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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:

$$\mathbf{T_o = T_e + T_p} : \text{PS in a broad sense}$$
$$\mathbf{T_1 = T_o + T_a = (T_e + T_p) + T_a}$$

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.

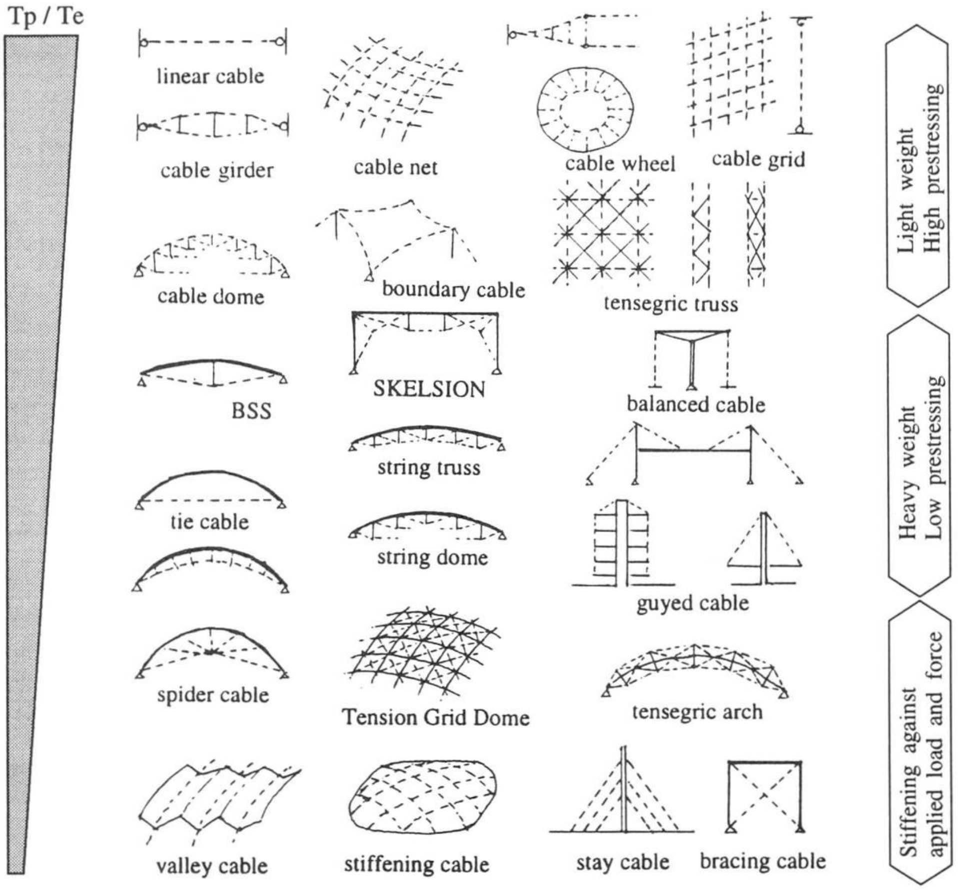
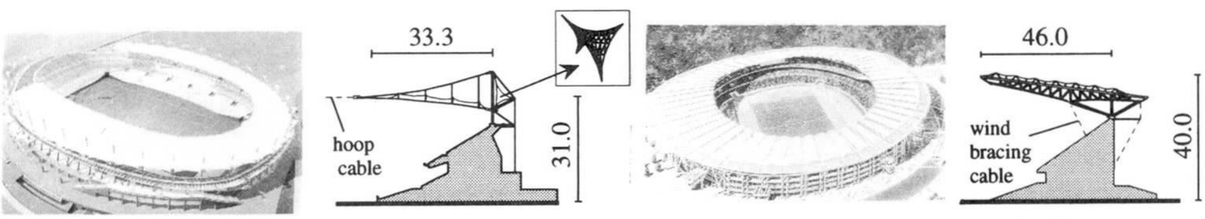


Fig.1 Classification of string structures by tensile force of string



• *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).

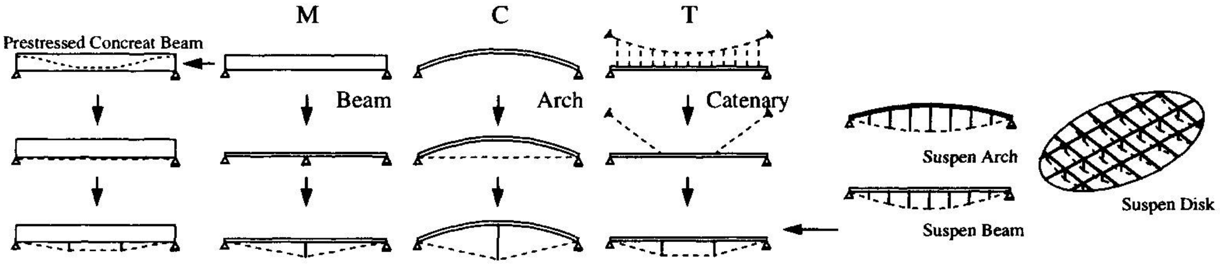
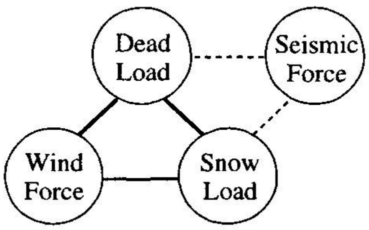


Fig.3 Birth of BSS

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

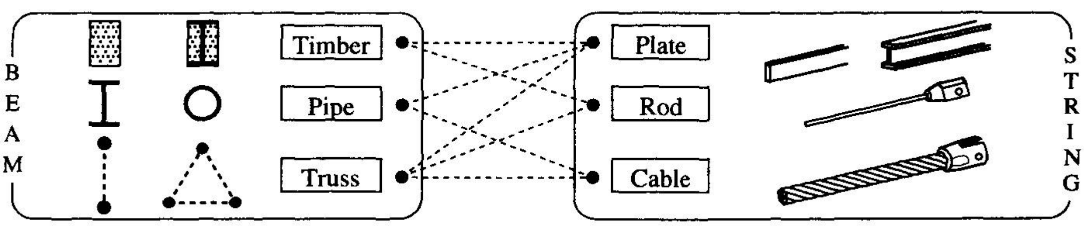
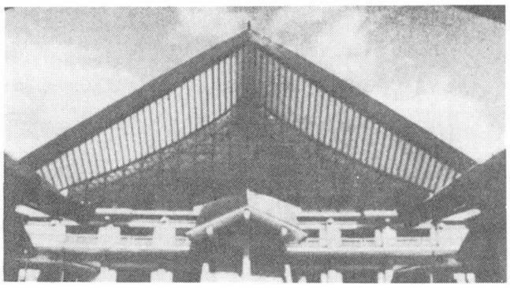
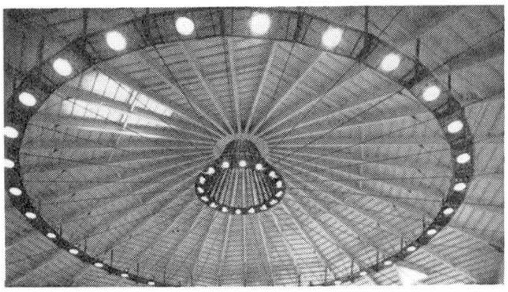


