Aesthetics and Technology of the Beam String Structures

Masao SAITOH

Department of Architecture
College of Science and Technology
Nihon University
1-8, Surugadai, Kanda, Chiyoda-ku, Tokyo, Japan 101-8308
Tel:+81-3-3259-0710 Fax:+81-3-3293-8253

1. Introduction - Tension Structures in Space Structure

How to obtain "non-column space" rationally and beautifully has been a dream of mankind throughout the every ages. The history of large-spanned structure for over 2000 years is that of technological challenge of mankind. Although it is difficult to define Space Structure strictly, two characteristics of space structure can be pointed as follows (Fig.1):
1) "Form resistant system", represented axial resistant structure such as arch and catenary. It is expected that this system has qualitative resistance by rise of arch or sag of catenary rather than quantitative resistance by depth of beam.
2) "Composition resistant system", arranged members effectively. The performance of three-dimensional resistance is more progressive by changing arch into grid arch and shell, catenary into cable net, the weight of structure is lighter.

"Form and composition" is closely related with structural expressions. To demand the aesthetic sense on structural design and the co-operative works by architects and structural engineers is the greatest characteristic of Space Structures.

In the basic type of Space Structure, the existence of tensile element, especially string and membrane is peculiar material. By themselves or combination each other, various light-weight structures are able to be produced. On the other hand, it is possible to make hybrid structures combined rigid beams and arches. Fig.1 shows the position of Tension Structure in the field of Space Structures.

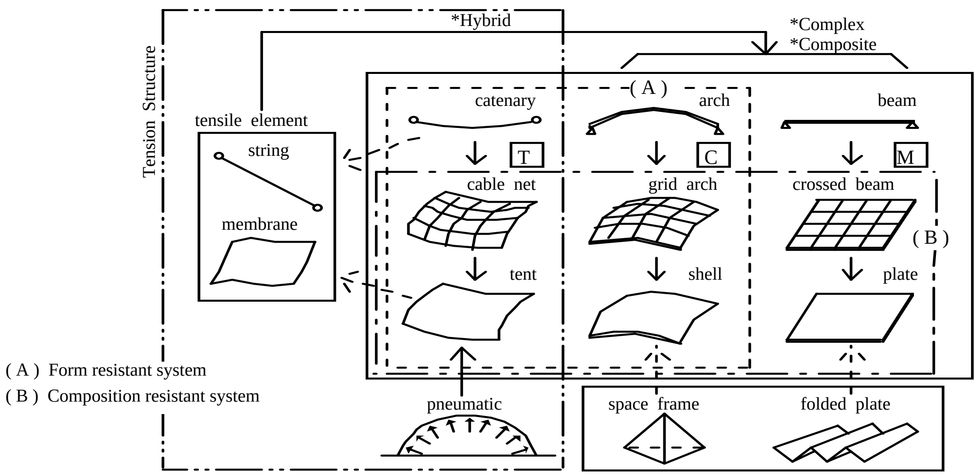


Fig.1 Basic Type of Space Structure

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 To which occurs in the string under the dead-load and the tensile force T1 which occurs in the string under the additional loads can be expressed by the following equation:

To=Te+Tp : PS in a broad sense
T1=To+Ta=(Te+Tp)+Ta
Te : existing tensile force caused by the equilibrium
Tp : tensile force which is introduced intentionally to control the structural behavior
(PS in a narrow sense)
Ta : incremental tensile force under the additional loads

Fig.2 shows the classification of string structures carried out under the amount of string tensile force. If the rate of Tp to Te (Tp / Te) 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.

