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Development of NS Tension System for Space Frame

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Abstract

Tension string structures using cable or high-strength rods are now becoming very popular for spatial structures such as sports gymnasium, convention center, entrance hall, and so on. These structures are one of the most rational structural systems, which use steel members under pure tension forces, without buckling. They are lightweight, high-strength/stiffness, and realizing elegant appearances. However, because of using special types of steel materials, individual approval is required for the practical construction, which obstructs the designers from adoption to building design. Since1990, Nippon Steel / Building Construction Div. has been endeavoring on the systematization of "Tension Roof System" and "Tension Grazing System", developing the market by authorizing the general approvals for building use. In this paper, parts of general technical information of this system are reported.

1. Introduction

In the main structural members (e.g., columns and beams) of a building, there are members in which tensile stress predominates. Structures which use steel rods or cables in those members are generally called tension structures or tension string structures. A tension structure is often applied to the frame that supports the roof of a gymnasium (**Photo 1**) and to the frame that supports the glass walls of an atrium (**Photo 2**). The tension structure is an excellent structure type that not only produces a highly aesthetic space but also functions as a main structural member capable of withstanding earthquakes and strong winds since an extra axial force is introduced thereto artificially.

It is the NS tension system that has been developed by systematizing the design, manufacturing and construction methods for the component parts of such tension structures (i.e., tension members and end joints) as turnbuckle-equivalent products for building use. Using this NS tension system as a powerful tool, the Building Construction Division of Nippon Steel has been positively engaged in the joint design/proposal of all kinds of tension frames and the fabrication/erection of steel frames containing tension frames as an integrated business. In this paper, the authors shall describe our activity to develop the NS tension system.

Photo 1 Tension structure No.1 (roof system)

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Photo 2 Tension structure No.2 (glazing system)

2. Outline of the NS Tension System

The component parts of the NS tension system (hereinafter referred to as “this system”) are shown in **Fig. 1**. As tension members, there are two types of steel rods (tie rod and PC bar) and three types of ropes (spiral rope, stranded rope and locked coil rope). In addition, there are three types of standard joints (socket, pin and cylindrical joints). Mechanical properties of the tension members are shown in **Table 1**, and those of the standard joints are shown in **Table 2**. The design of this system guarantees tensile loads in the range 56 kN (stranded rope 7 × 7, 14 mmϕ) to 2,799 kN (tie rod 90 mmϕ).

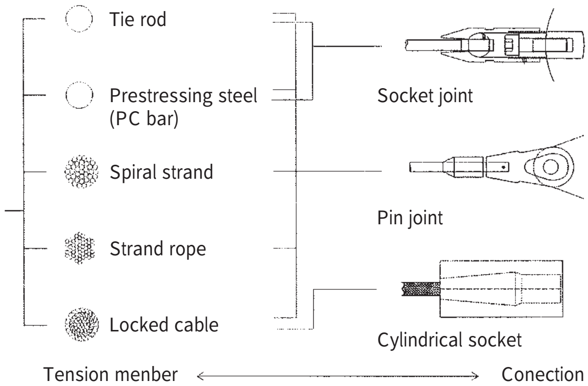


Fig. 1 Parts of NS tension system

Each of the component parts is available in more than 10 different sizes. In the case of the locked coil rope, in particular, the desired rope diameter can be selected from among 20 different sizes.

The socket joint is used exclusively with steel rods. The most salient characteristic of this joint is that it is capable of following up rod deformations three-dimensionally because a threaded tension part is fixed to its spherical nut. The pin joint is the most widely used joint since it can be used with any tension member. It is capable of following up centrifugal deformations in one direction. The cylindrical joint is a DIN-compatible product manufactured by a German rope maker as its exclusive joint. For each of these joints, the guaranteed load has been set after its shape was decided by using the permissible axial force of the tension member as the design load and confirming its structural characteristics through testing of actual-size test pieces.

An example of a frame using a tension structure is shown in **Fig. 2**. The tension roof system represents frames primarily supporting a fixed load and live load, or so-called dead load. It is used in buildings whose span is expected to be more economical than a single structural steel member, such as the H-beam. The tension glazing system represents frames primarily supporting the wind load. It is often applied to the glass walls of atriums. These frames cannot be