Fig.5 Combination of beam and string



• *Iwate Prefectural Budoh-kan*



• *Monoh Town Gymnasium*

Fig.6 Mount-shaped BSS

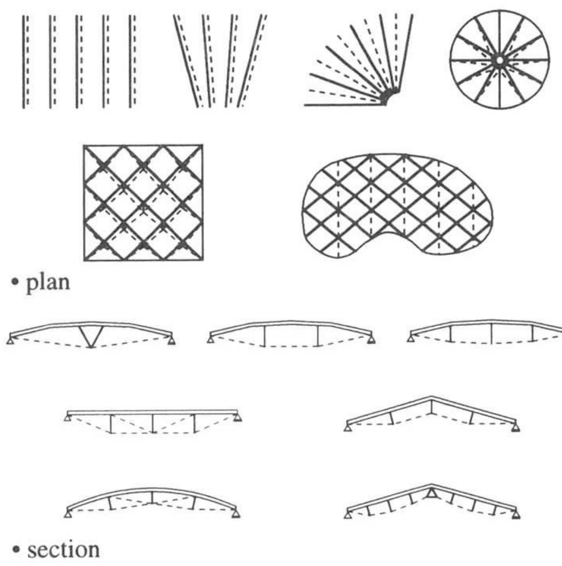


Fig.7 Variation of arrangement of string

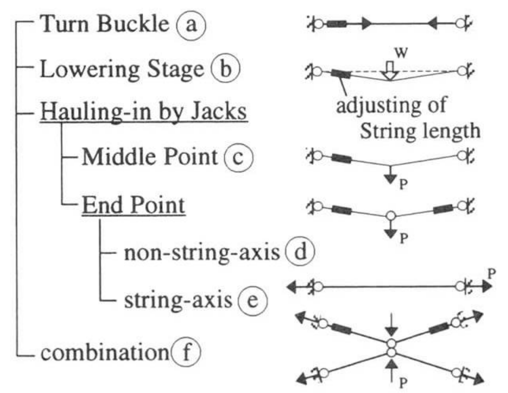


Fig.8 Method for introduction tensile force to string

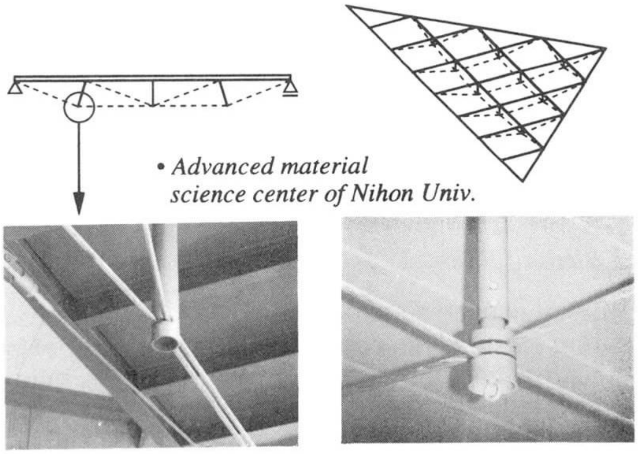


Fig.9 Hauling-in by pulling-down by small force

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.

