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Development Engineering of Special Large-Space Steel Structures at Building Construction Division of Nippon Steel

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Abstract:

The development engineering of special large-space steel structures based on steel structures at Nippon Steel's Building Construction Division can be divided into four levels: development of building frameworks, development of steel frames, development of structural parts, and development of steel structural material application technology. Among the recent development engineering results of large-space steel structures, a roof panel system and a composite floor panel system are described as examples of building framework development, and an NS tension system and a single-layer shell structure of the engagement joint type are introduced as examples of steel frame development.

1. Introduction

The development engineering of special large-space structures based on steel structures at Nippon Steel's Building Construction Division includes a space frame system (called the NS truss), a welded truss structure system composed of rectangular steel pipes welded at an angle of 45° (called the Y truss), a bolted single-layer shell structure (called the S dome), a retractable roof system, and an artificial ground structure system. The product groups that are outcomes of these technology development efforts can be classified into four levels according to the application of Nippon Steel's steel structure technology in the large-space structure market: development of building frameworks, development of steel frames, development of structural parts, and development of steel structural material application technology (see **Table 1**).

Table 1 Hierarchy in special large-space structure field

Hierarchy in special large-space structure field	Example of development engineering
Development of building frameworks	Retractable roof system and artificial ground structure system
Development of steel frames	NS truss, Y truss, and S dome
Development of structural parts	Technology for manufacturing parts, such as forged or cast parts
Development of steel structural material application technology	Fire-resistant steel, TMCP steel, titanium-clad steel, and stainless steel

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The development of building frameworks is based on steel structure technology or product technology and designed to propose a total building framework system, including finishing materials and equipment, as represented by a retractable roof system and an artificial ground structure system. This type of development is aimed at making the most of the characteristics of steel frames as structural members in building frameworks. The development of steel frames amounts to the development of steel structure products adapted to large space structures, as represented by the NS truss, Y truss, and S dome. These products are systematized structures by themselves. The development of structural parts is concerned with basic parts for building frameworks and steel frames, as represented by forged and cast parts for the NS truss. Lastly, the development of steel structure material application technology is a search for the methods of using new materials, such as fire-resistant steel, TMCP steel, titanium-clad steel and stainless steel, or engineering concerned with steel performance properties, such as weldability, impact strength and corrosion resistance.

Drawing upon the results of large-space steel structure development engineering at Nippon Steel's Building Construction Division in recent years, this article outlines a roof panel system that combines the roof finishing material and steel structure of a large space structure and a composite floor system for high-rise office buildings as examples of building framework development, and an NS tension system equivalent to a tension structure and a single-layer shell structure of the engagement joint type (a new joining method) as examples of steel frame development.

2. Roof Panel System

The roofs of large-space structures are classified into steel structures, represented by trusses, and roof finishing materials, including secondary members of main buildings. The conventional method of constructing a roof on steel frames can no longer accommodate the increasing size of long-span structures and the increasing diversification of roof shapes. It is necessary to develop a rational roof system that makes good use of the characteristics of a steel structure or to construct the roof finishing materials structurally. A rational roof panel system was developed by the adoption of the "stressed skin construction" method whereby the roof finishing materials are assembled into panels to provide a stiffening effect against the buckling of the roof structure and to make positive use of the shear rigidity of the panels.

The roof panel system adopted in the Sun Dome Fukui (see **Photo 1**) is introduced as an actual example. (Designed by Professor Shigeyuki Okazaki of Fukui University and Professor Mamoru Kawaguchi of Hosei University) The multipurpose hall measures about 115 m in diameter. A tension ring of steel pipe is installed at the outer circumference of the dome, and compression rings also made of steel pipe are installed at the inner circumferences of the dome. The tension and compression rings are joined by trusses (see **Fig. 1**). The truss structure has steel pipes arranged as upper chords in a lattice pattern and uses H shapes as upper chords and diagonals. The diagonals are alternately arranged vertically and horizontally. A dustpan-shaped roof panel is set in the space bounded by the diagonal and upper chord members (see **Photos 2** and **3**). The roof panel is composed of four steel plates. The vertical and horizontal steel plates are each fitted with slanting plates on the right and left sides and are connected to the structural framework at four intersections with the upper chord and at one intersection with the lower chord. The roof panels are designed to withstand a snow load (sustained load) of 600 kgf/m^2. They must be rigid enough to withstand the snow load and must carry the snow load to the four support points. The engineering of the roof panels may be summarized as follows:

(1) The four steel plates are made of 3.2-mm thick weathering steel and joined by welding. When the steel plates are joined by

