11 WCEE

Paper No. 1752. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

FULL-SCALE TESTS ON CABLE TRUSS STRUCTURE UNDER COMBINED AXIAL AND TRANSVERSE LOADS

H. TOKINOYA[1], H. TANIGUCHI[1], K. WATANABE[2],
S. TAWARA[1], Y. OKUDA[1] and Y. TAKAHASHI[1]

[1]OBAYASHI Co., 3, Kanda tsukasa-cho 2-chome, Chiyoda-ku, Tokyo 101, Japan
[2]Structural Design Group Co., Ltd., 9-9-101, Hiroo 5-chome, Shibuya-ku, Tokyo 150, Japan

ABSTRACT

Full-scale tests on a cable truss structure have been conducted to use it as a seismic member subjected to combined high axial load and transverse one. This report presents results of tests: tests on pre-tensioning construction of cables, such as measuring cables' stresses and cables' friction against their supporting equipment; and tests on elastic-plastic behavior of the cable truss under seismic loading conditions. The proper lubricant reduced the coefficient of friction to 0.1 under. Measuring the strain of cable-end equipment was the best method of measuring the cables' stresses. Yield of steel and the loss of some cables' tension reduced the stiffness of the cable truss after the loads exceeded the design ones. The maximum strength of the cable truss, however, exceeded two times the design loads. The cable truss had enough capacity for bearing seismic load. The comparison between the tests and the numerical analysis shows that the simple method, which neglected the cables' friction against their supporting equipment, simulated the behavior of the cable truss.

KEYWORDS

tension structure; cable truss structure; friction; lubricant; full-scale test.

