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Historical developments in the selection of structural form in relation to natural and other forces

Considérations historiques sur le choix du système et de la forme des structures, en relation avec les forces naturelles et les autres forces

Geschichtliche Entwicklung bezüglich der Wahl des Systems und der Form eines Tragwerks im Zusammenhang mit natürlichen und anderen Lasten

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SUMMARY
Since man started to build, he has had to contend with gravity, the wind, and often with other forces. The way in which he has selected structural forms to meet his needs has varied with the changing relative importance of different forces, with his understanding of their nature and of structural responses to them, and with the materials and other means at his disposal. Examples of his selections are discussed from before 1800, from the 19th century, and from the 20th century, to illustrate general trends.

RESUME
Dès que l'homme se mit à construire, il eut à lutter contre la gravité, le vent et souvent d'autres forces. La manière avec laquelle il choisit la forme des structures devant satisfaire à ses besoins évolua avec le changement d'importance relative des différentes forces, avec la compréhension de leur nature, du comportement de la structure ainsi qu'avec les matériaux et autres moyens à sa disposition. Des exemples sont présentés pour trois périodes, avant 1800, au 19ème siècle et au 20ème siècle et permettent de mieux comprendre cette évolution.

ZUSAMMENFASSUNG
Seit der Mensch zu bauen begann, hatte er sich mit der Schwerkraft, dem Wind und oft auch noch mit anderen Kräften auseinanderzusetzen. Das Vorgehen bei der Wahl des Systems und der Form eines Tragwerks, das alle gestellten Anforderungen befriedigt, wurde laufend durch neue Erkenntnisse bezüglich natürlicher und anderer Lasten sowie durch neue Materialien etc. modifiziert. Zur Illustration werden Beispiele aus drei Perioden, von vor 1800, aus dem 19. und 20. Jahr-hundert, gezeigt.

1. INTRODUCTION

Natural forms are shaped by the forces acting on them as they grow. We shape the structures that we build. As soon as building starts gravity comes into play. So may other forces like wind, wave, or earthquake. But they do not shape the structure so much as test it; subjecting it to a process of natural selection. We, as designers, propose. Nature, and use, dispose. This has always been so [1,2].

Whatever the primary reasons for building, designers have, of course, always sought to shape their structures so that they will pass the test - so that they will stand in the face of all the forces they will be called upon to bear and will not yield excessively to these forces in any way. Often it has been possible to do this simply by staying within the bounds of earlier choices that had already been shown by experience to be safe. But not always. Any innovation has meant moving outside these limits and has called for some other kind of assurance that all would be well.

Understanding of likely loads and responses to them has then become important. Even today our understanding of both is often less that we should like it to be in relation to the tasks we set ourselves or undertake. We are repeatedly faced with uncertainties about the probable magnitudes of forces, about the dynamic characteristics of some of them or their dependence on some of our design choices, and about important aspects of structural response. A hundred years ago understanding was virtually limited to static loads and statically determinate responses to them. Two hundred years ago a few simple predictions of strengths and determinations of the strengths needed to ensure static equilibrium under gravitational loading were being made almost for the first time. Before that, there was little understanding that was not purely intuitive - and therefore non-quantitative - other than that summed up in the simple laws of the balance.[3,4,5].

In the long prehistory of building, structural forms like simple domical and post-and-beam huts must have been developed by long processes of trial and error which probably differed little from those which taught birds to build their nests. Trial and error still play their part: innovation can still be hazardous. But, as understanding has grown, the hazards have become associated with much bolder steps into the unknown. And - of particular relevance to the topic of the first session of this symposium - they have tended also to be associated with new types of loading or response becoming potentially critical.

To illustrate this, it is possible to consider only a few examples of structures built over a period of some 1500 years. No records survive of the ways in which forms were selected over the major part of this period, at least not in relation to structural criteria of selection. We must therefore use a certain amount of imagination in trying to envisage the bases of selection. But I have chosen examples about which something useful can be said with reasonable confidence. The justifications for what is said will be found elsewhere.