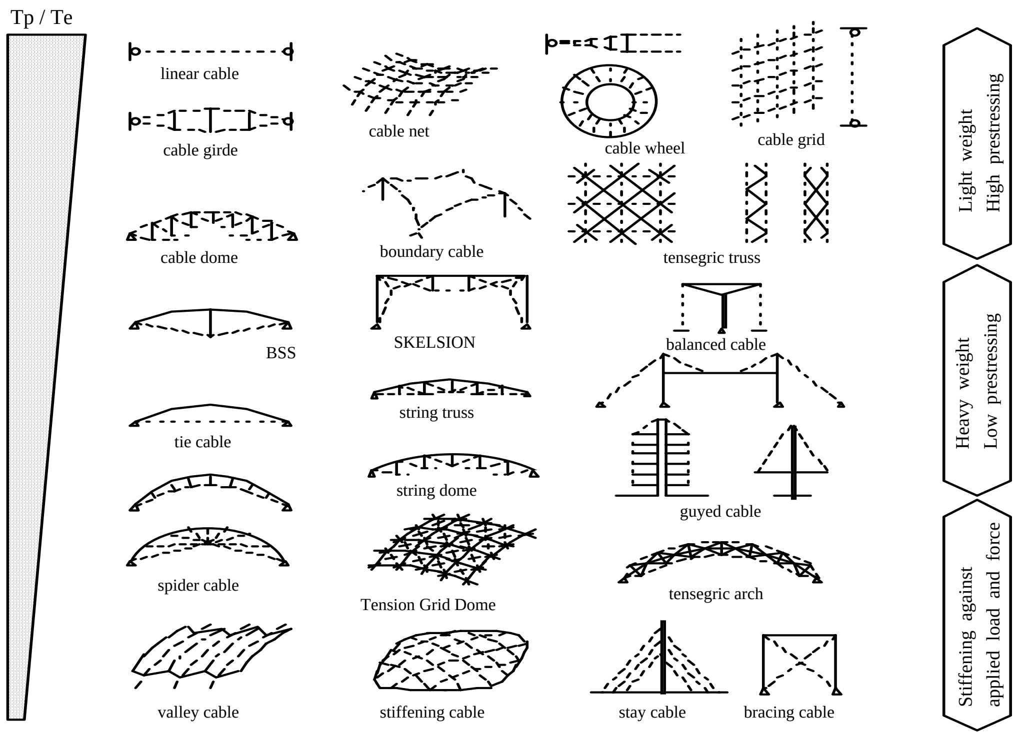


Fig.2 Classification of string structures by tensile force of string

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).

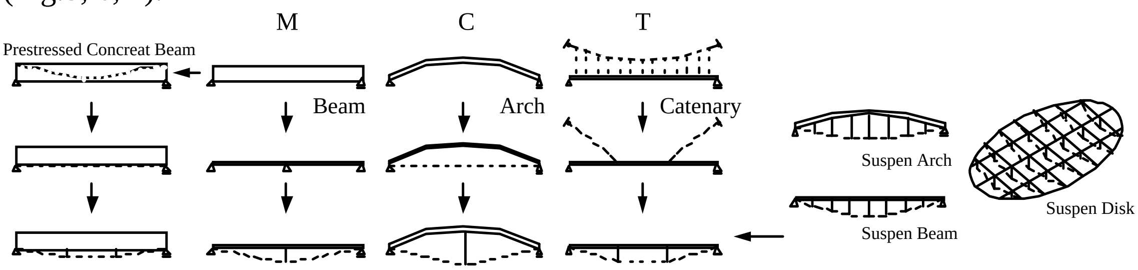
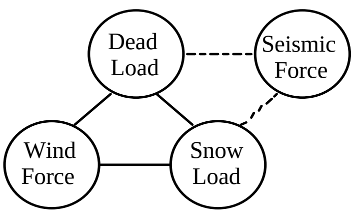


Fig.3 Birth of BSS

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>		<Dominant Load>		
	Finishing Load	Snow Load	Long Term	Short Term	light-weight
I	small	small		Wind F.	↑
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