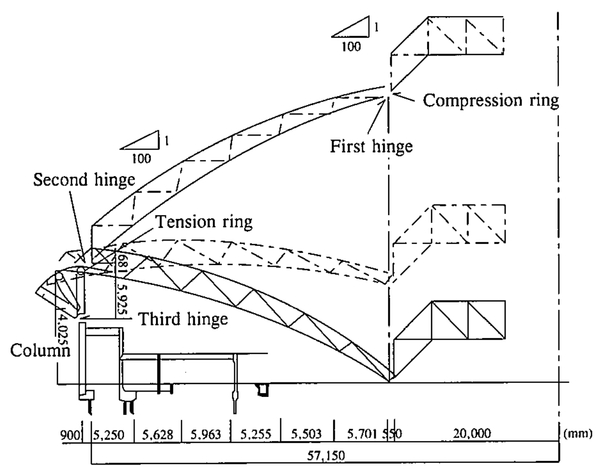

Fig. 1 Roof structure of Sun Dome Fukui

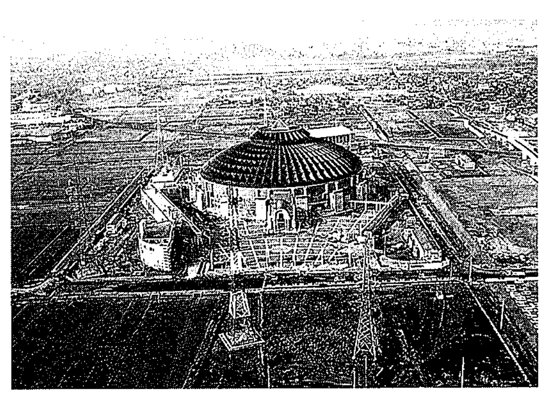

Photo 1 General view of Sun Dome Fukui

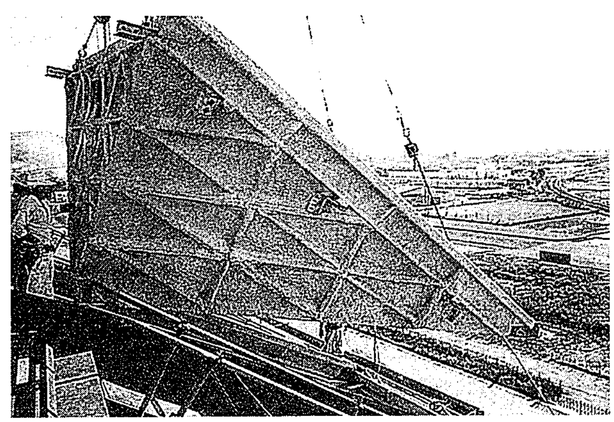

Photo 2 Roof panel of Sun Dome Fukui

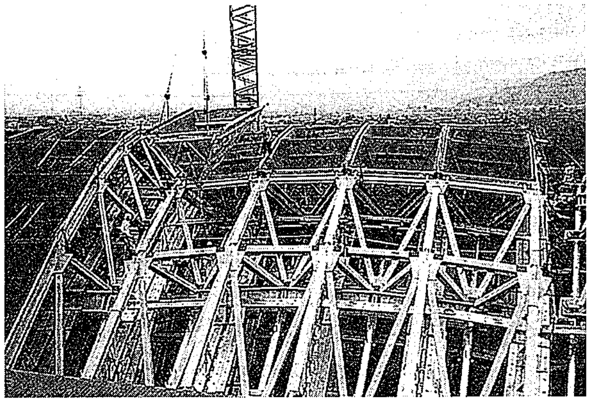

Photo 3 Roof panel system of Sun Dome Fukui

bolting and sealing, the seal may break and leak due to their dimensional variability and their expansion and contraction with temperature change.

(2) Panel reinforcing members are arranged to form a triangle similar to that of the panel as shown in **Photo 3**. The panel and the reinforcement work together to produce a shape effect, which in turn is expected to act effectively against the snow load.

(3) The roof panels form a trigonal pyramid and can be regarded as structural parts of high rigidity. They thus stiffen the upper chords and diagonals of the truss against buckling.

Another example is the wall panel system of the Beacon Plaza Global Tower, designed by Isozaki Arata Atelier and Mamoru Kawaguchi Structural Design Office, which are shown in **Photo 4**. The wall panels are finished with titanium-clad steel. The titanium-clad steel has 0.2-mm thick commercially pure titanium brazed to 2.0-mm thick carbon steel by interposing copper. This composite material combines the corrosion resistance of the surface titanium with the rigidity of the underlying carbon steel (see **Photo 5**). The titanium-clad steel was formerly used for bridge piers in the civil engineering field. In the Beacon Plaza Global Tower, it was formed into panels and used as the first finishing material of a building.

