Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 71 (1994)

Artikel: Conceptual design of long-span roofs

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DOI: https://doi.org/10.5169/seals-54113

Conceptual Design of Long-Span Roofs

Concept et projet de toitures de grande portée

Konstruktiver Entwurf weitgespannter Dächer

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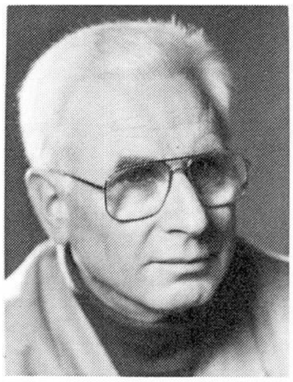

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SUMMARY

For long spans the dead load should be minimised, which simultaneously evokes the problem of stability under varying loads such as wind and snow. Balancing lightness and stiffness is a basic challenge of structural design. The different approaches are discussed and illustrated by two examples.

RÉSUMÉ

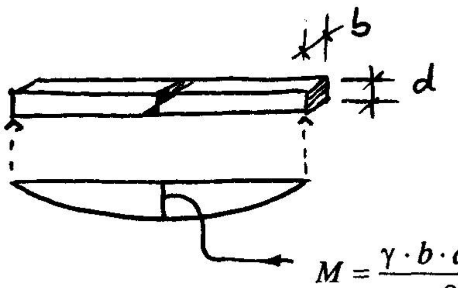
Dans le cas des grandes portées, il faut réduire le poids propre le plus possible tout en assurant la stabilité de la structure sous l'effet des charges variables du vent et de la neige. La recherche du juste équilibre entre la légèreté et la rigidité est l'un des aspects les plus intéressants du projet. Les méthodes adéquates sont présentées et illustrées par deux exemples.

ZUSAMMENFASSUNG

Für grosse Spannweiten muss man die Eigenlasten minimieren, aber gleichzeitig sicherstellen, dass die Struktur unter den zeitlich veränderlichen Wind- und Schneelasten stabil bleibt. Leichtigkeit und Steifheit richtig abzuwägen ist einer der interessantesten Aspekte des konstruktiven Entwurfs. Die dafür geeigneten Möglichkeiten werden diskutiert und mit zwei Beispielen illustriert.

1. DESIGN PRINCIPLES

In designing long-span structures engineers first of all must get rid of their habit to think in fix proportions, forgetting about the dominating influence of scale. It is misleading to give the required thickness d of a beam or girder as a fixed fraction d/L of its span L with d/L = 1/18 for a single span and 1/22 for multiple span or so. No: Simply by designing a beam or slab with rectangular cross-section to carry its dead load only we find:



$$M = \frac{\gamma \cdot b \cdot d \cdot L^2}{8}$$

γ: density of the material
β: strength of top and bottom fibre in tension and compression
L_{lim}: limit span of a beam under its own weight
d/L_{req}: required depth/L_{lim}

$$\frac{\gamma \cdot b \cdot d \cdot L^2}{8} \cdot \frac{6}{b \cdot d^2} \leq \beta \quad \rightarrow \quad \frac{d}{L_{req}} \geq \frac{3}{4} \cdot \frac{\gamma}{\beta} \cdot L_{lim} \neq const. \qquad \text{(see fig. 1)}$$

d/L is not a constant figure but increases linearly with the span and depends further on the efficiency of the material γ/β; the lighter the material and the higher its strength, the smaller will be the required thickness d of a beam of a given span. But its proportions will change dramatically with its absolute size, a fact which can be well observed from natural structures (fig. 1).

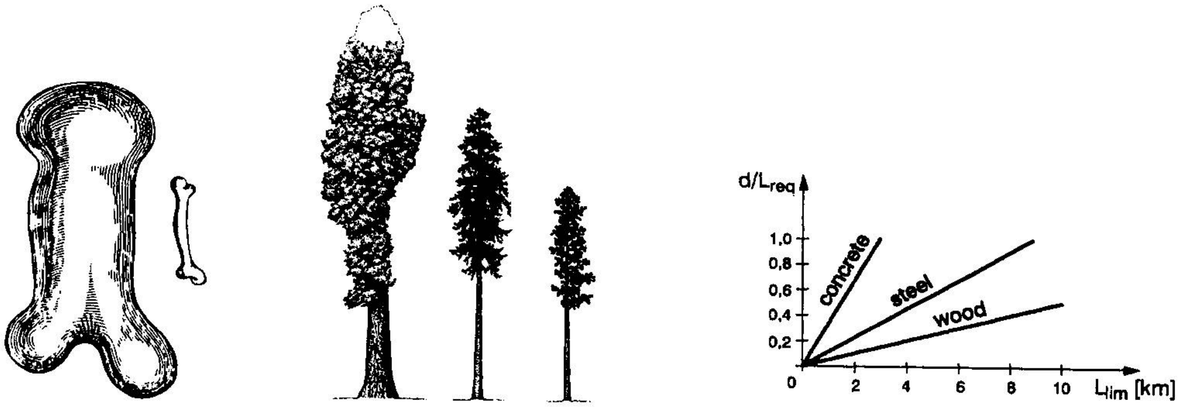


Fig. 1 The role of scale in natural structures [1][2]

With increasing span, solid girders become more and more clumsy, their dead load eats away their strength and for long-span structures something has to be done to by-pass this awkward situation.

