, Italy, Aldo Rossi, 1984. Rigorous orthogonality.

▲ **3.21** Princess of Wales Conservatory, London, England, Gordon Wilson, 1986. Pitched portal frame variations.

emptiness that are reminiscent of empty eye sockets in a skull. This reading corresponds with an understanding of the work as an 'unfinished, deserted house, a built metaphor of death'.[9] The building interior is also essentially hollow, except for stairs and galleries on a skeletal steel framework with contrasting scaffolding-like qualities.

Pitched portal frames consisting of two columns connected rigidly to sloping rafters structure innumerable light-industrial and other utilitarian buildings. This structural form that rarely graces the pages of architectural publications, integrates with architectural form in the Princess of Wales Conservatory, London. In realizing a 'glazed hill' design concept, the architect manipulates basic multi-bay portals (Fig. 3.21). However, unlike most portal frames, the side rafters connect directly to the perimeter foundations, successfully reducing the building's visual impact on its surroundings. The form-generating portals that span transversely are geometrically simple but subtle transformations that introduce asymmetry and volumetric complexity distance the conservatory from its utilitarian cousins. An uncommon structural system, yet similar to that at the Licorne Stadium, provides longitudinal resistance. Concerns about the humid corrosive environment and potential aesthetic distractions led to roof-plane moment-resisting frames substituting for the more conventional diagonal cross-bracing usually associated with portal frame construction.

Walls

The wall is another structural system capable of participating in the integration of architectural and structural forms. As exemplified by the

▲ **3.22** Faculty of Journalism, Pamplona, Spain, Vicens and Ramos, 1996. Walls visually dominate the exterior.

▲ **3.23** An interior architecture of walls.

Faculty of Journalism, Pamplona, walls not only dominate its façades, but also define interior spaces (Figs 3.22 and 3.23). In some areas of the building horizontal slots force the walls to span horizontally and function structurally like beams, and even balustrades read as low walls. Inside and out, walls dominate the architectural experience. Fortunately, any possible blandness arising from this architecture of walls is mitigated by exterior elevational and interior spatial variation, careful attention to surface textures, and the lightening of the concrete colour. The rectilinear form of the walls strengthens the orthogonal architecture they support, enclose and subdivide.

▲ **3.24** Casa del Fascio, Como, Italy, Giuseppe Terragni, 1936. Rational composition of frames and walls.

▲ **3.25** The central hall wrapped by frames.

This section concludes by observing how a combination of walls and frames can also synthesize architectural and structural form. In the Casa del Fascio, Como, widely acknowledged as Italy's most notable contribution to the Modern Movement, architectural and structural forms coalesce. Orthogonal frames, supplemented by several walls that provide lateral stability, order and structure a building square in plan with rectilinear façades. The expression of frames and walls is most overt on the front elevation (Fig. 3.24). The frames, and the walls to a lesser extent, organize interior space somewhat less rigidly than expected. As Blundell-Jones explains, the structural grid spacing varies subtly in several locations – to accommodate a large meeting room, to create more office depth and to reduce corridor width adjacent to the central gathering space.[10] The frames generally define room width and depth as well as circulation areas (Fig. 3.25). The Casa del Fascio, an epitome of orthogonality and rationality, is structured physically and conceptually by both walls and frames.

Consonant forms

Most buildings fall into this category where the architectural and structural forms neither synthesize, nor as discussed in the following section, contrast. Rather, a comfortable and usually unremarkable relationship exists between them. Often several different structural systems co-exist within the same architectural form. For example, frames and cross-bracing might resist gravity and lateral loads respectively. The following case studies illustrate several such buildings. Although their forms cannot be considered synthesized, they are nonetheless highly integrated. The buildings are discussed in a sequence that progresses from simple to more irregular architectural forms.

▲ **3.26** Mont-Cenis Academy, Herne, Germany, Jourda & Perraudin, 1999. A glazed box with an entry canopy.

▲ **3.27** Interior timber structure.

A glazed box encloses the Mont-Cenis Academy complex, a government training centre at Herne. An extended roof plane forms an entry canopy (Fig. 3.26). The self-contained campus includes three-storey accommodation blocks, library, administration, teaching spaces, dining rooms and spacious 'outdoor' areas. Responding to the site's coal mining history, a particularly environmentally friendly design approach is evidenced by the timber structure and the 'clouds' of photovoltaic cells that cover 50 per cent of the roof surface. A forest of poles supports continuous transverse timber trusses that in turn support composite timber and steel purlins. The vertical timber trusses that support the wall glazing provide face-load support for the walls, which exceed four storeys. Steel tension-only bracing in several bays within the perimeter walls and the roof plane ensures overall stability and wind resistance.