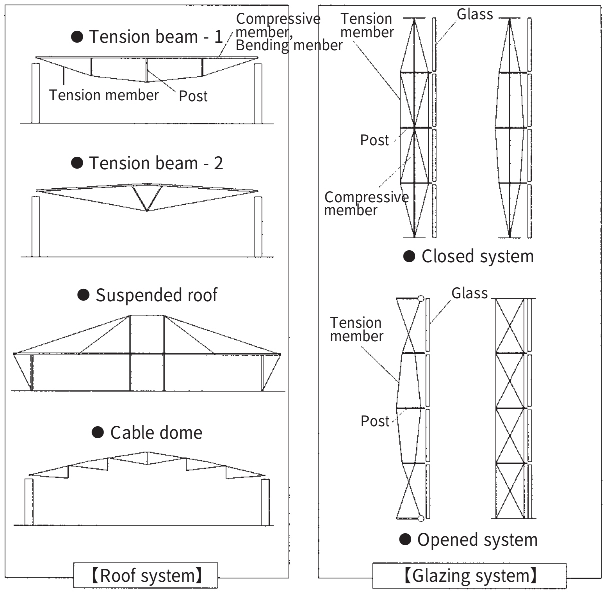


Fig. 2 The example of system used tension structure

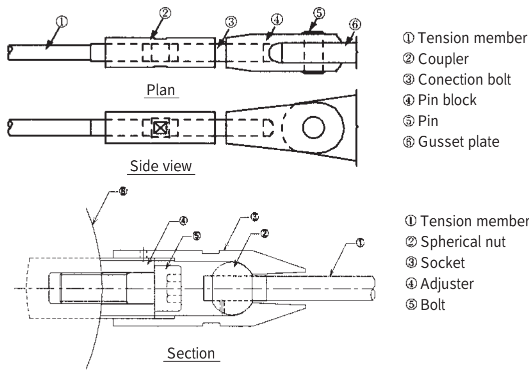
Table 1 Mechanical properties of tension member

Tension member	Standard	Grade	Yield point or yield strength (N/mm²)	Tensile strength (N/mm²)	Elongation (%)	Minimum diameter in blackets = P_s (kN)	Maximum diameter in blackets = P_s (kN)
Tie rod	Authorized products	690N/mm² grade steel	440 min.*1	690-810	20 min.	25mmϕ{215}	90mmϕ{2799}
PC bar	JIS G 3109	Grade B No.1	930 min.*1	1,080 min.	5 min.	13mmϕ{85}	40mmϕ{814}
Spiral strand	JSS II 04	ST1470	1,080 min.*2	1,470-1,720	3 min. (4 min.)*3	14mmϕ (1×19) {72}	45mmϕ(1×61) {734}
Strand rope	JSS II 03	ST1470	1,080 min.*2	1,470-1,720	3 min. (4 min.)*3	14mmϕ (7×7) {56}	33.5mmϕ(7×7) {325}
Locked cable						26 (VVS-2) {290}	77 (VVS-3) {2650}
Z-wires	DIN 779	—	—	1,570-1,830	—		
Diameter of wire 2.0mmϕ min.	DIN 2078	—	—	1,570-1,830*4	—		

*1 Yield point or the stress giving permanent elongation of 0.2%. *2 The stress giving total elongation of 0.7%.
*3 When diameter of round wire is > 2.8mm, the elongation is value in blackets.
*4 Maximum tensile strength of round wire is defined, when the diameter is ≧ 0.2mm but < 0.5mm, 1,960kN, ≧ 0.5mm but < 1.0mm, 1,920kN, ≧ 1.0mm but < 1.5mm, 1,900kN, ≧ 1.5mm but < 2.0mm, 1,860kN.

Table 2 Mechanical properties of connection parts

Connection	Parts	Standard	Symbol of grade	Yield point or the stress giving parmanent elongation of 0.2% (N/mm²)	Tensile strength (N/mm²)	Elongation (%)
Pin joint for bars	Pin	JIS G 4105	SCM 440, SCM 430	750 min.	850 min.	15 min.
		JIS G 4052	SCM 440H, SCM 430H	750 min.	850 min.	15 min.
	Pin block	JIS G 4105	SCM 440, SCM 430	500 min.	700 min.	15 min.
		JIS G 4052	SCM 440H, SCM 430H	500 min.	700 min.	15 min.
	Coupler	JIS G 4105	SCM 440, SCM 430	750 min.	850 min.	15 min.
		JIS G 4052	SCM 440H, SCM 430H	750 min.	850 min.	15 min.
Socket joint	Spherical nut	JIS G 4105	SCM 440, SCM 430	750 min.	850 min.	15 min.
		JIS G 4052	SCM 440H, SCM 430H	750 min.	850 min.	15 min.
	Socket	JIS G 4105	SCM 440, SCM 430	500 min.	700 min.	15 min.
		JIS G 4052	SCM 440H, SCM 430H	500 min.	700 min.	15 min.
	Adjuster	JIS G 4105	SCM 440, SCM 430	500 min.	700 min.	15 min.
		JIS G 4052	SCM 440H, SCM 430H	500 min.	700 min.	15 min.
	Bolt	JIS B 1051	12.9 (M20 max.)	(Depending on standard)	(Fllow the left)	(Fllow the left)
			10.9 (M22 min.)	(Depending on standard)	(Fllow the left)	(Fllow the left)



composed of tension members alone. Specifically, compression members and flexural members, as shown in the figure, are also indispensable. It is, therefore, necessary to design the entire frame by selecting suitable tension members and joints, including the above members, which meet the design and structural requirements of the frame.