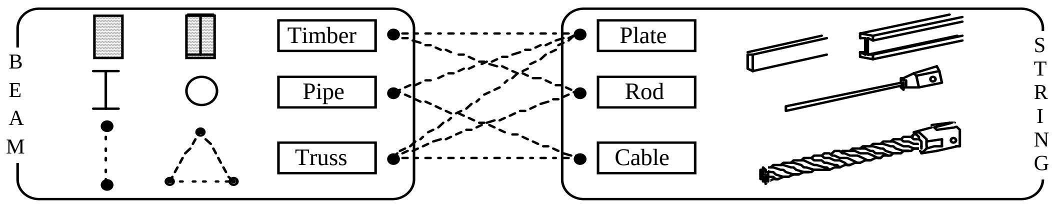
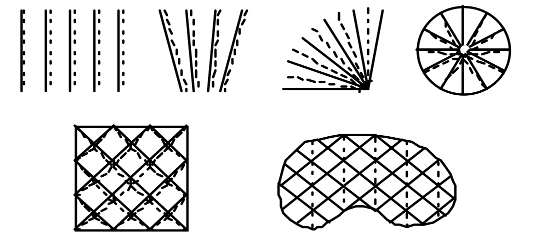


Fig.5 Combination of beam and string

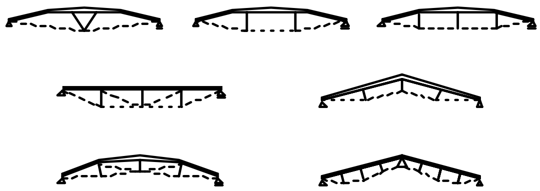
• *Iwate Prefectural Budoh-kan*

• *Monoh Town Gymnasium*

Fig.6 Mount-shaped BSS



• plan



• section

Fig.7 Variation of arrangement of string

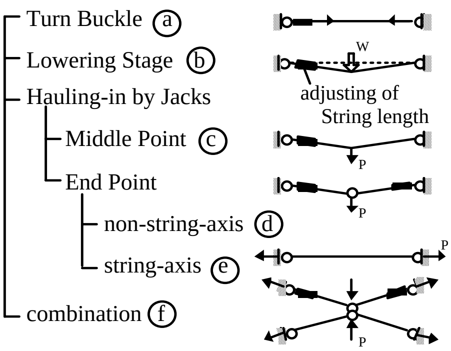


Fig.8 Method for introduction tensile force to string

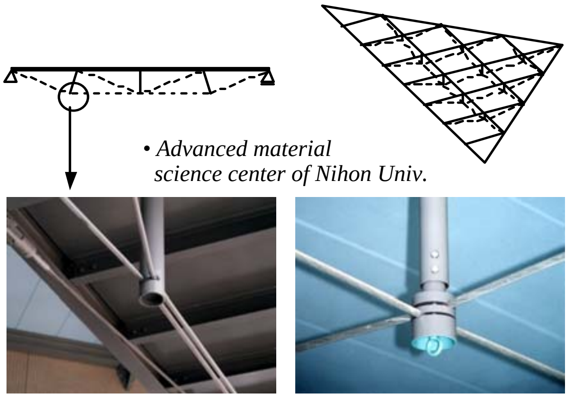


Fig.9 Hauling-in by pulling-down by small force

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.

