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Design and Construction Focused on Initial Tensile Force of Cable Structures - Latest Interesting Construction Examples -

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Abstract

Tension structure is mainly composed of the strings or the membrane that can resist only tensile force, and it is possible to shape light weight frames and have excellent mechanical rationality. Tension structure is one of a representative of spatial structures. In this paper, cable structure using cables as the string is discussed.

Cables cannot resist compressive force and have geometric nonlinearity. The installation of amount of initial tensile force corresponding to role of cables is important factor when cable structures are designed.

In addition, the selection of the introduction methods of prestress is also important factor for structural design or construction planning.

Firstly, in this paper, the authors focus on two types of the tensile force -the initial tensile force (under dead load) and the incremental tensile force (under live load and snow load) - and then categorize cable structures.

Secondly, the introduction methods of prestress are classified. Recent designs and interesting construction examples are instantiated, and the roles of cables, the introduction methods of prestress and the details are presented.

Keywords: cable structure, initial tensile force, prestress, construction

1. Introduction

In recent years, tension structures have been increasingly used to build not only large buildings such as stadiums and arenas but also small gymnasiums and glass facades for high-rise buildings. Because tension structures can be used to build lightweight frames that offer excellent mechanical rationality, and are suited to constructing large-space buildings and architectural spaces that require transparency.

Tension structure is mainly composed of the strings or the membrane that can resist only tensile force, form a representative group of spatial structures as shown with figure 1 (M. Saitoh[1], M. Saitoh *et al.* [2],[3]). Strings (one-dimensional materials) and membranes (two-dimensional materials) are the two representative tension members; this paper focuses on the strings. When designing tension structures using strings, it is important to define the role of strings and to set an appropriate initial tensile force for that role. The introduction methods of the initial tensile force to the strings are a major factor that affects structural and construction plans.

Focusing on the initial tensile force of strings, this paper discusses (i) the classification based on the tensile force levels and (ii) the classification of the introduction methods of the prestress. Recent projects are also introduced as examples (M. Suzuki *et al.* [4]).

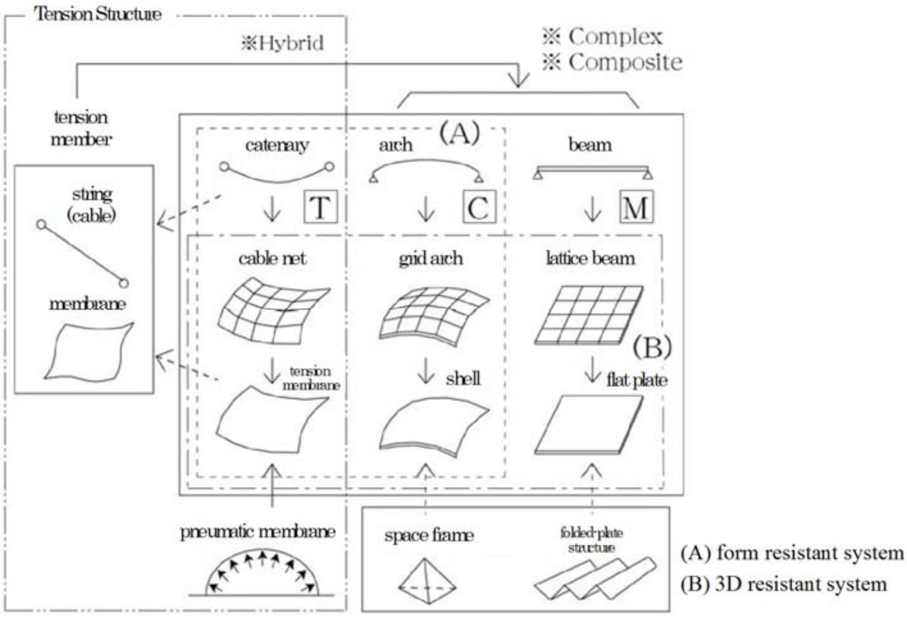

Figure 1: Classification of spatial structures

2. Classification of the tension structures

2.1. The initial tensile force of the string

The cable is the member that can resist only tensile force, so the initial tensile force in the cable is introduced beforehand in general. The amount of the introduced initial tensile force varies depending on a role of the cable.