3. Structural Characteristics of this System

3.1 Obtaining approval of the competent minister in accordance with the Building Standards Law

Materials used in the main structural parts of buildings must be those specified by the Building Standards Law. The materials for the component parts of this system have been selected based on the results of a detailed study of structural characteristics, formability, workability and the costs of many different materials. Therefore, they contain non-specified materials, such as the locked coil rope and Cr-Mo steel used for the component parts. When using any non-specified material, it is necessary to obtain either the approval for it of the Minister of Land, Infrastructure and Transport or a performance certificate certifying that the material in question is comparable in quality to the specified material. There is a tendency that many designers and constructors avoid the former procedure (i.e., obtaining the Minister's approval) because it not only incurs extra cost on the part of the client but also takes considerable time.

For this system, the authors decided to obtain a performance certificate for each of the non-specified materials, omit the troublesome legal procedures and ensure the system's flexibility. The evaluation for certification is applied to the performance of a complete product made of the non-specified materials in question. For example, the PC rod is a JIS-specified item as shown in Table 1. It is widely used as a pre-stressed material for pre-cast concrete. However, since the characteristics of this material as it is fitted to a joint have not been clarified quantitatively, it is necessary to test the combination of the PC rod and joint using actual-size test pieces. In addition, for this system that uses threaded joints and bearing joints, rather than bolt joints or welded joints, for the main structure, it was necessary for us to obtain not only performance certification but also the Minister's approval for the construction method.

3.2 Guaranteed load of this system

Here, the following will describe the full-scale structural experiment carried out to confirm the guaranteed load of each of the system products. The joints of this system have been designed for full strength by using the permissible axial force of the tension member as the design load. Therefore, concerning the product made up of a tension member and a joint (hereinafter referred to as "test piece"), its performance may be guaranteed in terms of the permissible axial force of the tension member. The guaranteed load (Ps) and tensile load (Pu) of the test piece are calculated using the following equations.

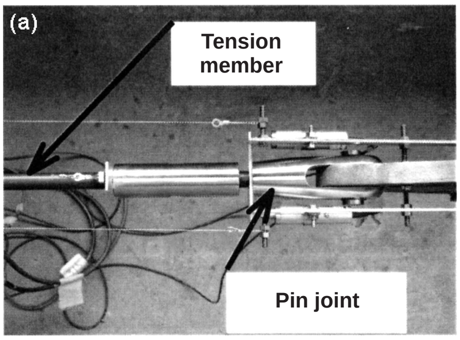
$$Ps = A_t \times F \quad (1)$$

$$Pu = 1.5 \times Ps \quad (2)$$

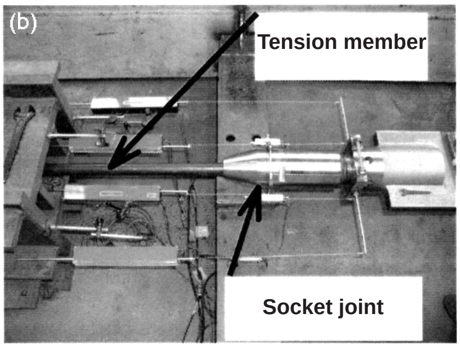
In the above equations, A_t denotes the axial cross-section area of the tension member, and F denotes the reference strength of the tension member. The reference strength of each of the non-specified building materials was decided in accordance with JIS after quality control standards for them were established.

In the experiment, each test piece was set on the jig as shown in **Photos 3** (a) and (b) and subjected to unconfined static load in the axial direction. The application of this load was stopped when the maximum load was confirmed. Examples of test results (tie rod 90 mmϕ, F = 440 Nmm²) are shown in **Fig. 3**. In the figure, the stress represents the load divided by the axial cross-section area of the tension member, and the strain represents the deformation of the tension member divided by its length. The short-time permissible stress and 1.5 times the short-time permissible stress are also shown in Fig. 3. It can be seen that the test piece remains in the elastic region till the short-time permissible stress is reached and that the maximum stress exceeds the short-time permissible stress multiplied by 1.5.