The visually dominant timber post-and-beam system with its regular grid layout, relates better to the architectural form than do the structural details. The roundness of the natural poles and the presence of the diagonal members in the roof and the wall-mullion trusses introduce non-orthogonal elements into an otherwise entirely rectilinear enclosure (Fig. 3.27). The diagonal steel rod cross-bracing in the roof plane and on the wall elevations also is at odds with the stark architectural form, but its fineness renders it barely discernible against the density of considerably larger timber members. An intriguing aspect about this project is the disparity of construction materials. Round timber poles, with little finishing other than bark removal, contrast strongly with the sleek glazed skin to highlight the differences between natural and artificial environments which lie at the heart of this project.

From the perspective of its architectural form, the European Institute of Health and Medical Sciences building, Guildford, represents a higher level of complexity. While in plan the building approximates a triangle

▲ **3.28** European Institute of Health and Medical Sciences, Guildford, England, Nicholas Grimshaw & Partners Ltd, 1999. The prow rises above the main entrance.

▲ **3.29** The curved roof structure.

with a rounded apex, in elevation the area above the main entry rises like a blunted ship's prow (Fig. 3.28). The roundedness of the prow in plan also appears in section at the roof level where a curved eaves area softens the architectural form. Several materials and systems constitute the structure. Vertical reinforced concrete walls concentrate in the front and rear plan areas and provide lateral stability, and columns elsewhere in plan support the weight of up to five flat-slab suspended floors. Inclined columns follow the building envelope profile to prop the cantilevering prow. Curved glue-laminated portal frames in the top floor achieve the exterior roundness of the roof form, and inside they strengthen the maritime metaphor implied by the architectural form (Fig. 3.29).

Similar curved timber members play a more extensive form-generating role in the two-storey Tobias Grau office and warehouse facility, Rellingen (Fig. 3.30). They wrap around the whole building, beginning from their connections above the ground floor slab, to define the ovoid-shaped envelope. The curved rafters are placed inside the metal roof but where they become columns they are exposed outside the skin of most walls where they support external glass louvres. Although the timber structure is the form-giver, most of the load-bearing structure is reinforced concrete. A first floor reinforced concrete flat-plate overlays a rectangular grid of reinforced concrete columns and several internal concrete walls provide lateral stability. Structure therefore comprises two different materials and three distinctly different structural systems, excluding the longitudinal steel cross-bracing at first floor level. Of all these systems only the curved timber portal frames relate closely to the tubular architectural form.

At the Pequot Museum, Mashantucket, Connecticut, the Gathering Space, the principal public area, takes a curved form in plan. Its spiralling

▲ **3.30** Tobias Grau headquarters, Rellingen, Germany, BRT Architekten, 1998. Glue-laminated ribs enclose the ground floor interior concrete structure.

▲ **3.31** Pequot Museum, Mashantucket, USA, Polshek Partnership Architects, 2000. Exterior view of the Gathering Space.

▲ **3.32** The horizontal arch supports the curved and sloping wall.

