EARTHQUAKE- AND WIND-RESISTANT DESIGN OF A SUSPENSION ROOF STRUCTURE

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A huge swimming hall with hanging roof was recently built in Tokyo and used for the Olympics. It has a racing pool of 22m x 50m and a diving pool of 22m x 25m and seats 15,000 of spectators. The structural features of the building are reported in this paper and earthquake- and wind-resistant consideration given to the design of the suspension roof structure is described.

OUTLINE OF THE STRUCTURAL FEATURES

As can be seen in the figures, a structural system similar to that of suspension bridges was adopted for the roof of the stadium. Two main cables span 126 meters between the two main pillars and 65 meters (visually 44 meters) outside them in the longitudinal direction, the sag of the cables at the center of the span being 9.653 meters. The cables are parallel for the side spans at an interval of 2.580 meters, but the interval is gradually increased up to 16.800 meters for the center span to provide a space for skylights and artificial lights.

Each of the main cables having an external diameter of 330mm consists of 31 ropes each with a diameter of 52mm and 6 ropes each with a diameter of 34.5mm. The design strength of the steel wires constituting the ropes was taken as 150 kg/mm^2, and actually the wires with the strength of 165$\sim$170 kg/mm^2 were obtained. Apparent Young's Moduli of the ropes are 16000$\sim$17000 kg/mm^2.

A series of hanging members span the area between the main cables and the boundaries surrounding the seats. The space between the adjacent hanging members is 4.500 meters. Crossing these hanging members, a series of bracing cables run approximately along the geodesic lines of the roof surface.

After the roof material was put in its correct position, the bracing cables were stretched to a tensile force of 20 tons per cable. Then the all members of the roof structure were prestressed by this and the rigidity of the whole structure was considerably increased. When the prestressing was completed, the tensile force in each of the main cables was 1350 tons and the stress in the individual wires was 25.1 kg/mm^2. The safety factor for the main cables is therefore around 5. It seems that the safety factors for the cables of suspension bridges are usually taken to be around 3, but, as this is a building, a larger section was preferred in order to obtain a greater rigidity.

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The tensile forces in the main cables mentioned above produce a compression of about 2000 tons in each of the main pillars and continue through the backstay cables down to the anchor block to produce an uplift force of 1270 tons in each anchor block and a compressive force of 2380 tons in the underground struts. The weight of each anchor block is about 2800 tons. Taking into account the weight of the soil just above the base slab of the anchor block, the total weight of about 4900 tons resists the above-mentioned uplift force. The two concrete struts have a cross section of 1.500m x 2.000m in the side spans, but in the center span the observation tunnels running along the sides of the swimming pools serve as the compression struts.

At the first stage of the design, ropes were proposed to constitute not only the main cables and the bracing cables but also the hanging members, with stiffening steel sections attached along them. However, it was concluded that the sharp roof surface desired by the architects would bring us uneconomical results if this shape was attempted by adjusting the tensions in the cable net work only. Therefore the design using ropes was abandoned and the stiffening steel members were designed to take the part of the hanging members, or, more correctly, the steel members designed in this way take three combined roles; ---they are essentially hanging members, but they have enough bending rigidity to maintain their shapes which differ from catenaries, and, moreover, they act as stiffeners to prevent deformations due to the partial loading. These I-shaped steel members, or hanging girders, which have the flanges of 22 x 190 mm and the 12mm thick webs vary their depth from 500 to 1000 mm. They are set at 4.500 meters, center to center.

The bracing cables running through the hanging girders are ropes of 44mm in diameter and of the same mechanical properties as the main cables. They are arranged along the approximate geodesic lines of the roof surface at intervals of 1.500 to 3.000 meters. They are clamped to the hanging girders at every intersection after the prestressing.

4.5mm thick steel roofing plates are bolted to the light gauge steel rafters fastened to the hanging girders at the interval of about 1.5 meters.

MODEL TESTS

Experiments were conducted on a 1/30 scaled model (fig. 3) with the purpose of understanding the statical and dynamical behavior of the roof structure. Combinations of the following two groups of conditions were used in the tests.