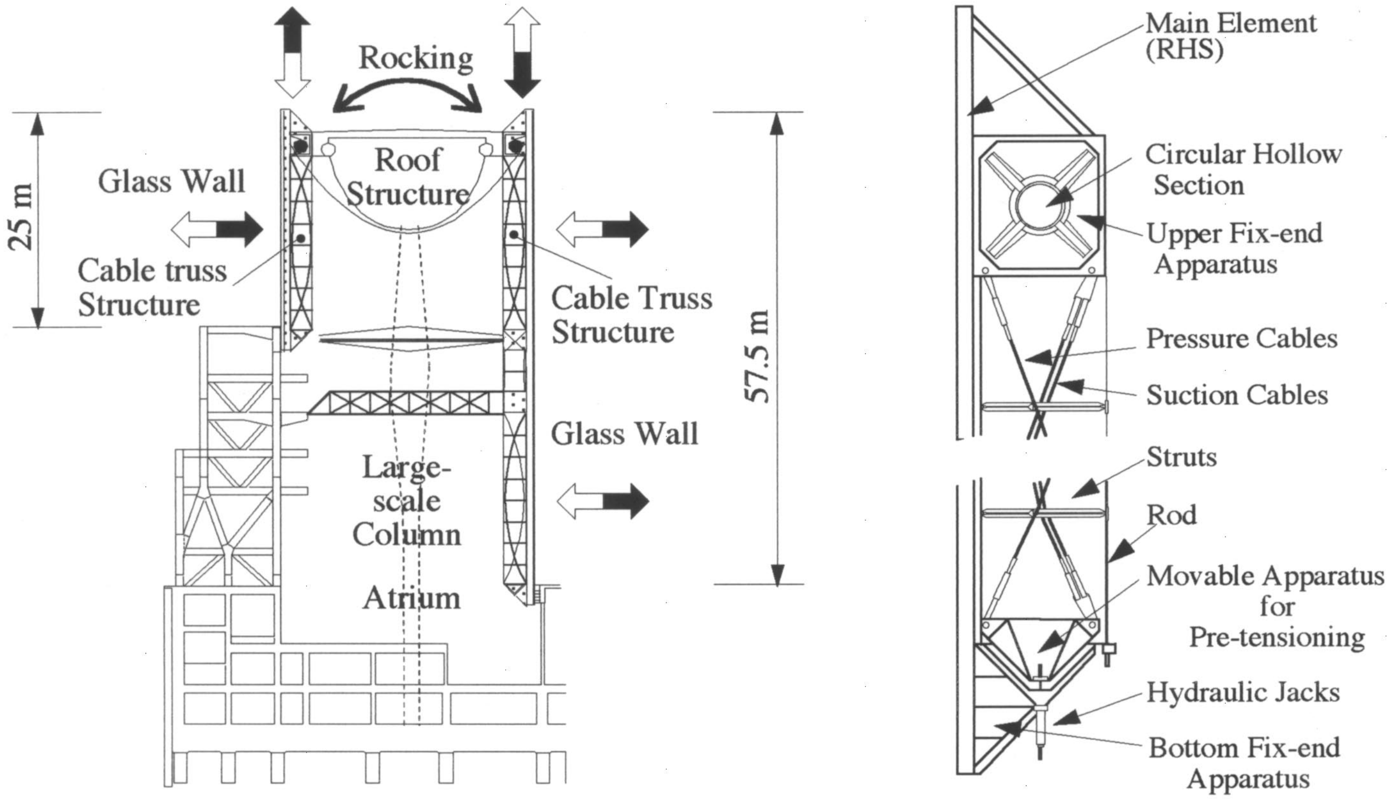
INTRODUCTION

As Eekhout (1990) and Houghton (1992) indicated, tension structures have been often used to many buildings to create transparent clear glass halls, facades and atriums. Most tension structures take over only the horizontal windforces. The tension structure used for GLASS HALL of TOKYO INTERNATIONAL FORUM designed by Rafael Vinoly Architect k.k. is unique because it resists combined transverse loads and vertical loads.

Fig. 1 (a) shows the cross section of GLASS HALL. GLASS HALL has large-scale glass walls, of which sizes are 57.5 m and 25 m high. The tension structures, called the cable truss structures, not only support the glass walls but also prevent the roof structure rocking during earthquake, therefore high axial forces and transverse forces apply to the cable structures. High axial forces reduce cables' tension and thus they reduce stiffness of the whole structure.

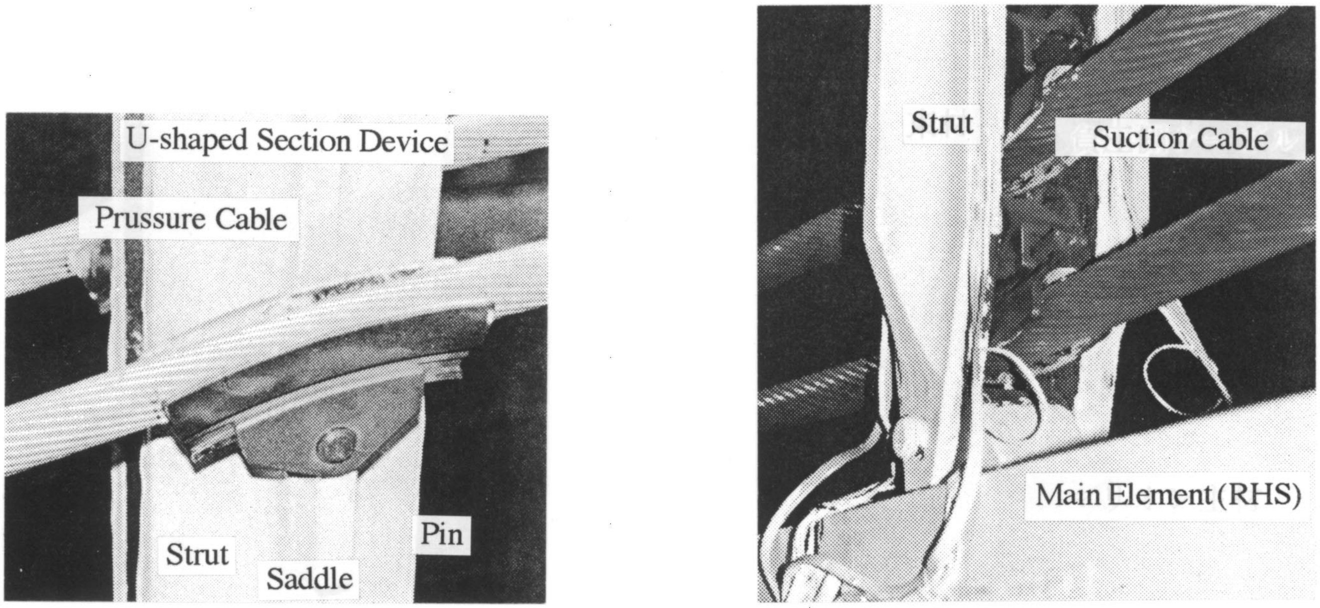
The cable truss structure consists of pre-tensioned cables and steel elements including main steel rectangular hollow section, struts and rods. The cables are attached to the struts loosely and move on their supporting equipment, and they consequently cause friction against their supporting equipment. Friction affects on the longitudinal distribution of cables' tension. These two phenomena of high axial forces and friction make it difficult to estimate the load bearing capacity of the cable truss. Thus, tests with a full-scale model were conducted to take basic data on pre-tensioning construction of cables, such as measuring cables' stresses and cables' friction against their supporting equipment; and to investigate load bearing capacity of the cable truss. All of details, materials and specifications were just same as those of the real structure, because details of the cables' supporting equipment affect on the friction mechanism.