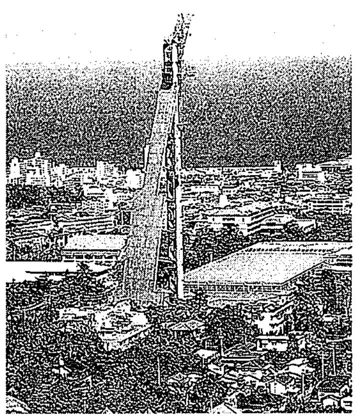

Photo 4 General view of Beacon Plaza Global Tower

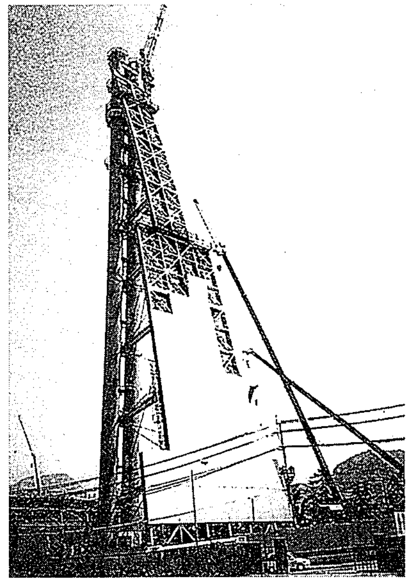

Photo 5 Wall panels of Beacon Plaza Global Tower

3. Composite Floor Panel System

The floor structure of high-rise office buildings generally consists of deck plates placed on steel girders and beams and concrete cast on the deck plates. Steel frames are often erected over a long span in excess of 15 m to make more effective use of office space. This increases the depth of the steel girders and beams and reduces the space available for office use. The conventional floor structure is characterized by many site jobs, such as deck plate installation, steel frame fire-resistant covering, and concrete placement. A composite floor panel system was developed to use steel and concrete in combination by making good use of their respective properties, thereby reducing the beam depth. The composite floor panel system can thus decrease the story height of office buildings and increase the number of stories for the same building height as compared with the conventional floor system. The construction cost of office buildings can be reduced as a result. As compared with the conventional floor construction method, the shop fabrication ratio of floor components can be increased to decrease the site construction labor and time requirements.

A composite floor panel is constructed as illustrated in **Fig. 2**. Flange plates (1.6-mm thick) and web plates (2.8-mm thick) are welded into a box. Concrete prestressing steel wires are arranged below the bottom surface of the steel box, the wires and the bottom flange plate are tensioned together, and concrete is cast and prestressed there. These composite floor panels are prefabricated at the shop, transported to the construction site, and set on the floor surface of the building. Concrete is then cast on the floor panels as shown in **Fig. 3**. Finally sandwiched between the concrete slabs, the composite floor panels are provided with high section modulus. The prestress is introduced from the steel plates to the concrete through steel plate projections, called cotters. The cotters serve as devices for transmitting the shear forces of the steel plates and concrete after completion. The fire-resistant performance of the composite floor panel system is assured by the concrete slabs. Fire