The answer is of course well known: We have to leave away all that material of our beam which is not fully used: at mid span, we need to keep only the top and bottom fiber and leave away the web and towards the supports we can reduce the chords but need the web. Thus, via T-, TT-, U-girders and hollow slab- and box-girders, we reach the different types of trusses (fig. 2, top):

Their main feature is that they avoid bending and carry loads only by axial forces, thus making full use of the material's strength and reducing their dead load to a minimum.

The next step towards lightness for increasing spans is to subdivide the girder into a primary structure acting either in compression (fig. 2, bottom left) or in tension (fig. 2, bottom right).

The primary structure in compression (tension) may either attribute its tension- (compression-) partner to the subsoil - in that case we speak of an earth-anchored or a true arch (suspension) bridge - or utilize its secondary structure (usually) for self-anchorage.

An earth-anchored structure is (usually) easier to erect but costlier, whereas for a self-anchored just the opposite is true. The cable-stayed system combines both advantages: it is self-anchored (resulting in cheaper foundations) and can be constructed free cantilevering without temporary falsework (fig. 3). Beyond its self-balancing function the purpose of the secondary system is to stiffen the primary system and to serve as an envelope in case of a building or as a road/railway in case of a bridge.

In case of a building - the theme of this symposium - the envelope needs not necessarily be straight or horizontal, as it does in case of a bridge, but also there these hybrid structures (M. Saitoh speaks of Beam-String-Structures BSS in case of the primary structure acting in tension) are functionally better adapted to the required space as double-curved space structures, which we shall discuss further below (fig. 4)[3].

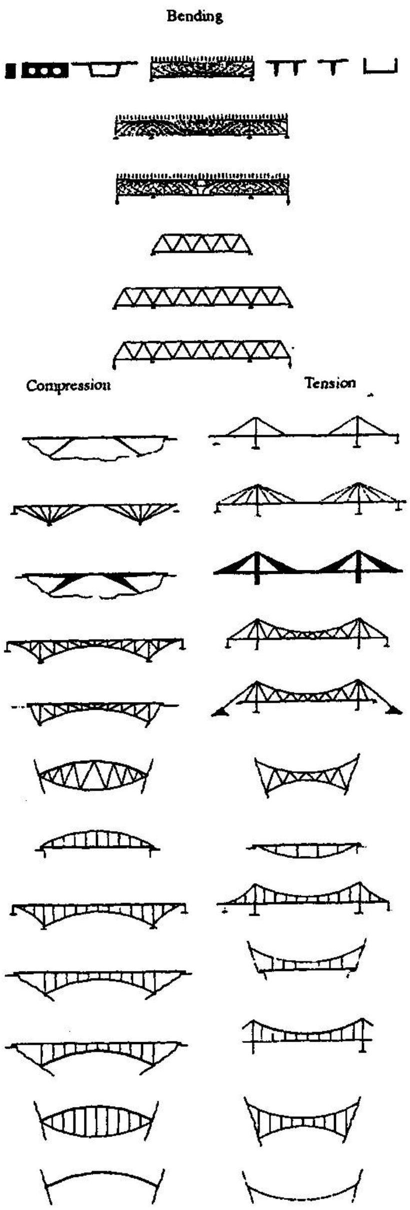


Fig. 2 The development of the girder

The primary structure, especially if it acts in compression, must be stabilized or stiffened by the secondary structure. Making use of all possibilities to stiffen the primary system

- the weight of the structure as a whole
- the bending stiffness of the girder (and the arch)
- the geometry of the primary system (triangular or quadrangular mesh)
- overall prestress (only applicable to cable bridges)
- and even combining them in an intelligent way
- not speaking of combining different materials in the same bridge

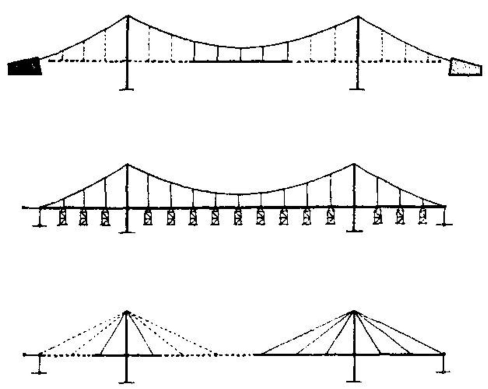
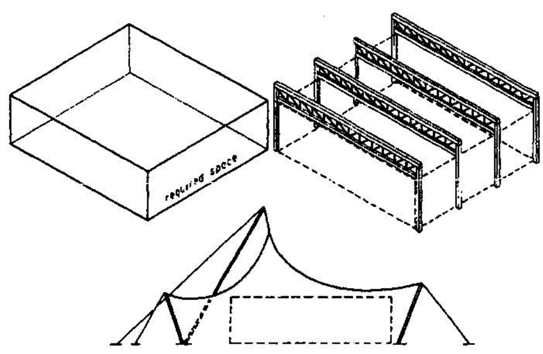


Fig. 3 The earth-anchored suspended girder needs abutments but can be built without falsework. The self-anchored girder needs temporary falsework but avoids horizontally loaded foundations. The cable-stayed girder combines both advantages.



stands for the intellectual appeal and the joy of structural design. Some examples of the behaviour of hybrid structures are given in figure 5. The further we proceed down along the list of girder types, as sketched in figure 2, the more flexible they become, but we simultaneously realize that the types further up in the list have to pay for their higher stiffness, resulting from triangular mesh, with improved fatigue strength and ductility of their structural elements, especially their cables.