2. SELECTION BEFORE 1800

Nothing of great importance happened in 1800. But it does roughly mark significant changes in the choices open to designers, in the requirements

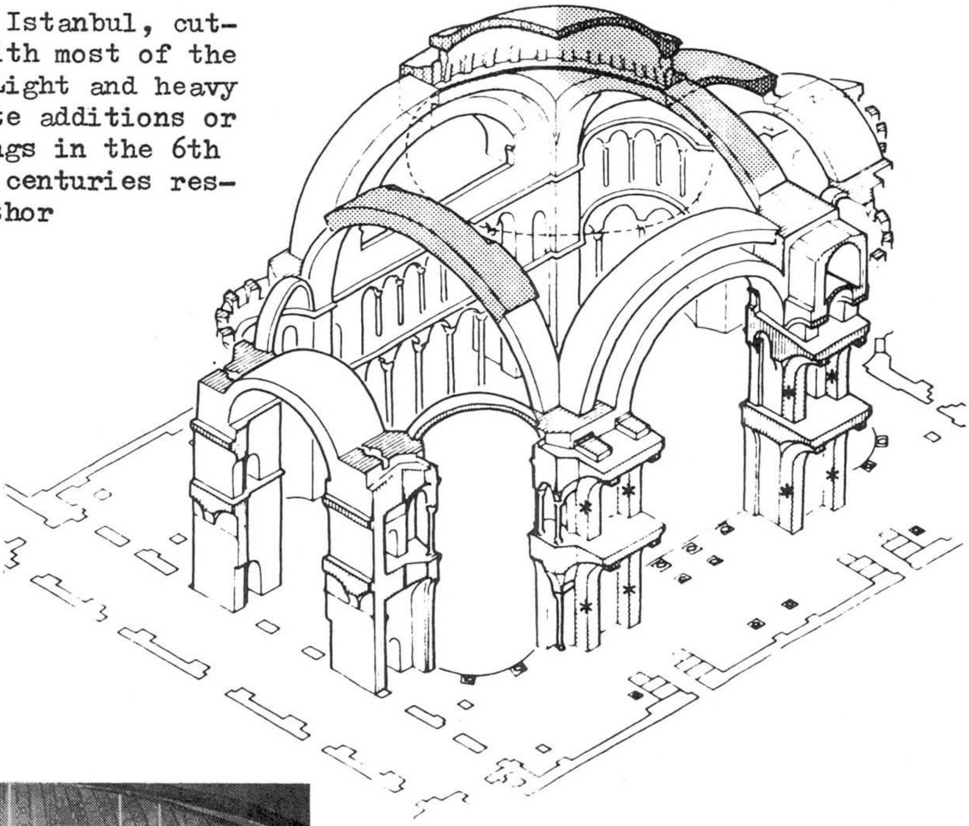

Fig.2 St Sophia, Istanbul, cut-away isometric with most of the vaults removed. Light and heavy stippling indicate additions or partial rebuildings in the 6th and 10th or 14th centuries respectively. © Author