This report presents results of tests on pre-tensioning construction of the cables and results of tests on elastic-



(a) Cross section GLASS HALL

(b) Details of cable truss structure



(c) Photo of details of pressure cable supporting equipment

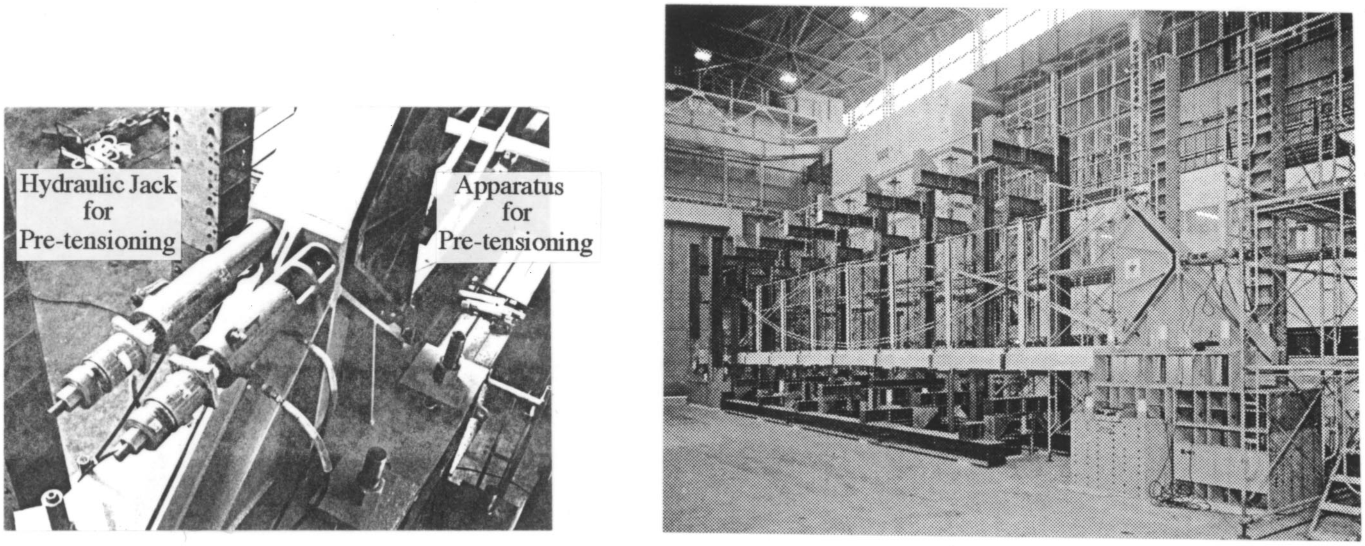
(d) Photo of details of suction cable supporting equipment

Fig.1 GLASS HALL and cable truss structure

plastic behavior of the cable truss under seismic loading conditions. Results of analytical study with simple models, comparing them with experimental results, are also described.

