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Long-Span Roofs: How to Reconcile Efficiency with Least Costs

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Summary

The designer of long-span roofs will strive for a minimum of dead load in favour of efficiency, lightness and beauty. This calls - as well-known from concrete shells - for double curved surfaces which are, however, costly to fabricate. Thus, especially in times of high labour and relatively low material costs, long-span roofs have a cost-problem. The paper will define this problem and propose some practical solutions, including a number of recent examples from the author's practise.

1. Introduction

The basic key to efficient long-span structures of any type including bridges and roofs, is to minimize the dead load by use of high strength materials, by avoiding bending in favour of direct axial forces and by choosing tension as against compression.

In applying these principles to long-span roofs, there are basically two different approaches:

- the addition of a series of girders (beams, trusses) or hybrid suspended systems (using arches, suspension- or cable-stayed systems) with the purpose to support an independent envelope;

- **the integration of the load-bearing and enveloping function into a double-curved surface.**

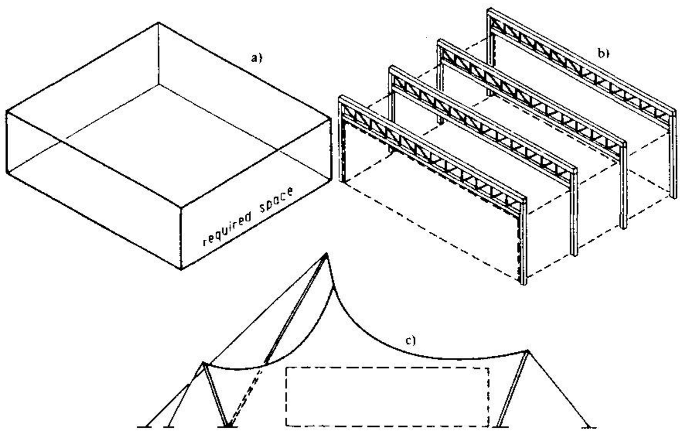

Fig. 1 Long-span roofs' basic classification: Addition of girders and double-curved surface structures.

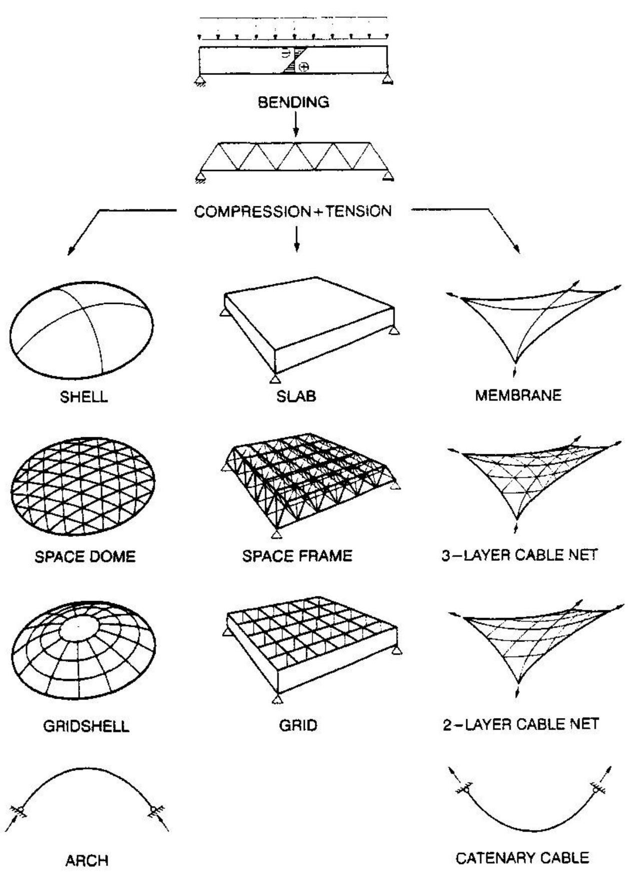

Fig. 2 The development of double-curved surface structures.

Roofs following the first approach usually adapt better to the functional requirements of large halls for sports- or exhibition purposes and are easier to construct. Thus in our times of high labour- and low material-costs they are more economical than those following the second approach. These, however, are more efficient as far as total material consumption is concerned and may therefore - if carefully done - be superior from an ecological, social and cultural point of view.