Fig. 4 Hybrid structures adapt better to the required space than double-curved structures which usually encase too much volume.

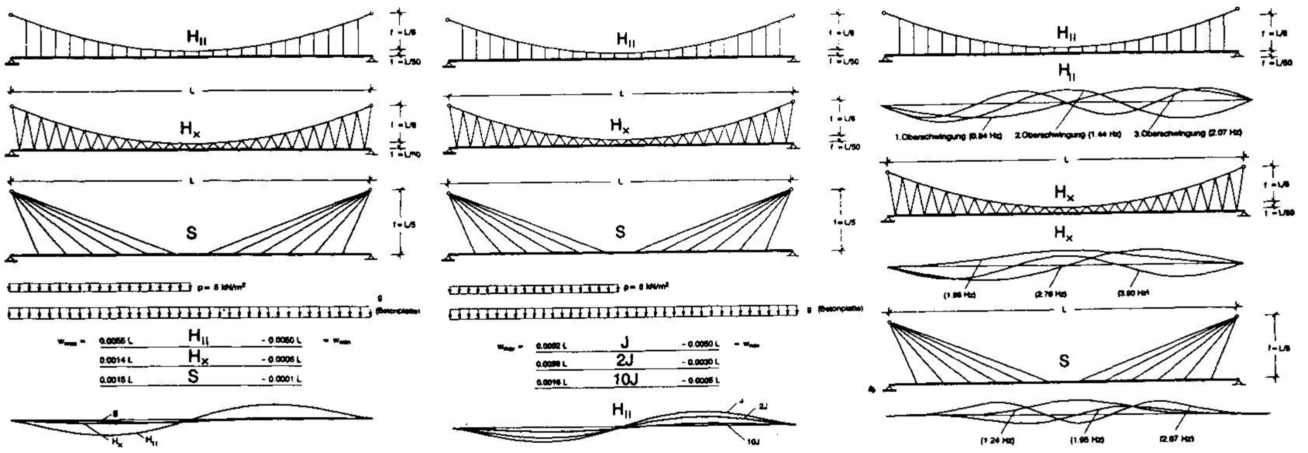
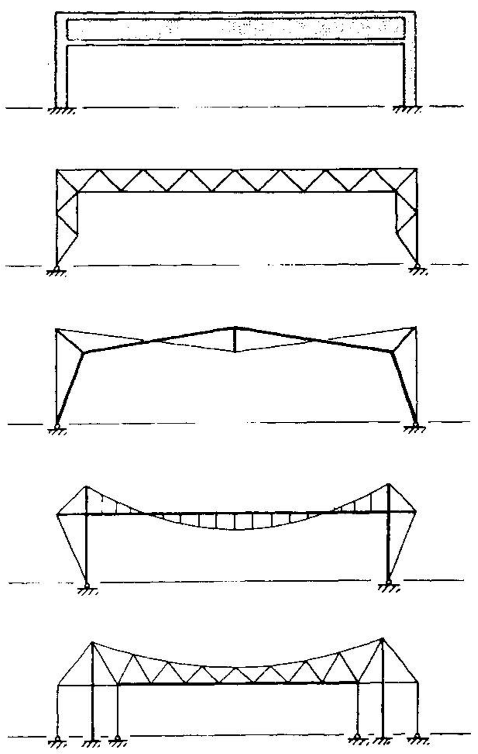


Fig. 5 Comparison of deformations and frequencies of suspended girders with vertical hangers (H"), inclined hangers (Hx) and of cable-stayed girder (S) with varying moment of inertia J of the girder.



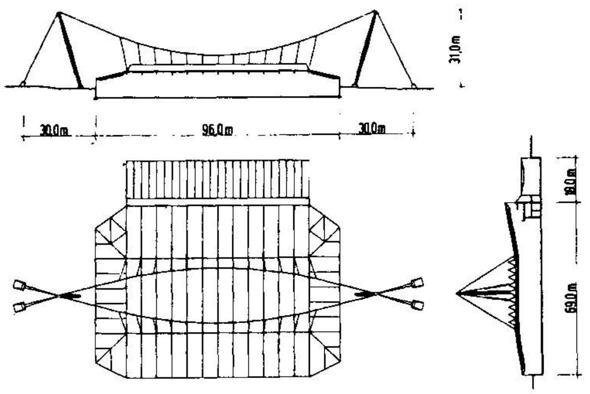


Fig. 6 Hybrid tension structures for an ice-skating hall at Memmingen (left, several alternatives) and for a multi-purpose hall at Karlsruhe [3]

If we are not too timid as far as deformations are concerned, we can make use of this whole catalogue also for long-span building roofs, as many examples recently built demonstrate (fig. 6). We are inclined to call this type of buildings "High Tech Architecture", insinuating that they are an invention of our times. This is not so as a stadium roof proposed as early as 1927 by Heinz and Bodo Rasch from Stuttgart clearly demonstrates (fig. 7).