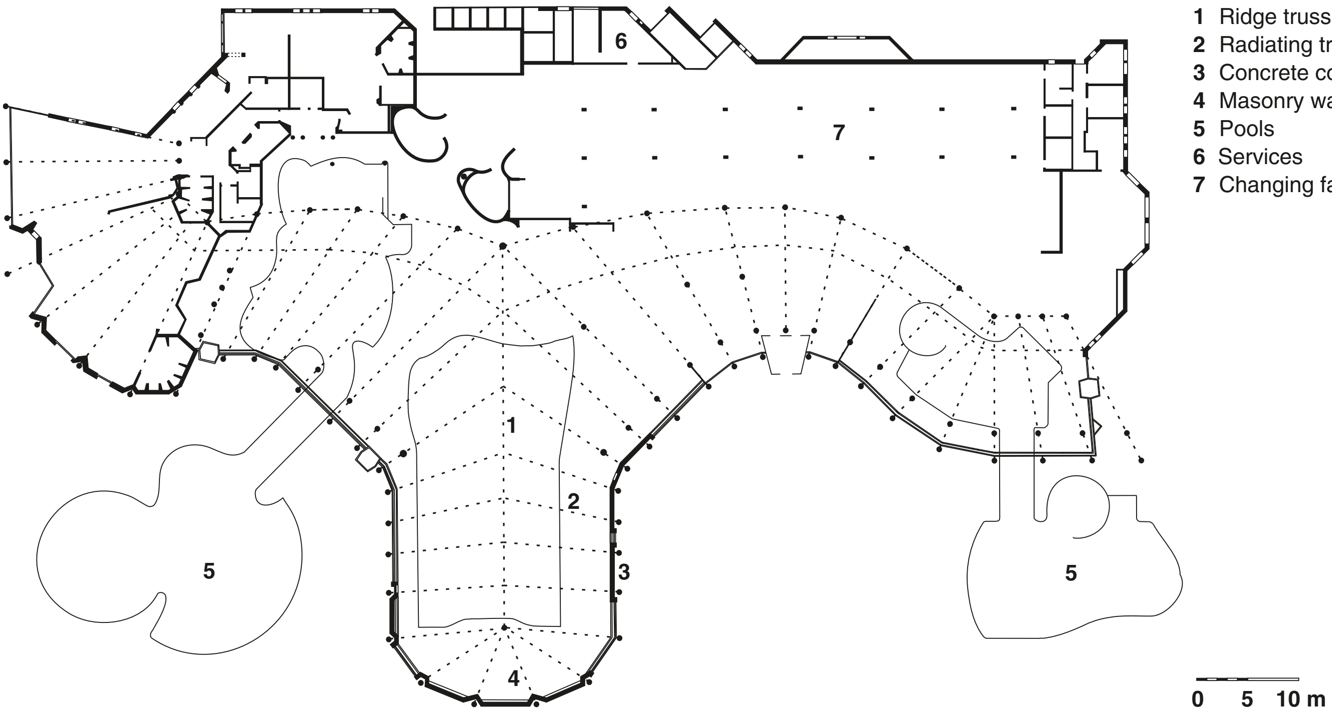
geometry recalls that of fortified Pequot villages whose palisades were laid out as two offset semi-circles, and its curves also evoke the forms of Pequot wigwams, rounded in both plan and section. The north-facing Gathering Space is equivalent to a three- to four-storey volume (Fig. 3.31). Its semi-circular wall is glazed and radiating roof beams that slope away from the centre of the space are supported on inclined perimeter steel posts. Their cross-sectional dimensions have been minimized by the introduction of a most unexpected structural system – a horizontal arch, but one that synthesizes with the architectural form (Fig. 3.32).

▲ **3.33** Säntispark Health and Leisure Centre, St Gallen, Switzerland, Raush, Ladner, Clerici, 1986. Creased and sagging roof.

Wind load acting at a right angle to the line of glazing over the centre half of the posts is resisted primarily by a semi-circular horizontal tube, anchored at each end. It functions either as an arch that works in compression, or as half a tension ring, depending on the wind direction. The arch, together with its stabilizing ties and connecting members back to the steel posts, adds another layer of structure that contributes complexity and interest to the interior space. An alternative to the steel tubular arch might have been to significantly increase the depth of the posts so they could span the whole height of the wall.

The roundedness of Pequot vernacular construction also finds expression in the roof structure. First, a bowstring truss spans the Gathering Space to support the radiating roof beams, and secondly, the two truss bottom-chords are curved in plan. Structural form is therefore very well integrated with architectural form which itself draws upon indigenous construction forms.

The following three examples illustrate consonant architectural and structural forms in the context of irregular architectural forms. When viewed from outside, the Säntispark Health and Leisure Centre, St Gallen, appears to have been distorted after construction. Was it originally configured differently in plan but then somehow moulded into its final curved and rounded forms, wrinkling and creasing the roof in the process (Fig. 3.33)? The ground floor plan and structural layout respond to the building form and function (Fig. 3.34). An essentially regular



▲ **3.34** Simplified ground floor plan.

structural grid in the changing rooms and ancillary spaces dissipates in the recreational and pools areas. Here, any grid-like influence vanishes leaving structure to follow the informal organic geometry. It is as if the designers considered a rectilinear grid antithetical to a recreational environment. Uneven exterior column spacing reflects the 'elongations' and 'compressions' that occurred during the building plan 'distortion'. Columns define a curving perimeter envelope which in turn suggests the plan orientation of the roof trusses. They are generally positioned normal to the perimeter walls, except over the main pool where secondary trusses deliberately avoid forming a rectangular grid. In plan each truss is straight, but an obvious sag acknowledges its informal architectural setting (Fig. 3.35). Within an irregular form two structural materials and numerous structural systems combine to form a coherent and attractive work of architecture.