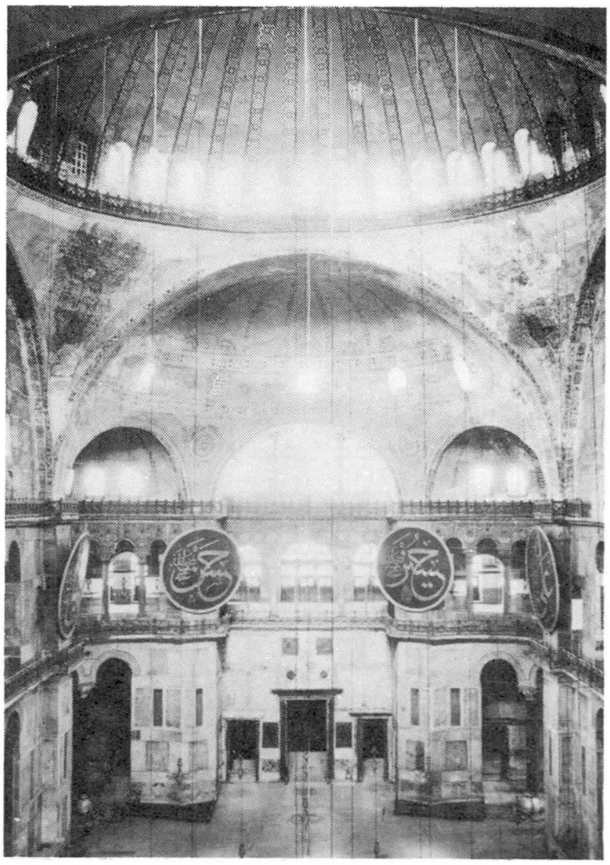

Fig.1 St Sophia, Istanbul looking westward. © Author

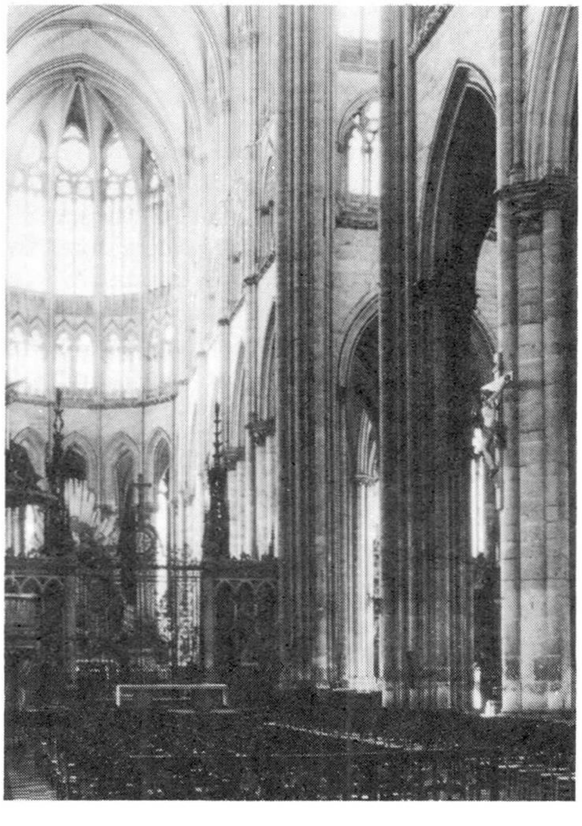

Fig.3 Amiens Cathedral. © Author

they had to meet, and in their structural understanding. Until almost the end of the eighteenth century they had to work almost exclusively with brick, stone, or concrete, and timber. Iron was available only in sufficient quantity for use as cramps or ties. This meant that major structures had to be capable of acting largely in compression, with a possible limited use of timber or iron ties to assist in containing the outward thrusts of arches or vaults. On the other hand user-imposed loads were small, self weight was usually high enough to make wind loads relatively unimportant, and it was not difficult to ensure (without any calculation) that average compressive stresses would be well within achievable unit strengths. Except for structures subject to unusual exposure or in areas of high seismic risk, the structural requirement was therefore largely reducible to that of selecting a form whose geometric configuration was potentially stable under self-weight gravitational forces and whose proportions were adequate to avoid buckling and high stress concentrations. Yet with little more than intuition to guide the selection, the only test of a design was to build it. Thus the development of new forms was highly empirical. Sometimes this can be seen in a single building. More frequently it is apparent in a sequence of similar buildings, each going a little further in some direction than its predecessors.

The greatest single step into the unknown was that taken by Justinian's architects, Anthemius and Isidorus, in the building of the 6th century church of St Sophia in Istanbul. The entire central space was covered by a vault of interlocking part-spherical surfaces rising to a central dome some 30m. in diameter (Figure 1). The architects were professional mathematicians and probably saw this vault system largely in terms of geometry, realising that it was virtually undeformable under gravitational load provided that its supports held firm. They were less able to see how much strength and stiffness the lateral supports should be given to resist both the outward thrusts generated and possible earthquake loads. The bracing arches at ground and gallery levels marked with asterisks in Figure 2 had to be added during construction to halt outward movements that were already taking place. And on three subsequent occasions the dome and main supporting semidomes had to partly rebuilt after earthquake damage, the rise of the dome being increased on the first occasion [6,7].

