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Plenary Session

Long-Span Roofs

Keynote Lectures

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Role of String: Aesthetics and Technology of Tension Structures

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Summary

"Space Structure" is able to realize the architectural space with long-span rationally. Its basic characteristic is the performance of form and axial restraint. String, a tension member, is not only able to make structures by itself but also in combination with such rigid members as beams and arches. This paper reports on aesthetics and technology at Hybrid Tension Structures, the degree of freedom in architectural expression and development in structural efficiency generated by the addition of strings, mainly cable through the examples which have been designed by the authors and constructed recently in Japan.

1. "Less is more" in Role of String

"Less is more" are the famous words spoken by Mies van der Rohe (1886-1969) which expressed the essence of modern architecture. It is the eagerness to make richer and more attractive spaces with less. It is said that modern architecture has gradually become universal, less has been selected without Mies's rigor, and the spirit of his words has been lost. Modernism changed to post-modernism with Robert Venturi's impeachment, "less is bore". But today the current of post modernism has flagged, "more is bore" has risen leading to the reconsideration of "less is more".

Architectural spaces realized with structures which make the full use of strings with maximum mechanical performance "tension", aim at the following target: Structures must not only have a lightness but also total structural rationality, including the fabrication and construction process. Furthermore, the visual impact of tensile expression and the clearness of strings is expected to generate a new structural expression and aesthetic which symbolizes our time.

2. Classification of String Structure

Tension structures are divided into two types: membrane structures (prestressed membrane structures and air-supported membrane structures) and string structures. Tension members such as cable, rod, chain (plate) and semi-rigid H steel all belong, in a broad sense to the string. This report focuses mainly on cable in string structure.

High-strength, flexibility and unlimited length are the basic characteristics of cable. At the planning and design stage of string structures, the following points must be noted in order to exhibit the characteristics and advantages of cable.

(1) Use the longest length of continuous cable possible, to reduce the number of metallic joints attached at the middle of cable and to simplify their mechanism.

(2) Introduce the designed amount of prestress (PS) accurately with little force at a reduced number of points.

With cable structures, it is important to realize these merits in the whole design including total system, detail, fabrication and construction. Furthermore, it is interesting that "slenderness" of cable both eliminates and emphasizes the existence of structural expression.

String structures can be classified by the amount of tensile force which occurs and exists in the string. In general, the initial tensile force T_o which occurs in the string under the dead-load and the tensile force T_1 which occurs in the string under the additional loads can be expressed by the following equation:

$\mathbf{T_o=T_e+T_p}$: PS in a broad sense

$\mathbf{T_1=T_o+T_a=(T_e+T_p)+T_a}$

T_e : existing tensile force caused by the equilibrium

T_p : tensile force which is introduced intentionally to control the structural behavior (PS in a narrow sense)

T_a : incremental tensile force under the additional loads

Fig.1 shows the classification of string structures carried out under the amount of string tensile force. If the rate of T_p to T_e (T_p / T_e) is larger, it is more necessary for the structural system to be demanded the strength in construction and the absorption of string expansion under the dead-load.

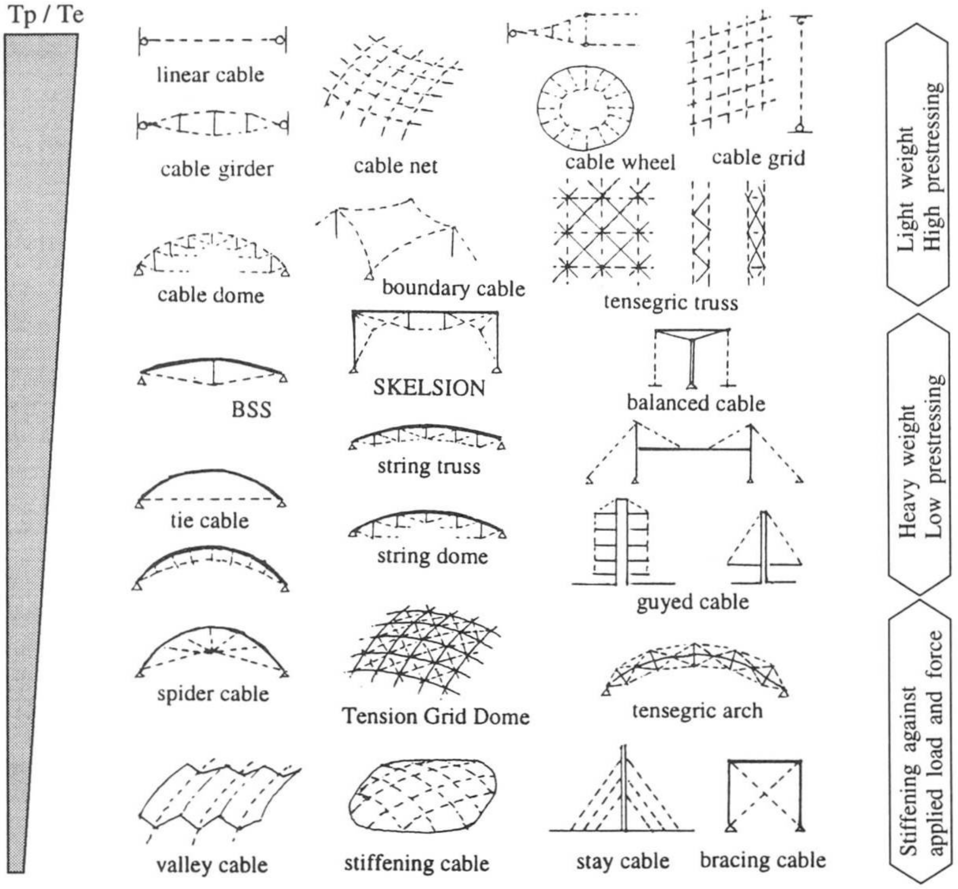
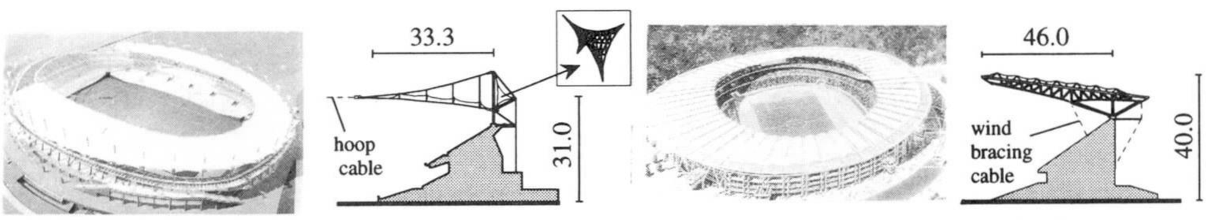


Fig.1 Classification of string structures by tensile force of string



• *Case I Okayama Stadium* • *Case II Ogasayama Stadium*

Fig.2 Different role of string in two cases of soccer stadium

3. Beam String Structure

3.1 Structural Concept

Beam string structures (BSS) belong to Hybrid Tension Structures made by combining string with such rigid members as beams, shallow arches and mount-shaped arches. The main characteristics of BSS are as follows :

(1) Self balancing system under the dead-load (passive effect).

(2) Stress control of bending or compressive members, and control of displacement and shape of frames (active effect).

Fig.3 shows the birth of BSS from structural principles. The primitive ideas of BSS have been known in bridges and architecture from the beginning of 19th century, but BSS hasn't spread as arches and trusses have been developed. Recently, why has this structural system again been applied not only in bridges but also in architecture?

First, it may be due to architectural design. The distinguished characteristic of BSS is the degree of freedom in selecting beams and strings befitting space, scale and form. Furthermore, such "architectural expression" is an extension of the degree of freedom in exterior design by using a self-balancing system, sense of transparency, lightness and delicacy expressed by eliminating and emphasizing the existence of the string, and expression of logic in systems. All these are noticeable characteristics of design in BSS (Fig.5, 6, 7).

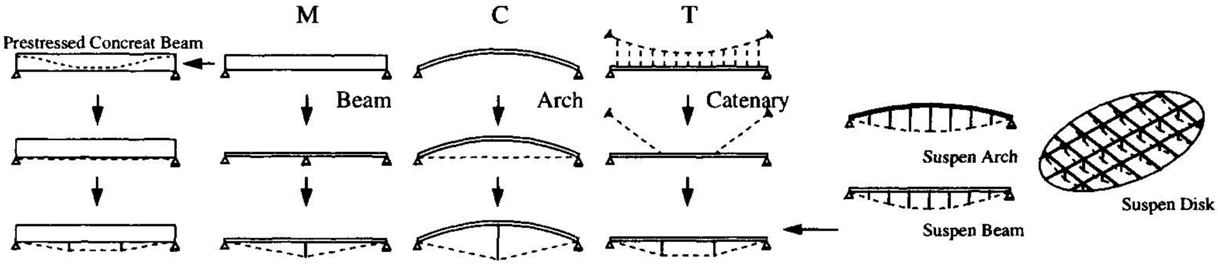
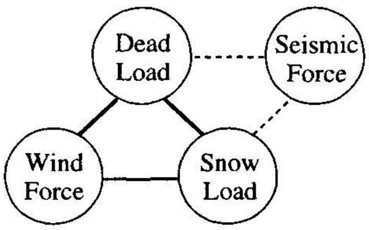


Fig.3 Birth of BSS

Secondly, it may be due to structural performance. To ascertain the dominant load and prepare the supporting frame is important in order to select the appropriate arrangement and combination of beams and strings in preliminary design (Fig.4). Furthermore, the stress control of the bending moment and the displacement of beams must be considered along with, the dead-load in installing strings, the supporting point (pin or roller end), and reaction on support (timing of jack down and up-lift) are all of importance for the introduction of PS into strings. Detail, mechanism and control methods for the purpose of introducing tensile force must be prepared in advance. Fig.8 and Fig.9 show the method for introducing tensile force into strings.