Light double-curved surface structures are ecological since they save materials by making optimum use of their strength thus wasting the least natural resources. These light structures can usually be disassembled and recycled. Light structures retard entropy and thus best fulfill the requirements of a sustainable development;

social because they provide jobs. Delicate and refined structures call for complex details resulting in mental efforts for designing and planning as against physical waste. Craft replaces stupid mechanical fabrication, joy of engineering against repetition. Of course, as long as our present economical system identifies labour with mere costs and does not include human dignity and as long as the value of natural resources accounts only for their mining costs and do not include "external costs", light structures are more costly than functionally equal, clumsy ones;

cultural if responsible and disciplined designers make use of their possible geometrical varieties in the interest of an enriched architecture. Light, filigree, transparent, variable evokes better feelings than heavy, clumsy, dark, monotonous. "Aesthetics relieve tension of mind and one feels relaxed in the vicinity of aesthetically beautiful natural scenes, sounds, personalities, statues, paintings and structures, Therefore, aesthetics are essential for human life" (C. V. Kand, Structural Engineer from Bhopal, India in a recent personal letter to the author). Light structures visualize their flow of forces which an enlightened modern person appreciates since he wants to understand what he sees. Thus light structures may win sympathy for technology and reintegrate structural engineering into culture.

Since in his key-note lecture and paper for the IABSE-Symposium in Birmingham 1994 called Conceptual Design of Long-Span Roofs [1] the author has already written extensively on the basic approaches to long-span roofs, this paper will start from there and now concentrate on one aspect only:

2. How to conceive these efficient double-curved surface structures with regard of an economical fabrication

Referring to [1] it makes sense to classify double-curved surface structures according to their overall loadbearing behaviour, i. e. whether they act predominately in

- compression resulting from synclastic curvature,
  the continuous concrete shells,
  the discontinuous space structure or grid domes;

- tension resulting from anticlastic curvature with mechanical prestress or from synclastic curvature with pneumatical prestress
  the cable-net structures,
  the continuous membrane or pneumatical structure made from textile or thin-sheet metal material;

- a combination of tension and compression
  the shells with anticlastic curvature without external prestress,
  the space frames and grids,
  the slabs.

Of course, these latter plane structures need not to be further discussed here, because they do not pose any special fabricational problems.

2.1 Concrete Shells

The predecessors of modern concrete shells are the historic masonry cupolas. Their builders were already very well aware of the fact that their success depends on an integrated view of their shape, their loadbearing behaviour and their fabrication process. Still today it is worth studying their basic features [2]. Milestones in the construction of masonry cupolas were the Pantheon in Rome, the Hagia Sofia in Istanbul, the cupola of the Florence Dome, St. Peter in Rome and St. Paul in London [3]. The Century Hall in Breslau, completed in 1912, though one of the earliest and for a long time the longest-span reinforced concrete structure, still does not make use of shell loadbearing behaviour but is a traditional frame structure built on formwork.

It is very interesting to remember that the first real concrete shells built by Dischinger and Bauersfeld for the Zeiss planetarium in Jena in 1922 followed a construction process which is unparalleled until today: First they constructed a spherical steel grid with triangular mesh and 16 m diameter. In order to be able to fabricate this grid from as many equal slats as possible, they based its layout on the icosaeder-polygone (as "invented" and patented by Buckminster Fuller some 20 years later under the name "geodesic dome"), so that for the total of 3,840 slats of about 60 cm length they needed only 51 different units (Fig. 3). The total weight of steel, which then served as formwork and reinforcement was 3,600 kg for the shell's 400 m² or 9 kg/m² corresponding to 1,1 mm average thickness only. After spanning this grid shell with wire-mesh it was gunnited or torkreted to result in an ideal concrete shell [4].

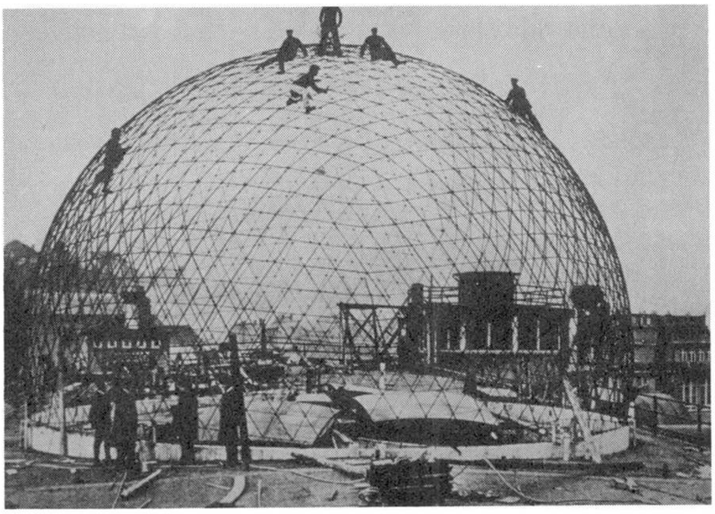

Fig. 3 Bauersfeld's 1922 cable-net dome, 16 m in diameter for an experimental reinforced concrete shell.