Irregularity of architectural form is not synonymous with curved forms. Consider the complex origami-inspired form of the Serpentine Gallery Pavilion 2001, London, also known as 'Eighteen Turns' (Fig. 3.36). Designed as a temporary building and constructed from planar sheets and ribbed elements, it was dismantled after the summer months of 2001 and relocated. The superstructure, excluding timber flooring, is fabricated entirely from aluminium – both structure and cladding. Ribs

▲ **3.35** Roof structure over main pool.

▲ **3.36** Eighteen Turns, Serpentine Gallery Pavilion 2001, London, England, Studio Libeskind Angular and planar surfaces.

▲ **3.37** Interior ribbed surfaces.

▲ **3.38** Verbier Sports Centre, Switzerland, André Zufferey, 1984. Complex stepping roof form.

form a post-and-beam structural system while the sheet cladding functions as shear walls, providing bracing for lateral loads. The orientation of the exposed interior ribs emphasizes each panel's non-orthogonal geometry (Fig. 3.37). The exposed structure enhances the shape and sense of panel directionality and intensifies the chaotic qualities of the assemblage. If a stressed skin or solid panel construction had been used its planar aesthetic would place this work into the category of synthesized forms.

The Verbier Sports Centre is the final example of consonant architectural and structural forms. The multiple pitched-roof form suits its surroundings. Roof planes step down to follow the mountainside slope and relate comfortably to the adjacent chalet pitched-roofs. Roof trusses run parallel to the slope and are articulated on the exterior where they bear on exposed concrete buttresses (Fig. 3.38). The stepping roof

▲ **3.39** Visually complex roof structure over the pool.

▲ **3.40** Exchange House, London, England, Skidmore, Owings & Merrill, 1993. Arches enable the building to span the site.

profile increases the truss complexity and reduces structural efficiency. Relatively large truss member sizes are required even though they are designed for heavy snow loads (Fig. 3.39). Although a lack of structural hierarchy among the many structural members obscures the primary structural form, a combination of timber's warm natural colour, unobtrusive timber connections and the filtering of natural light by the structure, contribute towards memorable architecture.

Contrasting forms

Architectural and structural forms contrast where a juxtaposition of architectural qualities such as geometry, materiality, scale and texture are observed. In the examples that follow, geometric dissimilarity between forms is the most common quality contrasted. At Exchange House, London, parabolic arches support a building rectilinear in plan and elevation (Fig. 3.40). The contrast between forms arises primarily from the need for the building to bridge underground railway lines, but even the exposed transverse cross-braced bays at each end of the building are unrelated to the architectural form (Fig. 3.41).

▲ **3.41** A transverse exterior cross-braced frame.

An element of surprise is also a feature common to buildings with contrasting forms. As one approaches a building and becomes aware of its architectural form one usually expects to discover a certain structural form based on one's previous architectural experience. If the actual form is considerably different from what is anticipated then it is likely that architectural and structural forms contrast.

Well-designed contrasting forms provide many opportunities for innovative and interesting architecture. Most examples of contrasting forms can be attributed to designers attempting to enliven their work, but

▲ 3.42 Fleet Place House, London, England, Skidmore, Owings & Merrill, 2000. Angled columns add interest to the main façade.

▲ 3.43 Stuttgart Airport Terminal, Germany, von Gerkan • Marg + Partner, 1991. Structural 'trees'.

occasionally reasons arise from pragmatic considerations. Exchange House, for example, has to literally span its site due to subterranean features – and at Fleet Place House, London (Fig. 3.42), angled columns are not intended to inject interest into an otherwise repetitive commercial building façade, but to reduce construction costs by locating new columns over pre-existing foundations.[11]