2.2. Types of the tensile force of the string

The tensile force of cable is broadly classified into two types - the tensile force under dead load and the tensile force under additional load. The tensile force of the cable under dead load (T0) is called "Initial tensile force" in general. On the other hand, "Initial tensile force" also means the purposely introduced tensile force which removes the existing tensile force, which occurs when dead load is applied, from the tensile force under dead load.

The tensile force in the cable under dead load (T0) is located as the tensile force in broad sense and the purposely introduced tensile force (Tp) is located as the initial tensile force in narrow sense.

These two types of the initial tensile force are related by the following equation using the existing tensile force (Te: the tensile force which occurs when dead load is applied).

$$T_0 = T_e + T_p \quad (1)$$

where T0: the initial tensile force in broad sense

Te: the existing tensile force

Tp: the initial tensile force in narrow sense

The amount of Te is varied by the amount of dead load, structural system, or degree of redundancy. Also the amount of Tp is defined by the introduction purpose of the initial tensile force - e.g. control of the stress or the deformation, avoidance of the development of the compressive force in the cable.

On the other hand, the tensile force in the cable under additional load (T1) is described as the following equation using the incremental tensile force under additional load (Ta).

$$T_1 = T_0 + T_a = T_e + T_p + T_a \quad (2)$$

where Ta: the increased tensile force under additional load

T1: the tensile force in the cable under the additional load

The size of the section area of the cable is designed by considering safety factors of T0 and T1. The section area of the cable is corresponded to the breaking tensile load (Tb). Furthermore Tb is related to the tensile force in the cable (T0, T1) by the safety factor, and it is possible to assess the value of the dominant load quantitatively by a ratio of Tb and T0.

2.3. Classification of the tension structures focused on the tensile levels of the cable

In this part, the cable structures are classified by focusing on the initial tensile force introduced to the cable. The ratio of purposely introduced tensile force (Tp) or the existing tensile force occurring by dead load (Te) against the breaking load (Tb) is focused on as a index of expressing the role of the cable in the tension structures. It is possible to describe whichever is dominant - the initial tensile force, deal load, or additional load - by a combination with the amount of Te/Tb and Tp/Tb.

Figure 2 shows the classification of the tension structures from the point of view mentioned above, and practical examples corresponding the classification are shown in figure 3 (M. Saitoh *et al.* [5], N. Miyasato *et al.* [6]).

As for each case, the structural characteristics and the considerations for the construction planning are described.

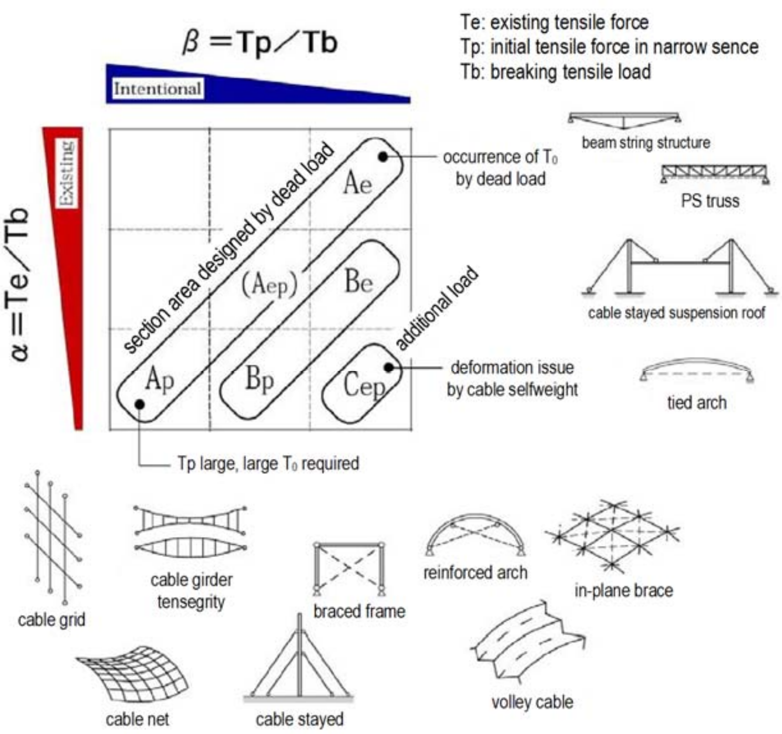

Figure 2: Classification of tension structures focused on tensile levels of the cable