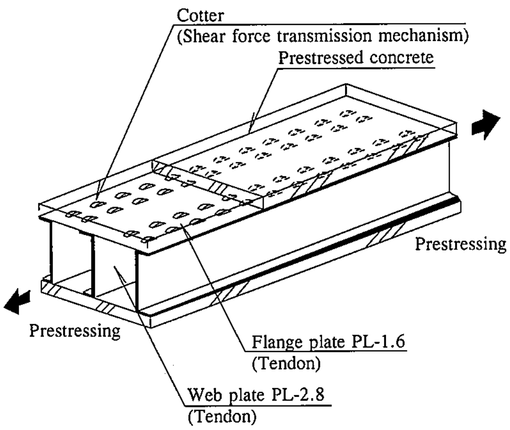

Fig. 2 Schematic illustration of composite floor panel

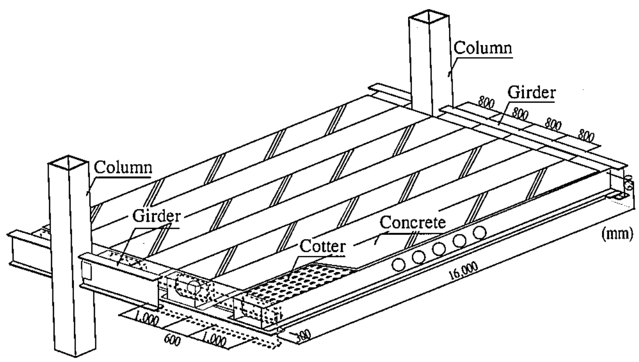

Fig. 3 Installation of composite floor panels

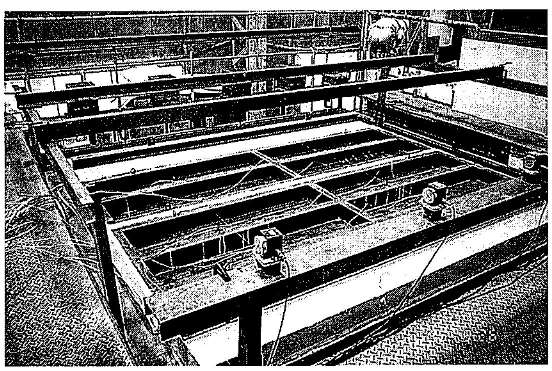

Photo 6 Fire resistance test of composite floor panel

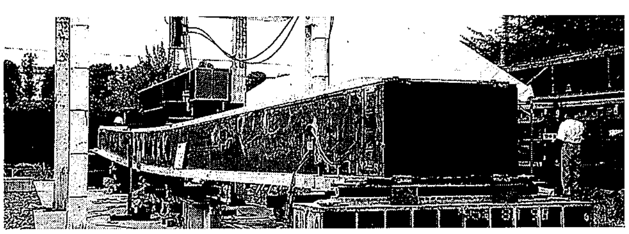

Photo 7 Cyclic bending test of composite floor panel

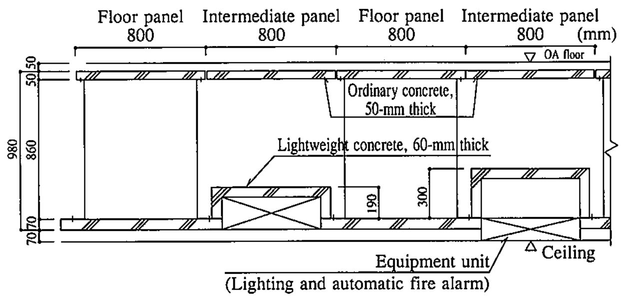

Fig. 4 Composite floor panel equipment drawing

resistance test results confirm that the composite floor panels meet the 2-hour fire rating without steam spalling in the concrete (see **Photo 6**). The service performance of the composite floor panels was also checked by conducting various experiments, such as an experiment to confirm the prestressing force transmission efficiency of the steel plates, an experiment to verify the shear strength of the shear force transmission mechanism, and an experiment to determine the cyclic bending strength of the composite panel (see **Photo 7**).

Air-conditioning ducts, lighting equipment, smoke exhaustion equipment, and the like can be installed in the composite floor zone of the floor structure to reduce the story height of the office building. As shown in **Fig. 4**, the composite floor panels can be spaced to provide for installation of such equipment.

4. NS Tension System

The string beam structure that uses steel ropes or rods as tension members, the suspension structure, the cable dome structure (see **Fig. 5**), and the sashless glass facade all support facilities, among other things. These structures have come into frequent use as methods for creating a light and open space.

The tension members used in these roof structures can be grouped into steel wire ropes, such as strand ropes, spiral ropes, and parallel wire strand (PWS) ropes used in bridges; rods, such as tension rods and concrete prestressing high-strength steel rods; steel pipes; and flat steel bars. Steel tension ropes are highly responsive to deformation and easy to use, but they call for special wire anchoring methods and are difficult to paint. Application of an organic coating or a hot-dip galvanized coating or use of stainless steel wires make such steel tension ropes expensive tension members. Steel tension rods can be painted and matched with sur-

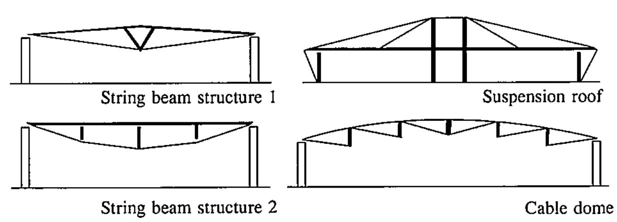

Fig. 5 Tension structures

rounding steel frames in finish, but respond poorly to large deformation and develop excessive bending stress when they move or rotate at their ends. These conditions make it difficult to join them.

A tension system, called the NS tension system, was developed to make up for the shortcomings of conventional tension members. The NS tension system has joints with a rotation follow-up function to connect steel wire ropes or rods and is fitted with mechanisms to introduce the initial tension (prestress) and adjust the length.

Three types of joints with excellent appearance and compact shape were developed for the NS tension system. **Fig. 6** shows the socket type of joint. A spherical nut is fitted at the end of a steel rod or wire and encased by a spherical socket. The spherical socket is then connected to a node with a bolt or an NS truss bolt. This type of joint is best suited for combined use with the NS truss. **Fig. 7** shows the embedded type of joint. A spherical nut is embedded in a solid joint, and a spherical cover is screwed onto the spherical nut. This type of joint involves a high degree of fabrication, but presents the most neat appearance. **Fig. 8** shows the pin type of joint. A joint pin is combined with a length-adjusting coupler, and a prestressing mechanism is added to the combination. This type of joint can be used to connect tension members to columns and beams through gusset plates.

The socket type and the embedded type can accommodate the rotation of the tension members to 2 to 3° in each direction, while the pin joint type can allow the tension members to rotate 90° or more in one direction. The length of the tension members is adjusted by the rotation of the socket, spherical cover, and coupler for the socket, embedded, and pin joint type, respectively. The tension members are prestressed by applying an external force with an oil jack or the like, tightening the length adjusting mechanism, and releasing the external force.