In the Gothic cathedral of the 12th and 13th centuries, the ribbed vault became the spanning and space enclosing element. In successive structures designers lifted the vaults higher and higher and, at the same time, reduced their immediate supports to isolated piers to allow large areas of glazing (Figure 3). Even under the predominant gravitational load, this called for additional support to resist outward thrusts. In principle, iron ties across the springings of the vaults would have served. But lateral support was now required also against wind forces. After several mishaps, or near mishaps, that called for the addition of external props, the flying buttress was developed as an integral part of the total structural system [8].

In the early 15th century we see the outstanding example of selection of another kind. The Florentines had committed themselves half a century before to the construction of a vast octagonal dome over the crossing of their new cathedral (Figure 4). Amply strong piers surmounted by an octagonal drum had been built to carry it, and there was no reason to doubt that, once completed, it would safely stand. The problem was to build it - to ensure its stability at all stages while still incomplete. The octagonal form presented problems here that do not arise with a circular

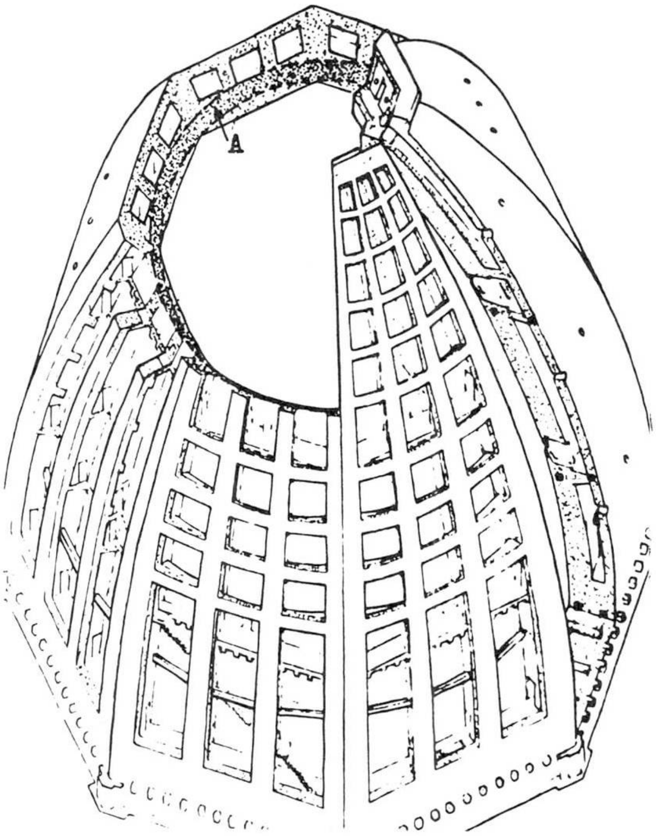

Fig.4 (above) Florence Cathedral. © Author

Fig.5 (right) Florence Cathedral, isometric of the dome partly cutaway to show construction. A circular dome is contained within the thickness of the inner octagonal shell as shown at A. © Author