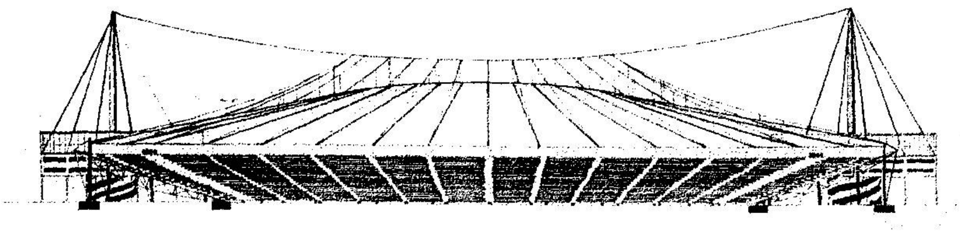


Fig. 7 Stadium project by Heinz and Bodo Rasch

With these hybrid structures the load bearing and the enveloping functions are usually independent or additive. As mentioned, this may be an advantage as far as the encased volume is concerned (fig. 4) but of course if both functions are combined, the overall result must be more efficient. This brings us to the double-curved surface structures (fig. 8).

Similar to the girders (fig. 2), they either combine compression and tension or they work primarily in compression or in tension. And again, proceeding down the list, they become increasingly flexible or deformable, depending on the type of stiffening respectively the topology of the surface
- the continuous surface
- with triangular mesh
- with quadrangular mesh

At their base, both lists (fig. 2 and fig. 8) meet with the same unstiffened arch or catenary cable.

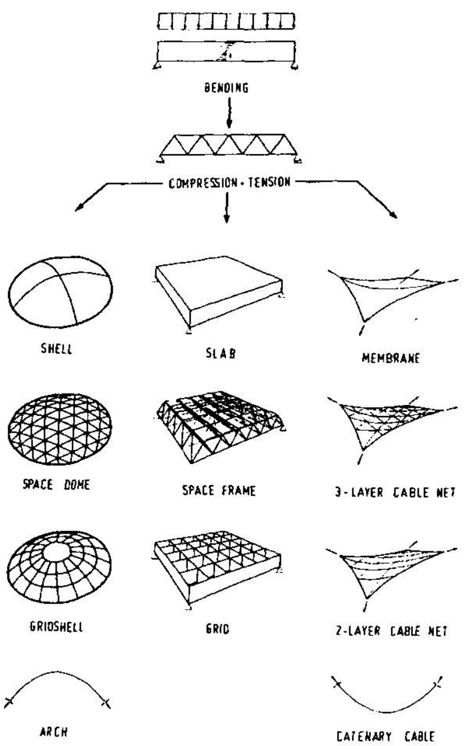


Fig. 8 The development of double-curved surface structures

Of course, beyond these pure surface structures there is again the possibility of combining them with other structural members, e.g. the shells may be stiffened by cables in the shape of spokes wheels or the cable nets by interaction with a roofing which avails of some shell action.

We further recognize again prestress, mechanically applied to surfaces with anticlastic curvature or pneumatically applied to surfaces with synclastic curvature.

And again, there is a close interrelation between the topology of these structures and their construction method, usually prefabrication and erection: The concrete shells, though most efficient structures, and the very concrete structures, suffer from their costly frameworks, since double-curved surfaces are non-developable. Several efforts have been made to revive concrete shells. Heinz Isler is most successful with that, as demonstrated by his beautiful shells. Another approach is the use of pneumatic formwork (fig. 9). More common than concrete shells are today the spherical grid domes in their different topologies, amongst them best known the geodesic dome [5]. The problem is how to cover a double-curved surface with triangular mesh with as many as possible elements, struts and nodes, of equal geometry (see example 1 in section 2 of this paper).

On the tension side of figure 8 we face in principle the same manufactural problem. Some basic answers are compiled in figure 10.

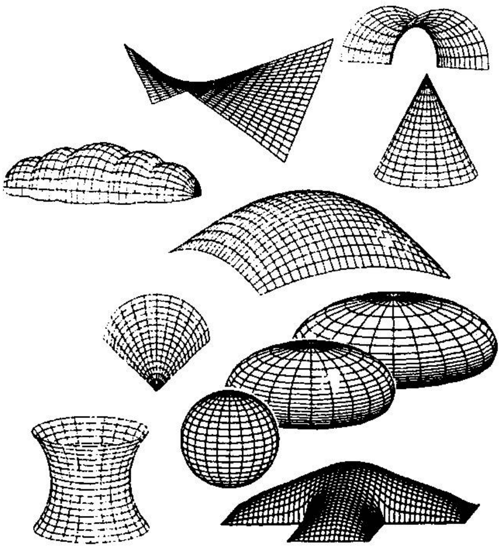


Fig. 9 Pneumatic formwork for concrete shells: suitable shapes [4]