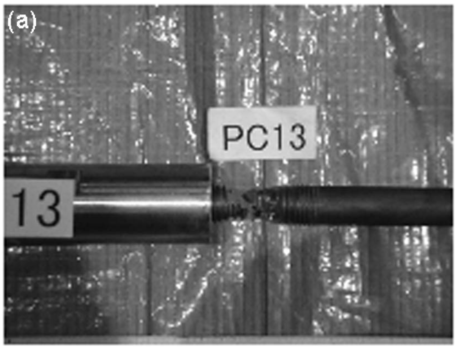
The test piece conditions after testing are shown in **Photos 4** (a) and (b). The joint fitted to the PC rod remained almost unchanged, and the PC rod ruptured at the threaded part (Photo 4 (a)). The tie rod was ultimately constricted at a point on the axle (Photo 4 (b)).



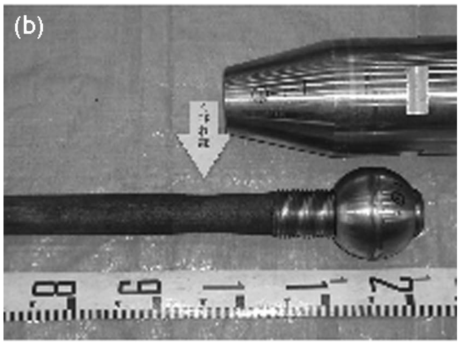
(a) Pin joint



(b) Socket joint
Photo 3 Test setup



(a) Fallure of PC bar



(b) Thined tie rod
Photo 4 Test pieces after the test

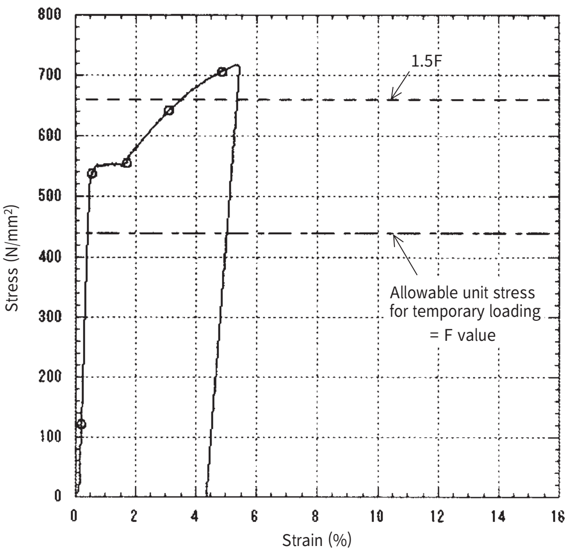


Fig. 3 Stress - strain curve (TR90)

This result suggests that the tie rod will or might rupture at the smallest part of the cross-section area. None of the test pieces experienced rupturing of the joint, although some pins were subjected to flexural deformation. It may be said that the performance of the pin joint, which was designed in anticipation of shear fracture and flexural fracture, was close to its design parameters. Concerning the socket joint, a joint fitted to a tension member at an inclination of 2 degrees was subjected to a load test. The test result was almost the same as that of the unconfined load test.

As the performance requirements of building materials have become increasingly diverse, it is important to confirm their dynamic and ultimate performances. Among others, knowledge about the fatigue characteristics of high-tensile steel rods, which are exposed less frequently than cables, and those of joints which are often custom-designed, is increasing in importance[1]. The Building Construction Division has conducted fatigue tests on high-tensile steel rods and joints. In the fatigue test on the steel rods, it was confirmed that their fatigue characteristics varied according to the thread cutting method used. At present, the methods used to cut threads on PC rods and tie rods largely fall under the following three categories:

1) Machining threads directly onto steel bar
2) Cutting threads by rolling
3) First distressing the part to be threaded to increase the stem diameter, and then machining the thread.

According to the results of a simple tensile test, those test pieces that fractured at the threaded part were the ones whose threads had been cut by methods 1) or 2). In a fatigue test, all test pieces fractured at the threaded part (**Photo 5**). The reason for this is probably that such machining, which dissects the crystal grains in the steel material during threading, adversely affects fatigue performance. Since at present no criteria necessary for fatigue checking are available, we will have to wait for some time until specific criteria are established. Even so, it may be assumed that the method used to cut threads needs to be reviewed at the design stage.