Though the further development of reinforced concrete shells is connected with such illustrious names a Torroja, Nervi, Candela, Esquillan, Tedesko, Bini - and still active Heinz Isler, after a certain boom in the 1960s it almost disappeared in recent years. Those who were or still are successful all tackled the problem of economical fabrication of these double curved surfaces in their special way: Candela restricting himself to hypar surfaces which can be produced from straight members following the generatrices, Esquillan applying prefabrication, Bini placing the reinforcing steel and the concrete on a membrane which then is inflated and Isler by making repeated use of the same formwork for ideal shell shapes derived from either pneumatic, inverted hanging for oam floating form finding [3], [5]. Isler and other engineers as well used pneumatic cushions as reusable formwork for gunniting concrete shells; pneumatically feasible shapes which are suitable for concrete membrane shells as well were studied in [6] (Fig. 4).

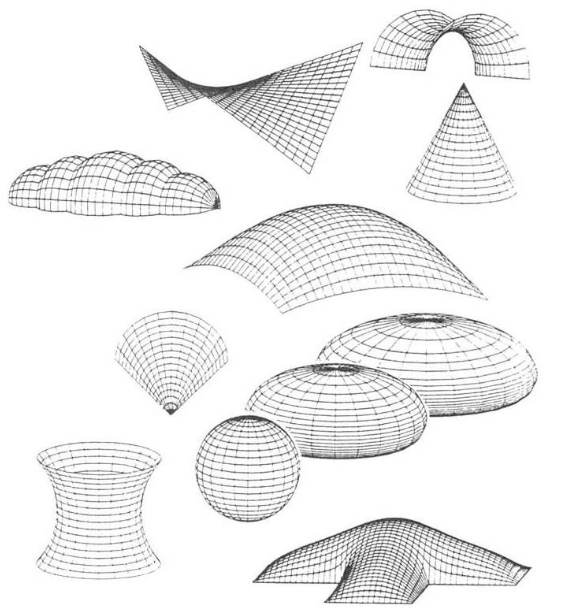

Fig. 4 Suitable shapes of pneumatic formwork for concrete shells [6]

The author himself further made an effort to revive shell construction by use of glass-fiber concrete. A shell, 31 m in diameter and only 12 mm thick, similar to Candela's Xochimilco restaurant roof was built using prefrabrication, profiting from the light weight of the thin shell (Fig. 5).

But all these efforts were not really successful and the beautiful and efficient concrete shells are further losing ground against more primitive structures. Those who care for genuine concrete structures should apply all their fantasy to revive concrete shells through economical fabrication.

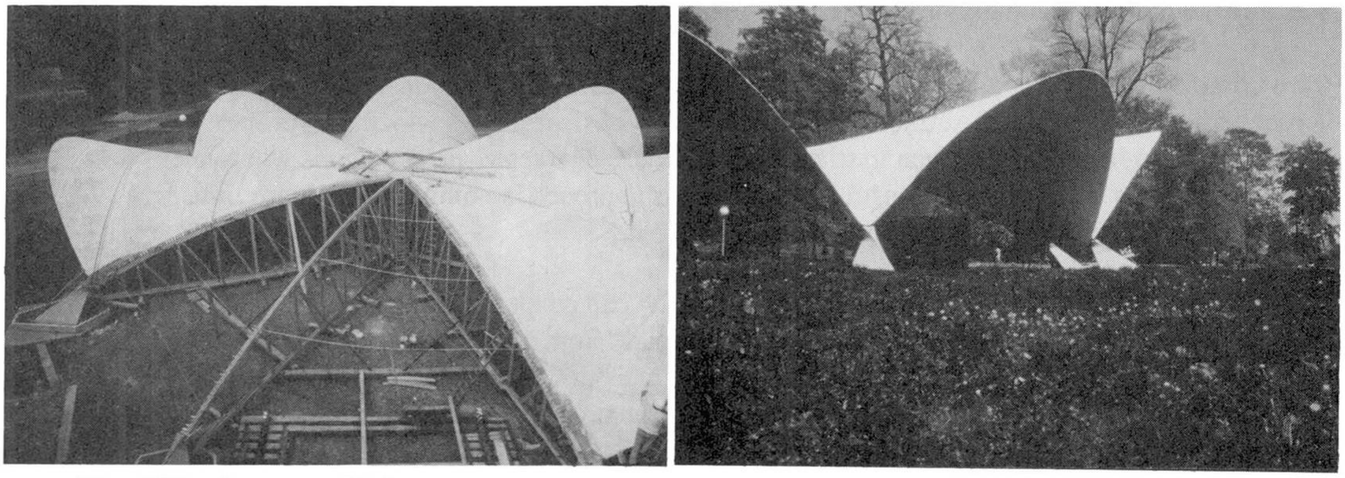

Fig. 5 The Stuttgart CRC-(glass-fiber reinforced concrete-)shell, 1977 during construction and as completed structure.