A. Loading Conditions
   1. Own Weight
   2. Additional Loads
      a. Over the whole area
      b. Over the half area
      c. Partial Loading
   3. Temperature Change

4. Vibration

B. Prestressing

1. P S Coefficient: 20%
2. ditto : 40%
3. ditto : 60%

P S Coefficient (Prestressing Coefficient, Vorspannungsbeiwert) here means the ratio of the vertical component of the tension in the bracing cables to the own weight of the roof for the unit covered area. In the vibration tests, oscillation was caused in the roof structure by applying periodic changes in force to a point on the roof surface through a coil spring connecting this point and an eccentrically fixed pin to the axis of an electric motor.

Fig. 4 shows the load-deflection relationships of a central point of the main cable for the various prestressing coefficients in the statical tests.

The conclusions drawn from the test results were as follows:

1. Within the limits of loading applied in the experiments, the relationship between load and deformation is almost linear, with or without prestressing.

2. Statical rigidity of the roof increases two to three times through prestress by the bracing cables.

3. The rigidity mentioned above seems to increase with the magnitude of prestressing, but the actual relationship is not clear.

4. Prestressing of 20% (P S Coef.) is enough in this case in the sense that none of the cables loosen under any loading conditions.

5. The periods of symmetrical and antisymmetrical vibrations with respect to the longitudinal axis of the structure are rather close to each other, both being around 0.9 sec. for the actual building.

EXAMINATION OF SAFETY FROM EARTHQUAKE AND WIND

As previously stated, steel plate was used as the roofing material to accomplish a light weight roof which is essential for not only economy but safety from earthquakes. The own weight of the roof including the 4.5mm thick steel plate, hanging girders, bracing cables and the ceiling is less than 80 kg/m^2.

Flatness of the roof is also favorable to the structure in regard to horizontal forces. Statical calculations revealed that the horizontal force corresponding to the seismic coefficient of 0.3 produces only 13% increase in tension of the hanging girder spanning the maximum length and 18% increase in tension of the bracing cable with the maximum length. Therefore we can conclude that the structure is sufficiently safe from earthquakes as far as the statical consideration concerns.

The light weight of the roof which was attempted for the sake of the safety from earthquakes made it indispensable to examine the safety of the roof from gale. Design wind loads were determined through wind tunnel tests on a 1/300 scaled model. These tests showed that a suction of $30 \sim 60\ kg/m^2$ is predominant with a partial positive pressure of $250 \sim 300\ kg/m^2$ on the steep parts for a gale with the velocity of 60 m/sec.

Dynamic behaviors of the roof were then qualitatively examined with a model of cut out cross section of the roof made of 0.2mm thick aluminum plate in an air stream. This examination showed that the wind pressure coefficient at the resonance is about 1.5 times the coefficient for the constant wind, but no sign of the possibility of such unstable states as flutter or self-excited vibration could be observed.

DESIGN OF A DAMPING SYSTEM

From the results of the above examinations we can say in usual sense that the structure is sufficiently earthquake- and wind-resistant. Taking into consideration, however, the facts that the scale of the structure is very large and that it is hardly possible to predict the complete dynamic behavior of the structure under violent earthquakes or gales, we decided to take extra precautions against the conditions severer than expected. This thought led us to the design of a damping system.

As shown in fig. 5, the damping system consists of a group of oil dampers and steel rods connecting some points on the main cables to the oil dampers fitted to the surfaces of the upper parts of the pillars. The number of the oil dampers is 12; 6 dampers on each pillar. The system provides one way damping---- the dampers work only when the steel rods are pulled down.

The damping ratio of the system to the critical damping of the roof was chosen as 1/8. The required damping coefficient of each damper was then 2.8ton/cm/sec. As the damping force is taken by bending of the pillars, it has a limit determined by the bending capacity of the pillars. The maximum damping force of a damper was thus determined as 12 tons. An example of characteristic curves of the dampers is shown in fig. 8 in comparison with the idealized design curve mentioned above. The dampers were treated as an architectural element for expression, and are visible from outside of the stadium as shown in fig. 6.