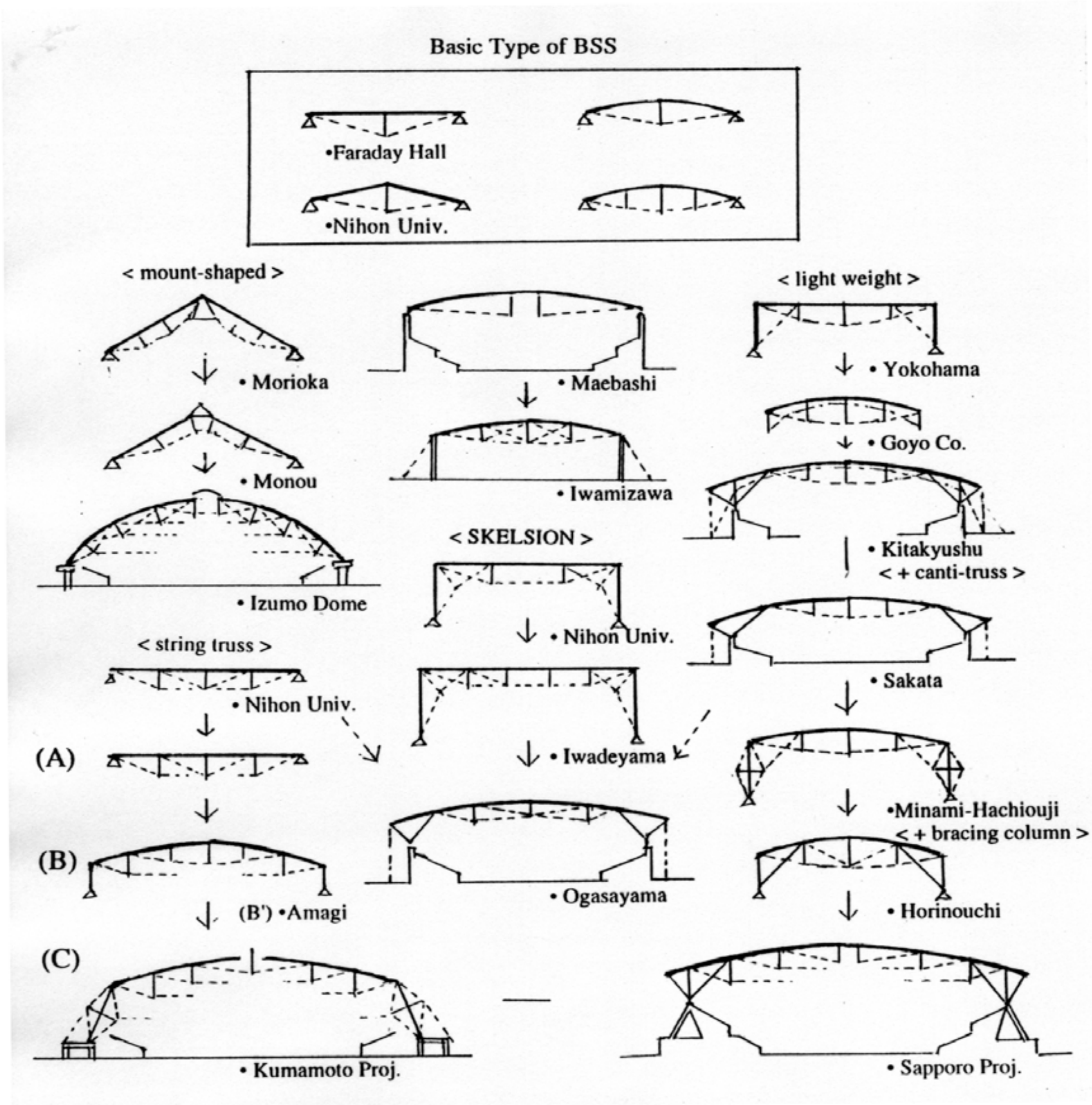


Fig.10 Various application from basic type of BSS

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 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

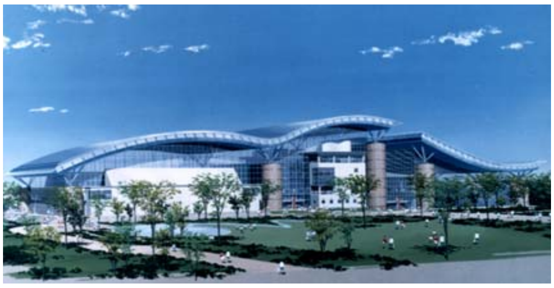
[1] Image of external appearance

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.

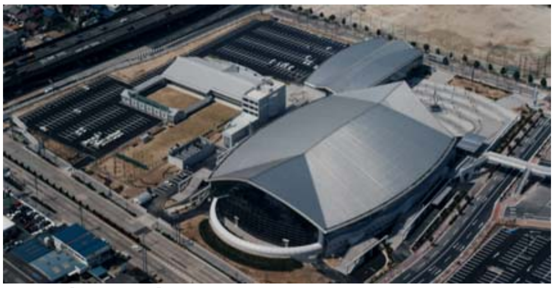
• Station Plaza Roof (Tokyo, 1997) 45m x 60m
Light weight membrane roof with a sense of "Gentle breeze" covers the shops and restaurants.