TYPE	<Load Condition> Finishing Load	Snow Load	<Dominant Load> Long Term	Short Term	
I	small	small		Wind F.	light-weight
II	small	large	Snow L.	Wind F.	↑
III	large	small	(Dead L.)	Seismic F.	↓
IV	large	large	(Dead L.) Snow L.	Seismic F.	heavy weight

Fig.4 Dominant load and force for BSS

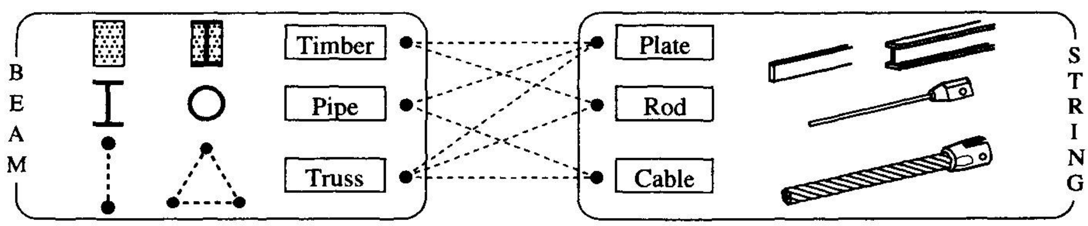
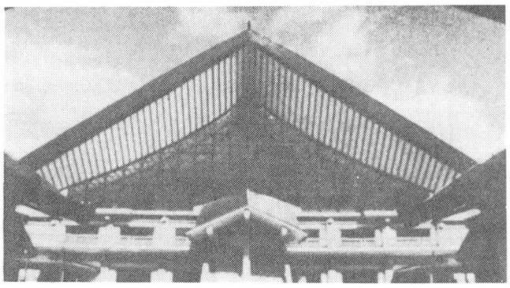
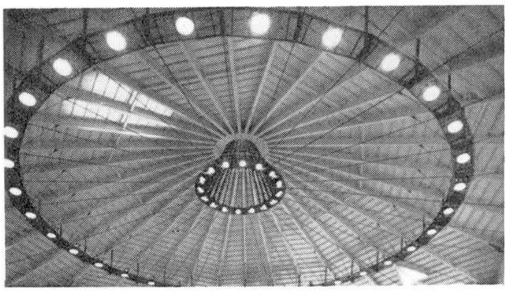


Fig.5 Combination of beam and string



• *Iwate Prefectural Budoh-kan*



• *Monoh Town Gymnasium*

Fig.6 Mount-shaped BSS

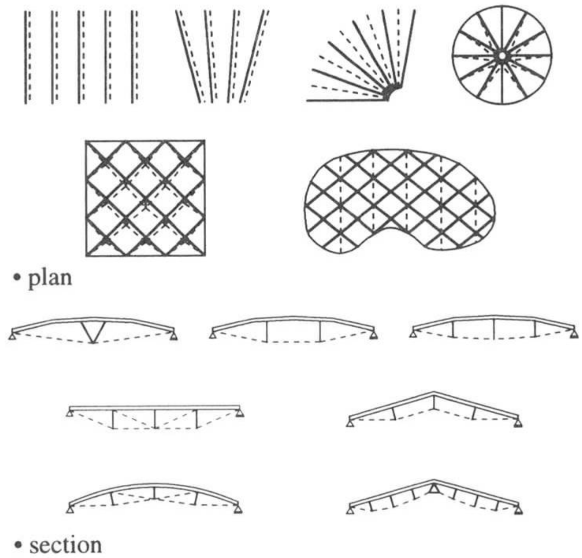


Fig.7 Variation of arrangement of string

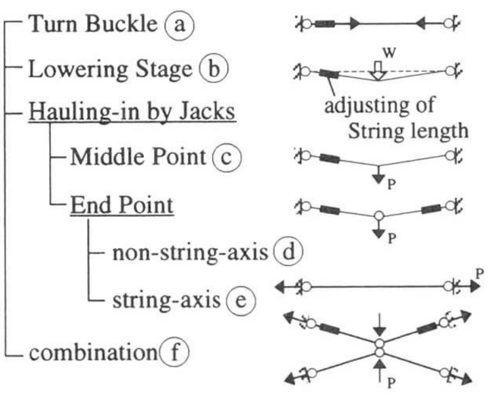


Fig.8 Method for introduction tensile force to string

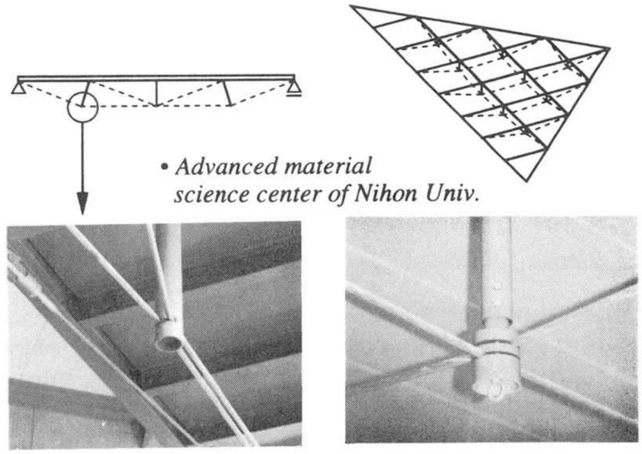


Fig.9 Hauling-in by pulling-down by small force

3.2 Development of BSS

The basic model of BSS is a simply supported system where the dead-load is large and the additional load (snow load and hanging equipment load) is small. Advantages of BSS are performed most effectively in this model. In the case the supporting structure is rigid, BSS of flat or shallow types are free from seismic forces and the best amount of PS under the dead-load is decided.

On the other hand, the following points must be noted in order to establish a structural system of BSS.

(1) To obtain the ceiling height, since BSS are suitable for flat roof: Development into tension truss, mount-shaped BSS, combination with cantilever truss or diagonal post, and BSS with multistage strings are examples of the solutions.

(2) In the case where the supporting structure is low-rigid: SKELSION is invented to add horizontal resistance to slender post or frame. The characteristics of SKELSION is to balance high PS force by arranging hanger strings and bracing strings.

(3) In the case where finishing materials are very light, such as in membrane and steel decks: Wind braces and valley cables are an effective method to resist typhoon wind loads.

Considering these points the structural system can be expanded in many variations. Fig.10 shows actual examples which the authors have designed during the last 20 years.

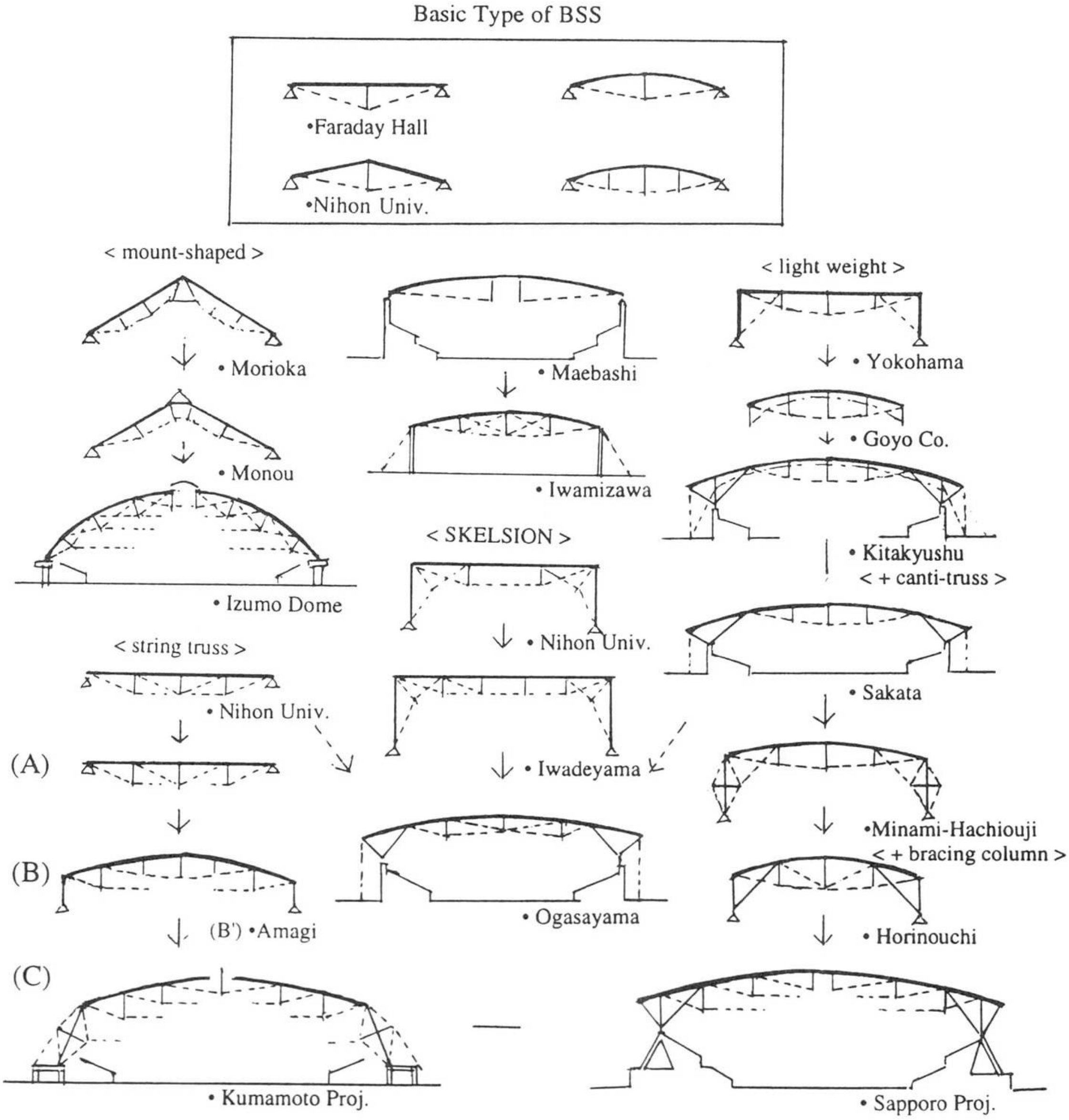
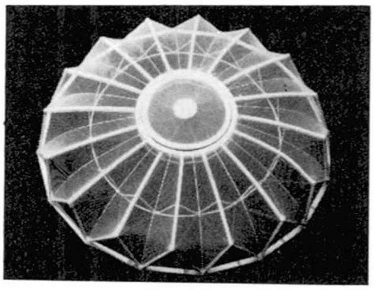
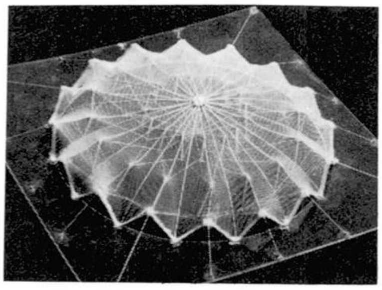


Fig.10 Various application from basic type of BSS

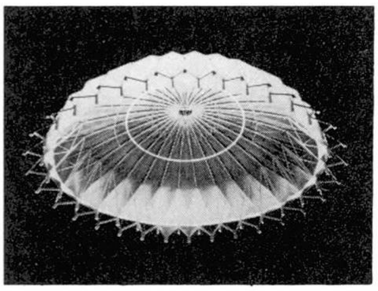
In the circular type of BSS, the height of string can be lifted up by installing a hoop cable at the lower end of the outer strut (A). By replacing radial beams (B) with radial cables the the horizontal force is resisted at the boundary, a shallow cable dome can be achieved ((B') Amagi Dome). Another development of prototype (B) is shown in the Kumamoto Project (C) which is characteristic of an oval plan and anti-spherical shape.