Contrasting forms at Stuttgart Airport enrich its architecture and surprise building visitors in two ways. First, the structural geometry of the interior is totally unrelated to that of the enveloping form. Secondly, the meanings inherent in each form are so divergent – an interior structure that exudes meaning by virtue of its representational nature contrasts with the plain architectural form, essentially a truncated wedge. The monoslope roof rises from two to four storeys from land-side to air-side. Glazed roof slots subdivide the roof plane into twelve rectangular modules, each of which is supported by a completely unexpected structure in the form of a structural tree (Fig. 3.43). The 'trees', all the same height, bear on floors that step-up, one storey at a time. 'Trunks' consist of four interconnected parallel steel tubes which bend to become 'boughs' and then fork into clusters of three and four progressively smaller 'branches'. Finally, forty-eight 'twigs' support an orthogonal grid of rafters. Each 'tree canopy' covers an area of 22 m by 32 m, and contributes towards a unique and interesting interior space.

The architectural form of the Lille TGV Station is similar to that of the Stuttgart Airport Terminal. In cross-section the TGV Station floors also step-up two storeys across the site, but the roof shape, although approximating a monoslope, profiles as a gentle undulation (Fig. 3.44). What interior structure might be expected? Roof beams or trusses

▲ **3.44** TGV Station, Lille, France, SNCF/Jean-Marie Duthilleul, 1994. Side elevation.

▲ **3.45** Stazione Termini, Rome, Italy, Montuori, Vitellozzi, Calini, Castellazzi, Fatigati & Pintonello, 1950. Curved roof beams over the main concourse.

▲ **3.46** Unexpected interior arches in the TGV Station.

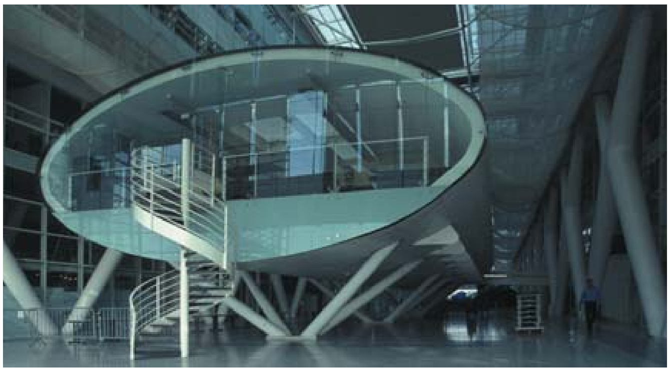
following the roof profile like those at the Stazione Termini, Rome (Fig. 3.45), or like those at the better known Kansai Airport Terminal, by Renzo Piano? What is actually encountered is a series of paired steel arches that do not even follow the cross-sectional profile closely (Fig. 3.46). Disparities between the arch profiles and the roof wave are accounted for by vertical props that support secondary trusses directly under the roof. Because the prop diameters are similar to those of the primary arches, no clear structural hierarchy is established. Consequently an opportunity for the interior space to be characterized by a visual flow of arches is lost. Nevertheless, the combination of slender compression members and a filigree of stabilizing cables represents the designers' attempt to realize a vision of a roof structure with as few

▲ **3.47** Hôtel du Département, Marseilles, France, Alsop & Störmer, 1994. Office block behind the Delibératif.

structural supports as possible and an appearance of 'fine lace floating above the train'.[12]

Contrasting geometries between architectural and structural forms, and even between structural forms within the same building, are evident at the Hôtel du Département (Regional Government Centre), Marseilles (Fig. 3.47). The project can be read as an amalgamation of at least four distinct architectural forms – two slab office-blocks linked by a transparent atrium, and two exterior elongated tubular forms. One, the Delibératif or council chambers, is free-standing while the Presidential offices sit above the higher office block.

The most obvious contrast between forms occurs within the first three storeys of the office blocks where exposed three-storey X-columns align longitudinally along each side. They visually dominate the lower storeys, both on the exterior where they are painted blue, and in the atrium where they are white. One reviewer describes them thus: 'the X-shaped concrete *pilotis* line up one after each other, their unexpected geometries ricocheting through the glazed atrium like sculptures by Barbara Hepworth, Frank Stella or the Flintstones'.[13] While their structural form does not relate to any other architectural qualities within the project, they function as transfer structures for gravity loads. They support columns located on a 5.4 m office module at third floor level and above and extend to a 10.8 m grid at ground floor level that is suitably large for basement car parking beneath. The architects deliberately expose the dramatic X-columns on the exterior by moving the building



▲ **3.48** The Mediatéque 'hovers' and expresses instability in the atrium.