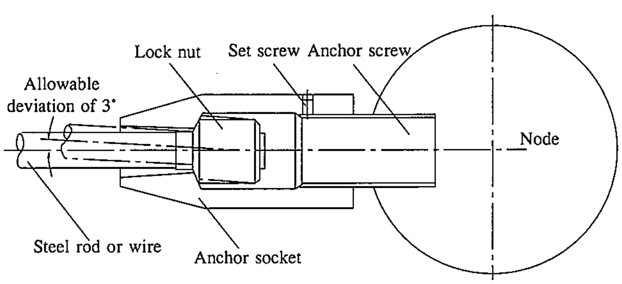

Fig. 6 NS tension system (socket joint type)

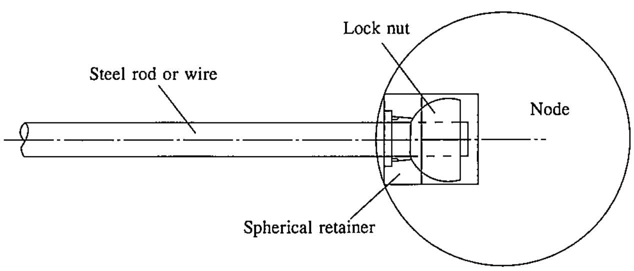

Fig. 7 NS tension system (embedded joint type)

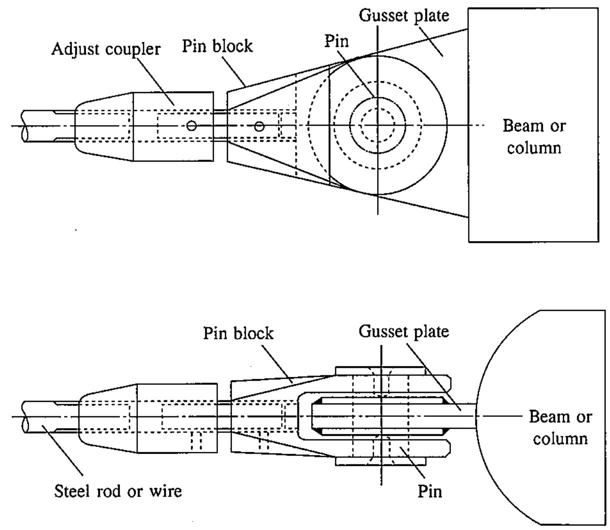

Fig. 8 NS tension system (pin joint type)

The NS tension system is used in tension roof systems, such as string beam structures, suspension structures and cable dome structures, and tension glazing systems for sashless glass facades. Examples are presented below.

The string beam structure of the atrium roof of the IK Building (designed by Nikken Sekkei Ltd.) (see **Photo 8**) is cited as an example of the tension roof system. The roof is an H-shape grid conforming to the building module and supported by tension and bundle members. The tension members are concrete prestressing steel bars (Grades A and C and 32 mm in diameter), and the bundle members and nodes are NS truss parts. The tension members have socket joints at their ends.

The atrium of the head office building of the Long-Term Credit Bank of Japan (designed by Nikkei Sekkei Ltd.) (see **Photos 9** and **10**) is introduced as an example of the tension glazing system. The atrium is divided into south and north sides. The south side is a glass system of Pilkington of the United Kingdom, and the north side is a glass system termed the RFR system. The NS system is adopted to support both glass systems.

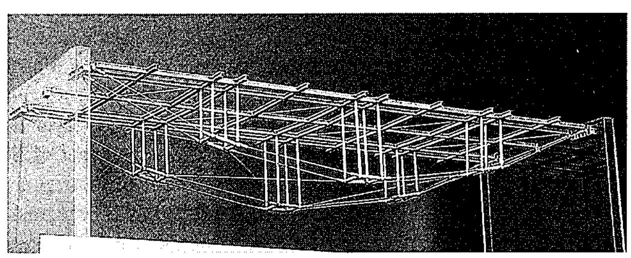

Photo 8 Model of atrium structure of IK building

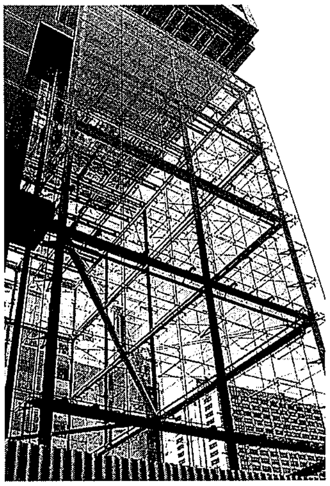

Photo 9 Atrium of head office building of Long-Term Credit Bank of Japan

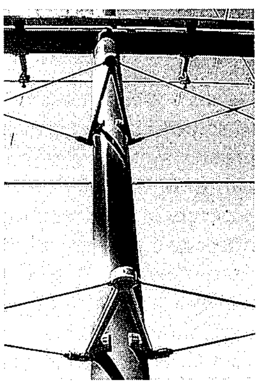

Photo 10 Detail of atrium of head office building of Long-Term Credit Bank of Japan

5. Single-Layer Shell Structure with Engagement Joints

Unlike conventional steel structure joining methods like welding and bolting, an engagement joint connects members by tensioning and tightening the rings at the ends of the members. The engagement joint was initially developed for connecting steel columns and beams. It is also a suitable method of connection for single-layer shell structures over a long span.