(B)



(B')



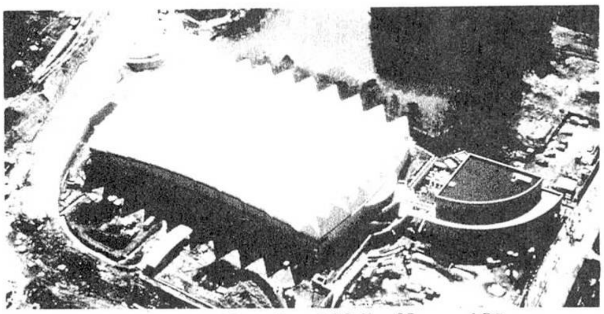
(C)

Fig.11 Development of BSS

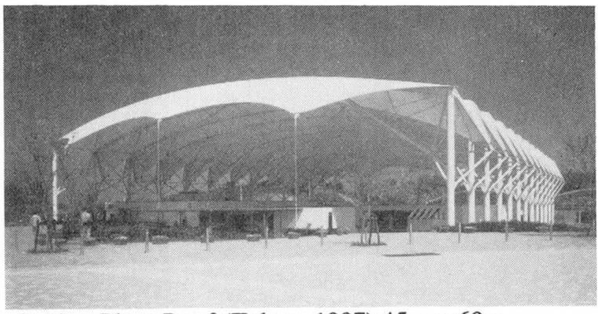
3.3 Diversity of Architectural Expression in BSS

[1] Image of external appearance

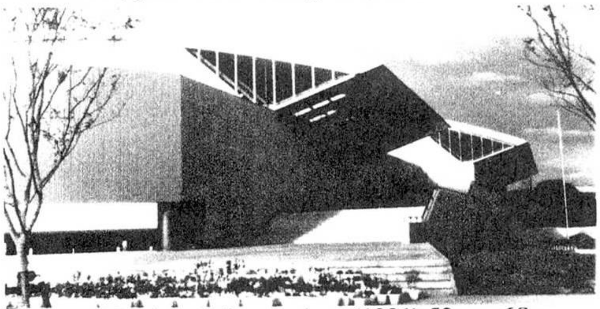
In general, the dead-load is predominant in long-span structures. Self balancing systems with strings and beams can let the boundary structure be free from horizontal reaction, allowing for light and free exterior design creating a variety of images (Fig.12).



• Anoh Dome (Kita-Kyushu, 1994) 62m x 108m
"Paraglider" flying from the summit of a nearby mountain, just landed on a green forest.

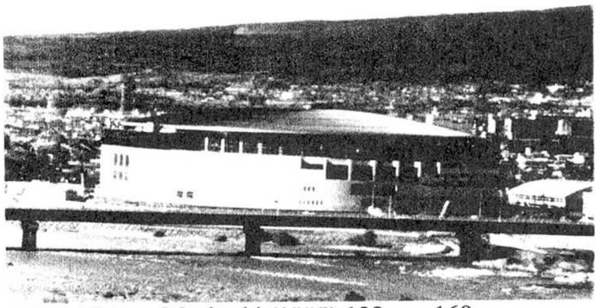


• Station Plaza Roof (Tokyo, 1997) 45m x 60m
Light weight membrane roof with a sense of "Gentle breeze" covers the shops and restaurants.

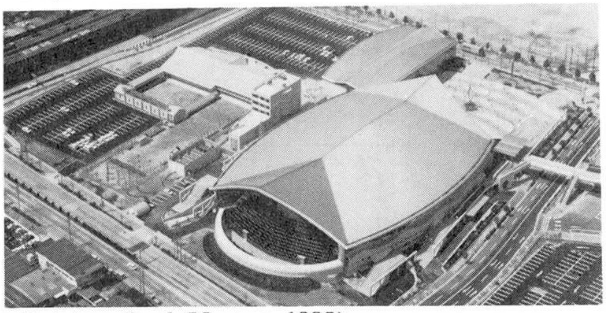


• Sakata Municipal Gymnasium (1991) 53m x 68m
A pair of "Water bird" are flying up from green field.

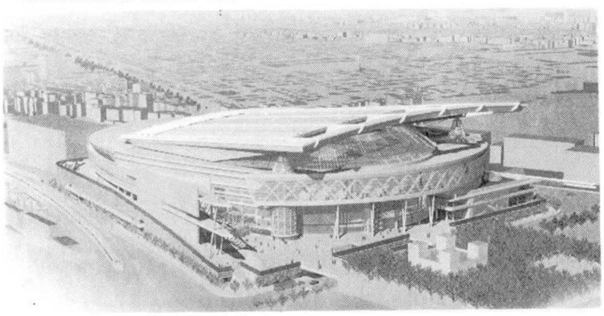
• Urayasu Municipal Sports Center (1995) 52m x 108 m
Large and small "Waves" coming ashore on Tokyo Bay.



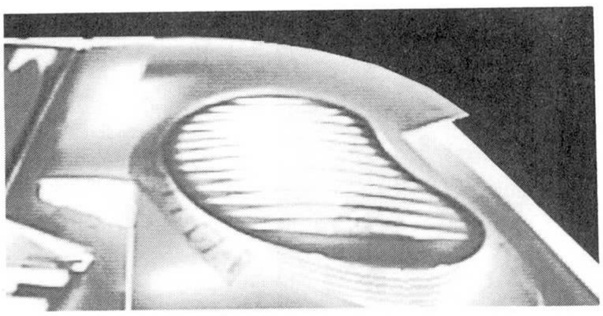
• Green Dome Maebashi (1990) 122m x 168m
"UFO" landing at scenic site surrounded with mountains and river.



• Rainbow Pool (Nagoya, 1992)
"Flying fish" swimming dynamically on the ocean.



• Saitama Arena (2000)
A huge sharp "Sky wing" with a moving internal theater sends a message for the 21st century.

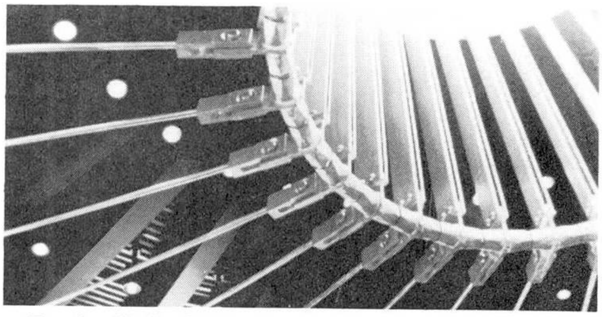


• Kyoto Swimming Pool Project
Organic shape like a "Cocoon" originated from the concept of harmony and utilization of nature.

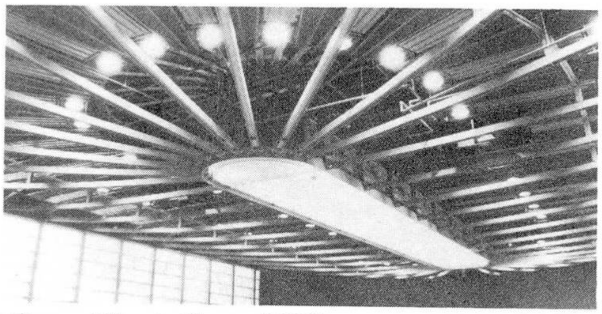
Fig.12 Various image for external feature

[2] Structural Expression of Inside Space

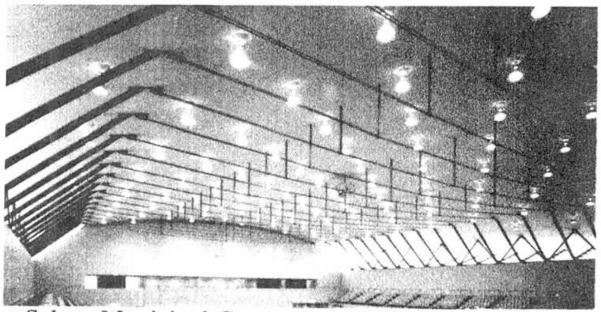
The delicate and sharp sense of strings can create various individual expressions in combination with thick beams. As an interior feature, four types of structural expressions can be considered by either eliminating or emphasizing each beam or string (Fig.13).



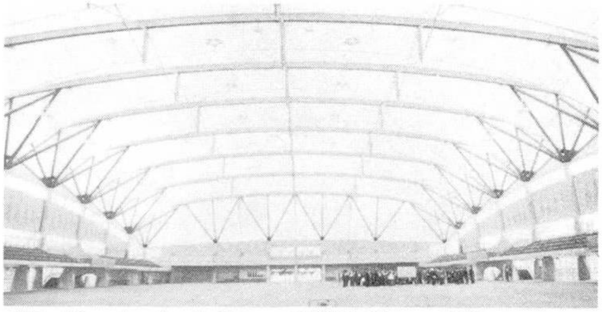
• Faraday Hall of Nihon Univ. (1978) 20m in diameter
Radial rods and central ring in a golden color are expressed strongly.



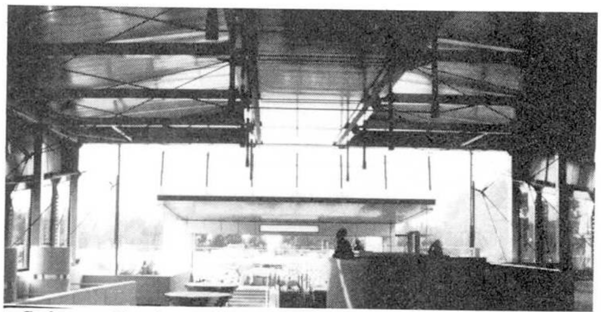
• Koganei Sports Center (1988)
Curved H-shaped steel strings reflect the light from a glass facade.



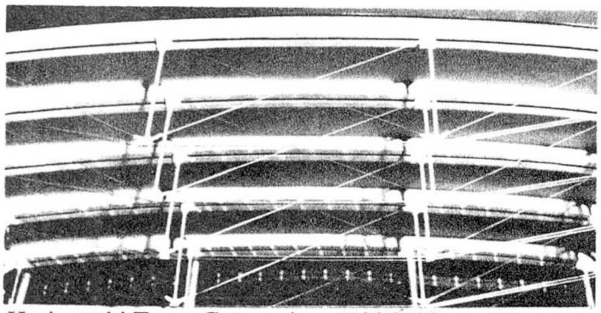
• Sakata Municipal Gymnasium (1991) 53m x 68m
Cables and struts colored with Turkish blue float in the natural light from deep eaves.



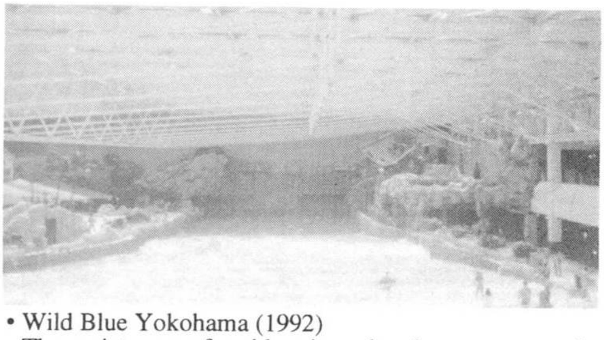
• Kita-Kyushu Anoh Dome (1991) 62m x 108m
Hybrid members of H steel and laminated timber give the impression of being in a forest.