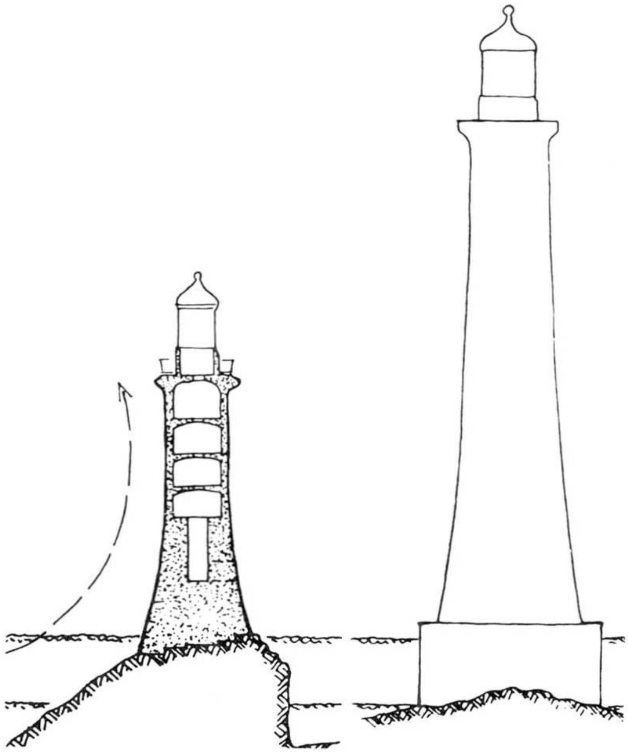

Fig.6 Eddystone Lighthouses: Smeaton left showing by dashed line the observed wave action in a storm; Douglass right. © Author

form because the centres of the sides tend to fall inwards even when there is a completed ring at the top. Previous practice - on a much smaller scale - had been to use centering for temporary support against gravity. Brunelleschi saw the difficulties of erecting and afterwards removing the huge timber frames that would be required and saw that he could entirely dispense with them if he constructed the dome as if it were, in every respect but that of surface geometry, a circular one (Figure 5) [9,10].

In all these cases consideration of the need to ensure stability played a part in the final development of the design. But interest in the space-enclosing and aesthetic qualities of the forms, and even in their symbolic connotations in some instances, was probably more important in the initial selection. Structural concerns came more to the fore in some of Leonardo's and Wren's dome designs [11], and they became dominant in Smeaton's design for the third Eddystone Lighthouse [12].

Smeaton undertook to replace the previous largely timber tower with a permanent structure of stone. It was a formidable task on account of the frequent fury of the sea. He chose to oppose the force of the waves with the enduring dead weight of masonry and selected a curved tapered profile on the analogy of that of an oak tree (Figure 6). At about the same time he carried out experiments on the forces exerted by wind and water, but he failed to appreciate the extent to which his choice of profile would lead to water being thrown up the side of the tower. The discovery that this happened was probably the first instance of the recognition of a major influence of the selection of form on loading other than self weight. It led to the selection of a modified profile for most similarly situated later towers as seen to the right of Figure 6.

3. THE NINETEENTH CENTURY

During the 19th century first cast and wrought iron, then steel, and finally reinforced concrete were added to the materials readily available to the designer. Their higher unit strengths, especially in tension, opened up a wider choice of structural forms. The new forms were mostly lighter than the old, so that they could span further or rise higher. This meant that loads other than self weight became more important - loads such as those imposed by wind and use. The former became particularly important on suspension bridges and the latter on railway bridges. (Neither had been of much importance on earlier arch bridges carrying only light road traffic.) And, since neither was related in any simple invariant way to the structural form, each called for explicit consideration when the form was selected. As the century progressed, this became increasingly possible through the acquisition of new data and the development of analytical tools for calculating structural responses. The chief limitations were that these tools were largely restricted to the calculation of statically determinate responses to static forces, so that wind loads and the loads exerted by moving locomotives had both to be considered as quasi static.

The influence of force on form is seen most clearly in the suspension bridge (Figure 7). The flexibility of the main chains or cables means that the designer does not have the freedom to select their profile that he has in the case of an arch. Given the span, he can choose the sag at the centre. The profile must then be that required for equilibrium with the loading, the relevant loading here being just the total self weight of