The single-layer shell structure covers a space with fewer members than the double-layer space frame, can be reduced in height, and can create a more lighthearted space. To span a large space, the single-layer shell structure calls for fully strong and rigid and highly reliable joints. Particularly with a single-layer lattice structure whose out-of-plane rigidity is lower than that of the double-layer space frame, the buckling safety factor of the frame is low, and the buckling load is greatly reduced by initial irregularities, such as upper member fabrication errors and erection errors. The single-layer lattice structure also demands a joint system of high accuracy. The engagement joint is a mechanical joint, is free from distortion of welding and play of bolting, eliminates clearance between members, and is extremely high in accuracy.

Fig. 9 shows the composition of the engagement joint system. Partially cylindrical plates (end plates) are welded to the ends of members. Upper and lower prestressed rings are installed onto the end plates to fasten the end plates to the cylindrical steel pipe (core drum) at the center of the joint. The contact pressure introduced into the joint transfers the stress from one member to the other. The end plates and the prestressed rings are tapered in cross section. When the prestressed rings are installed onto the end plates by a hydraulic jack as shown in **Fig. 10**, tension is introduced into the prestressed rings. The magnitude of the prestressing force introduced into the prestressed rings depends on the hoop tension produced by the tensile force applied by the end plates to the prestressed rings. Caps and steel bars are installed through the core drum to prevent the prestressed rings from coming off.

To investigate the strength and deformation performance of the engagement joint system, 1/2-scale specimens were loading tested. Some of the loading test results are introduced below.

Fig. 11 schematically shows a specimen and a loading apparatus. Each specimen consists of an engagement joint and some pipe parts. Simple tension test, simple bending test, and bending test while monotonically increasing load in constant tension were conducted on the loading apparatus. In the simple compression test, specimens, each composed only of an engagement joint, were directly loaded on an Amsler versatile testing machine. Specimens were prepared in two types with different ring thicknesses. The