ACKNOWLEDGEMENT

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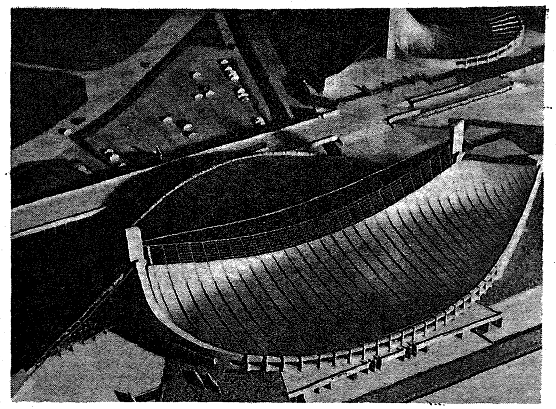


fig.1 Architectural Model

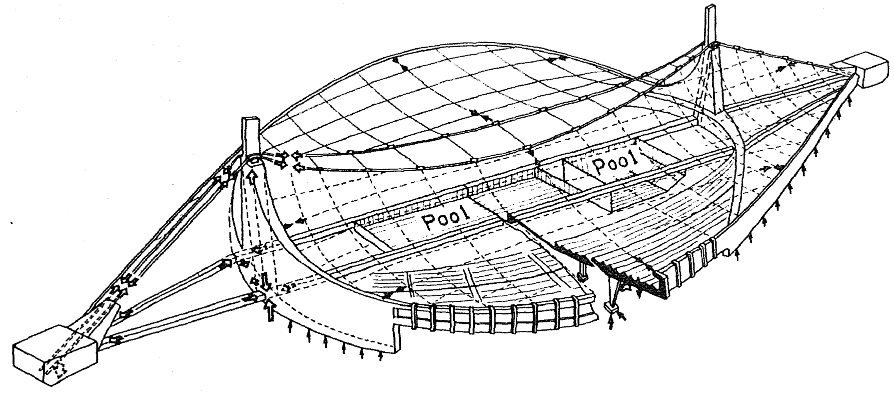


fig. 2 Structural System

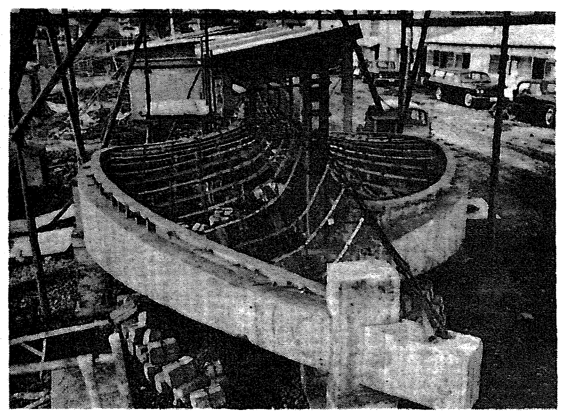