Fig.7 Clifton Bridge.
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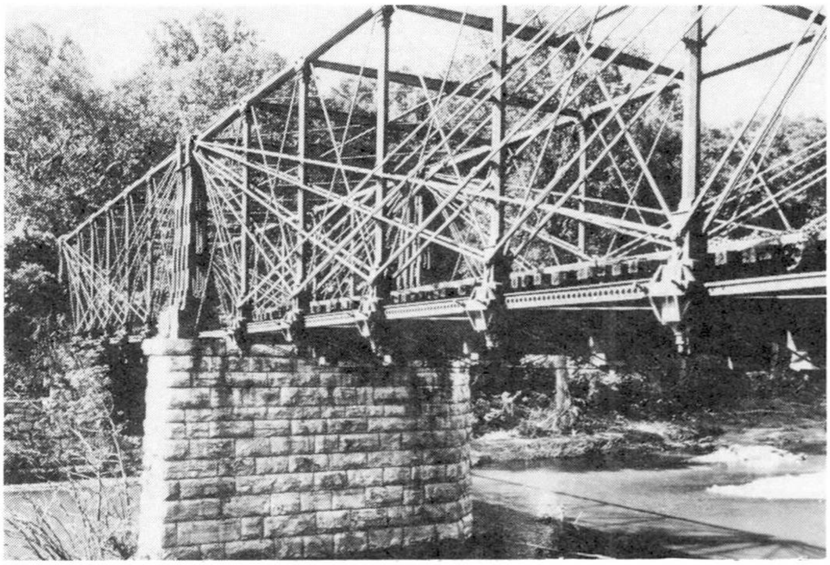

Fig.8 Savage Bridge, Md.
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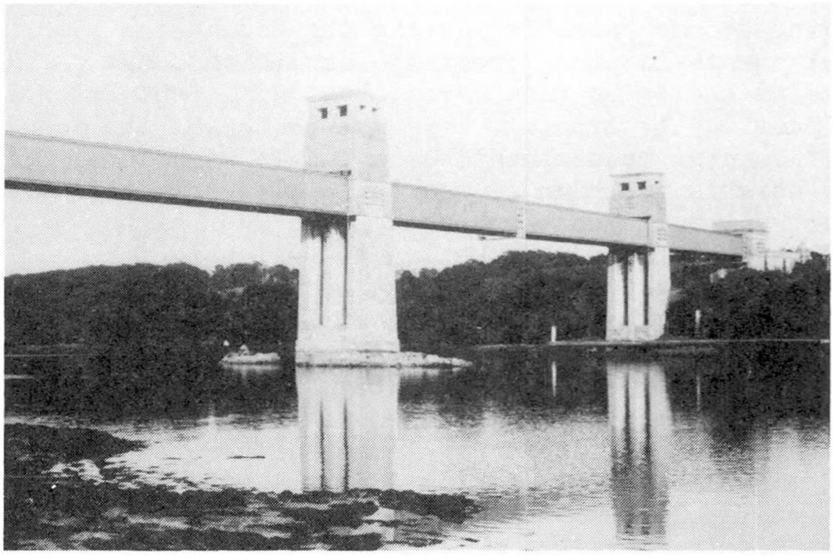

Fig.9 Britannia Bridge.
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whole span. Stiffness to resist wind and to distribute concentrated imposed loads moving over the span has to be provided by the deck. The hazard of wind induced oscillations became apparent, however, only from repeated collapses of decks that were too flexible, and the requisite stiffening remained largely a matter of judgement [13].

Increasing railway loadings led to the development of many new types of truss and girder bridge - forms which were inherently stiffer and thus preferable over most spans to the suspension bridge. While truss action remained imperfectly understood, the forms selected tended to be highly redundant. An example is seen in Figure 8. The top chord seems here to have been envisaged as the principal member, stiffened in each span by five independent sets of struts and inclined ties to assist in supporting a load moving over the span. Later, when analysis of the internal forces became possible, simple statically determinate forms were preferred. An outstanding example of the girder form was the Britannia Bridge (Figure 9). Here the final selection of the form was guided by extensive tests on models as well as calculations of the effects of the expected loads [14]. Wind was considered but not thought to call for any special provision. Longitudinal thermal expansion was, however, provided for. After the Tay Bridge collapse a static wind pressure of 2.7 kN/m^2 was assumed in the design of the Forth Railway Bridge and the cantilever arms were splayed in plan and transverse profile to help resist it [15].