2.3.1. A group

Most of the tensile forces in the cable occur under dead load and most of the structural systems in which section area of cable is designed by deal load are involved. Additionally, they are roughly divided into Ae and Ap by the amount of Te and Tp.

In case of Ae, most of the tensile forces in cables are introduced by the existing tensile force (Te), and it is important how to add the selfweight of the structure and the selfweight of the finish material to the cable. In case of Ap, the self-balanced structural system which is stabilized by introducing Tp is involved. Because it has possibilities that the structure is unstable during construction, it is important that not only the introduction method of Tp but also the verification of stabilization of the structure when the construction planning. When degree of redundancy is large, the introduction procedure of the tensile force and the amount of the tensile force under construction are necessary.

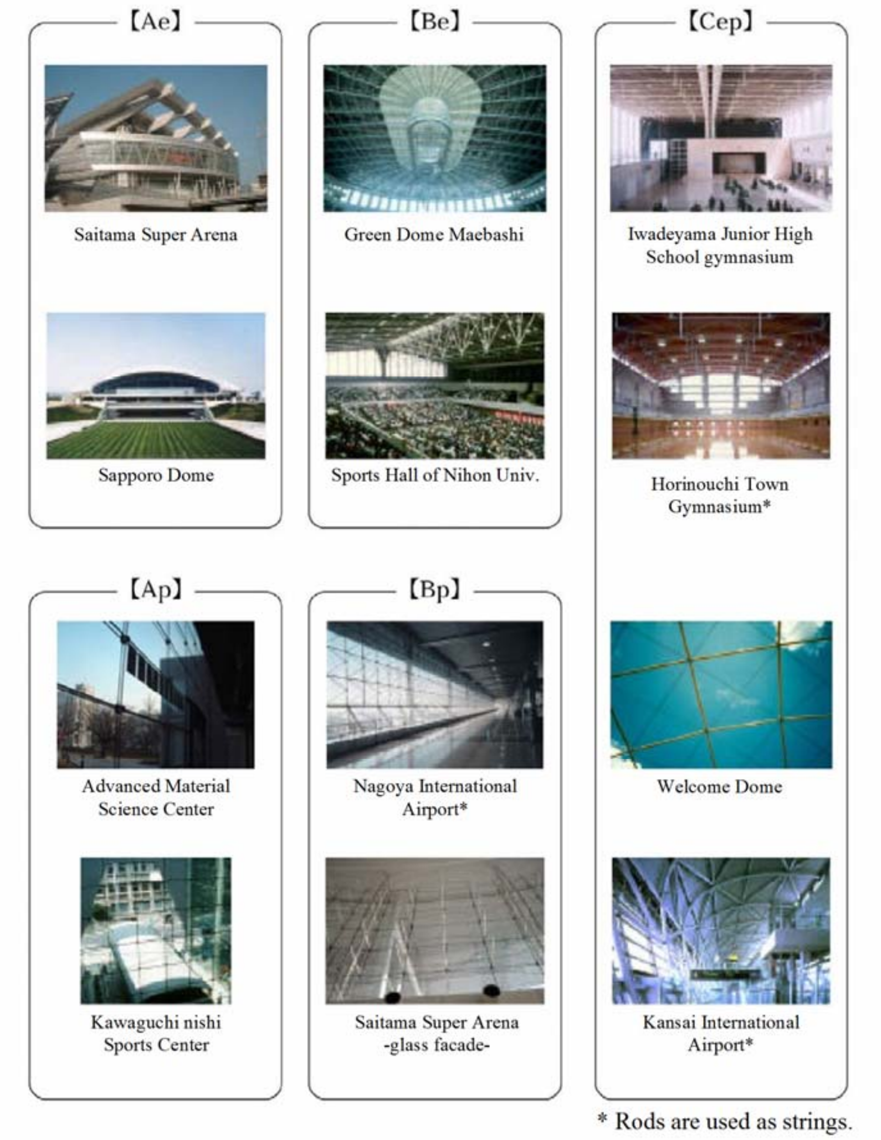

Figure 3: Practical examples corresponding classification of tension structures

2.3.2. C group

The structural system which is described by a small ratio of both Te/Tb and Tp/Tb is involved.