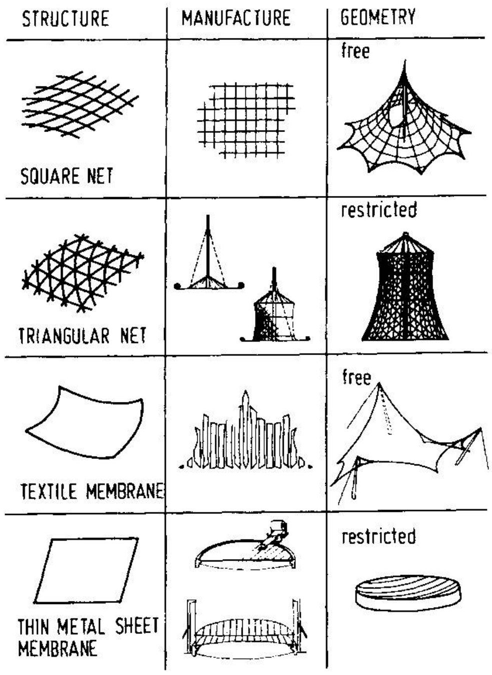


Fig. 10 Double-curved tension structure: The interrelation between type of structure/ manufacture/geometry or load bearing behaviour

The 2-layer cable net with quadrangular mesh is easy to manufacture and permits a variety of forms, unmatched by any other structural type, but it has to pay with large forces, large deformations and finally high costs. The Munich Olympic Roof (1972) is up to date the largest application [6]. The 3-layer cable net has an ideal membrane-shell load bearing behaviour but out of manufactural reasons, its geometry is limited to rotational shapes. The cable-net cooling tower at Schmehausen (1975) was the largest application [7]. Textile membrane structures can be completely prefabricated in the shop using a cutting pattern, are brought to the site, unfolded there and erected without any falsework. They can be combined with primary cable structures (as shown by example 2 of this paper). Convertible roofs are the high art of membrane structures [8]. Finally metal membrane structures, rarely applied up to now, can either be made from strips and welded on site, as done for the Moscow Olympic Structures [9], or thin stainless steel sheets can be pneumatically deformed utilizing their immense plasticity, as demonstrated with the manufacture of solar concentrators [10].

The authors are aware that the above was only a short summary of basic design principles of long-span roofs. But instead of filling all pages allotted for this paper with abstract considerations, a short presentation of two structures, recently designed by the authors, may be more illustrative.

2. TWO EXAMPLES: A GLASS COVERED GRID SHELL AND A HYBRID MEMBRANE STRUCTURE

2.1 The glass roof over a courtyard of a museum in Hamburg

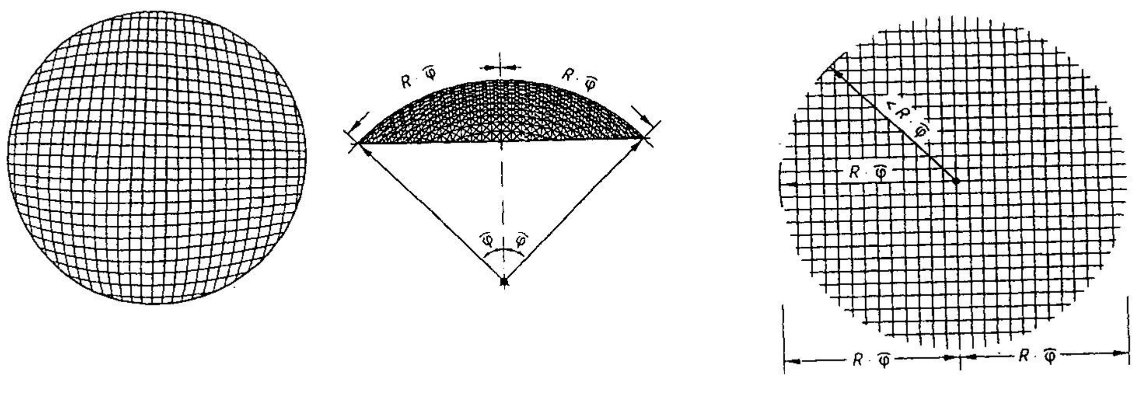
Glass roofs are attractive from an architectural as well as climatical point of view. Having already been the symbol of the new architecture of the Industrial Revolution during the 18th and 19th century, they experienced a revival during the second half of this century through the work of pioneers like Walther Bauersfeld, Konrad Wachsmann, Buckminster Fuller, Max Mengeringhausen, Frei Otto and others.

Obviously the most favourable basis for a translucent roof is the double-curved reticulated spatial structure with triangular mesh. Such structure, however, especially if directly glazed without intermediate glass frames, evokes three basic problems:

- The geometrical problem to cover a double-curved, i.e. non-developable surface with triangles, having for manufactural simplicity as many as possible members and nodes of equal size. (This problem obviously got some relief through recent progress in CNC-manufacturing.)
- Glass panels are preferably produced in quadrangles, of course permitting a variation of their angles. Therefore only two out of three members of the triangle constituting the structure should support the glass.
- Especially for double glazing the quadrangular glass panels must either be produced double-curved to fit the structure's surface, or the geometry of the structure must be chosen so that the four node points of each mesh are in one plane and may be glazed with plane glass panels. For single glazing, however, some warp of the glass panels is acceptable.