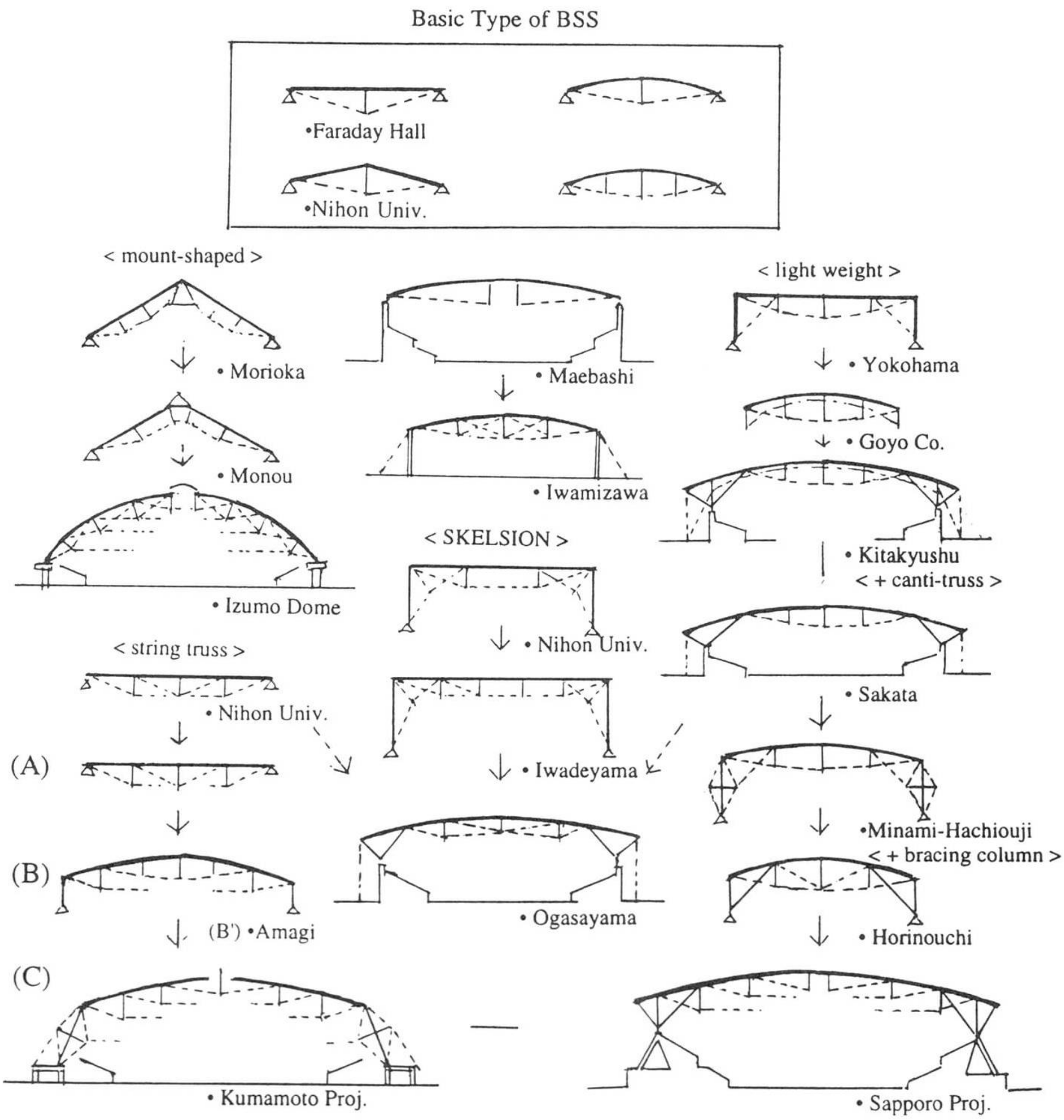
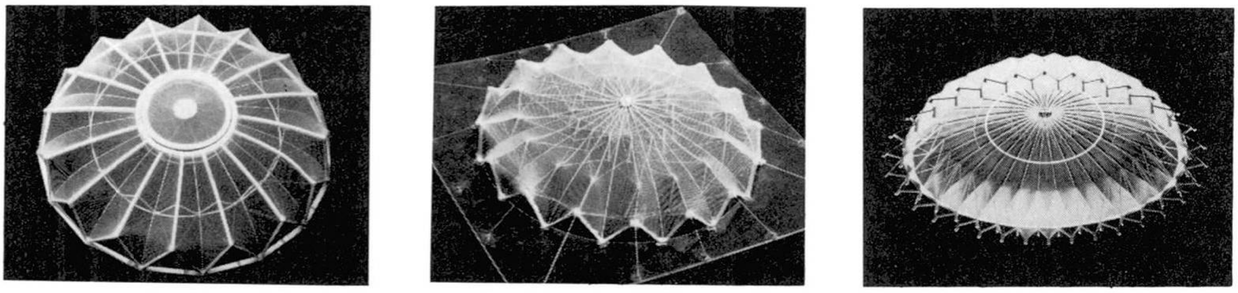


Fig.10 Various application from basic type of BSS

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.



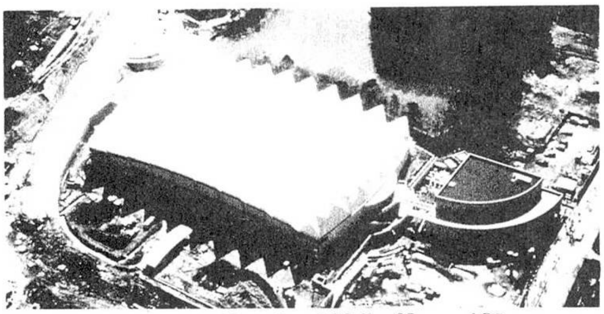
(B) (B') (C)

Fig.11 Development of BSS

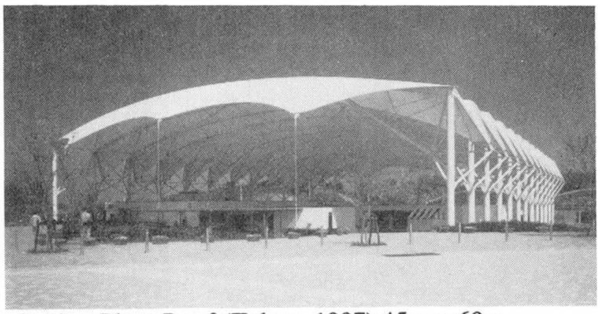
3.3 Diversity of Architectural Expression in BSS

[1] Image of external appearance

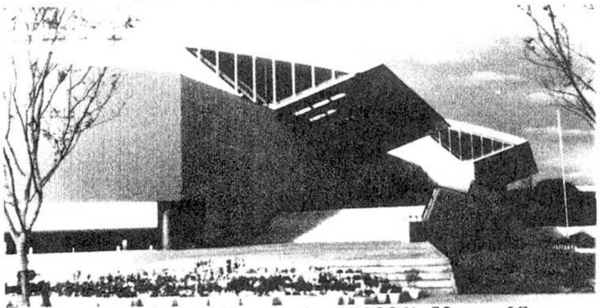
In general, the dead-load is predominant in long-span structures. Self balancing systems with strings and beams can let the boundary structure be free from horizontal reaction, allowing for light and free exterior design creating a variety of images (Fig.12).



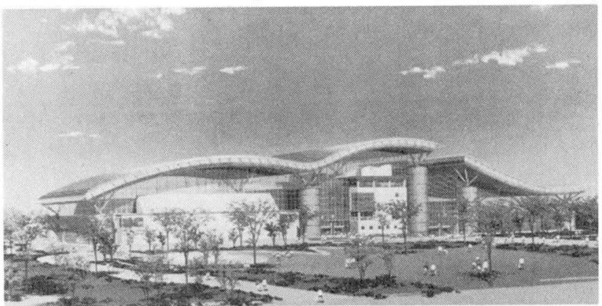
• Anoh Dome (Kita-Kyushu, 1994) 62m x 108m
"Paraglider" flying from the summit of a nearby mountain, just landed on a green forest.



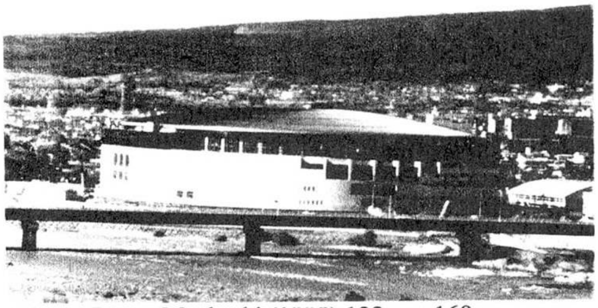
• Station Plaza Roof (Tokyo, 1997) 45m x 60m
Light weight membrane roof with a sense of "Gentle breeze" covers the shops and restaurants.