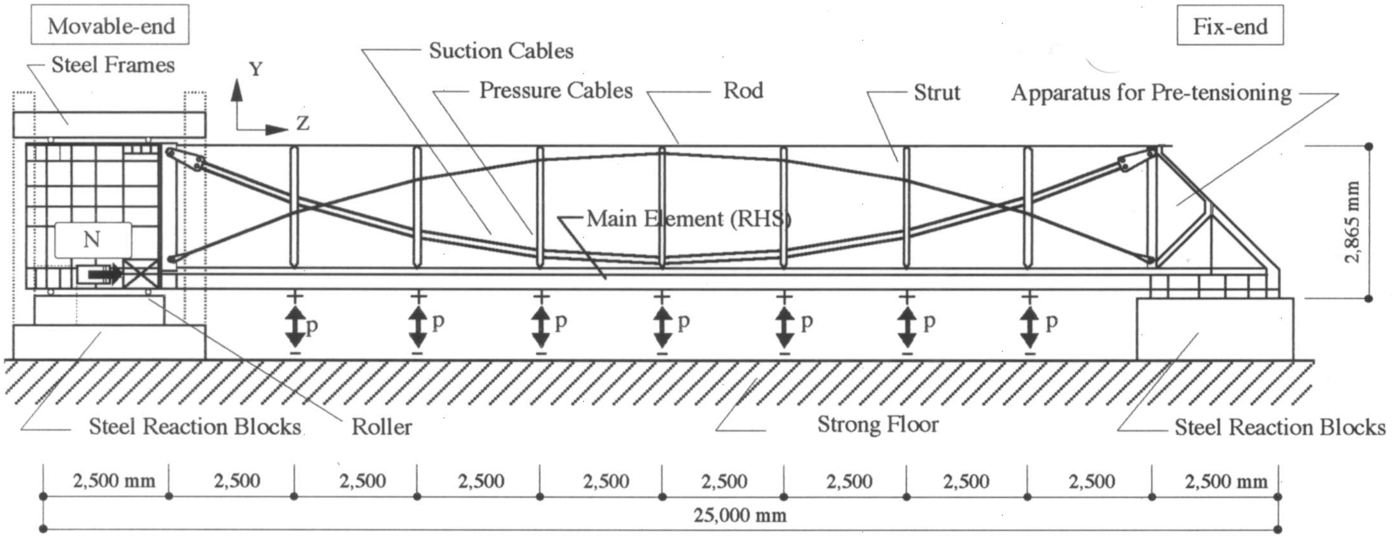
CABLE TRUSS STRUCTURE

Fig. 1 (b) shows details of the cable truss, for example, of 25 m height. The cable truss consists of two pairs of pre-tensioned cables, a main element (rectangular hollow section), struts and a rod. Each cables is fixed to a



(a) Photo of details of fixed-end and hydraulic jacks for pre-tensioning

(b) Photo of specimen and loading apparatus



(c) Elevation of specimen

Fig.2 Set up of specimen

rectangular steel plate at an upper end and a triangle steel plate at a bottom end. Each cables is pre-tensioned to 18 tf, 23 % of ultimate strength, by pulling the triangle plate down. Each struts is pinned to RHS and a rod. A rod is fixed to the top rectangular plate and the bottom triangular plate.

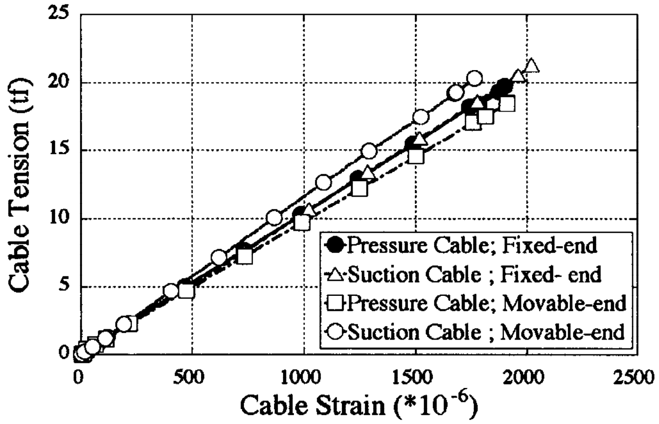
Fig. 1 (c) and (d) shows details of crossover point of cables and struts. The cable supporting equipment consists of three devices, a U-shaped section device, a saddle and a pin. The cables can move on the U-shaped section device because they are not fastened, and interface between cable and the U-shaped section device is coated with lubricant. Further, interface between the U-shaped device and the saddle is coated with PTFE. The U-shaped section device moves on the saddle only after pre-tensioning, because a stopper fixes the U-shaped device to the saddle during pre-tensioning.

PRE-TENSIONING CONSTRUCTION TEST

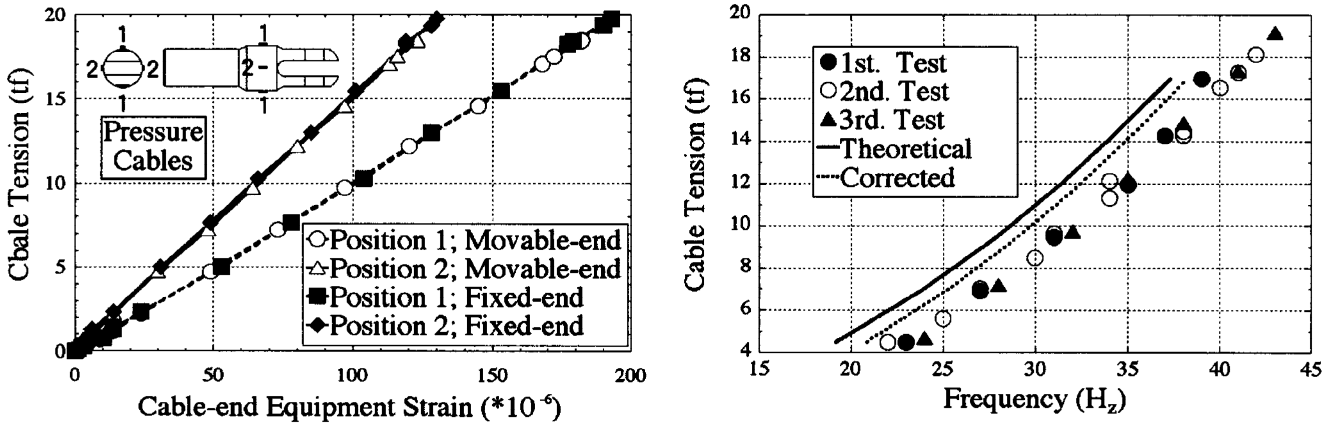
Tests on cables' friction against their supporting equipment and measuring cables' stresses were conducted, on erecting a specimen for the structural test mentioned below. In the tests on cables' friction, two types of