It is impossible to discuss this whole issue and all possible solutions here. Therefore, one solution, recently developed by the authors, shall be presented and exemplified [11]. The aim is to arrive at a structure corresponding to what is called "space dome" in figure 8 but suitable to be built for non-mathematical free shapes, too.

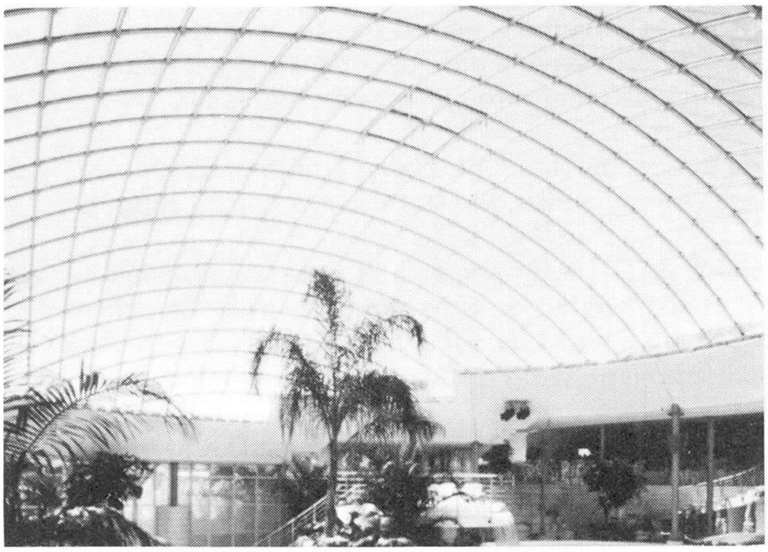
The basic grid of the structure when developed into a plane is a square net consisting of flat bars (fig. 11). This plane square net may be turned into almost any type of shape by changing the original 90° mesh angle. The quadrangles become rhomboids. This way any double-curved structure suddenly becomes "developable", and accordingly simple is the assembly of the basic grid. It entirely consists of bars, identical in length, bolted together, pivoting at their intersections. Bars of different length occur only at the outer edge as dictated by the structural geometry. The mesh angles are determined by the intended structural shape.



a) View b) Elevation (with diagonal cables) c) The bar grid, developed into a plane (= plane square net)

Fig. 11 The structure when developed into a plane is a right-angled, square grid of bars of equal length.

However, this basic quadrangular mesh pattern does not yet have the favourable structural characteristics of a shell to withstand wind and snow loads. Hence, the square mesh is braced diagonally with thin cables to achieve the required triangles. Diagonal bars would all vary in length, entailing the never ending task of cutting and fitting them. Therefore, instead of bars, cables are used, running beneath the bars from one edge to the other, fixed by clamping plates at the joints. Therefore, there is no need for measuring the constantly changing length of the diagonals. Later the cables are simply fitted, prestressed and clamped over the entire length without any problems. The prestressed cables work both ways, in tension and compression, and very efficiently support the structure. The glazing is clamped directly onto the flat bars. Consequently the glass panels are rhomboids with constantly changing angles (fig. 12).



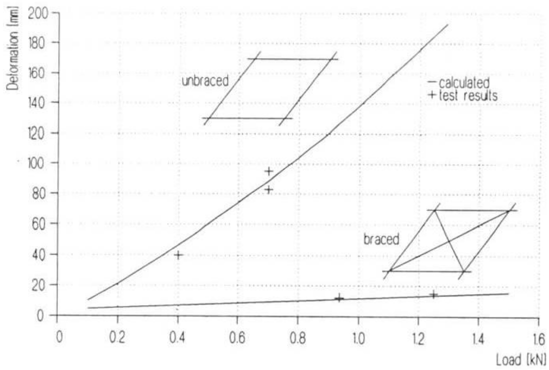


Fig. 12 Grid dome braced with cables and test results for a braced and unbraced dome

For the L-shaped courtyard of the Hamburg museum, the lightest and most transparent structure had to be designed, which would burden this historical building as little as possible - in both senses of the word: it was not to alter the overall appearance, and must only transmit minimal additional loads to the historical building.

The net dome has two barrel-vaulted sections, with spans of 14 m resp. 18 m, with a smooth transition between them. There the geometry is the result of an optimization, transferring the majority of the roof loads via membrane compressive forces and avoiding bending stresses (fig. 13).

The structure consists of 60 x 40 mm flat bars of St. 52.3, galvanized and painted white - in other words, hardly any more than the minimal dimensions of supporting members for a glass cover. These bars form a quadrangular net with a uniform mesh of about 1.17 x 1.17 m. Cables, installed afterwards, prestressed and clamped down at their joints form the varying diagonals.