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

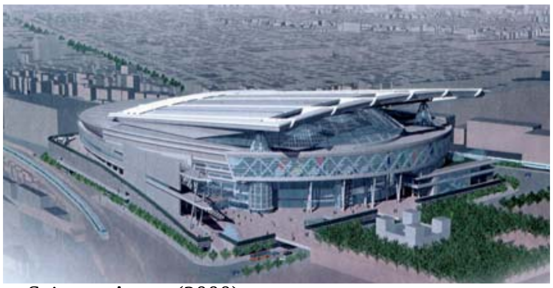


• Urayasu Municipal Sports Center (1995) 52m x 108 m
Large and small "Waves" coming ashore on Tokyo Bay.

• 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.

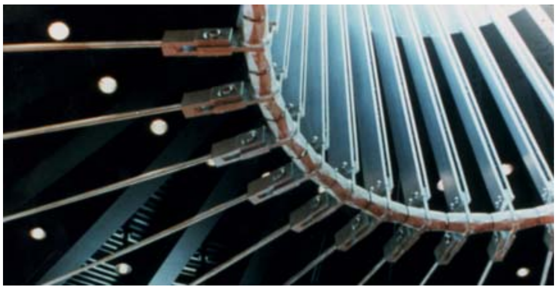
• Kyoto Swimming Pool Project
Organic shape like a "Cocoon" originated from the concept of harmony and utilization of nature.

Fig.12 Various image for external feature

[2] Structural Expression of Inside Space

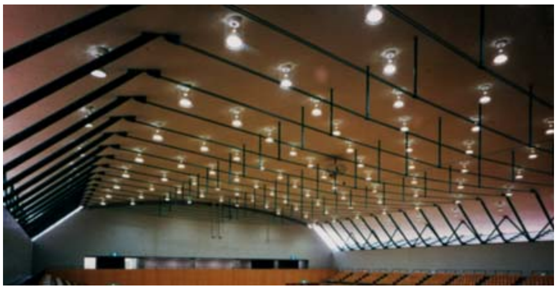
The delicate and sharp sense of strings can create various individual expressions in combination with thick beams. As an interior feature, four types of structural expressions can be considered by either eliminating or emphasizing each beam or string

(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.

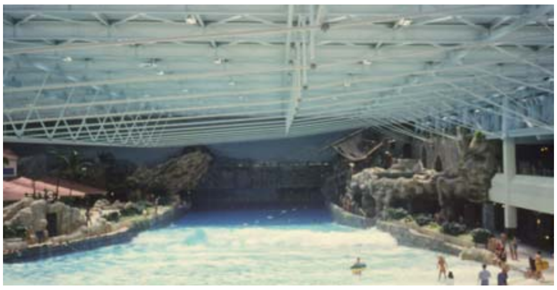


• Sakata Municipal Gymnasium (1991) 53m x 68m
Cables and struts colored with Turkish blue float in the natural light from deep eaves.

• 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.



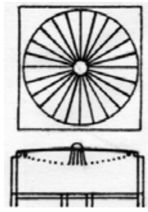
• Wild Blue Yokohama (1992)
The existence of cables is reduced to express the transparency of the resort space.

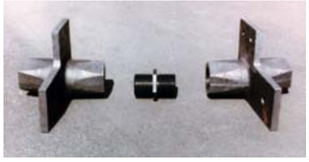
• Green Dome Maebashi (1990) 122m x 168m
Through visual effect, curved beams and sub arches produce a dramatic interior of a shallow dome.

Fig.13 Example of structural expression for interior view

3.4 Structural Technology of BSS

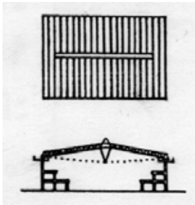
The method of introducing PS into strings in order to realize structural systems greatly depends upon construction and details, and have to be considered as a whole. Actual examples of Fig.14 and Fig.15 can be seen in Fig.7.