2.2 Grid Domes

As against concrete shells, grid domes have experienced a remarkable break-through in recent years. When replacing the continuous surface by a steel grid, which can be easily constructed from prefabricated tubular membranes or slats, there are of course numerous approaches at hand (Fig. 6).

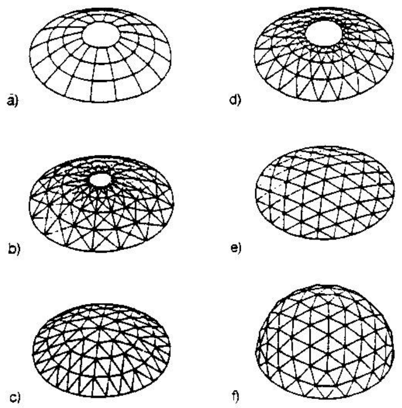

Fig. 6 Various layouts of grid domes
a) frame with quadrangular mesh requiring bending stiffness
b) Schwedler's dome; c), d) grid shells;
e) lamella shell; f) geodesic dome

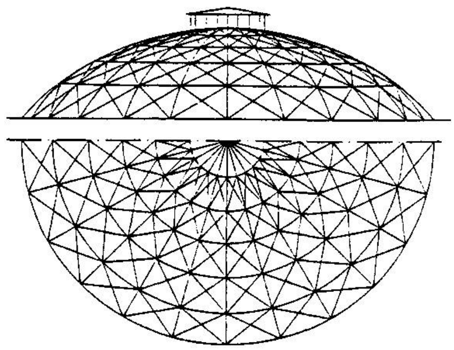

Fig. 7 Schwedler's dome

Leaving aside the frame-approach (Fig. 6a) which results in relatively heavy members, the basic problem is to cover the double-curved surface with a triangular mesh, where as many members and joints as possible are equal. This recalls the names of J. W. Schwedler, K. Wachsmann, B. Fuller (and F. Dischinger with W. Bauersfeld), M. Mengeringhausen, F. Otto. Schwedler's approach was very successful since 1874. The largest Schwedler-dome was built in 1955 in North Carolina with a diameter of 101 m (Fig. 7). The disadvantage of any concentric arrangement of the meridian members (Fig. 6a - d) is an unpleasant congestion in the zenith of the dome, which by gradually omitting certain members cannot really be compensated.

Two completely different approaches solve this problem: B. Fuller's geodesic dome, where the icosaeder is projected on the surfaces resulting in 20 geodesic triangles which are further subdivided into hexagons and then in triangles, with these characteristic pentagons where the 20 triangles meet and which demonstrate that also this approach is nothing but a compromise towards equal members and joints (Fig. 8) [3].

The other approach is based on the square mesh, which can adapt to any shape - not only the regular sphere - by changing its angles and which is made from solid slats. After erection it is stiffened by prestressed ropes running along the diagonals of the grid (Fig. 9) [7]. The disadvantage of this system with quadrangular mesh is that the cladding panels must warp and cannot be plane which is detrimental to double-glazing. By using translational surfaces, for which all four corners are always in one plane H. Schober has shown that there is an immense variety of forms (Figs. 10, 17) [8].

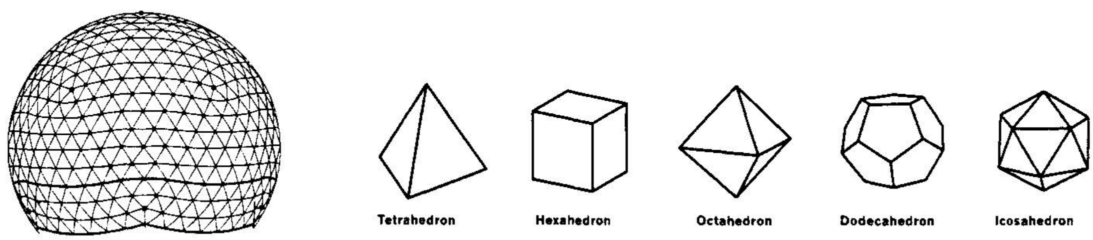

Fig. 8 Geodesic dome, based on the icosaeder-layout for the mesh.