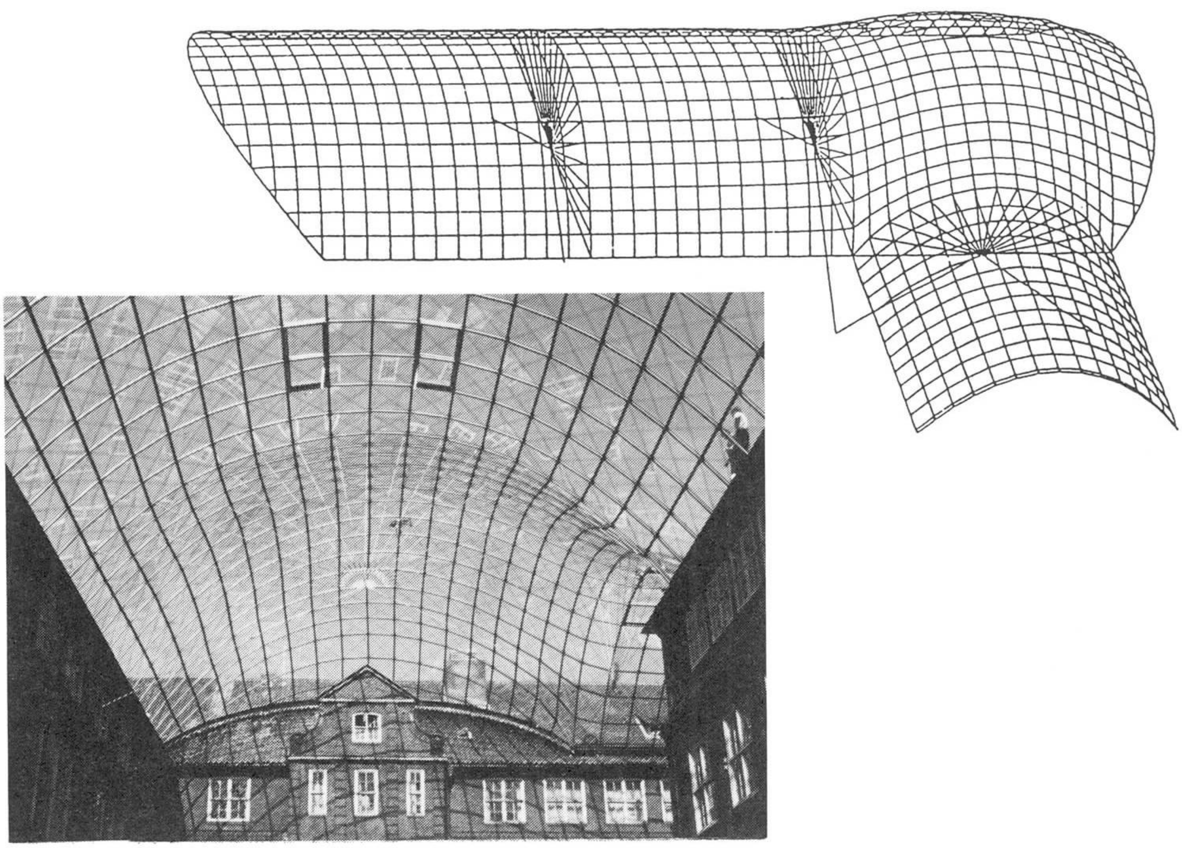


Fig. 13 Three-dimensional graph and interior view of the Hamburg grid shell

These minimal cross-sections enable the grid shell structure to transfer dead load as well as snow and wind loads. Since extremely high snow loads on one side due to drifting or trapping of snow in the roof valley could not be ruled out, the "somewhat softer" areas of the barrel vault were additionally stiffened with spokes wheels consisting of cables radiating from a "hub".

The glazing, 2 x 5 mm laminated safety glass, was placed directly on the flat bars and secured with plates at the joints. A heating wire was inserted between the glass support and the steel bars to prevent condensation.

The roof was designed and built in just 6 months.

2.2 The membrane roof over the grandstands of the Gottlieb-Daimler stadium at Stuttgart

For the 1993 Field and Track Worldchampionship in Stuttgart, within 18 months the largest membrane roof in Europe, covering 34,200 m^2, has been planned and built, covering an existing stadium.

The requirements to protect at least 90 % of all spectators, the poor soil conditions and restricted space were the main parameters which made this light weight structure, designed to be mostly self-anchored, obviously superior to other alternatives, like steel cantilevers or roofs with longitudinal and transverse truss girders (fig. 14).

Fig. 14 Aerial view of the completed roof

The roof length along the main axes comes to 200 and 280 m respectively. The outer edge of the roof in plan is formed by two partly circles, showing a radius of 104 m in the curves and of 248 m behind the main grand stands. The roof width or cantilever length is constanly all around. The main roof structure consists of two rectangular steel box compression rings, supported by 40 tapered steel box columns at 20 m spacing, further of 40 radial cable girders, leading from the compression rings to the inner cable tension ring, which keeps all cables under sufficient prestress (fig. 15). This primary structure, formed by the steel and cable elements, is sufficiently stabilized in itself and needs no further stiffening by the secondary structure. Horizontal wind forces are transferred down to the foundations by bracing cables between some support columns, arranged in the roof quarterpoints.