The authors conducted a fatigue test of pin joints, which are among the most widely used joints. There are no established formulae for designing pin joints. Because of this, at present, pin joints are designed using formulae for designing rivet/bolt joints, BS standard formula or Hertz's formula, which is often used in the fields of civil and mechanical engineering[2]. However, since these formulae take plate crevices into account and are supposed to be applied to mechanical parts and bridges whose load repetition environment is far more severe than that of architectural structures, it is necessary to

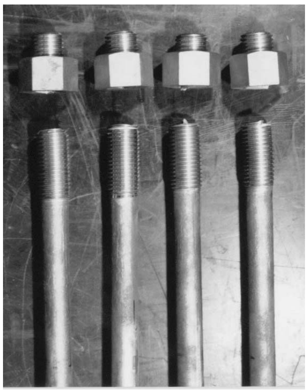


Photo 5 Fatigue failuer of PC bar

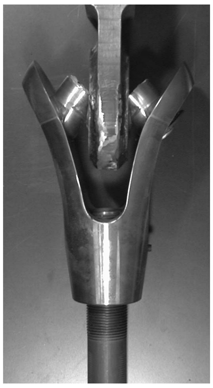


Photo 6 Fatigue failure of pin joint

carefully study the validity of applying them directly in the design of building components. In view of this, from the fracture modes revealed through static tensile tests, the authors devised a new design formula and confirmed the fatigue properties of the test pieces designed using the new formula in a fatigue test. Those test pieces ruptured at the threaded part of the tension member after about 28,000 cycles. On the other hand, test pieces prepared using the rivet/bolt joint design formula fractured at the joint after about 14,000 cycles (**Photo 6**). From these results, it was confirmed that the joints used in this system offer higher fatigue performance than the steel rod and threaded parts.

4. Conclusion

Of the NS tension system, the pin joint type obtained the Minister's approval as a turnbuckle-equivalent product for buildings in 2002 and the socket joint type achieved the same in 2003. These achievements not only enhanced the convenience of this system but also proved that the system has sufficient structural characteristics as a main structure. In addition to the activities described in this paper, the authors have been tackling some significant activities, such as the development of a new tension system equipped with a damping mechanism, although they are not discussed here. As shown by the application examples (**Table 3**, **Photos 7 through 10**), structures

Photo 8 Constractional case (entrance hall)

Photo 7 Constractional case (atrium)

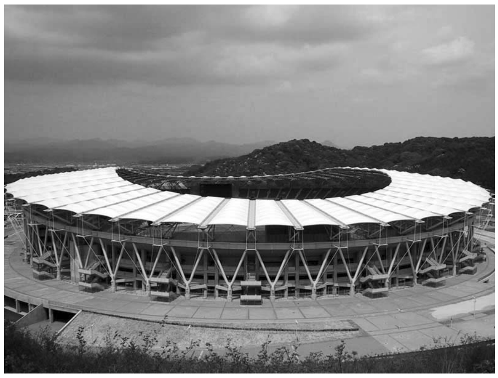


Photo 9 Constractional case (stadium)

Table 3 List of constractional case

Photo No.	Name of building	Application place of tension structure	Main use	Design company	Construction company	Completion year	Remarks
1	Gymnasium of Kure City "Oak Arena"	Roof	Gymnasium	YASUI ARCHITECTS & ENGINEERS, INC.	KAJIMA Corporation J.V.	2002	Tie rod 2-42mmϕ pin joiunt
2	Sasebo Saikai Pearl Sea Center	Wall	Museum	FURUICHI & ASSOCIATES	TAISEI Corporation J.V.	1993	Stainless wire 19mmϕ pin joint
7	I·K Building (atrium)	Roof	Office	NIKKEN SEKKEI	OBAYASHI Corporation	1991	PC bar 32mmϕ socket joint
8	SHINSEI BANK (entrance hall)	Wall, roof	Office	NIKKEN SEKKEI	TAKENAKA Corporation	1992	PC bar 13mmϕ buried type joint
9	Ogasayama Sports Park "ECOPA"	Roof of seat	Stadium	AXS SATOW INC., Prof. Masao Saitho, Structual Design PLUS ONE joint venture (J.V.)	KAJIMA Corporation J.V. (No.1 building construction area)	2001	Tie rod 75mmϕ with damping device
10	Suzukake Hall of Tokyo Institute of Technology	Roof	Hall	Educational Facilities Institute	KONOIKE Construction J.V.	2002	PC bar 13mmϕ, 32mmϕ both with pin joint and socket joint

Photo 10 Constractional case (hall of university)

employing this system have been constructed at various parts of the country, demonstrating the superb characteristics of this system. In the future, the authors intend to continue developing new structural systems that offer a wide variety of attractive spaces.

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2) Takeuchi, T.: Systematization of Tension Structures and their Dynamic Performance, Doctor Thesis, Tokyo Institute of Technology, 2001