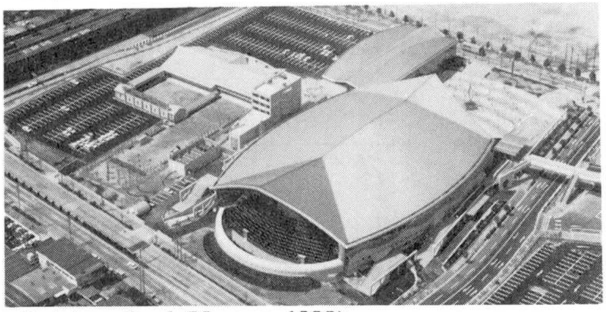
• Sakata Municipal Gymnasium (1991) 53m x 68m
A pair of "Water bird" are flying up from green field.



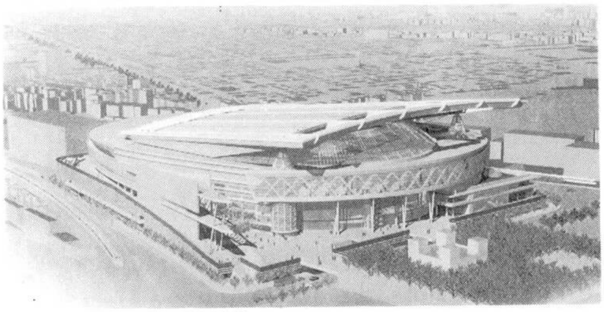
• Urayasu Municipal Sports Center (1995) 52m x 108 m
Large and small "Waves" coming ashore on Tokyo Bay.



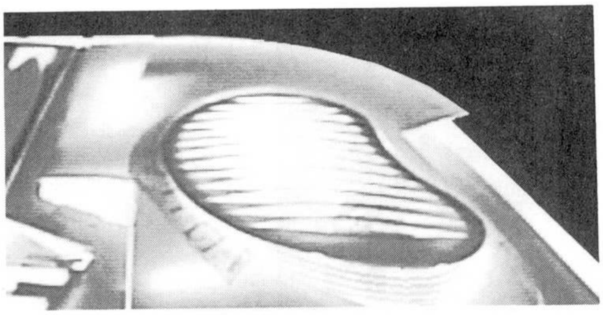
• Green Dome Maebashi (1990) 122m x 168m
"UFO" landing at scenic site surrounded with mountains and river.



• 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.

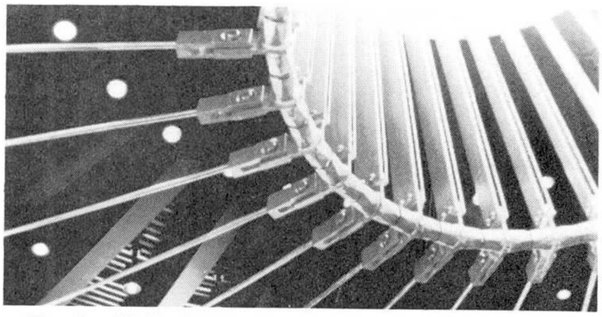


• Kyoto Swimming Pool Project
Organic shape like a "Cocoon" originated from the concept of harmony and utilization of nature.

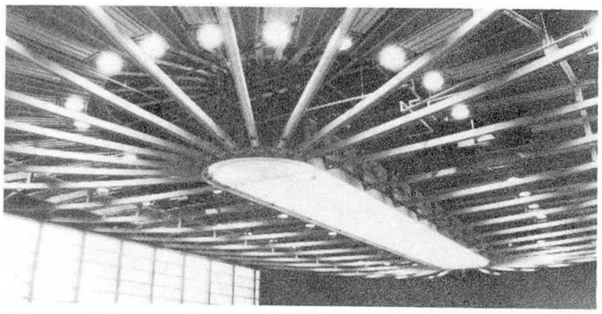
Fig.12 Various image for external feature

[2] Structural Expression of Inside Space

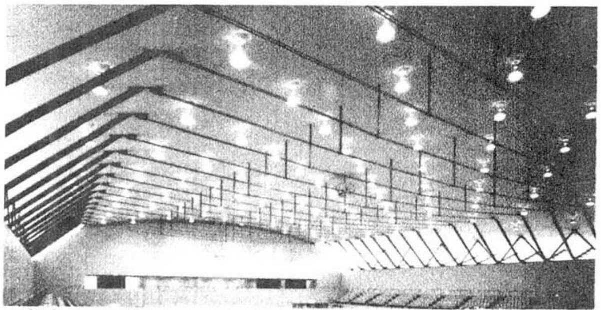
The delicate and sharp sense of strings can create various individual expressions in combination with thick beams. As an interior feature, four types of structural expressions can be considered by either eliminating or emphasizing each beam or string (Fig.13).



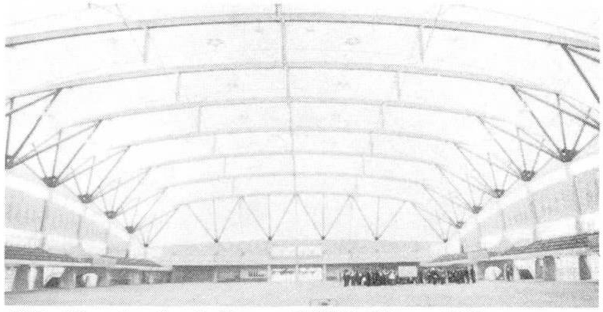
• Faraday Hall of Nihon Univ. (1978) 20m in diameter
Radial rods and central ring in a golden color are expressed strongly.



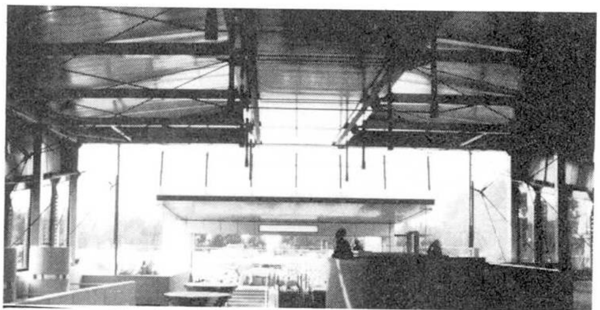
• Koganei Sports Center (1988)
Curved H-shaped steel strings reflect the light from a glass facade.