The structure system which has section area of cable designed by the tensile force under additional load is categorized. When the additional load is extremely large, it is required that large section cables are installed with small tensile force. In this case, it is required to consider the occurrence of deformations by the selfweight of the cable.

2.3.3. B group

It is located between A group and C group.

The structural system which can not distinguish by the ratio of Te/Tb and Tp/Tb is involved. Be has a same problem as Ae. However, depending on the amount of the tensile force, it is possible to install the cable without the stress condition by devising the construction procedure, and to achieve the specified initial tensile force with construction procedure afterwards - e.g. adding finish load and so on.

2.4. Classification of the introduction methods of the prestress to the cable

In this part, the construction methods of the introducing the prestress (the initial tensile force in broad sense) to the cable are classified from 4 viewpoints - "(A) supervision of the structural performance", "(B) analysis", "(C) construction efficiency" and "(D) construction planning".

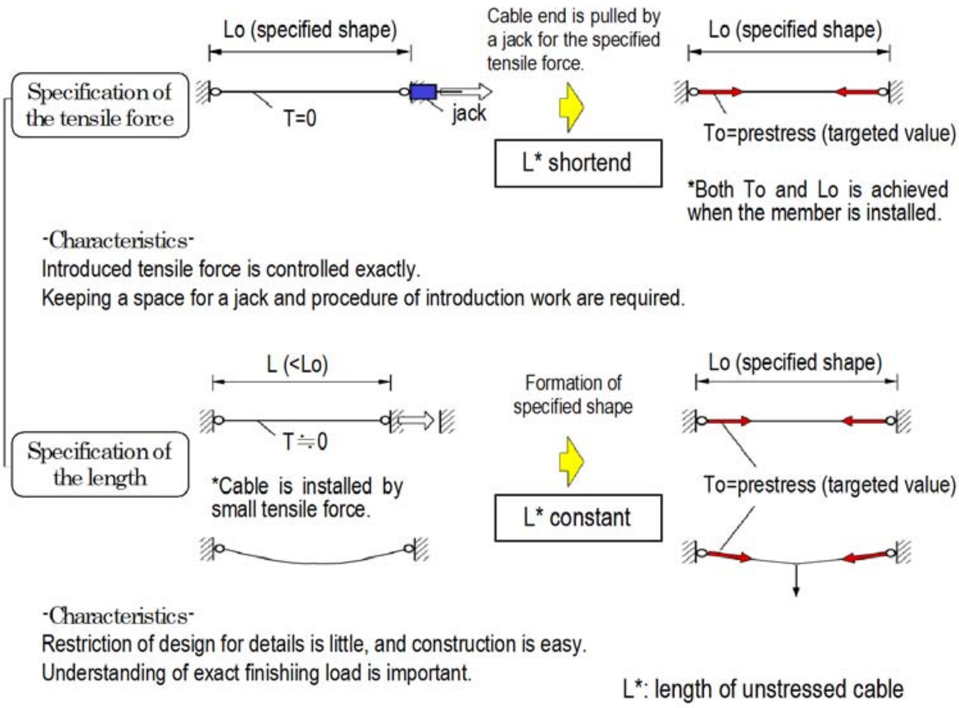

Figure 4: "Specification of the tensile force" and "Specification of the length"

2.4.1. "Specification of the tensile force" and "Specification of the member's length" (supervisory point of view)

According to "(a) Installation method of the cable", or "Installation method of unstressed cable which is supposed to have the specified tensile force and the length at the completion", the introduction method of the prestress to the cable is roughly divided to "specification of the tensile force" and "specification of the length". (see figure 4)

2.4.2. The occurrence factor of the prestress (analytical point of view)

According to "(b) analytical viewpoint", the occurrence factors of the prestress force are classified into 2 methods, the case that length (L*) of unstressed cable is shortened and the case that the cable's length is extended while keeping the length (L*) constant.