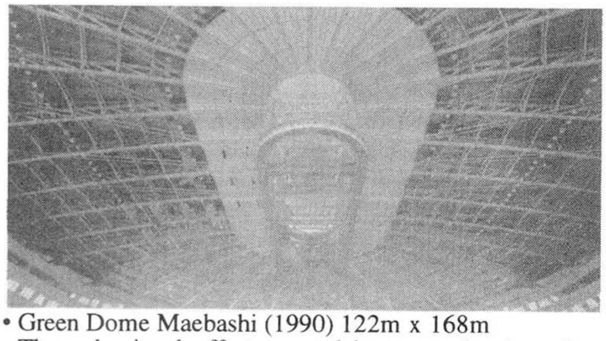
• Subway Station of Nihon Univ. (1996) 20m x 40m
Two kind of strings with different role are colored with Japanese traditional red and produce dome-like space.



• Horinouchi Town Gymnasium (1996) 38m x 42m
The row of curved beams composed of laminated timber produces a human space during winter.



• Wild Blue Yokohama (1992)
The existence of cables is reduced to express the transparency of the resort space.

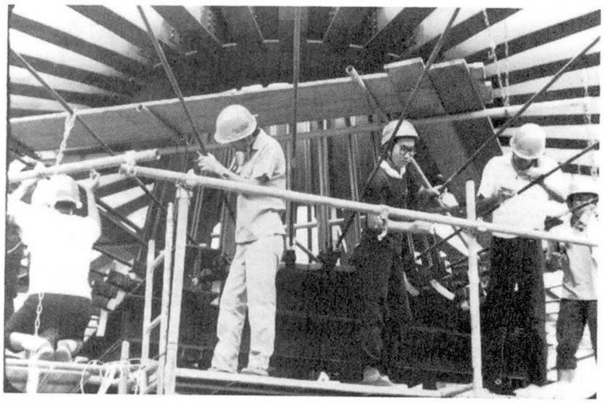


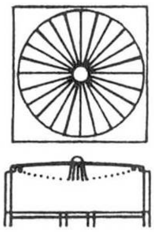
• Green Dome Maebashi (1990) 122m x 168m
Through visual effect, curved beams and sub arches produce a dramatic interior of a shallow dome.

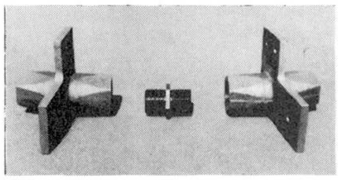
Fig.13 Example of structural expression for interior view

3.4 Structural Technology of BSS

The method of introducing PS into strings in order to realize structural systems greatly depends upon construction and details, and have to be considered as a whole. Actual examples of Fig.14 and Fig.15 can be seen in Fig.7.

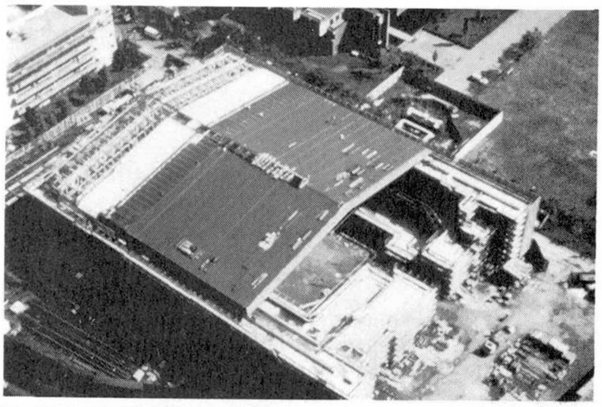


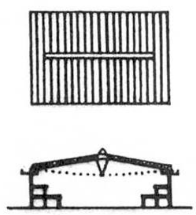


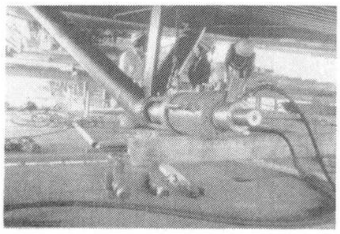


cast steel elements of central tension ring

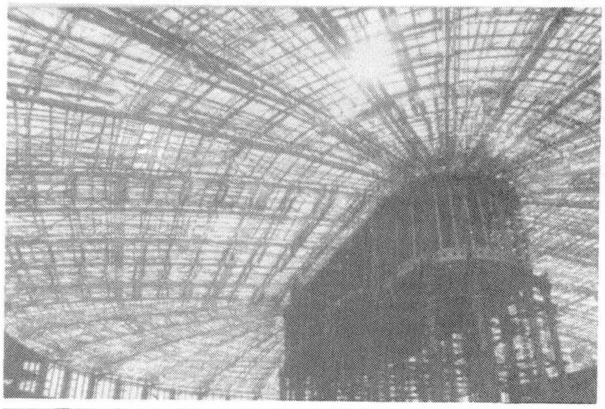
- Faraday Hall of Nihon Univ. (described above)
  After prestressing to some extent, by bolting the nuts at the rod end, the central ring was jacked down to get the final tensile force due to the dead-load.

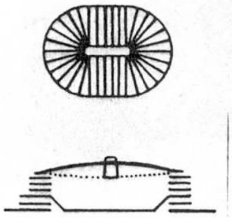


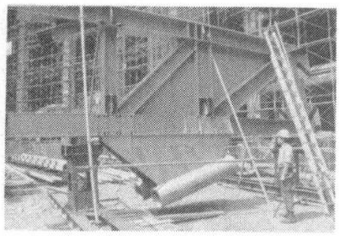




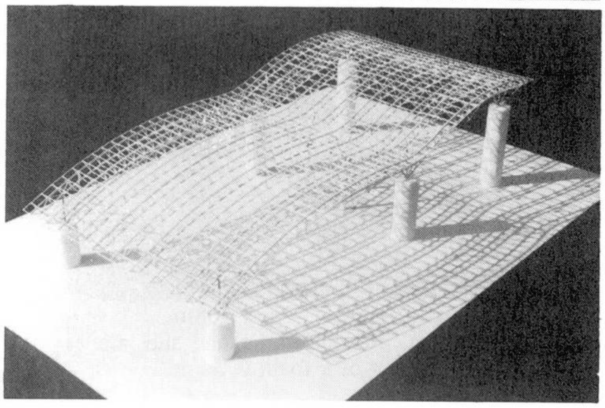
- Sports Hall of Nihon Univ. (described above)
  By the introduction of a design force due to the final weight, each truss beam was lifted up from the support. The whole roof (1000tf) was slid up gradually by two small jacks on either side.

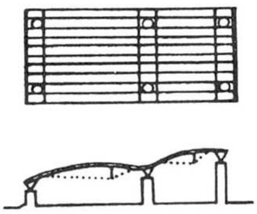


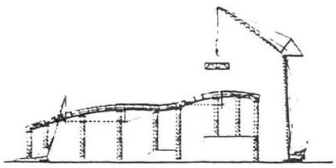




- Green Dome Maebashi (described above)
  For each truss girder assembled on the central support, prestressing force was introduced by 68 oil jacks under the central ring to lift up the whole roof (3000tf).

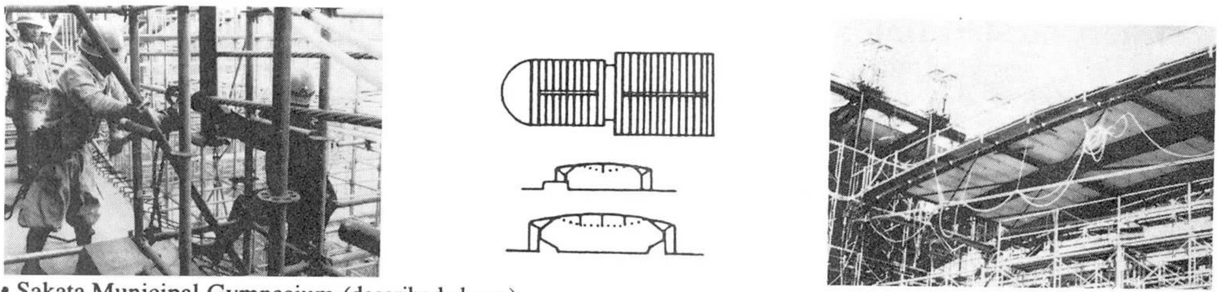




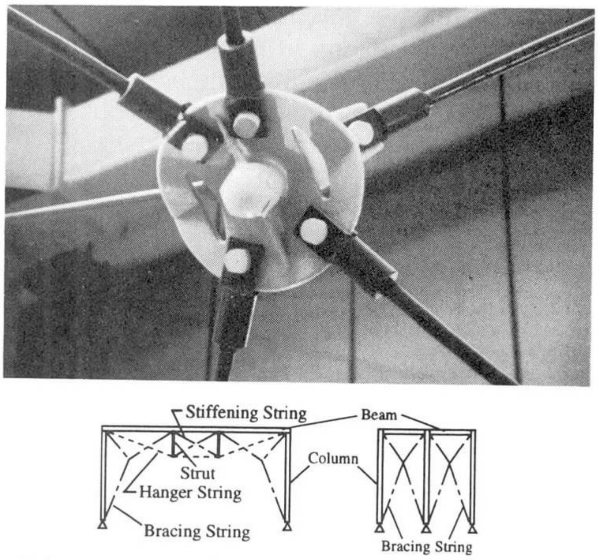


- Urayasu Municipal Sports Center (described above)
  After assembly of the whole trussed beam has been completed, the cables of the BSS were tightened gradually, and the supports were removed one by one.

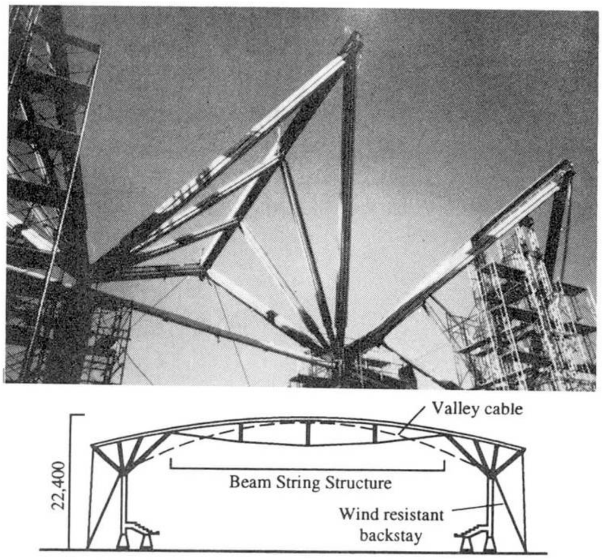
Fig.14 The example of prestressing and construction method (1)