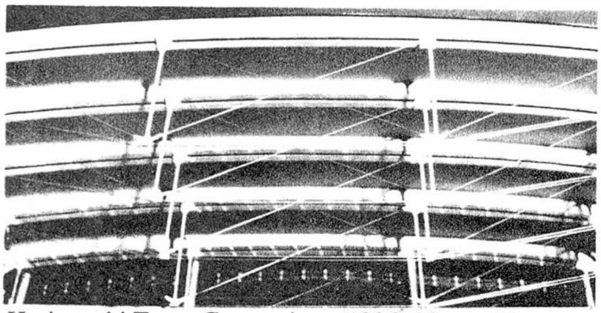
• Sakata Municipal Gymnasium (1991) 53m x 68m
Cables and struts colored with Turkish blue float in the natural light from deep eaves.



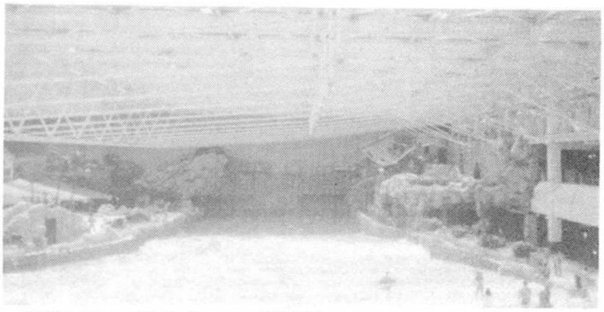
• Kita-Kyushu Anoh Dome (1991) 62m x 108m
Hybrid members of H steel and laminated timber give the impression of being in a forest.



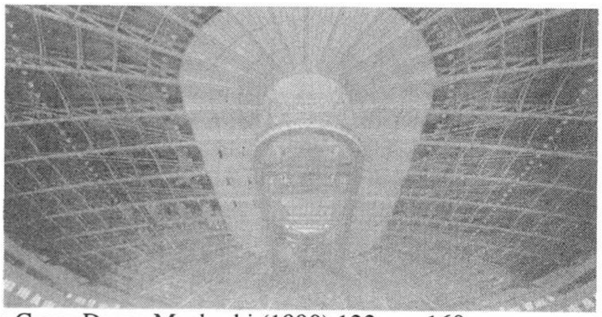
• Subway Station of Nihon Univ. (1996) 20m x 40m
Two kind of strings with different role are colored with Japanese traditional red and produce dome-like space.



• 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.

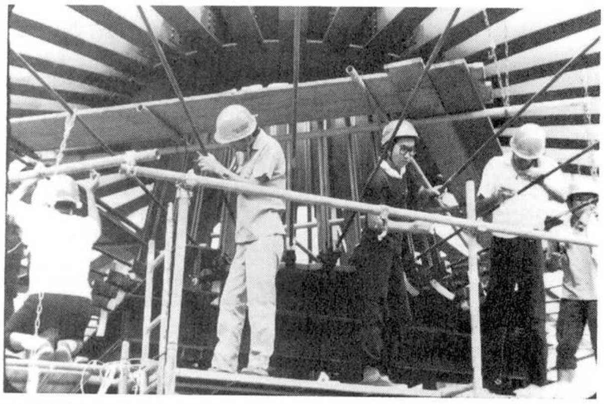


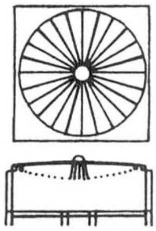
• Green Dome Maebashi (1990) 122m x 168m
Through visual effect, curved beams and sub arches produce a dramatic interior of a shallow dome.

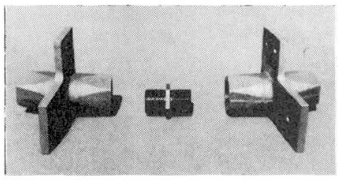
Fig.13 Example of structural expression for interior view

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.

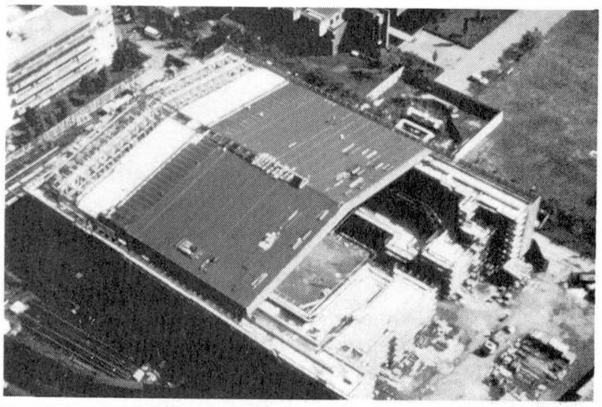


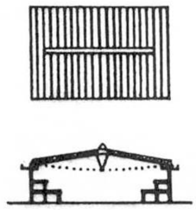


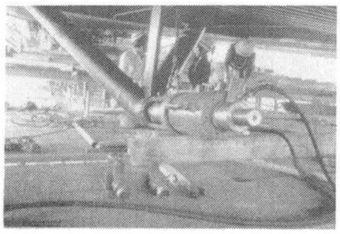


cast steel elements of central tension ring

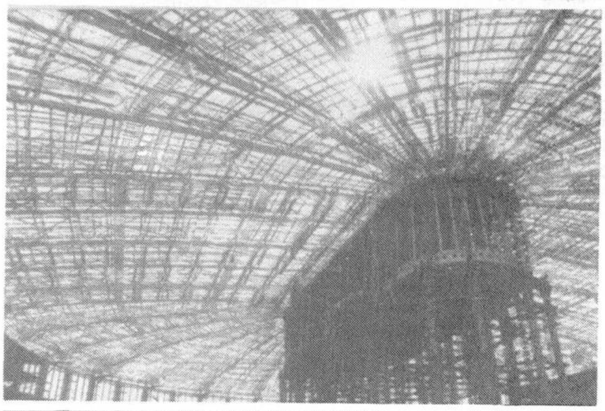
• Faraday Hall of Nihon Univ. (described above)
After prestressing to some extent, by bolting the nuts at the rod end, the central ring was jacked down to get the final tensile force due to the dead-load.