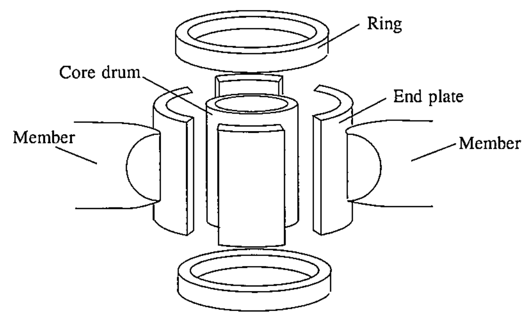

Fig. 9 Composition of engagement joint system

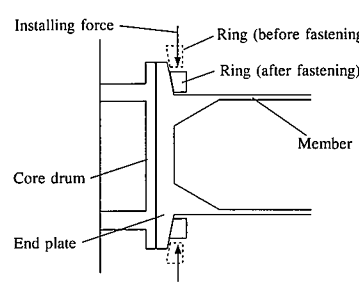

Fig. 10 Method for introducing tension into ring

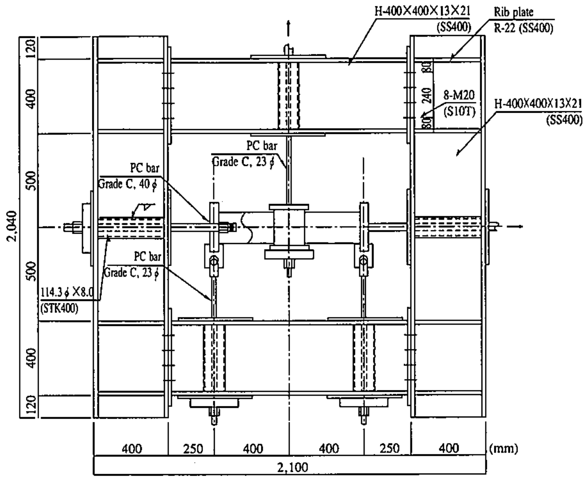

Fig. 11 Schematic illustration of specimen and loading apparatus

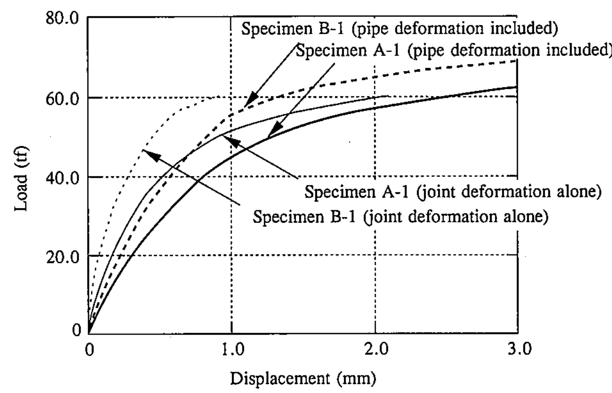

Fig. 12 Load-displacement curves in simple tensile test

Table 2 Required maximum load capacity

Loading condition	Required maximum load capacity	
	Full scale	Reduced specimen (1/2)
Tension	200 tf	50 tf
Compression	300 tf	75 tf
Bending	35 tf·m	4.4 tf·m

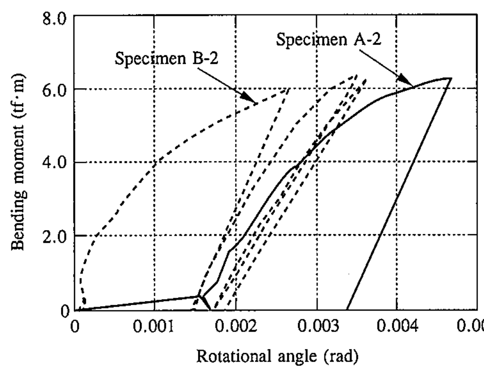

Fig. 13 Bending moment-rotational angle curves in simple bending test

average ring thickness was 12.7 mm for type A specimens and 19.1 mm for type B specimens. The tensile force introduced into the prestressed rings is designed at 19 tf. This translates to a stress of 60 kgf/mm^2 (strain of 0.29%) for type A specimens and a stress of 40 kgf/mm^2 (strain of 0.19%) for type B specimens. Specimens are 1/2-scale models of joints designed for use in a cylindrical roof with a span of 36 m. The required maximum load capacity is set as shown in **Table 2**, based on the stress produced in the cylindrical roof. The results of the respective tests are summarized below.

(1) The simple tensile test results are shown in **Fig. 12**. The load-displacement curves start to exhibit nonlinear properties of the softening type at such a low load level that the strain is below the elastic limit. This finding suggests that the disengagement of the end plates from the core drum before the onset of plasticization reduces the rigidity of the joint.

(2) The simple bending test results are shown in **Fig. 13**. In the initial stage of loading, pronounced distortion is observed in the specimen A-2. The straight lines shown at the lower left corner of **Fig. 13** indicate the flexural rigidity of the most rigid of semirigid ball joint specimens of approximately the same scale as the engagement joint specimens in loading tests. This result means that the engagement joint system has extremely high rigidity as compared with the conventional ball joint system.

(3) The simple compression test results are shown in **Fig. 14**. The engagement joint specimens retain high enough rigidity and strength in compression as well. They exhibit stable deformation characteristics as noted in the simple tensile test.

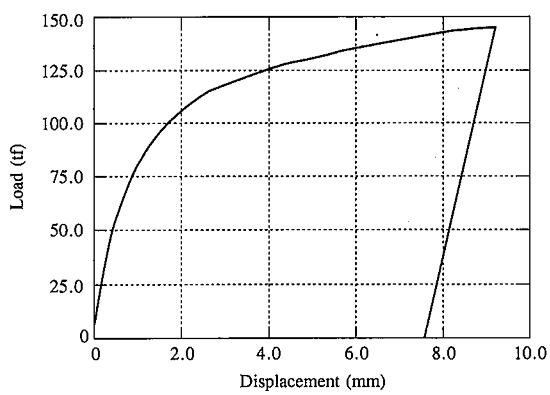

Fig. 14 Load-displacement curve in simple compression test

(4) The fracture load results are shown in **Fig. 15**. The type of fracture is the bending shear fracture of the end plates for all specimens.

The engagement joint was modeled by an expansion spring and a rotational spring, based on the joint loading test results. The linear stress analysis and geometrical nonlinear analysis of a single-layer space frame were conducted to investigate the effects of the engagement joint system on the mechanical properties of the single-layer space frame.

The analytical model was a cylindrical single-layer space frame with a span of 36 m as shown in **Fig. 16**. The analytical load conditions are given in **Table 3**. The nodes 1 and 2 are pin supported, and the nodes 3 and 4 are roller supported. The nodes 1 and 3 and the nodes 2 and 4 are connected by tie bars, respectively. The space frame is constructed of round pipe members, measuring 350 mm in diameter and 20 mm in wall thickness. The tie bars are of the same cross section as the round pipe members. Young's modulus is 2.1×10^3 kgf/mm². A pseudo pin joint condition was given as 1/1,000 of the in-plane flexural rigidity of the joint. The out-of-plane and axial rigidity of the joint were represented by expansion and rotational springs, respectively. A member model was established as shown in **Fig. 17**. The constants of the expansion and rotational springs were determined from the results of the simple tensile, simple compression, and simple bending tests. A completely rigid joint model that does not evaluate the rigidity of the joint and a model that simulates a joint of relatively low rigidity like a ball joint (the rigidity of the rotational spring is put at 1/20 of that of the engagement joint) were also analyzed for the purpose of comparison.