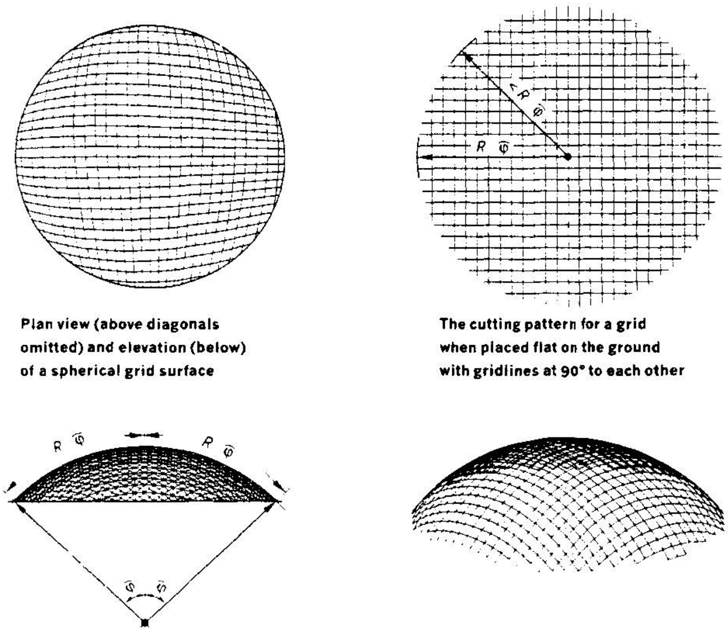

Fig. 9 The grid shell made from a quadrangular grid and diagonal cables.

Of course, today with computers and CNC-fabrication it is easily possible to produce members or slats and joints with ever varying lengths and geometries and thus these approaches for unification lose their significance. But nevertheless, they maintain their appeal because order and harmony are important ingredients of natural beauty.

Speaking of fabrication of grid domes, M. Kawaguchi's pantadome system must be mentioned. By leaving out certain members, the kinematic system is erected near the ground and then lifted in its final position adding the missing members for stability (Fig. 10) [9].

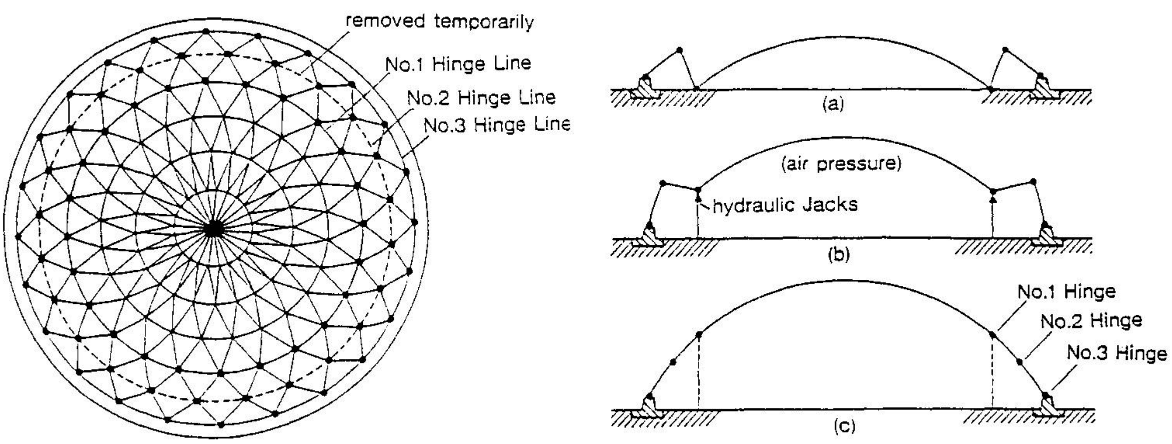

Fig. 10 The principle of the Pantadome system.