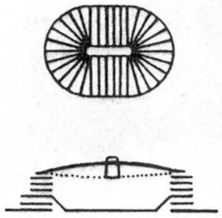


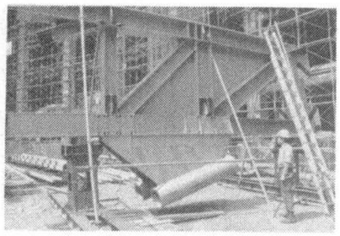




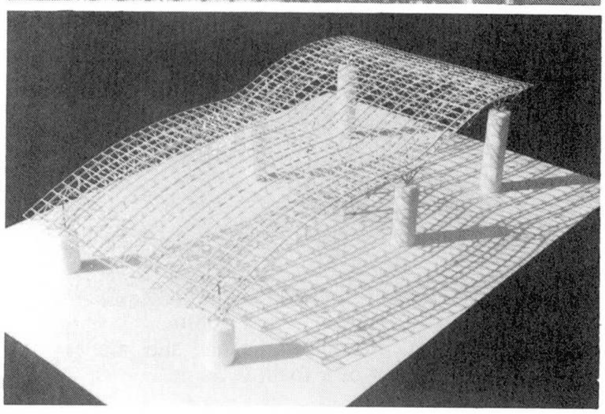
• Sports Hall of Nihon Univ. (described above)
By the introduction of a design force due to the final weight, each truss beam was lifted up from the support. The whole roof (1000tf) was slid up gradually by two small jacks on either side.

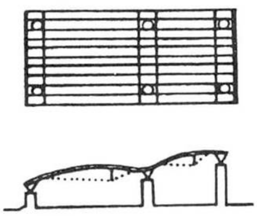


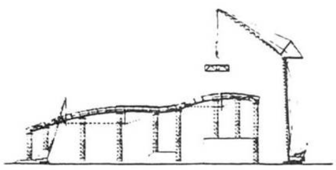




• Green Dome Maebashi (described above)
For each truss girder assembled on the central support, prestressing force was introduced by 68 oil jacks under the central ring to lift up the whole roof (3000tf).

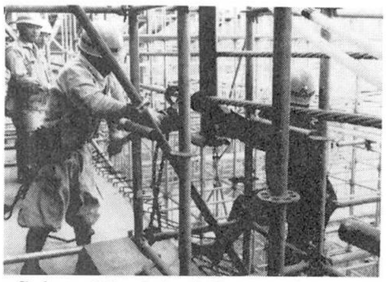


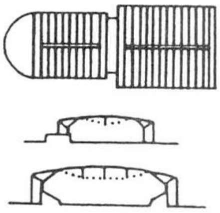


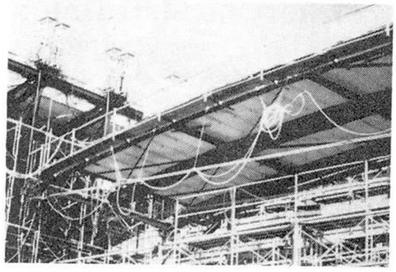


• Urayasu Municipal Sports Center (described above)
After assembly of the whole trussed beam has been completed, the cables of the BSS were tightened gradually, and the supports were removed one by one.

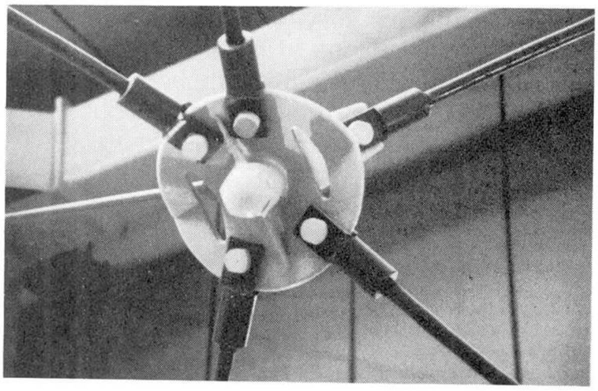
Fig.14 The example of prestressing and construction method (1)

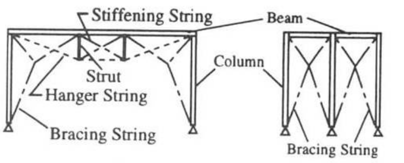




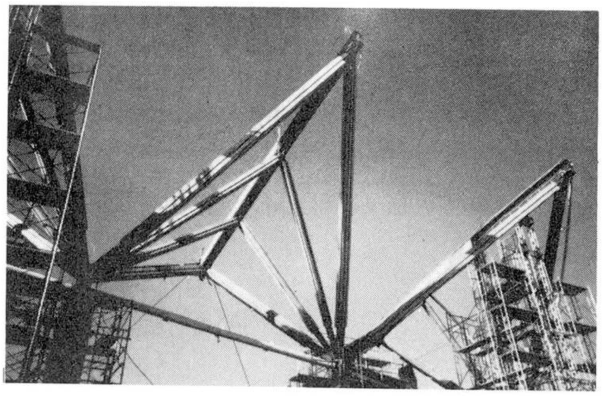


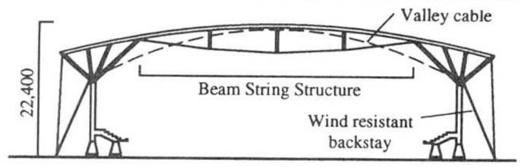
• Sakata Municipal Gymnasium (described above)
The prestressing of cables was executed by hauling down and attaching the end of struts on the ground. A set of three pieces of BSS loaded with final finishes was pulled up by temporary ropes from the top of the cantilever truss



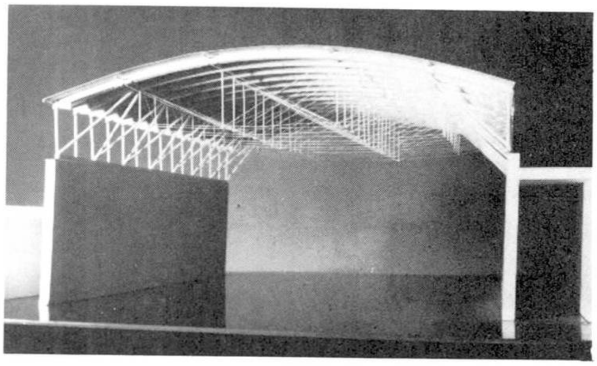


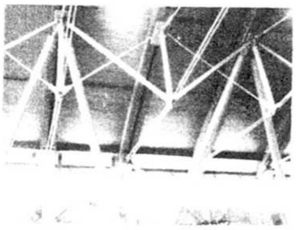
• Subway Station of Nihon Univ. (described above)
By using small jacks, two pieces of plate of "Face Joint" was hauled together to introduced the prestressing force of six bracing rods.