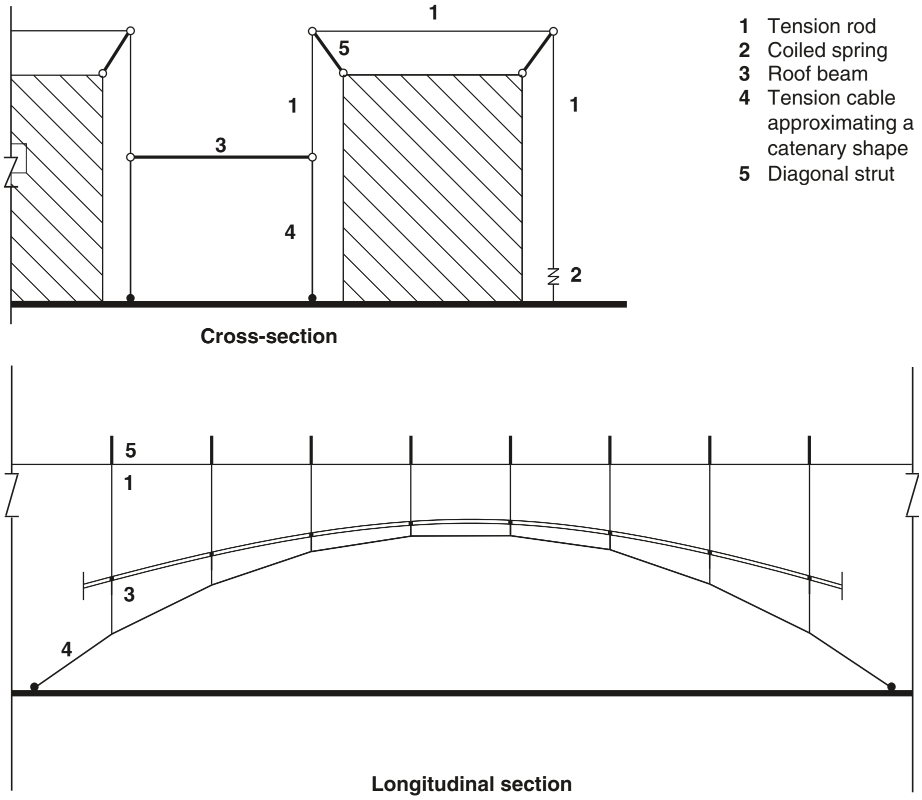
▲ **3.49** Schools of Geography and Engineering, Marne-la-Vallée, Paris, France, Chaix & Morel, 1996. Vault-like roofs between blocks.

envelope into the building, behind the structure. Unexpected and spectacular, structure enriches both the interior space and the building exterior.

Upon entering the atrium, one discovers a third 'tube', the Mediatéque. Compared to the supporting structures of the Delibératif and the Presidential offices, which due to either splaying or tapering legs appear very stable, the clusters of props under the Mediatéque suggest instability due to the way they converge towards a point at floor level (Fig. 3.48). It seems that unequal floor loading could cause the tube to topple. Only the relatively large diameters of the props themselves and their considerable bending strength avert such a catastrophe. So, within the space of a few metres where the giant X-columns ground and strongly brace the building, a quite different structural form is encountered that speaks of fragility and creates an impression of the Mediatéque 'hovering' or at least resting very lightly on its supports.

The new Schools of Geography and Engineering complex, Paris, also incorporates contrasting architectural and structural forms (Fig. 3.49). Three parallel rectilinear blocks are separated by courtyards partially enclosed by curved vault-like forms. While the main blocks are structured with conventional reinforced concrete walls and frames, the curved infill forms do not rely, as one might expect, on arches, but on an elaborate tension system. Their roof curvature follows concave catenary cables tied down at each end to foundations and pulled upwards at eight points along their lengths by tension rods hanging from the main blocks (Fig. 3.50). The fineness of the cables and rods contribute to achieving that often sought-after impression of 'floating' (Fig. 3.51).

This unusual structural system plays a significant pedagogical role in the school life, illustrating principles of structural mechanics to generations



▲ **3.50** Diagrammatic representation of the curved-roof support structure.

▲ **3.51** Curved 'floating' roof.

▲ **3.52** Exterior tension rods and springs.