2.4.3. "active" and "passive" (construction efficient point of view)

According to "(c) occurrence condition of the prestress", the introduced prestress at the completion (T0) is described as a sum of the tensile force introduced purposely by the construction work directly related to the prestress (Tac: active tensile force) and the tensile force introduced indirectly by other work - e.g. adding finishing load, introducing Tac to other member, etc. - (Tpa: passive tensile force).

2.4.4. The amount of introduced prestress (construction planning point of view)

Large or small of introduced prestress affects the introduction work of the prestress when construction. Then according to "(d) construction planning viewpoint", the amount of the introduced prestress is able to be compared with a ratio of the prestress (T0) / the breaking load (Tb).

2.5. Typical introduction methods of the prestress and several practical examples of cable structures

The typical introduction methods of the prestress in the cable structures are classified with above four viewpoints and shown in figure 5. Among them, only introducing the prestress by a jack enables to introduce comparatively high tensile force by "specification of the tensile force". The introduction method or the prestress by a turn buckle is useful both the construction which managing only member length ("specification of the length") and the construction which managing torque ("specification of the tension force"), however this method is not suitable when a level of the prestress is high. Construction by compulsory displacing the frame is the method which introduces the tensile force by installing the cable having the specified length at the completion compulsorily. The indirect introduction of the prestress is a combination of "specification of the tensile force" and "specification of the length", and it is possible to introduce the high prestress with comparatively low force. Also according to an occurrence condition of the prestress, only introduction of the prestress by adding selfweight is "passive" introduction of the prestress, and the other methods require any "active" energy.

Introduction method of the prestress \ Classification	Installation method	Change of L*	Occurrence of the prestress	Prestress level
[Jack] (jack)	specification of the tensile force	yes	active	low ⇔ high
[Turnbuckle] (turnbuckle)	specification of the tensile force specification of the length	yes	active	low
[Support down] (support; selfweight applied; dn)	specification of the length	no	active	low (existing tensile force)
[Addition of frame selfweight or finishing load] (selfweight, finishing load)	specification of the length	no	passive	low ⇔ middle (tension change)
[Compulsory displacement of the frame] (compulsory displacement)	specification of the length	no	active	low ⇔ middle
[Indirect introduction]	specification of the tensile force specification of the length	no	active	low ⇔ high

L*: length of unstressed cable

Figure 5: Typical introduction methods of prestress

3. Introduction method of the prestress in practical examples of cable structure

This section discusses (i) the types of tension members that have been used in recent projects and (ii) the methods of the prestress.

3.1. Jissen Joshi Gakuen Junior & Senior High School Gymnasium

In constructing this gymnasium, it was necessary to comply with local height restrictions, and so a trapezoidal roof had to be employed(I. Nakakawaji [7]). In particular, it was difficult to set up large structural members to increase the effective height of the indoor space. To reduce the thrust force acting on the roof frames, cables were arranged in a ring pattern at the center of the gymnasium (37.8 m × 32.9 m). The ring cables were connected with stay rods with capitals of each support set up radially.

In the construction planning phase, it was decided to introduce the prestress to the ring cables and stay rods during the steel frame works. The design tensile force introduced to the cables was 395 kN; the design axial force introduced to the stay rods was 61–100 kN. To minimize the scope of introduction of the tensile force and the simple introduction method of the prestress , it was planned to connect the ring cables with stay rods based on configuration management with the configuration at the time of completion in mind and to introduce the tensile force only to the ring cables.

The ring cable consists of two semicircular cables. The prestress was introduced to the two joints at the same time using hydraulic jacks. As a result, the difference between the design prestress of the stay rods and the actual prestress measured after introducing prestress to the ring cables was within −5.2 to +6.9%, which was almost as designed.