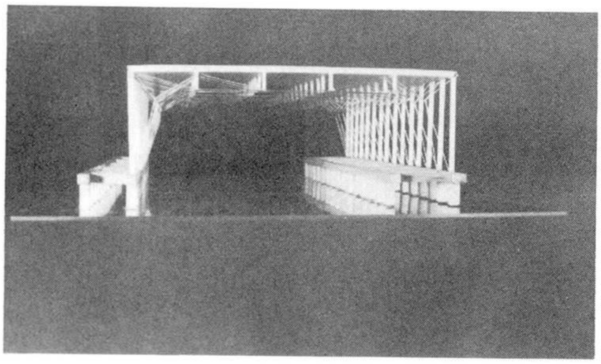


• Kita-Kyusyu Anoh Dome (described above)
Before installing of BSS adjusted for length and force, pre-loading was carried out by pulling down the top of cantilever truss to obtain strict accuracy for welding of beams.





• 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.

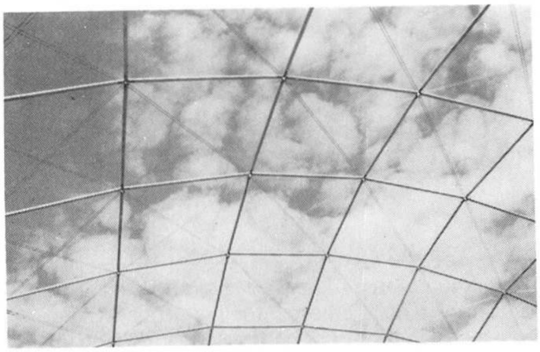
Fig.15 The examples of prestressing and construction method (2)

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)".



• *Aluminium plate*

• *System truss with screw bolts joint*

Fig.17 EP dome with four columns (1997)

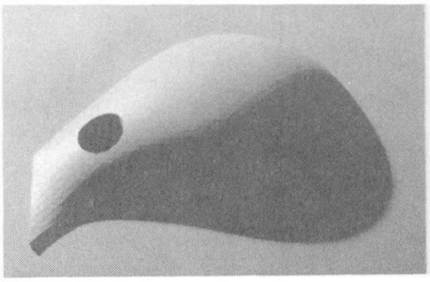


Fig.16 Organic form for Sports Arena Project (1996)

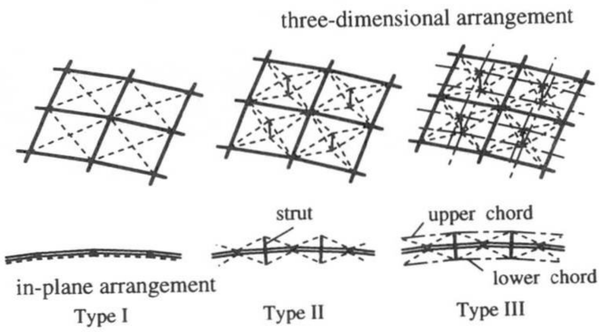


Fig.18 Three types of Tension Grid Dome

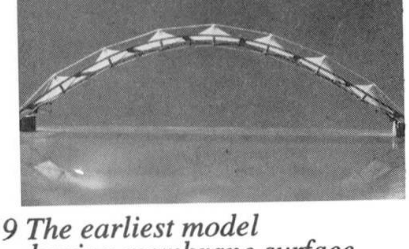


Fig.19 The earliest model having membrane surface and upper string (1985)

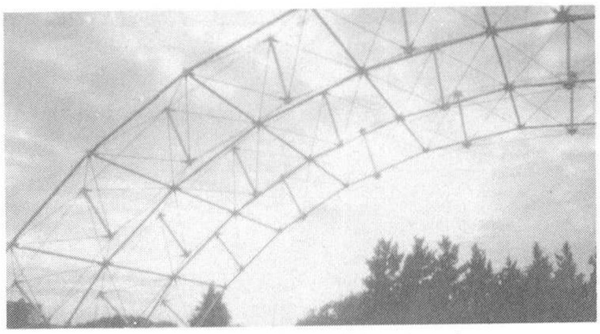


Fig.20 Tensegric arch stiffened with upper and lower chord cables (1997)

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.

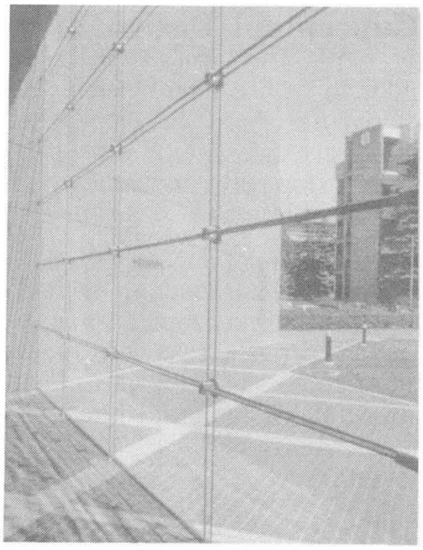


Fig.21 Facade of advanced science material center of Nihon Univ.

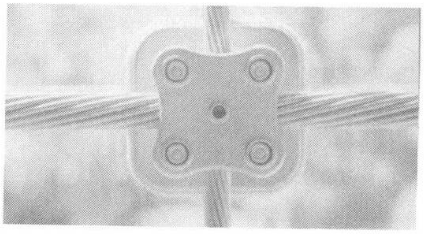
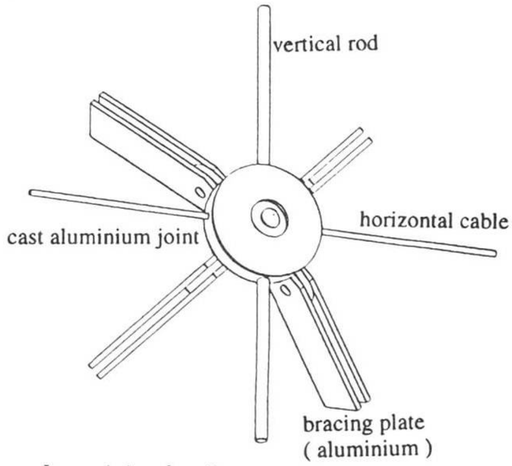