	Lubricant	Coefficient of Friction				
		Pressure Cables		Suction Cables		Mean
		1	2	1	2	
TEST1	5510	0.118	0.144	0.124	0.139	0.131
TEST2		0.078	0.148	0.130	0.149	0.126
TEST3		0.102	0.151	0.133	0.147	0.134
Mean		0.099	0.148	0.129	0.145	0.130
TEST4	5510 + PTFE	0.123	0.100	0.086	0.068	0.094
TEST5		0.122	0.122	0.094	0.066	0.101
TEST6		0.120	0.121	0.092	0.066	0.100
TEST7		0.117	0.105	0.074	0.073	0.097
Mean		0.120	0.112	0.086	0.068	0.097

(a) Measured coefficient of Friction between Cable and Supporting Equipment



(b) Measured Cable Strain versus Strain



(c) Measured Cable tension versus Cable-end equipment strain

(d) Measured Cable Tension versus Frequency compared with Theory

Fig.3 Test results of pre-tensioning tests

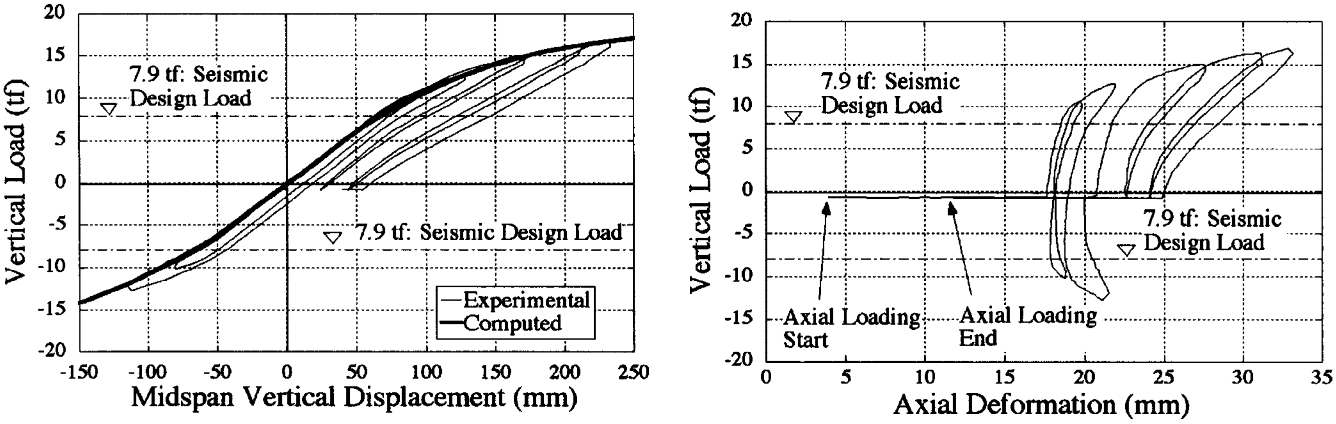
lubricant, moribdenic lubricant (5510) and tefronic one (PTFE), were used. In the tests on measuring cables' stresses, three methods were examined: (1) Measuring the strain of cables by strain gauges, (2) Measuring the strain of cables' end equipment by strain gauges, (3) Measuring frequency of cables' vibration.

Test Specimen, Steup and Procedures

Fig. 2 shows setup of a specimen, which is a model designed just same as the cable truss of 25 m height shown in Fig. 1. The specimen lies on a strong floor, although the cable truss in GLASS HALL stands. Boundary conditions of left side end, top end of the real structure, is roller with freedom for only z-direction, on the other hand those of right side end, bottom end of the real structure, is fixed for all directions. Each connection point between RHS and struts is restrained from moving in x-direction with roller apparatus. RHS has the yield strength of over 35.7 kgf/mm2, the ultimate strength of over 54.4 kgf/mm2 and the elongation of over 21.9 %. Struts have the yield strength of over 34.7 kgf/mm2 and the ultimate strength of over 58.7 kgf/mm2. The elastic modulus of cables are 16000 kgf/cm2, the ultimate strength of which is 79.5 tf. Rod has the yield strength of over 4500 kgf/cm2, the ultimate strength of over 7000 kgf/cm2 and the elongation of over 20 percent.