Fig. 18 shows the load-displacement curves obtained by geometrical nonlinear analysis with fixed load taken as the load mode. The displacement is the vertical displacement at the midspan. The difference in behavior between the structures is small as compared with the difference in rigidity between the joints. The displacement of the ball joint model is about twice as large as that of the completely rigid joint model, while the displacement of the model that evaluates the rigidity of the engagement joint is increased by only about 20%.

As an example of single-layer shell structure constructed with engagement joints, the canopy of Ohmori Bell Port (designed by Yamashita Sekkei) is shown in **Photos 11** and **12**.

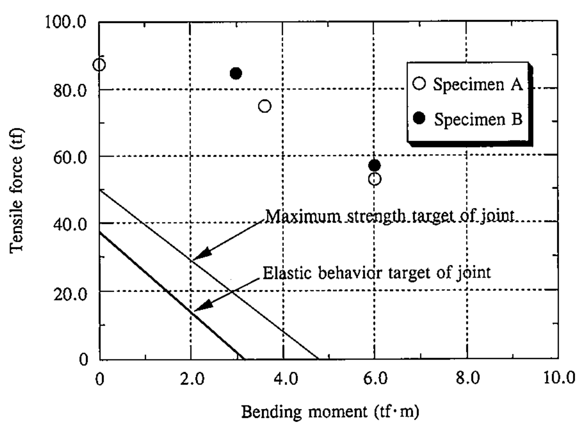

Fig. 15 Fracture load

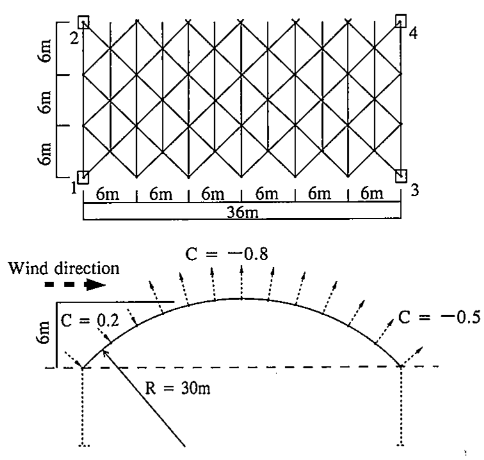

Fig. 16 Space frame analytical model

Table 3 Analytical load condition

Dead load	Node load = 150 kgf/m²
Wind load	Design wind speed pressure = 280 kgf/m²

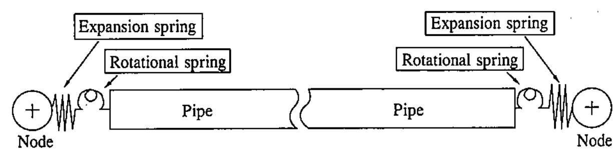

Fig. 17 Joint-member model

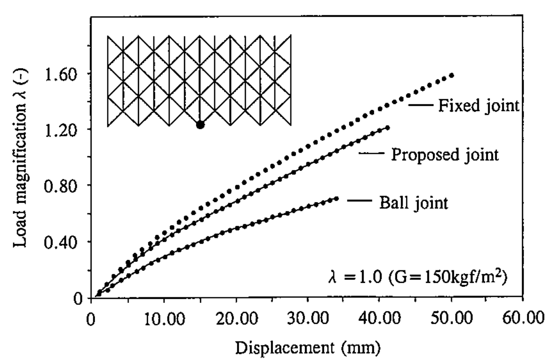

Fig. 18 Load-displacement curves in geometrical nonlinear analysis

Photo 11 General view of canopy of Ohmori Bell Port

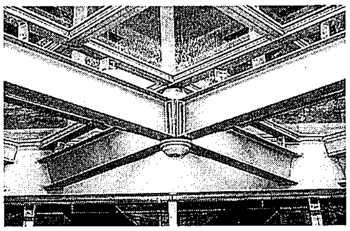

Photo 12 Engagement joint in canopy of Ohmori Bell Port

6. Conclusions

A roof panel system, a composite floor panel system, an NS tension system, and a single-layer shell structure constructed with engagement joints have been introduced as examples of development engineering in the field of special large-space structures based on steel structures at Nippon Steel's Building Construction Division. It is important to carry out development engineering not only for the development of commercial structural systems, such as the NS truss, Y truss and S dome, but also for the development of steel structural material application technology for building frameworks. The authors will continue their work to accomplish these goals in cooperation with people in various areas.