Fig.22 Detail of MJG



• *Inner joint detail*

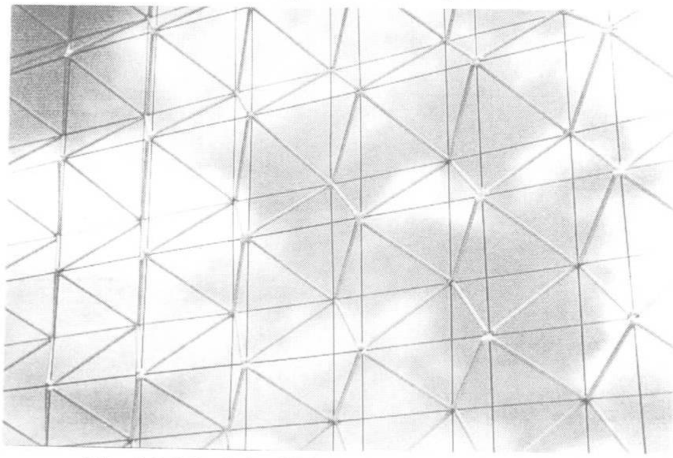


Fig.23 Model of Tensegric Truss Facade

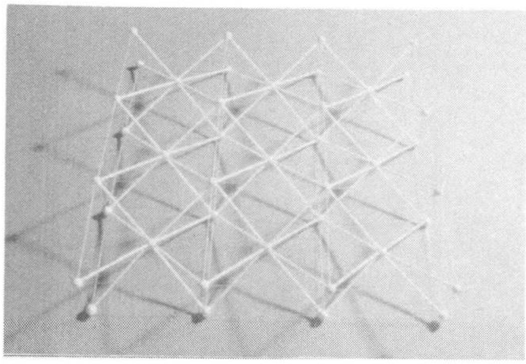


Fig.24 Model of Tensegric Truss unit

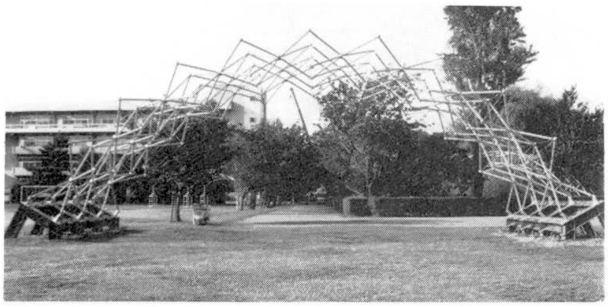


Fig.25 Test building of Tensegric Truss Arch (1997)

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.

References

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(2) From Image to Technology –The Role of string in Hybrid String Structures- ; proc. of IASS (1996, Stuttgart)

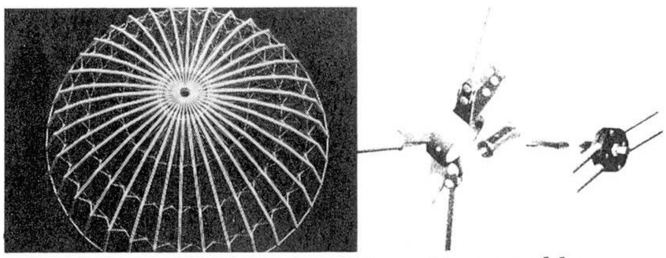
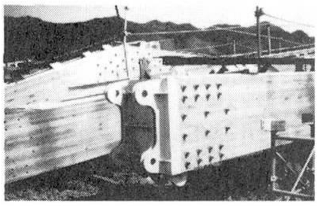
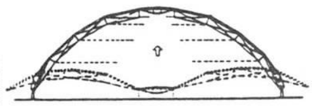


Fig.26 Detail of pre-stretching of hoop cable

Fig.27 Pushing-up system





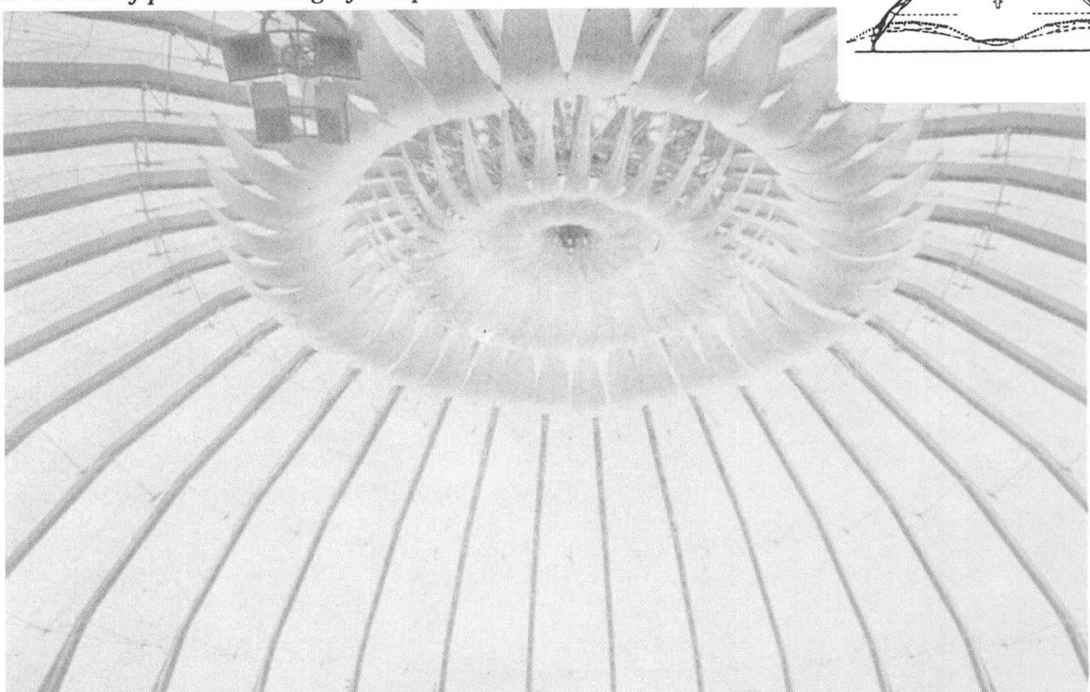


Fig.28 Interior view of IZUMO DOME (1992)