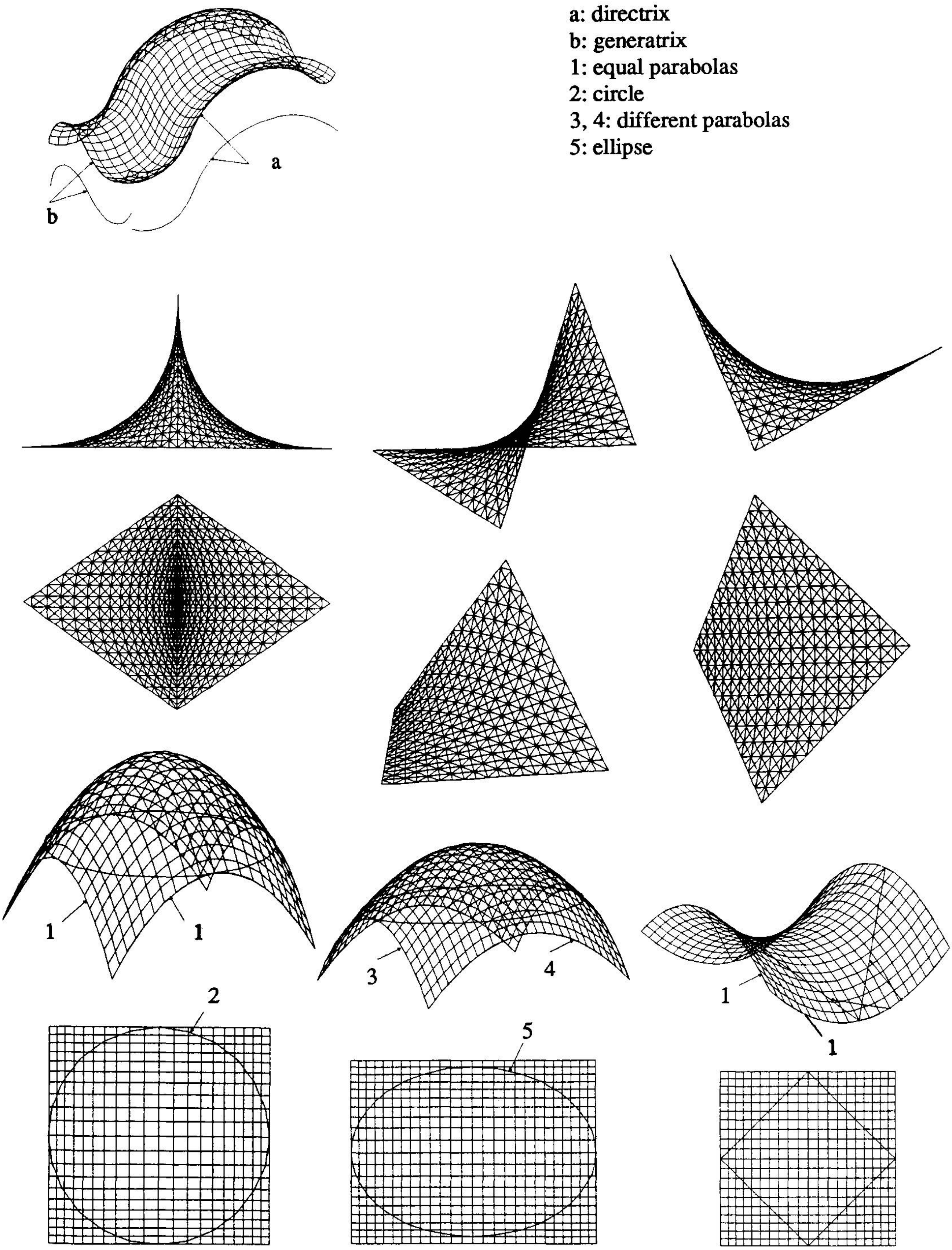

Fig. 11 Some translational surfaces with quadrangular mesh of equal lengths and permitting plane cladding [8].

2.3 Cable-Net and Membrane Structures

This type of structure, more than any other, emphasizes that conceptual design of structures calls for the engineer's capability to find an optimum compromise. The square cable-net is easy to manufacture and permits almost any shape, but has a poor load-bearing behaviour. For the triangular cable-net just the opposite is true. Textile membranes are very successful these days, because in combination with a primary cable structure, they have a favourable load-bearing behaviour and are easy to manufacture and construct. They permit a large variety of shapes and are beautiful and transparent. There main draw-back is that their single-layer membrane does not provide temperature insulation and therefore they are unsuitable for permanent use (Fig. 12) [1], [10].

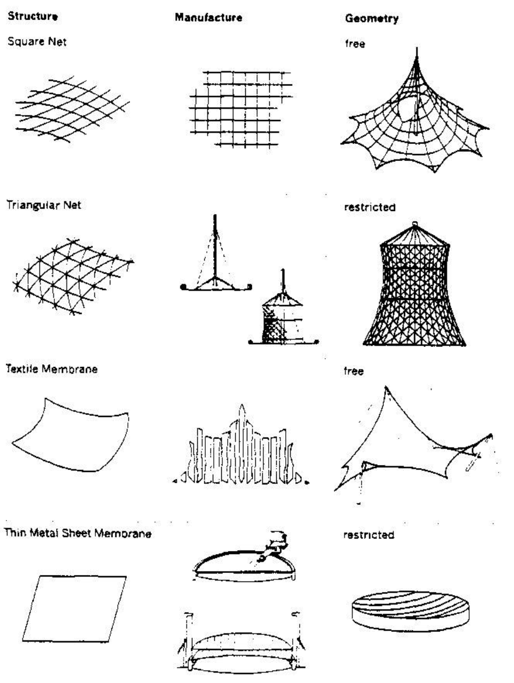

Fig. 12 Manufacturing double-curved light weight surfaces acting in tension.