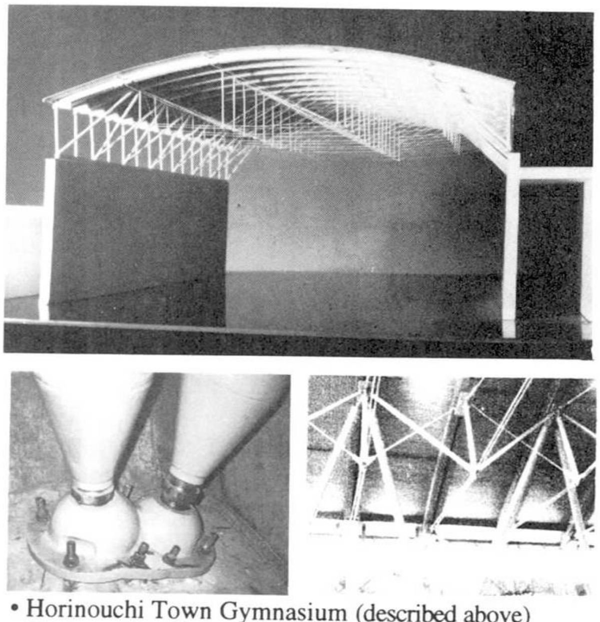
• Sakata Municipal Gymnasium (described above)
The prestressing of cables was executed by hauling down and attaching the end of struts on the ground. A set of three pieces of BSS loaded with final finishes was pulled up by temporary ropes from the top of the cantilever truss



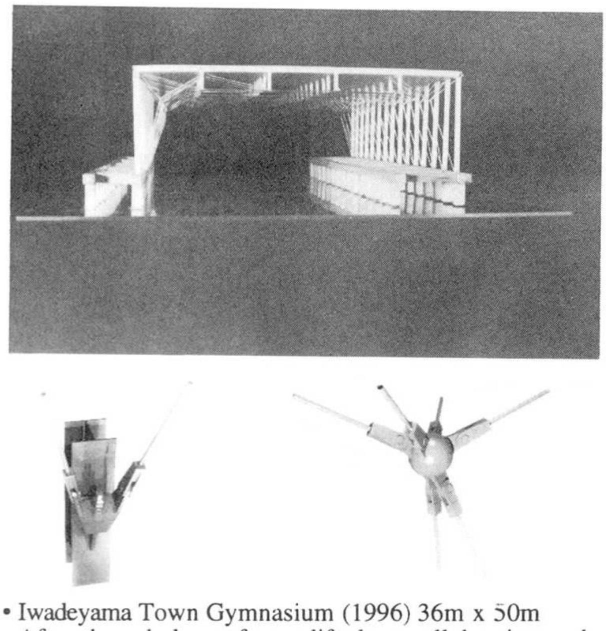
• Subway Station of Nihon Univ. (described above)
By using small jacks, two pieces of plate of "Face Joint" was hauled together to introduced the prestressing force of six bracing rods.



• Kita-Kyusyu Anoh Dome (described above)
Before installing of BSS adjusted for length and force, pre-loading was carried out by pulling down the top of cantilever truss to obtain strict accuracy for welding of beams.



• Horinouchi Town Gymnasium (described above)
Compression force of the diagonal column due to the finishing load was released by turning a screw bolt at the lower end, then the dead-load was resisted only by the BSS.



• Iwadeyama Town Gymnasium (1996) 36m x 50m
After the whole roof was lifted up, all bracing rods were installed and end connectors were pulled down to introduce prestressing force.

Fig.15 The examples of prestressing and construction method (2)

4. Tension Grid Dome

Beyond the works of B. Fuller and F. Otto, Dr. J. Schlaich has exploited the innovative "Grid Shell" which is consists of equal length slats and continuous diagonal cables. Compared with the usual trussed dome with a regular mathematical shape, Grid Dome has the remarkable advantage of not only to reducing the cost of fabrication and construction, but also achieves a high visual expression of lightness and transparency.

Inspired by such accomplished developments such as Neckerslum swimming pool (1989), Museum of the History of Hamburg (1990) and Mineral Spa at Stuttgart Bad Cannstatt, the authors proposed a Sports Arena Project which has huge Grid Dome where the organic form is generated by an equal tension membrane technique (Fig.16).

As a variation of Grid Shell,the authors tried to build small Temporary Space in the campus of Nihon Univ. with the collaboration of students (Fig.17). By the installation of struts supported four rods into each grid, a tensegric system can be formed. Furthermore by connecting both ends of the strut by prestressed continuous cable cords, the whole grid can be stiffened against applied snow and wind loads (Fig18). This principle has been demonstrated and tested in the vault models of Fig.19 and Fig.20. The authors would like to name these types of Grid Domes, "Tension Grid Dome (T.G.D)".

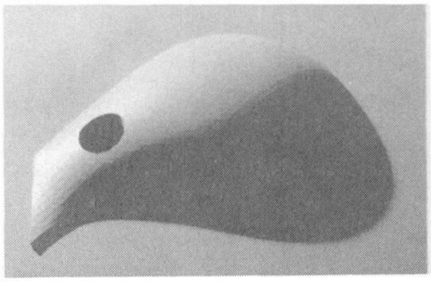
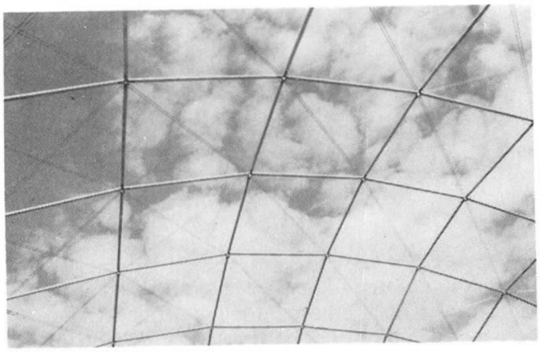


Fig.16 Organic form for Sports Arena Project (1996)



• *Aluminium plate*

• *System truss with screw bolts joint*

Fig.17 EP dome with four columns (1997)

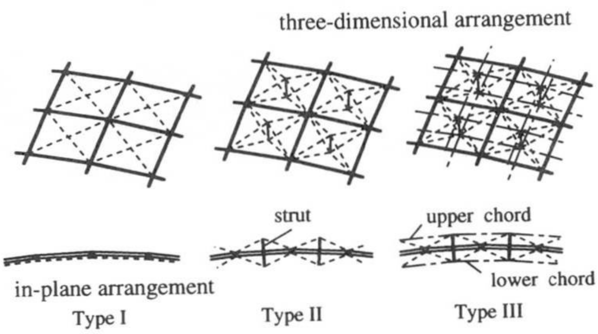


Fig.18 Three types of Tension Grid Dome

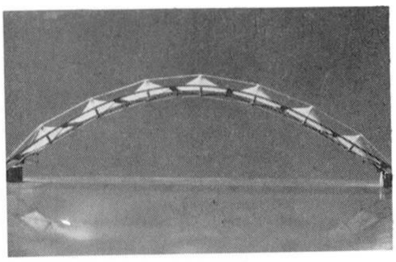


Fig.19 The earliest model having membrane surface and upper string (1985)

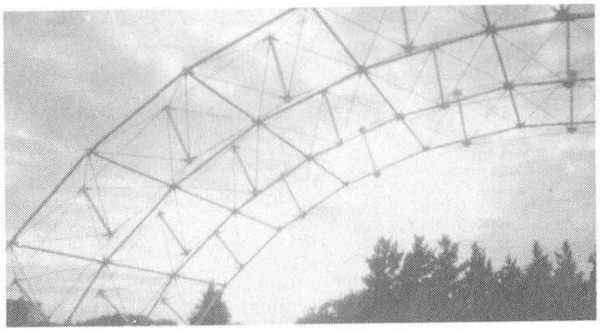


Fig.20 Tensegric arch stiffened with upper and lower chord cables (1997)

5. Tension Grid Facade

With the increasing of requirement for atrium and public space in architecture, various glass facades have been developed. The sense of transparency is pursued not only for glass material itself but also for its supporting system. Compared with the cable truss system in Peter Rice's glass facade at La Villete in Paris, the cable grid system for the atrium of the Kempinski Hotel at Munich (1994) was even bolder.

The genesis of this innovative glass glazing system can be found in the ice-skating rink at Munich by Schlaich. Considering the rather strict wind force conditions in Japan, the author has applied this principle with similar success to the facade of Nihon Univ. building in 1995 (Fig.21).

By using a clamp which is able to grasp four glass panels at their corners, a Tensegric Truss Facade has been studied (Fig.23). In this system the outer and inner string are pre-tensioned to a smaller degree than in the cable net system, and small diagonal plates were installed.

As the plate clamping system was originated from the idea of saving energy and minimizing material from constructional and aesthetical view points, this system was named as MJG (Minimum Joint Glazing) system. Fig.24 and Fig.25 show another development applying MJG for glass facades and glass roofs with the Tensegric Truss System.

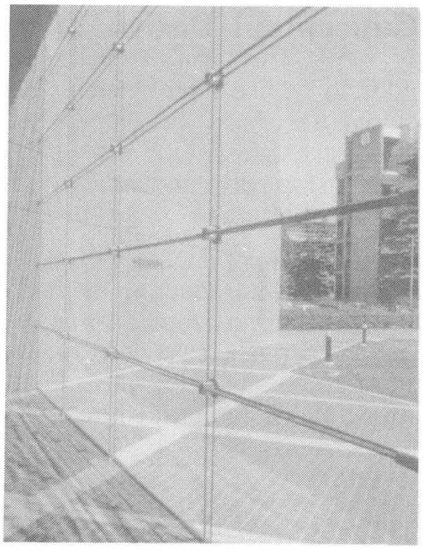


Fig.21 Facade of advanced science material center of Nihon Univ.

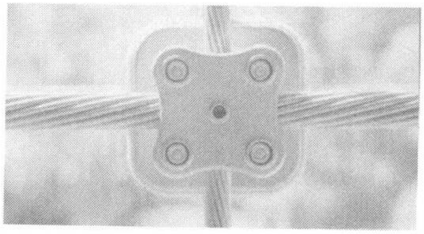
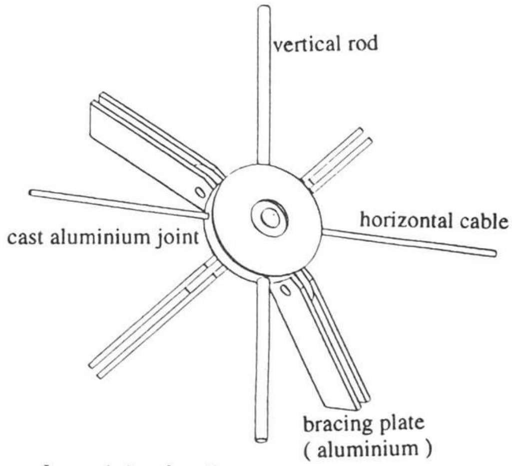