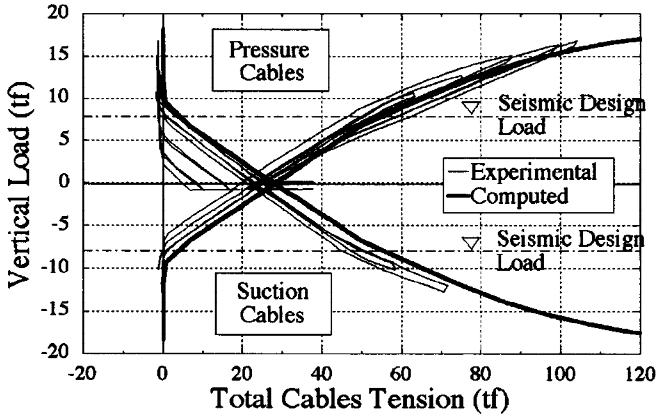
Pre-tensioning of cables are carried out by the method as mentioned above. Correct cable's tensile force is measured by measuring strain of steel rod, which is previously calibrated and built-in both ends of each cables.

Test Results and Discussion



(a) Vertical load versus
mid span vertical displacement

(b) Vertical load versus
axial deformation



(c) Vertical load versus total tension of each pairs of cables

Fig. 4 Test results of load bearing tests

Fig. 3 (a) shows the results on the friction tests. All of values mean the averaged coefficient of friction measured until cable tension reached 17 tf. Using 5510 and PTFE together restricted the coefficient of friction to 0.1 under, thus using them together is effective as lubricant.

Fig. 3 (b) shows the relation between averaged force of a pair of cables and strain measured at both ends of each cables. Although each line has linearity, each of them has different gradient respectively. It means that calibration is necessary for all cables to measure cable tension by this method. Thus this method is unsuitable in practice.

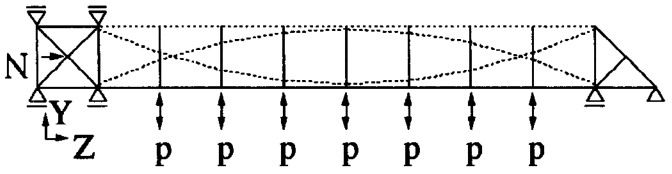
Fig. 3 (c) shows the relation between cable tension and strain of cable-end equipment at both ends of each pressure-cables. Although each line of strain gauges on different positions has different gradient respectively, each line of strain gauge on the same position has the same gradient. Calibration of only a few types of cable-end equipment is necessary for this method. Consequently this method is available for the practice.

Several marks shown in Fig. 3 (d) illustrate the relation between measured cable tension and frequency. The solid line means a theoretical relation between bow and tension, while a broken line means corrected relation including affection of bending stiffness of cables. Although differences between measured values and calculated values appears, this method is a handy one to measure about tension.

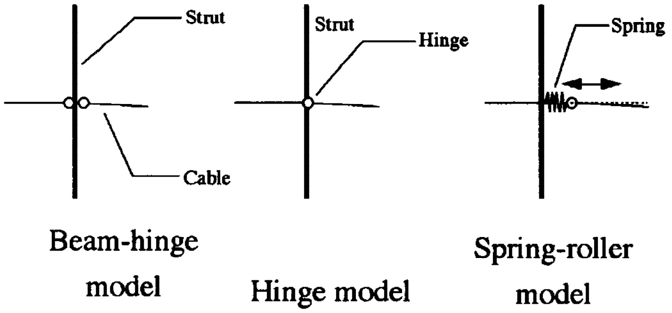
TEST ON LOAD BEARING CAPACITY

Experimental Procedure

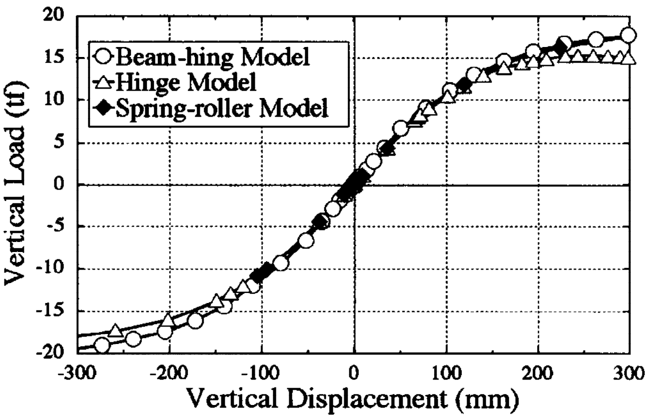
The cable truss is designed to keep elastic state under the design loads. In this experiment, the capacity for