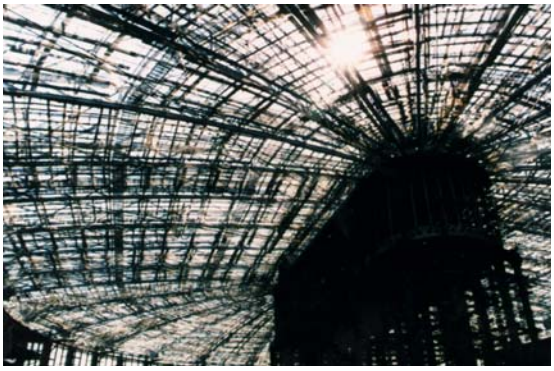


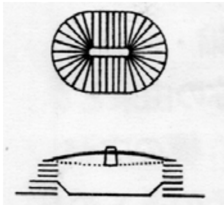
cast steel elements of central tension ring

• 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.

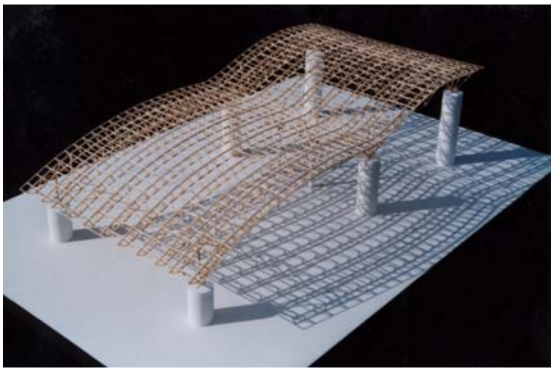


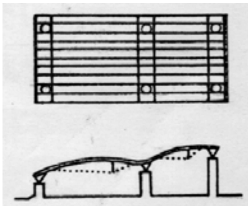
• Sports Hall of Nihon Univ. (described above)
By the introduction of a design force due to the final weight, each truss beam was lifted up from the support. The whole roof (1000tf) was slid up gradually by two small jacks on either side.

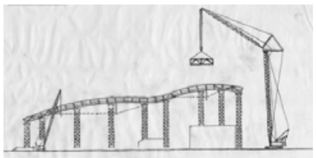




• Green Dome Maebashi (described above)
For each truss girder assembled on the central support, prestressing force was introduced by 68 oil jacks under the central ring to lift up the whole roof (3000tf).

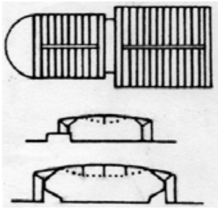




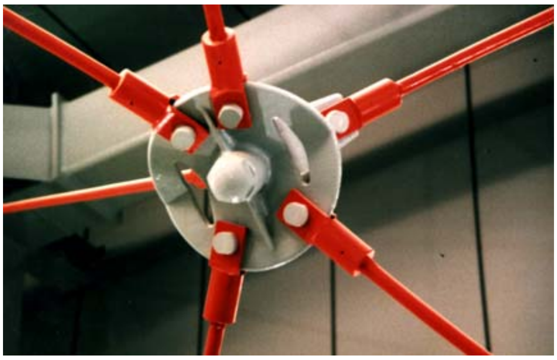


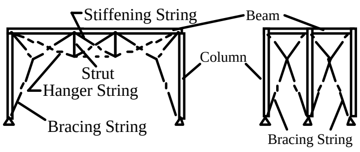
• Urayasu Municipal Sports Center (described above)
After assembly of the whole trussed beam has been completed, the cables of the BSS were tightened gradually, and the supports were removed one by one.

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

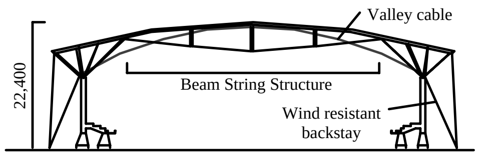




• Sakata Municipal Gymnasium (described above)
The prestressing of cables was executed by hauling down and attaching the end of struts on the ground. A set of three pieces of BSS loaded with final finishes was pulled up by temporary ropes from the top of the cantilever truss.