Fig.22 Detail of MJG



• *Inner joint detail*

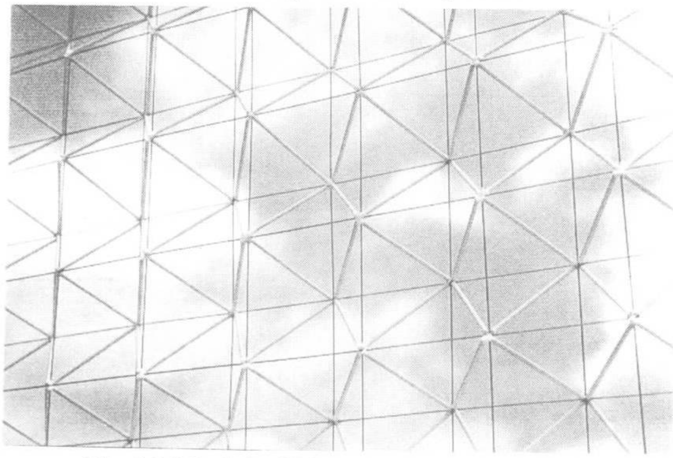


Fig.23 Model of Tensegric Truss Facade

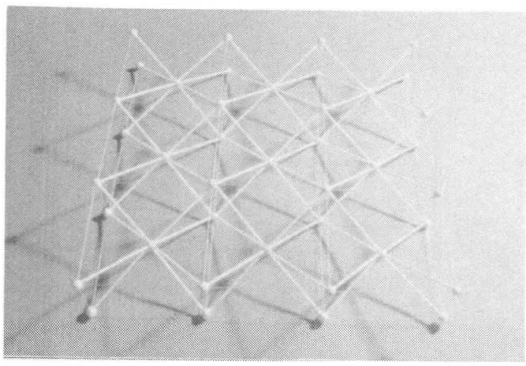


Fig.24 Model of Tensegric Truss unit

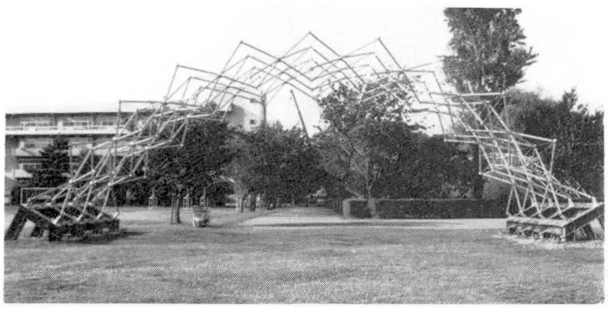


Fig.25 Test building of Tensegric Truss Arch (1997)

6. Conceptual Design of String Structures - Conclusion

In order to realize large span or column-free space, the distinguished characteristics of string structures has been developed recently from the viewpoints of structural efficiency and architectural expression. On the other hand, it should be emphasized that in the string structures the relationship between whole system, detail, fabrication and construction is much more stronger than usual structures.

The role of string, due to various load conditions has to be grasped clearly at the preliminary design, and the introduction method of the initial string force is to be carefully considered. As an example, in Izumo Dome, laminated timber arches were stiffened by diagonal rods and hoop cables, and a pushed-up construction method was adopted. In such Hybrid Tension Structures the most important thing is to keep the conceptual mind over both aesthetics and technology during whole design procedure.

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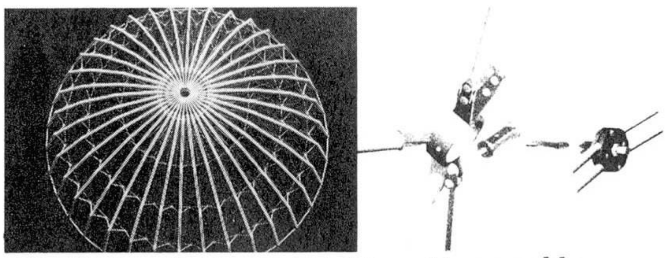
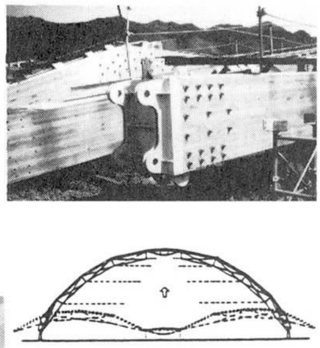


Fig.26 Detail of pre-stretching of hoop cable

Fig.27 Pushing-up system



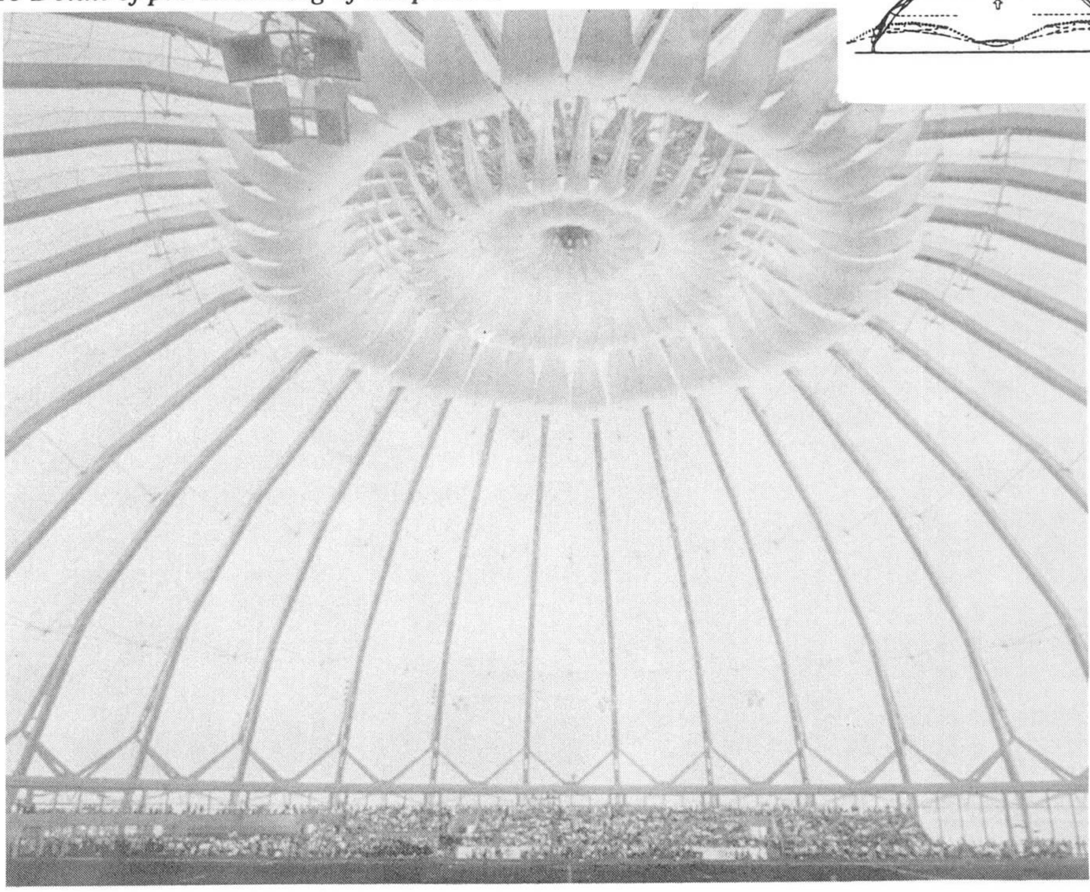


Fig.28 Interior view of IZUMO DOME (1992)

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.**

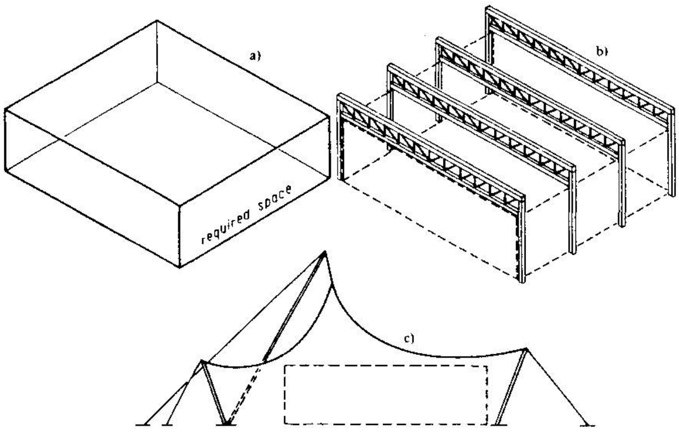

Fig. 1 Long-span roofs' basic classification: Addition of girders and double-curved surface structures.

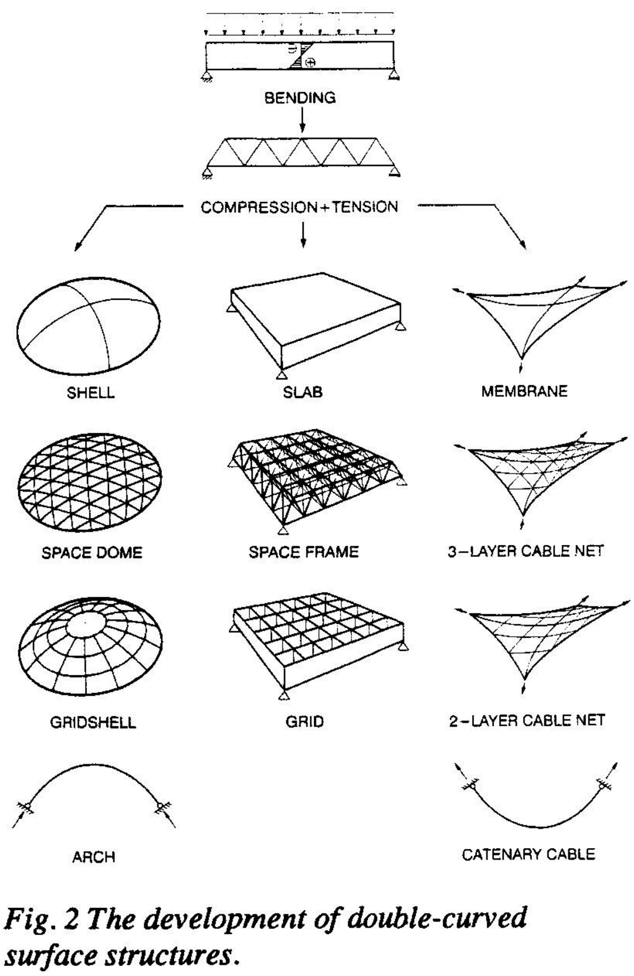

Fig. 2 The development of double-curved surface structures.

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 m^2 or 9 kg/m^2 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].

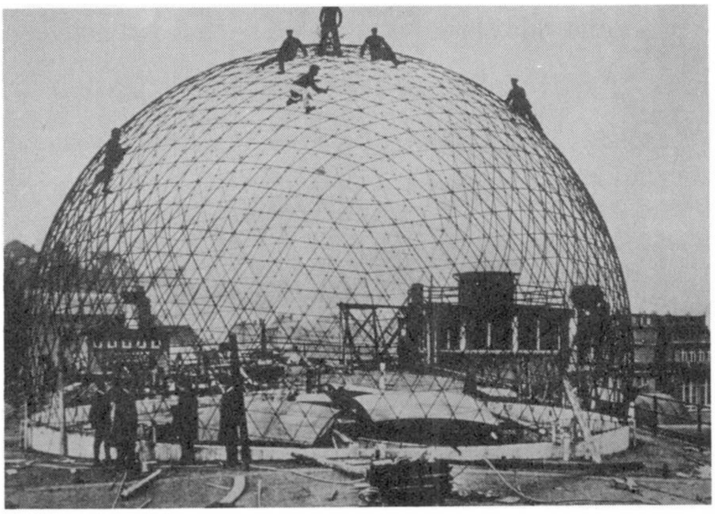

Fig. 3 Bauersfeld's 1922 cable-net dome, 16 m in diameter for an experimental reinforced concrete shell.