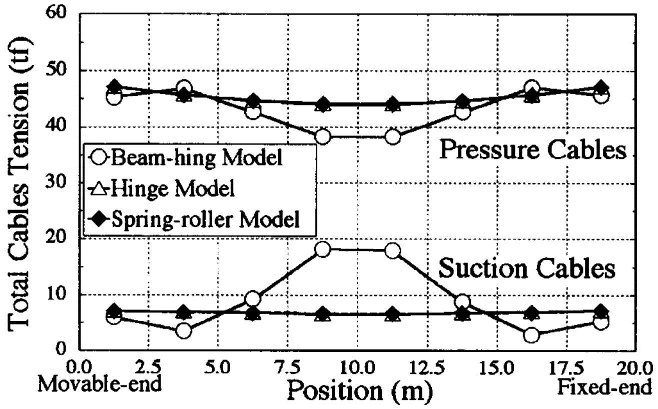
(a) Analitical model for specimen

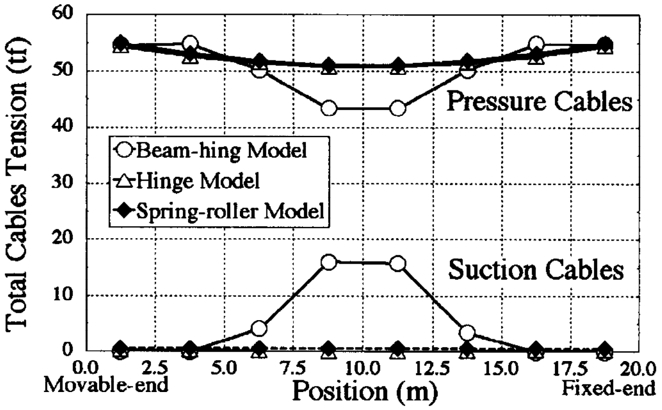


(b) Modeling of crossover point between cable and strut



(c) Comparison of models in vertical load versus mid span vertical displacement





(e) Comparison of models in longitudinal distribution of cable tension at load of 6 tf

(f) Comparison of models in longitudinal distribution of cable tension at load of 8 tf

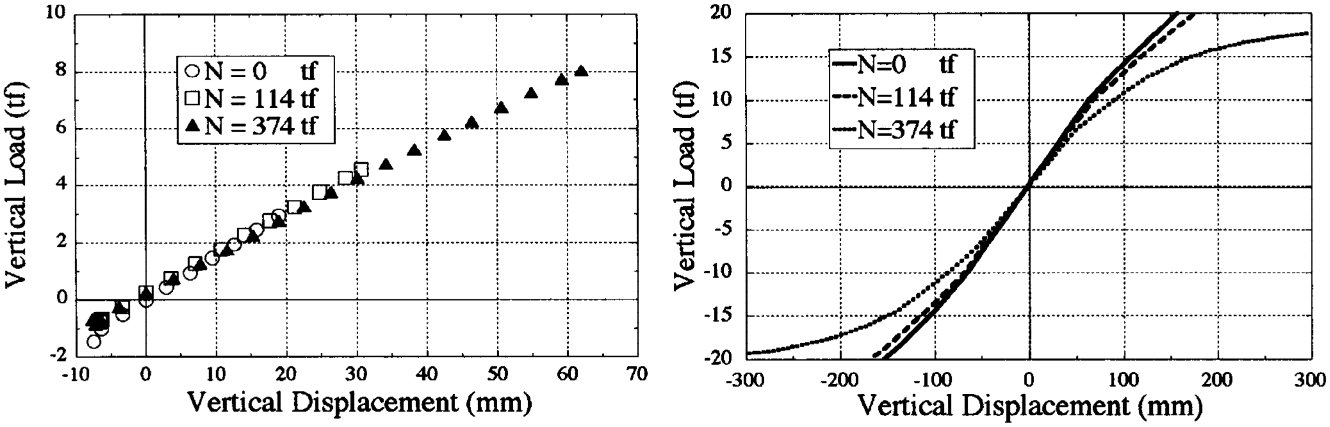
Fig. 5 Analytical model

bearing load over the design load is examined.

Constant axial force of 374 tf, the design seismic axial load, is applied to the left-side end of the specimen using a pair of hydraulic jacks as shown in Fig. 2. Vertical loads are applied to each crosspoints between RHS and strut using a set of seven hydraulic jacks, all of which is controlled to balanced each other. The loading pattern consisted of two cycles at load amplitude of p=8 tf, namely the design seismic load, a cycle at 10 tf and 12 tf. After that, upward loads (positive loads) are applied until jack stroke or differential transducers' limitations are reached and then reduced to zero. Hydraulic jacks and differential transducers are reset and loads are applied again until those limitations. These operations are carried out over until the loads reach what are two times higher than the design loads.