▲ **3.53** Stealth Building, Culver City, USA, Eric Owen Moss Architects, 2001. Triangular form at the northern end.

of civil engineering students. Vertical steel rods at regular centres support the curved roof. They hang from projecting diagonal compression struts that are tied to identical struts on the other side of the higher rectilinear block roofs by horizontal rods. On the far sides of the two end rectilinear blocks, horizontal rod tensions are resolved by vertical rods that connect to large coil tension-springs tied to the foundations (Fig. 3.52).

While the curved roof is pulled upwards by this sprung tensioned system, its catenary cables are tensioned down to a different set of springs and foundations. The roof therefore hovers, simultaneously held in space by opposing tension forces – totally reliant upon the tensioned ties for its equilibrium. In these buildings contrast occurs not only between the linear and curved architectural forms, and vaulted forms reliant on tension rather than on compression, but also between the innovative tensioned roof system and the conventional reinforced concrete framing elsewhere. One form is clearly 'grounded' and the other 'floats', although securely tethered to the ground.

Contrasting architectural and structural forms are also evident at the geometrically challenging Stealth Building, Los Angeles. For a start the architectural form itself transforms along the building's length – from a triangular cross-section at the northern end to a conventional rectilinear shape at the south (Fig. 3.53). While the moment-resisting frames that structure the southern end relate closely to the reasonably rectilinear form of that area, the structure elsewhere responds to other issues. For example, at the north end, four columns support two longitudinal trusses that carry the second floor, the mezzanine and the roof. These trusses enable the building to span over an outdoor sunken theatre and maintain the proscenium arch opening through its rear wall into the building behind. Making up the third structural system, in the central area which accommodates vertical circulation and bathrooms, steel tubes on an axis angled to the main structural axes support cantilevered triangulation to which light-weight eaves and balcony construction is attached.

Apart from these structural elements, structure maintains an orthogonality that flies in the face of the angled lines and the sloping planar surfaces of the building enclosure. Floor plate geometry does not follow the lines of structural support but rather ignores the generally rational structural layout to satisfy the goal of completing the global geometrical transformation. As described by the architect: 'The aspiration is to investigate a changing exterior form and a varying interior space; to construct a building whose constant is constantly moving, re-making both outside and inside . . .'[14] Structure and construction clash, but both systems maintain their integrity and independence (Fig. 3.54).

All the previous examples in this section are drawn from relatively new buildings completed in and around the 1990s. Contrasting architectural and structural forms are part of their original designs. Yet we commonly

▲ **3.54** An interior office space where the sloping wall angles across the line of the truss.

encounter other examples of contrasting forms in additions or modifications to existing buildings, particularly given significant age differences between the old and new work.

The Reichstag cupola, discussed previously, is one of many such examples reviewed by Byard.[15] While architectural and structural forms synthesize in the cupola itself, both contrast with those of the original building. A similar situation arises at the Great Court of the British Museum, London. A new canopy covers an irregularly shaped space between the circular Reading Room and numerous neo-classical load-bearing wall buildings surrounding the courtyard (Fig. 3.55). The canopy, a triangulated steel surface structure, differs dramatically from the buildings it spans between. Greater differences in architectural and structural forms, materiality, and degrees of lightness and transparency are hardly possible.

As expected, the canopy has attracted considerable comment. Reviewers generally admire it. They point to its design and construction complexity, its controlled day-lighting, and note its elegance, describing it as 'floating', 'delicate', and 'unobtrusive', at least when compared to an original scheme with heavier orthogonal structure and reduced transparency. However, its billowing form is easier to comprehend from above than from within, where one experiences a visual restlessness from the continuous triangulation of the doubly-curved surfaces. An

▲ **3.55** The Great Court, British Museum, London, England, Foster and Partners, 2000. Triangulated lattice roof with the circular Reading Room on the left.

absence of structural hierarchy contributes to this reduction of spatial and structural comprehension, further highlighting the contrast between the new and the old.

Summary

In order to discuss the relationships between architectural and structural form an understanding of the term *architectural form* is intentionally narrowly defined as the massing or the enveloping form. The reality of most architectural design practice is that structure rarely generates architectural form, but rather responds to it in a way that meets the programme and ideally is consistent with design concepts. Selected buildings illustrate three categories of relationship between architectural and structural form – synthesis, consonance and contrast. No one category or attitude to the relationship between forms is inherently preferable to another. The examples provided merely hint at the breadth of potential similarity or diversity of forms that can lead to exemplary architecture.

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