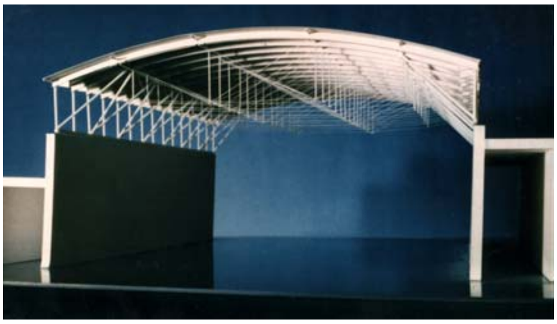




• Subway Station of Nihon Univ. (described above)
By using small jacks, two pieces of plate of "Face Joint" was hauled together to introduced the prestressing force of six bracing rods.



• 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. 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

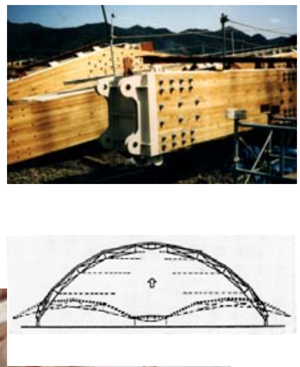
M. Saitoh et all.

(1) Principle of Beam String Structure ; proc. of IASS (1979, Madrid)

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

Fig.16 Detail of pre-stretching of hoop cable

Fig.17 Pushing-up system



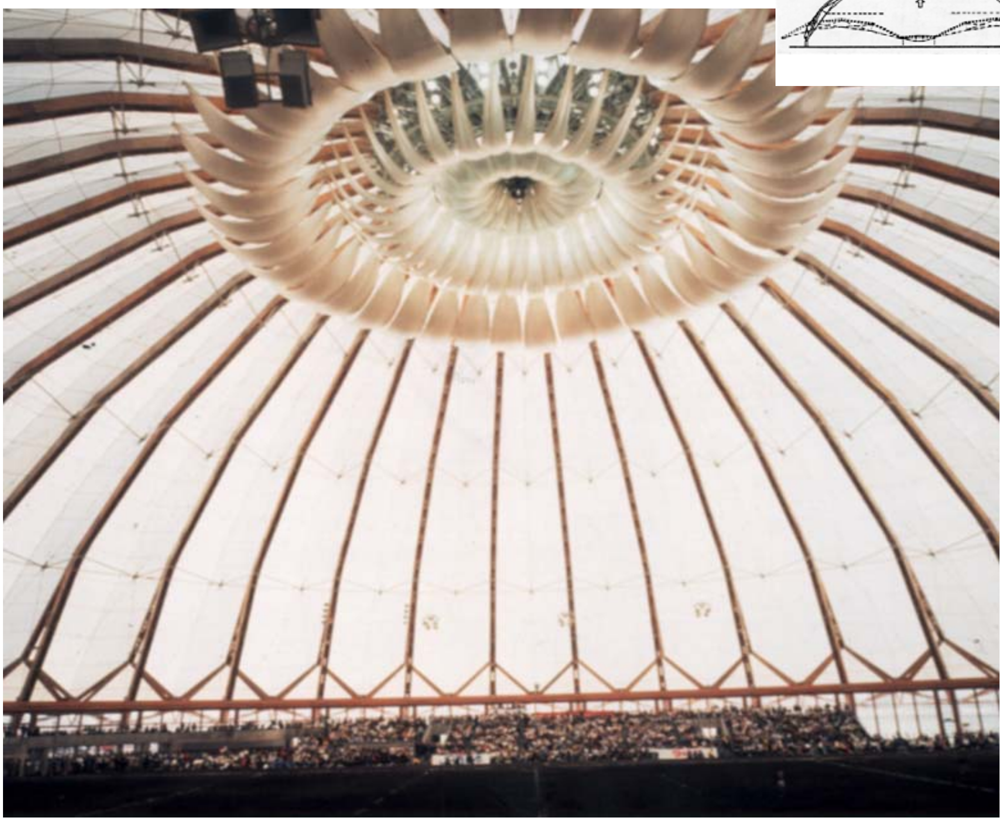


Fig.18 Interior view of IZUMO DOME (1992)