First row: A cable net with an initially square mesh, is "developable". Manufactured flat on the ground it is able to adapt itself during lifting to any double-curved shape by changes in the angles of intersection of the cables. Only the meshes at the edges need to be trimmed to suit a specific shape. This versatility is gained, however, at the cost of poor loadbearing behaviour and low rigidity, because loads at any node can be transmitted basically only in two directions.

Second row: A cable net with a triangular mesh is non-developable and thus must be manufactured in situ, in its destined form. Only a limited number of geometries provide a desirable regularity of node spacing. These disadvantages are compensated by the ideal load-carrying and stiffness characteristics associated with membrane shell behaviour.

Third row: Textile membranes, like articles of clothing, are manufactured in the workshop by cutting initially flat pieces of fabric to a predetermined pattern and joining them along seams. They may then be folded, packed, and brought to the site, where they are attached to a primary structure which usually consists of foundations, edge beams, masts, and cables with cast steel joints. Stretched (or inflated) between these elements they may, like square nets, adopt any predetermined form, including double-curved shapes. Disadvantages are that their load-bearing behaviour depends on the make-up and orientation of the weave and the type of coating, and that the plastic materials employed have a limited life (Figs. 13 - 15).

Fourth row of Fig. 12: Metal membranes of stainless steel have greater durability and perfectly controlled material characteristics. However, they cannot be folded. Double-curved surfaces may be obtained from flat sheets through plastic deformation of the metal using pneumatic or mechanical loading. The range of geometries achievable is limited (cf. triangular nets) but ideal membrane shell behaviour is ensured (Fig. 16).

2.4 Recent Examples

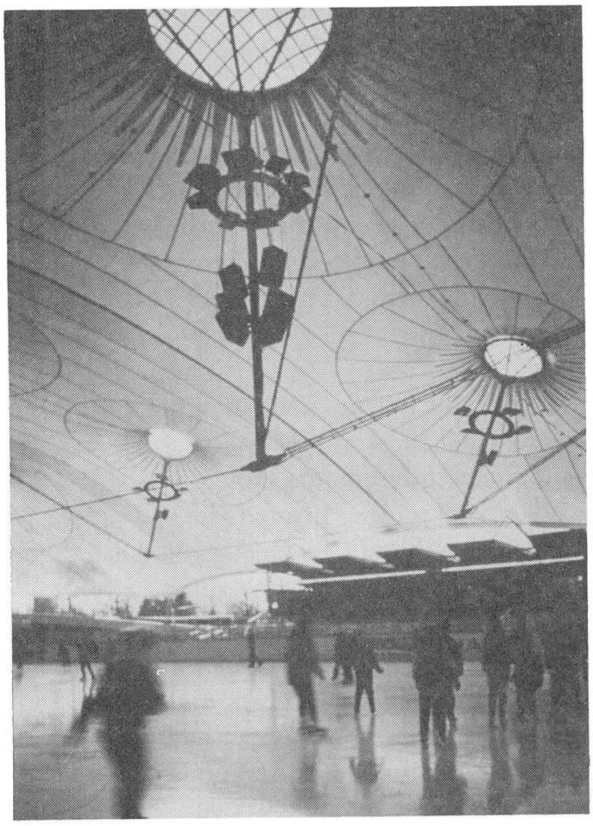

Fig. 13 Ice-skating rink, Hamburg Stellingen.
Covering an area in the form of an ellipse with main axes of 120 and 70 m, the membrane is held up by 4 main masts and 8 cable supported props and tied down at it periphery by 26 short guyed masts. This roof uses the cutting pattern and arrangement of the membrane strips to show the flow of forces thus enhancing the natural beauty of membrane structures.