Test Results and Discussion

Fig. 4 (a) through (c) shows the vertical load-vertical displacement of mid span, the vertical load-axial deformation and the vertical load-total tensile force of each pair of cables, respectively. From (a), non-linearity began to appear after over the design load, because yield of RHS and lost of the cable tension occurred as



(a) Stiffness reduction caused by axial force (experiment)

(b) Stiffness reduction caused by axial force (computed)

Fig. 6 Effect on geometrical non-linearity caused by high axial force

shown in (c). (b) indicates that the cyclic loading in the plastic region caused accumulation of axial deformation. The axial deformation reduces the cable tension and the vertical loads at which the cables lose tension. Hence, the vertical loads at which the cable truss begins to reduce the stiffness are decreasing in every positive cyclic loading. The cable truss, however, kept the positive stiffness after the non-linearity appeared. Although displacement of about 40 mm was left, the strength exceeded two times the design load. The cable truss consequently has enough strength and ductility.

ANALITICAL STUDY

Analitical Mdel and Procedure

It is difficult to simulate exactly the slip with friction between the cables and their supporting equipment. Three types of modelings were prepared.

The specimen used for load bearing test is modeled as shown in Fig. 5 (a). A pair of cables, illustrated as broken lines, are concentrated to one element that bears only tensile force. Analyses were carried out with ABAQUS considering non-linearity of geometrical and materials. The steel stress-strain relations were modeled to bi-linear models of which second gradients after yielding were 1 % of the elastic modulus.

Fig. 5 (b) illustrates the three types of modeling of crossover points between the cables and the supporting equipment. First model, called the beam-hinge model, treats the strut as a beam-element that can bear bending moment. The cables are connected to the strut with hinges, and they hence can not move on the crosspoints. This model corresponds to the state of infinite friction. Second model, called hinge model, connects the cables to the strut with a hinge. Thus strut can bear only axial force. Third model, called spring-roller model, connects the cables to the strut with springs that lengthen and shorten only horizontally. This model corresponds to the state of non friction.

Fig. 5 (c) shows analytical results by three models of vertical load-vertical displacement at mid span. Little difference among these models appears under the design load. Because little difference appears between the beam-hinge model with infinite friction and the spring-roller model with little friction, slip with friction, which occur on the cables' supporting equipment, hardly affects on the load-displacement relation. On the other hand, differences among the models appear in longitudinal distribution of the cables' tension. Fig 5 (d) shows the distribution at the load of +6 tf and +8 tf. While the beam-hinge model remarkably unbalanced the distribution because of the truss effect, the other models have the even distributions. However, both ends' tensions of each model become zero at the load of +8 tf where all the models began to reduce the stiffness in vertical load-displacement relation.

The analytical results by the beam-hinge model are illustrated in Fig. 4 comparing with the experimental results. The stiffness in the load-displacement (Fig. 4 (a)) and changing ratio of cables' tensions (Fig, 4 (c)) are estimated.

Effect of Geometrical Non-linearity Caused by High Axial Force

Fig. 6 shows experimental and analytical results in case where axial force (N) is 0 tf, 114 tf and 374 tf. The higher axial load subjected, the more the cable truss reduces the stiffness as shown in (a). Comparing at the displacement of 20 mm, The stiffness of N=374 tf is 87 % of that of N=0 tf. (b) indicates that in large displacement region, obvious reduction of stiffness occurs because of high axial force.

To estimate exactly the load when the cables lost the tensions is important, because losses of cables' tensions cause the reduction of the stiffness and change structural performances. In the case of N=374 tf, computed load of cables' tensions lost with considering geometrical non-linearity is 41 % higher than that without considering geometrical non-linearity.

CONCLUSIONS

(1) The proper lubricant could reduce the coefficient of friction to 0.1 under, which occurred on the cables and their supporting equipment. The best method of measuring cables' tensions was to measure the strain of cable end equipment.

(2) The cable truss kept elastic behavior up to the seismic design load and the maximum strength was two or more times of the design load. Thus the cable truss had enough strength and ductility.

(3) Even a simple model neglecting the friction could simulate the behavior the cable truss under seismic load conditions. P-delta effect caused by high axial force had a great influence on the behavior of the cable truss.

REFERENCES

Eekhout, E. (1990). Glass Space Structures: International. J. Space Structures, vol. 5, No. 2, 68-89.
Houghton S. (1992). Marine technology in architecture. STEEL CONSTRUCTION TODAY, Nov. 244-248.

ACKNOWLEDGMENTS

The authors acknowledge Prof. Michikatsu Hirano of Science University of Tokyo, Prof. Kimio Saitoh of the NIHON University, Prof. Jun Kanda of Uviversity of Tokyo, Prof. Takeshi Ohkuma of Kanagawa University and Rafael Vinoly Architect k.k. for their valuable guidance and suggestions. Special thanks to the stuff of the joint venture of TOKYO INTERNATIONAL FORUM GLASS HALL construction, who assisted the authors during erection of the specimen and the tests.