4. THE TWENTIETH CENTURY

Choice has now been further widened by improvements in materials and fabrication and construction techniques and by vastly increased understandings of loads, structural responses, and the not infrequent partial dependence of load on response. In particular we are now able to consider loads like wind and earthquake dynamically and to compute structural responses involving high degrees of statical indeterminacy. Selection can now focus more of the basic choice of form, mode of action, and manner of construction. As the chosen forms are analysed, possibilities of reducing some of the loads by suitable further choices of significant parameters like stiffnesses and damping can be explored. There will be further discussion in the following papers, so a few examples must suffice here for comparison with those from earlier periods.

The tall multi-storey building became possible towards the end of the 19th century as a result of developments in steel framing, foundations, and servicing possibilities. Wind had to be considered, but sufficient lateral stiffness could readily be provided by bracing. In the choice of the form of the building as a whole, planning requirements came before structural ones. At the much greater heights to which we now build, lateral stiffness is not so easy to ensure without excessive cost. The much higher wind loads, and in some cases possible earthquake loads, call also for careful consideration of dynamic responses. Planning requirements still strongly influence the choice of overall form. But, for structural efficiency and economy, the type of framing system seen at the right of Figure 10 has had to give way to others seen further back in which the whole perimeter of the building becomes, in effect, a stiff tube [16,17]. Several recent progressive collapses have demonstrated a further need, even in the case of buildings of moderate height, to consider the effects of possible extreme loads such as local explosions and to ensure that any resulting damage will be limited in extent.

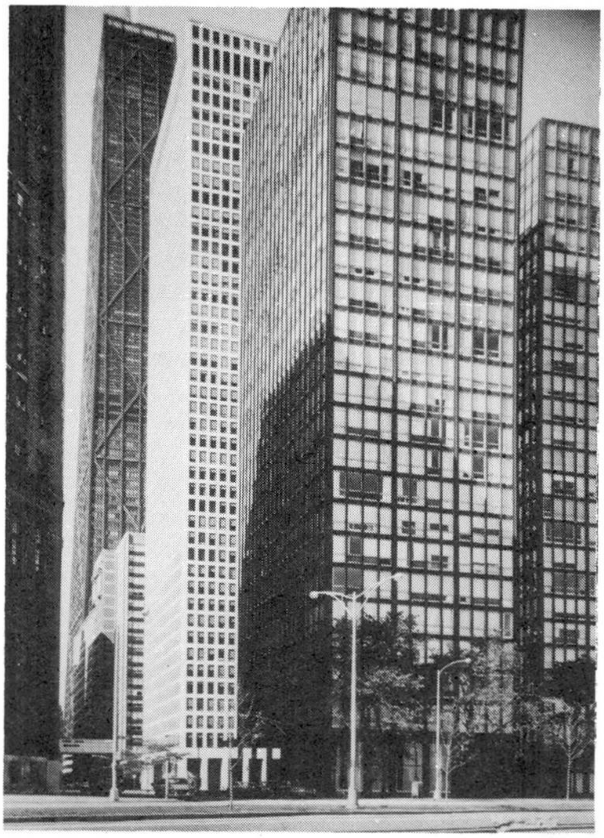


Fig.10 Lakeshore Drive Apartments, De Witt Building, Hancock Building, Chicago (right to left). © Author