Figure 6: Interior of the Gymnasium and Prestress introduction

3.2. Pergola in the Marunouchi Park Building

This structure consists of an oval frame 8.6 m in the major axis, 5.4 m in the minor axis. There are the inner and outer rings and the upper and lower strings that connect the inner ring with the outer ring; it looks like a tilted bicycle wheel (T. Yoshihara *et al.* [8]). The upper and lower strings are arranged such that the inner and outer rings are turned in opposite directions. The self-weight of the outer ring is supported using upper strings, and the turning attributed to the self-weight of the outer ring is restrained by the lower strings. A pair of upper and lower string are continuous cable . The cable is used to reduce the number of terminal clamps and simplify the structure on the outer ring side. Intermediate clamps resist the sliding force of the upper and lower strings. In terms of the classification of tension structures discussed above, the tensile force of the upper and lower strings are characterized by high Te and high Tp, respectively. The upper and lower strings are categorized in the Be group and Bp group, respectively.

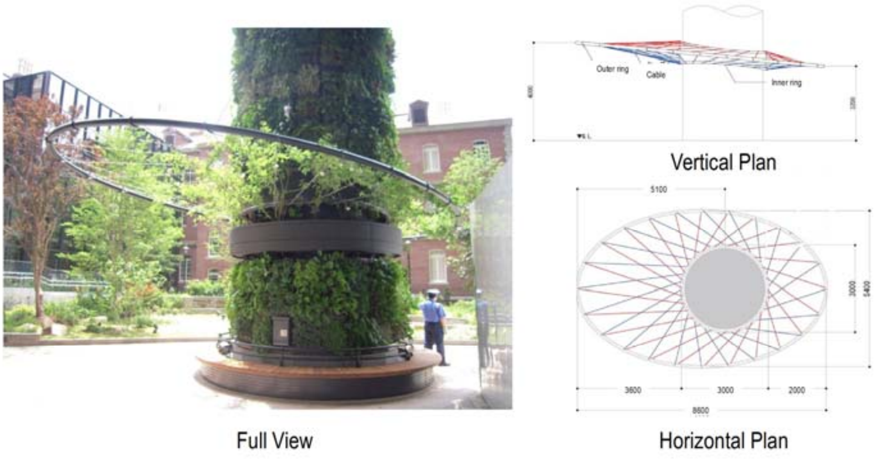

Figure 7: Pergola

Based on pre-construction tests and analysis results, it was decided to support the outer ring with scaffolding at a position higher than the target height before setting the outer ring to the upper and lower strings. A tensile force of 3 kN was introduced manually to remove cable flexure. After the scaffolding was removed, a tensile force was introduced to some members that had lost tensile force. In the final process, tensile force was introduced by tightening all the cables, which was controlled by the number of turns of nuts.

3.3 Kyowacho Syougai Gakusyu Center

A beam string truss structure was employed for the roof frame spanning 34 m of this arena built in a snowy area (S. Ohtsuka *et al.* [9]). This structure was used to support the self-weight of the steel frame with self-anchored beam strings and to change the load flow from the truss beam to knee braces against emergency loads after completion. This structure has created an open space with a tense atmosphere compared with a structure using a simple beam or truss beam for the same span.

The beam was basic-assembled before setting up the beam strings. In the basic assembly process, the cables were set up and The prestress just under 30 kN was introduced by manually tightening nuts at the ends. The basic assembly process also involved a procedure to remove the scaffolding that supported the center of the beam to add the self-weight of the steel frame and Introduction a passive tensile force. The beam string precision was controlled by measuring the flexure of the beam in the perpendicular direction. Knee braces and other rod materials which form the beam string truss structure were set up after the beam string unit basic-assembled to cope with the additional load was installed at the specified position.

4. Conclusion

This paper discussed the classification of (i) tension structures from the focusing of the initial tensile force of strings and (ii) introduction methods of prestress, based on recent projects.

Tension structures of different structural system, size, and configuration can be classified by the initial tensile force. Tension structures in each classified group are considered to have common issues and characteristics in terms of construction (e.g. introduction methods of prestress to tension members) and detailed design.

When designing tension structures, it is important to pay attention to the initial tensile force, make an overall judgment from the viewpoint of design, structure, and construction, and determine the details and select introduction method of prestress.

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