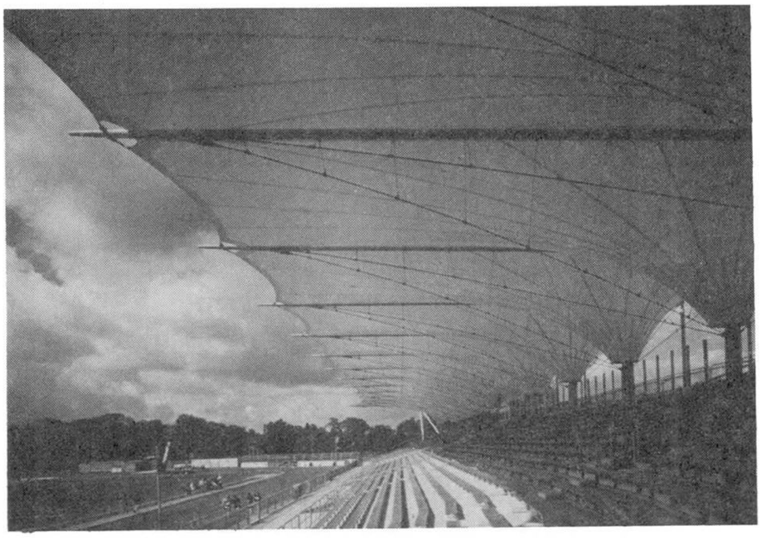

Fig. 14 Roof over a grand stand at Oldenburg.
Covering 5.000 seats, arranged in 21 rows, 130 m long consisting of a steel tube, cable and membrane structure with 14 rectangular or trapezoidal elements, connected at upper horizontal level by their adjacent edges along radial struts and each tensioned downwards to a low point. The rectangles are 9.25 x 23 m in plan and their lower points are 4 m below the horizontal edges; roof projection is 17.6 m over seating area and 5.4 m behind. The horizontal struts are cable suspended from masts, 11.45 m high and held down by another set of cables. At each end of the whole roof a triangular cable truss in plan collects the horizontal forces to a point carried on steel trestle supports.

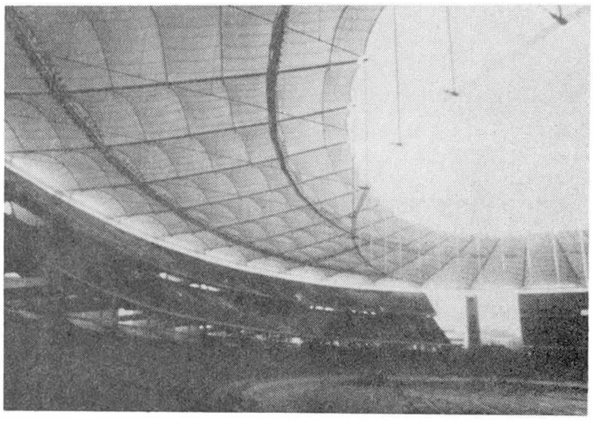

Fig. 15 Lightweight Roof structures for the Outdoor Stadium Kuala Lumpur, Malaysia.
This cable membrane roof covers 100,000 seats and with 38,500 m² roof area has become the largest stadium of the world.

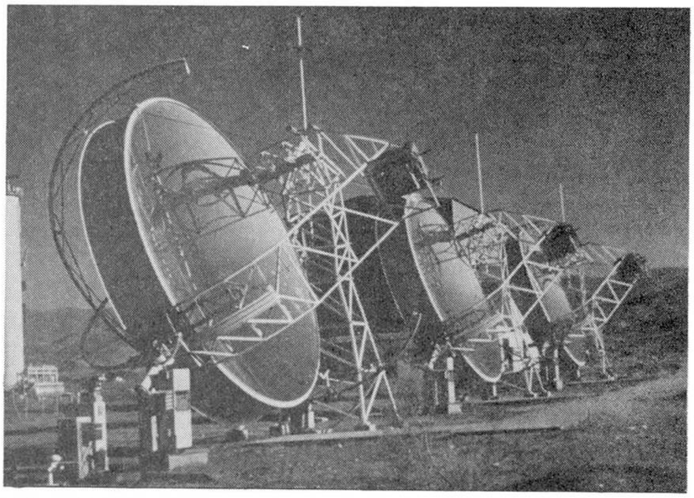

Fig. 16 Metal membrane technology is also useful to build cheap and precise dish concentrators.
They are needed in large numbers for solar power plants. Six prototypes have been operating successfully in Almeria, Spain for several years.

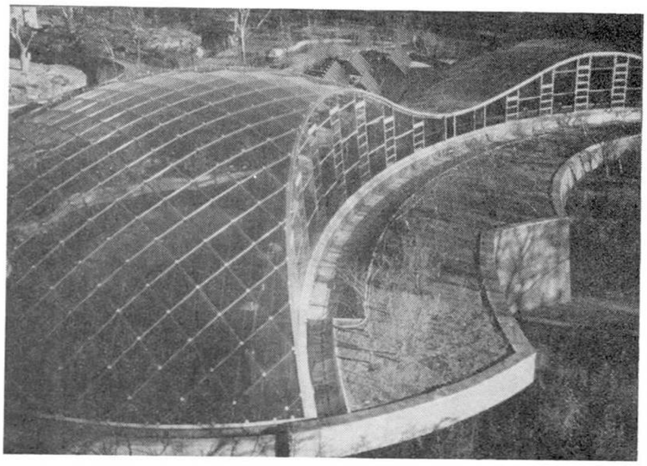

Fig. 17 Glass Roof for the Hippo House at the Berlin Zoo.
Covering two circular pools, one about 21 m in diameter and the other approx. 29 m in diameter.

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