Fig.11 Severn Bridge deck. © Author

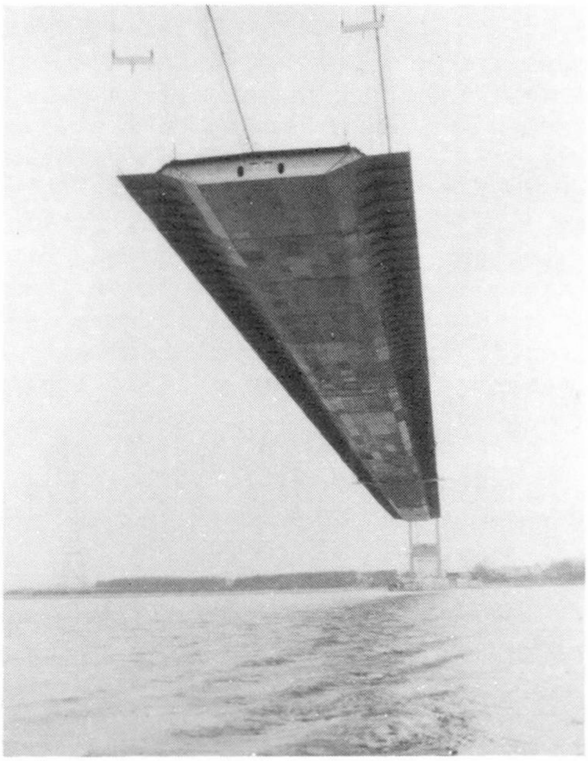
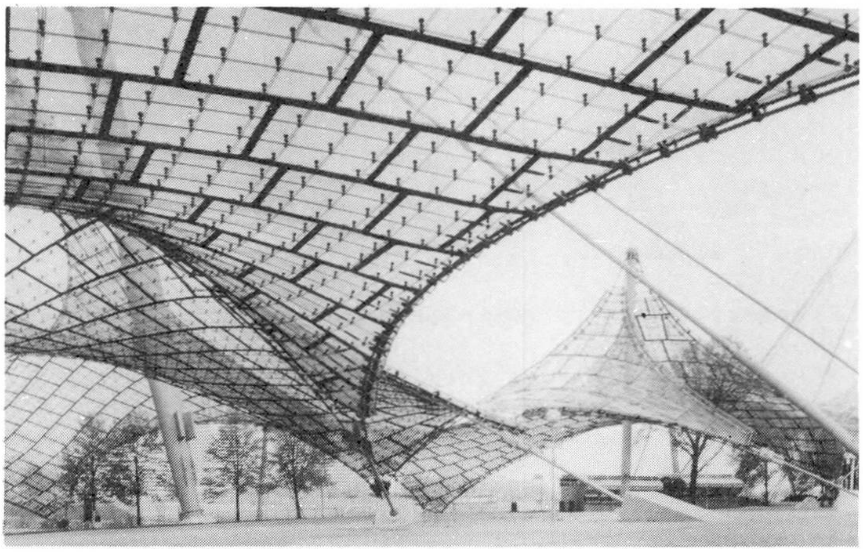


Fig.12 Tension roofs for the Munich Olympics. © Author



The dynamic characteristics of wind loading and response came to the fore with the collapse of the Tacoma Narrows Bridge deck. In the George Washington Bridge, built a decade earlier, it had been found possible to dispense with a deck stiffening truss on account of the great preponderance of the self weight of deck and cables over other forces on such a long span. Partly on this precedent, the Tacoma Narrows deck was stiffened only by shallow plate girders. Though designed to withstand static wind forces, it was twisted to destruction by a fluctuating combination of lift and drag forces. Later, in the Forth Road Bridge, torsionally stiff open trusses were used in place of plate girders and longitudinal gaps were left in the deck to help equalize pressures above and below. Then,in the Severn Bridge, a streamlined box girder was substituted for the truss-stiffened deck (Figure 11). This virtually eliminated eddies from the air flow, thereby greatly reducing the wind forces to be resisted. Supplementary damping was provided by a modified suspension system from the main cables [18].

Today, the chief counterparts of the wide-span structures considered in section 2 are shell, membrane, and cable-net forms. Membranes and cable nets are so light that wind and snow loads become the principal ones to be considered. With this lightness goes a natural flexibility, so that it becomes as important as in the case of the suspension bridge to ensure adequate stiffness. The desirability of a reasonable uniformity of stress also places constraints on the selection of geometry of surface and boundaries. In cable net roofs, stiffness is best provided by the adoption of anticlastic surface geometries which permit the prestressing of the cables in one direction against those in the other if adequate anchorage is provided along the boundaries (Figure 12). In some small membrane structures (tents) it is similarly ensured. Alternatively the whole membrane may be prestressed by internal inflation. Here, particularly in the case of the single-skin pneumatic structure, a man-made load - the internal pressure - becomes an element of the structure, though this might almost be said of all prestressing forces. Moreover it will significantly affect the external dynamic wind forces - an interesting situation which we are still exploring.

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