The 40 cable girders are made by the upper "snow"-cable and the lower "wind"-cable, stressed against each other by the suspender cables at 7.5 m distance. Since the tension ring cable and the compression rings form concentric circles in plan, the steel box elements get merely axial compression forces without any bending under prestress and dead load.

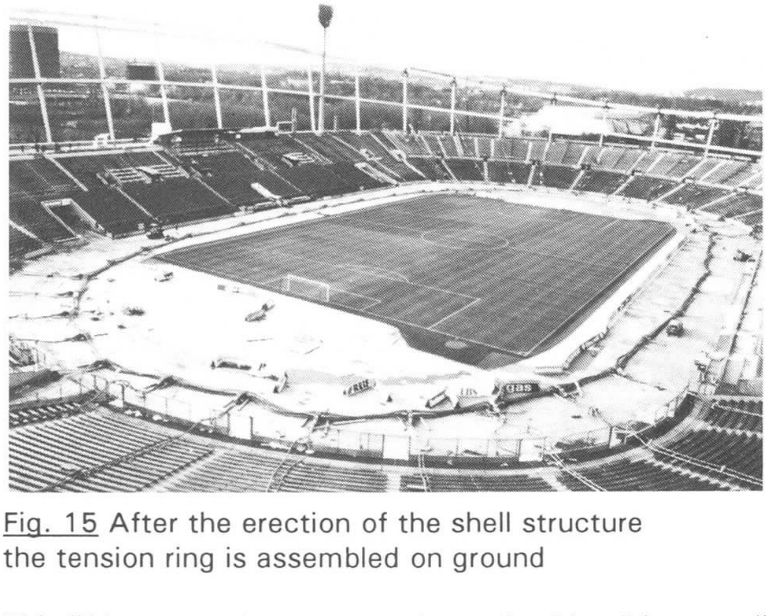


Fig. 15 After the erection of the shell structure the tension ring is assembled on ground

After placing the 40 columns, followed directly by the assembly of the two compression rings, the 8 cables of the inner tension ring were laid out on the ground, connected to one ring and the 40 radial cable trusses also preassembled and attached to the inner ring as well as to 40 lifting devices, which from the upper outer ring pulled the cable structure up and into the final position .

This lifting procedure was predetermined in all intermediate stages and carefully controlled by continuous force- and geometry measurements until the structure reached its final position after 3 weeks only. All radial cables were then attached to the rings by inserting the bolts into the hinges and the primary structure was ready for the membrane installation. Geometrical measurements confirmed that very close tolerances, necessary for the membrane structure, can be reached and confirmed by carefully planned application of 3-D computer software for analysis as well as for the preparation of drawings during shop fabrication.

Tubular steel arches with a tie span the distance between two "wind"-cable/suspender cable nodes in circumferential direction. Seven such arches are needed for each of the 40 panels, producing 6 saddle-shaped membrane roof parts inbetween and two steeper outer elements, running from the last arch to the edge cables (fig. 16).

This secondary structure weighs only about 8 kg/m^2 roof area. The front and rear membrane edges are circular with thin diameter flexible cables in pockets prestressing the membrane. The radial membrane panel edges are fixed and clamped by metal strips, which are anchored to the "wind"-cable from both sides, thus balancing the horizontal tangential forces directly. A secondary membrane, welded to the main panels, and overlapping, makes this radial joint watertight. The welded seams in the membrane run in radial direction, due to fabrication and aesthetic reasons. The PVC-coated polyester membrane with an additional Fluorpolymer-protective layer on the upper surface is of Güwa Type III, specified with a minimum translucency of 8 % and a white colour.

Within an extremely short period for design and construction, an elegant and filigree roof structure has been created, providing the adequate light and cheerful ambiente for sportive events (fig. 17).

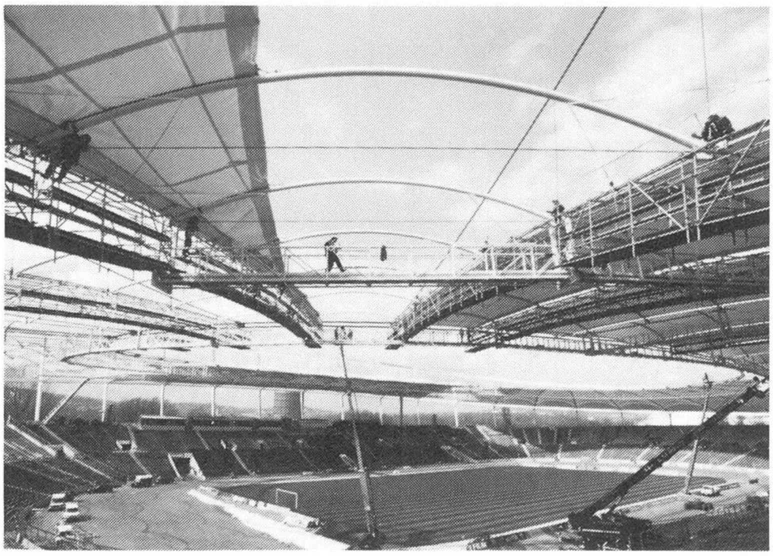


Fig. 16 Installation of membrane panels

Fig. 17 Interior view of the completed roof

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