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).

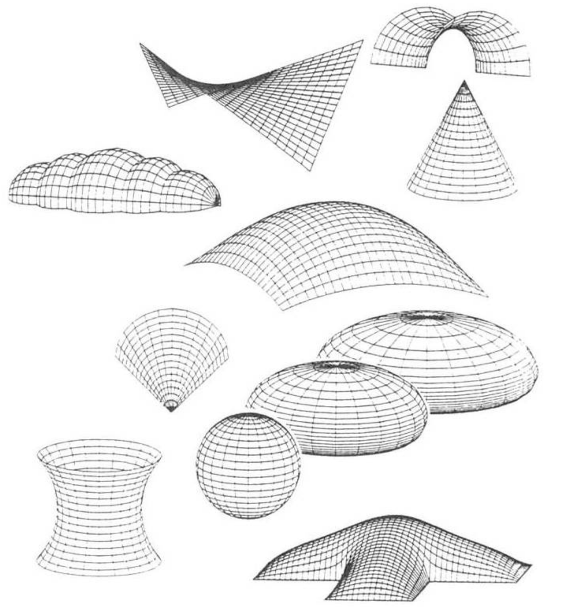

Fig. 4 Suitable shapes of pneumatic formwork for concrete shells [6]

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.

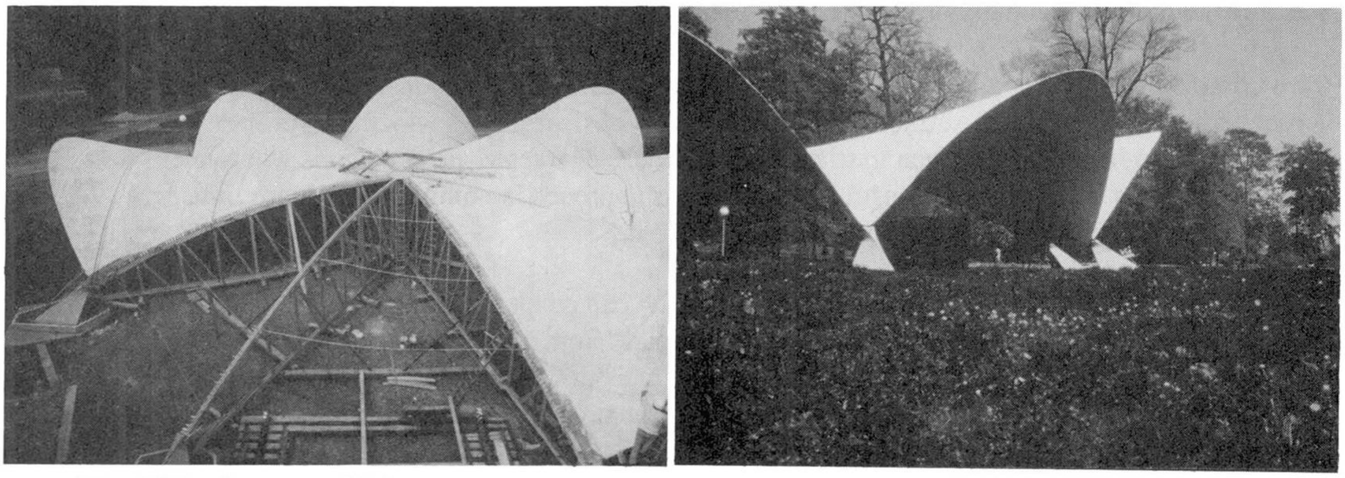

Fig. 5 The Stuttgart CRC-(glass-fiber reinforced concrete-)shell, 1977 during construction and as completed structure.

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).

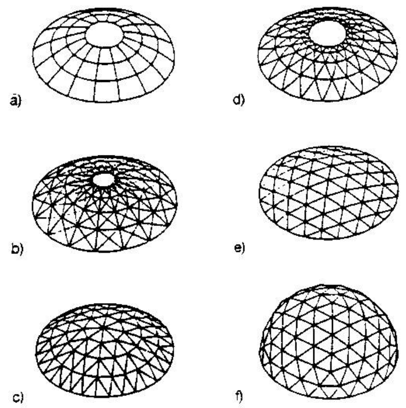

Fig. 6 Various layouts of grid domes
a) frame with quadrangular mesh requiring bending stiffness
b) Schwedler's dome; c), d) grid shells;
e) lamella shell; f) geodesic dome

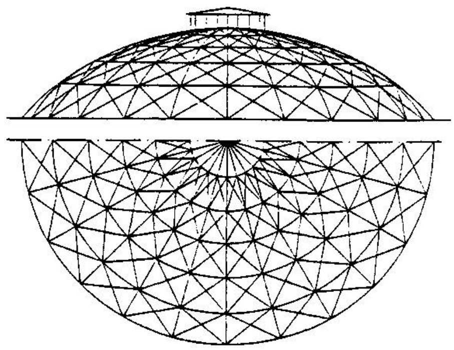

Fig. 7 Schwedler's dome

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].

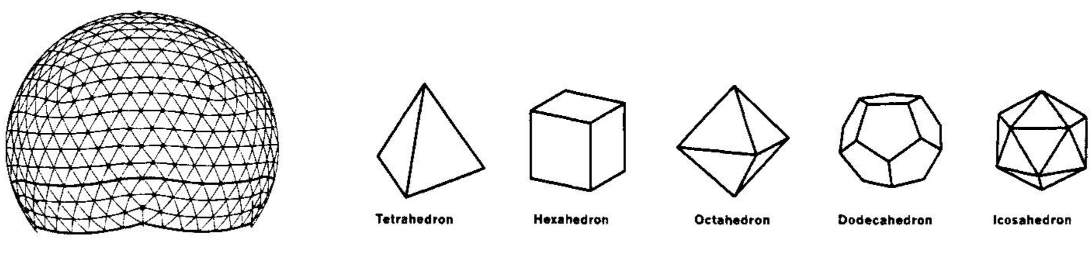

Fig. 8 Geodesic dome, based on the icosaeder-layout for the mesh.

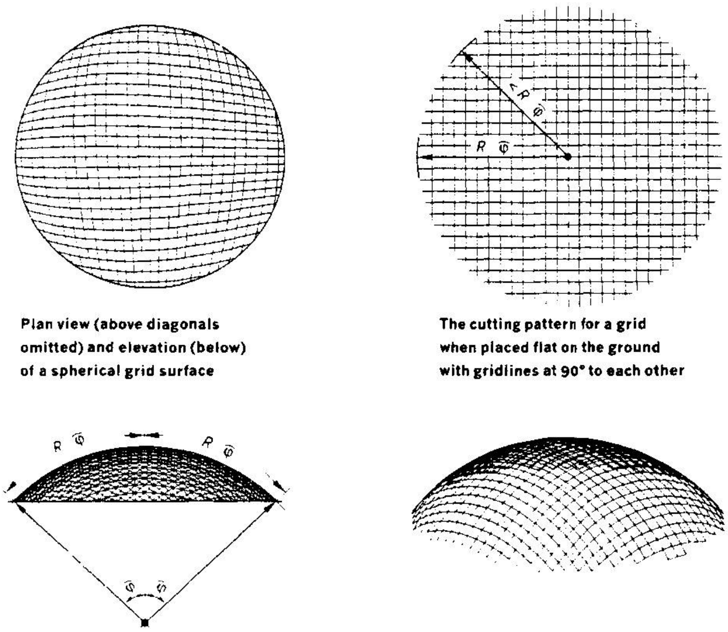

Fig. 9 The grid shell made from a quadrangular grid and diagonal cables.

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].

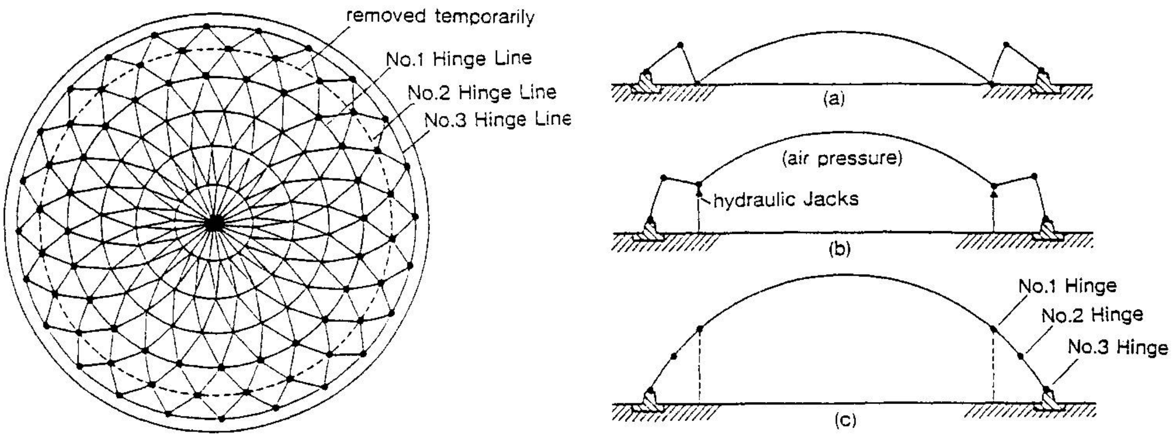

Fig. 10 The principle of the Pantadome system.

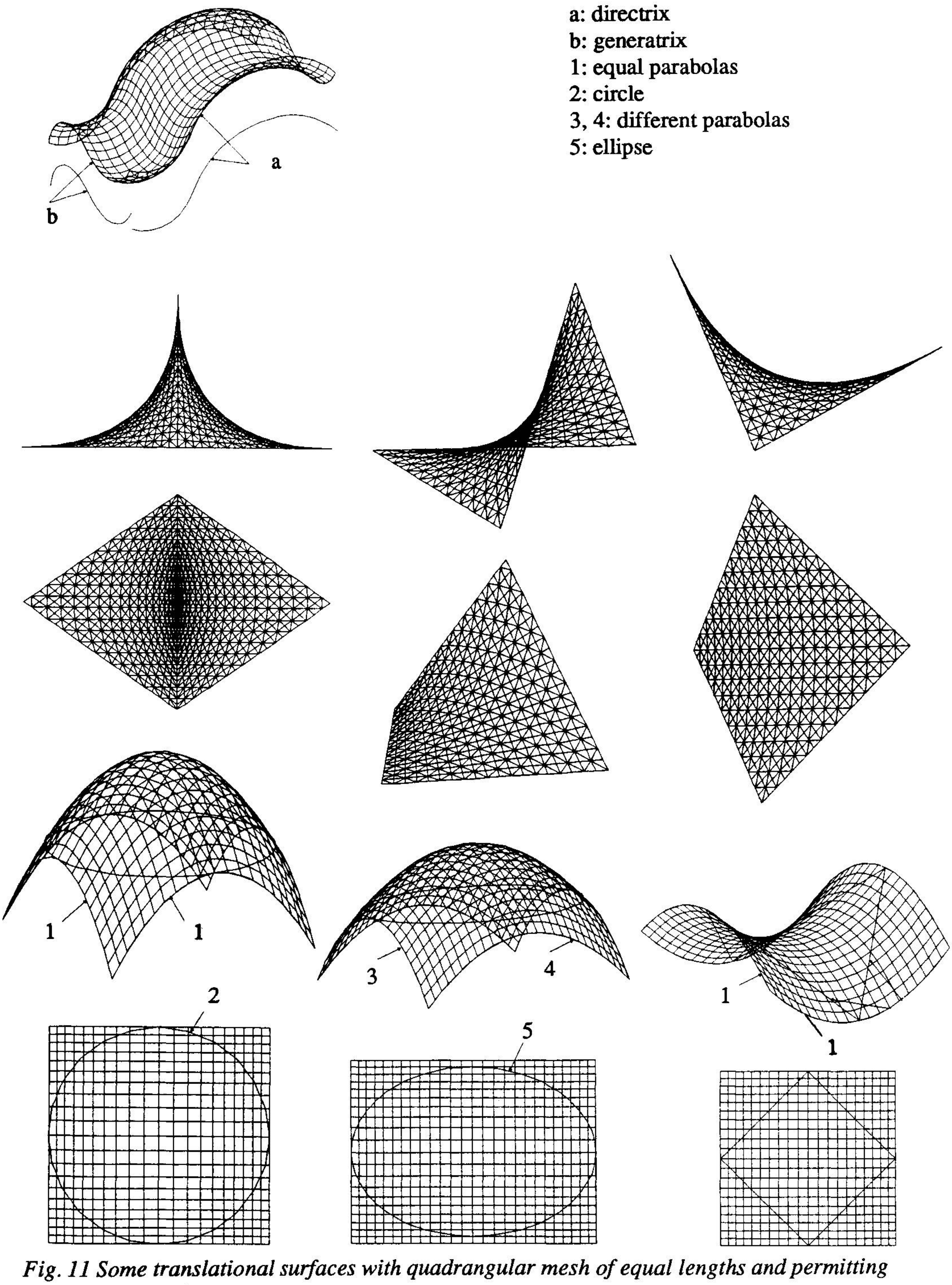

Fig. 11 Some translational surfaces with quadrangular mesh of equal lengths and permitting plane cladding [8].

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].

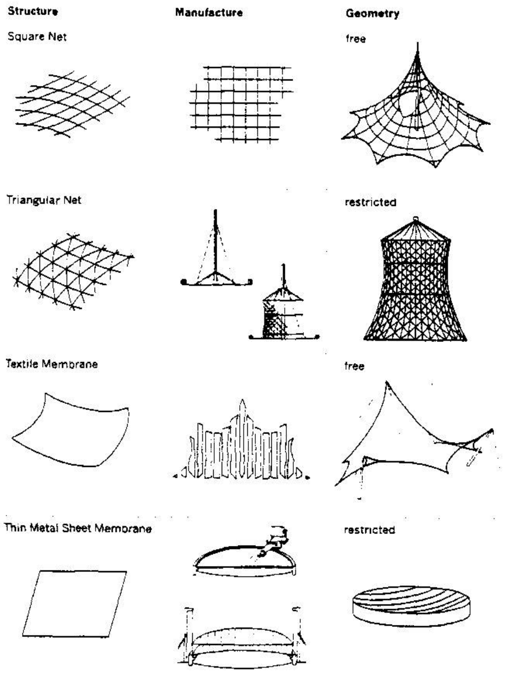

Fig. 12 Manufacturing double-curved light weight surfaces acting in tension.

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

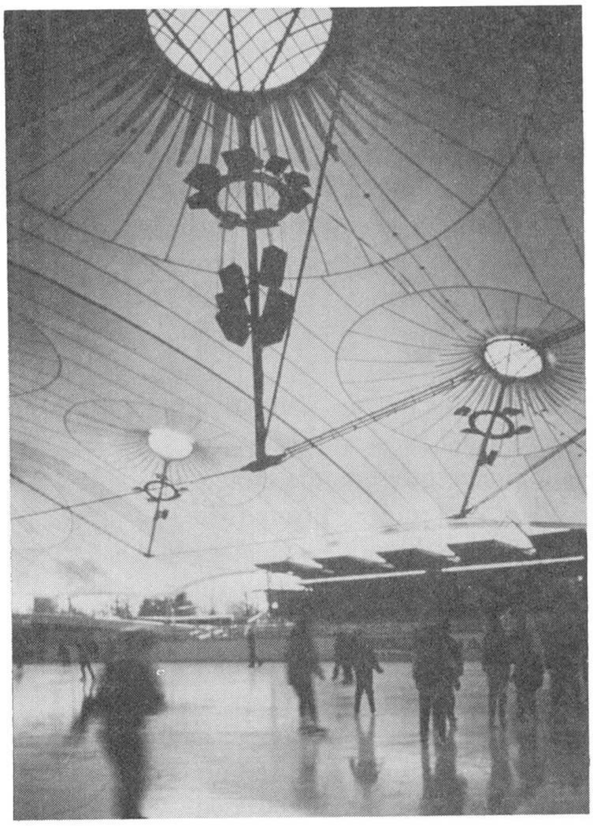

Fig. 13 Ice-skating rink, Hamburg Stellingen.
Covering an area in the form of an ellipse with main axes of 120 and 70 m, the membrane is held up by 4 main masts and 8 cable supported props and tied down at it periphery by 26 short guyed masts. This roof uses the cutting pattern and arrangement of the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

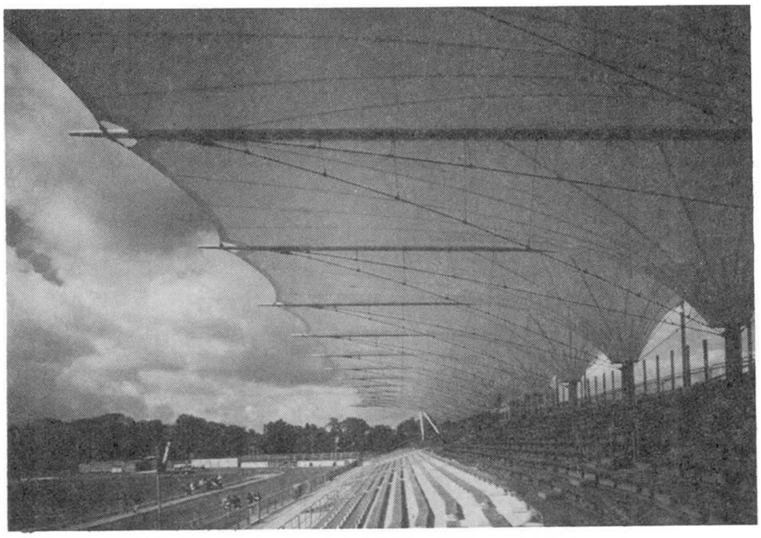

Fig. 14 Roof over a grand stand at Oldenburg.
Covering 5.000 seats, arranged in 21 rows, 130 m long consisting of a steel tube, cable and membrane structure with 14 rectangular or trapezoidal elements, connected at upper horizontal level by their adjacent edges along radial struts and each tensioned 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.

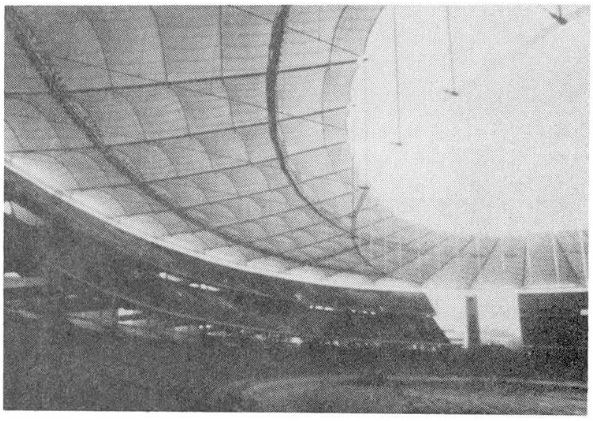

Fig. 15 Lightweight Roof structures for the Outdoor Stadium Kuala Lumpur, Malaysia.
This cable membrane roof covers 100,000 seats and with 38,500 m² roof area has become the largest stadium of the world.

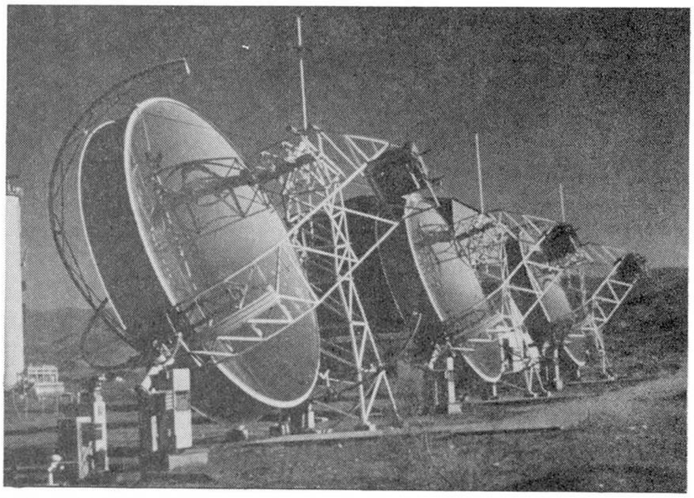

Fig. 16 Metal membrane technology is also useful to build cheap and precise dish concentrators.
They are needed in large numbers for solar power plants. Six prototypes have been operating successfully in Almeria, Spain for several years.

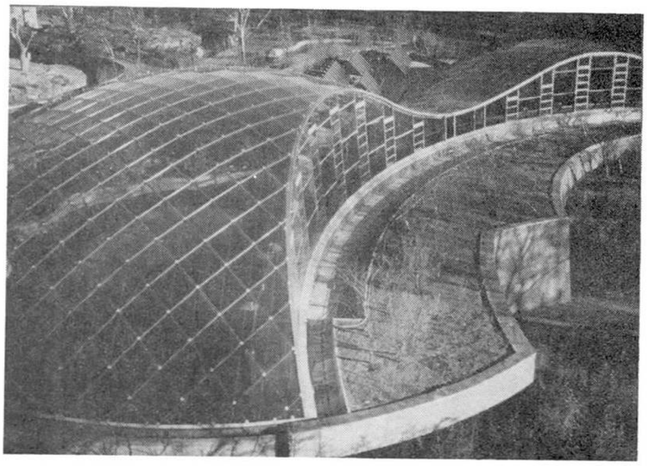

Fig. 17 Glass Roof for the Hippo House at the Berlin Zoo.
Covering two circular pools, one about 21 m in diameter and the other approx. 29 m in diameter.

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