fig. 3 Structural Test Model

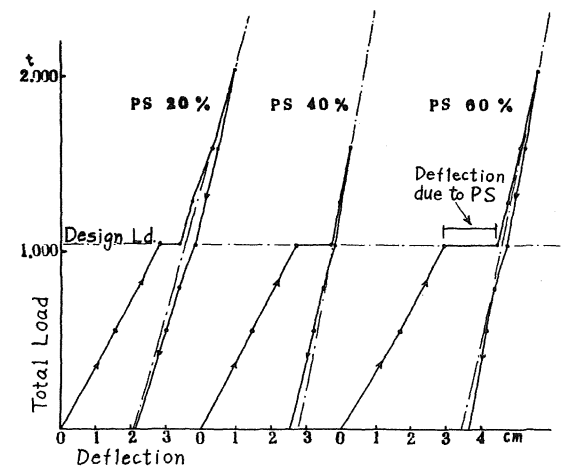


fig. 4 Load-Deflection Curves

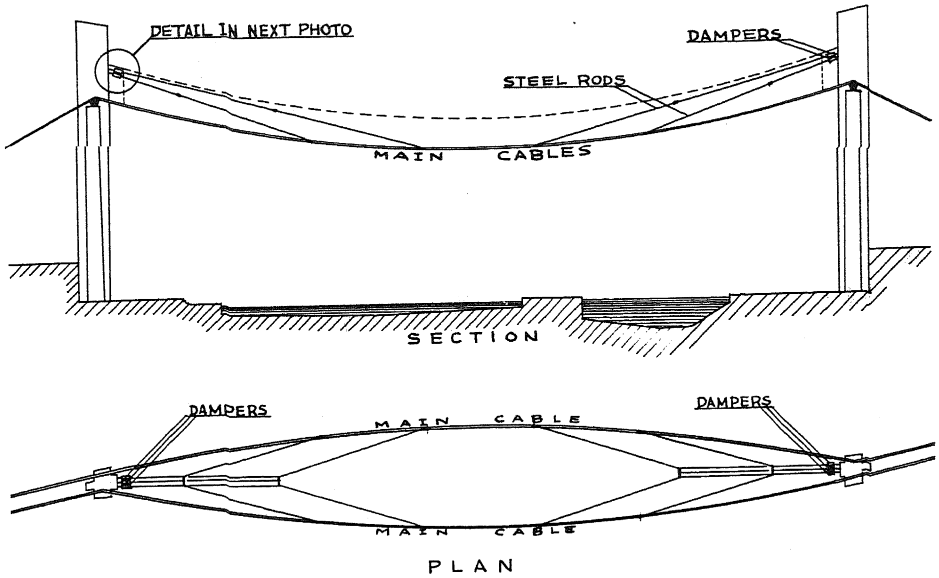


fig.5 Damping System

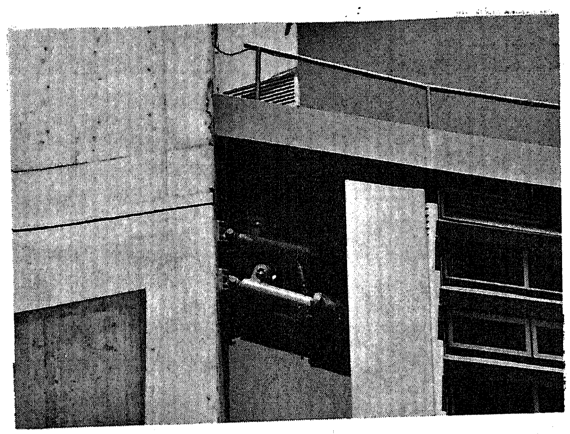
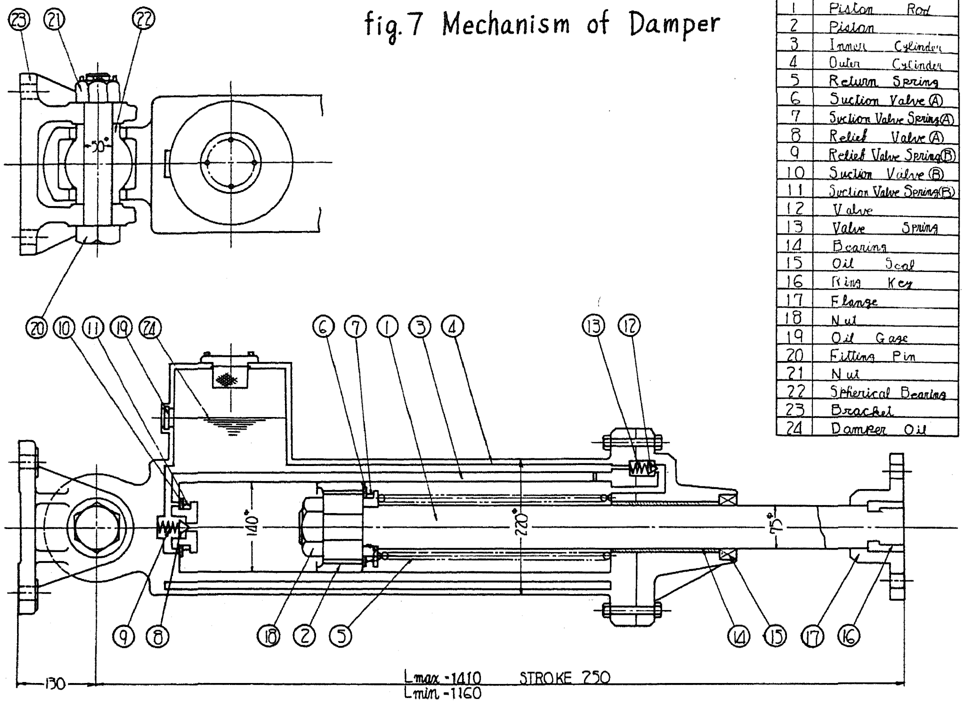


fig.6 Dampers

fig. 7 Mechanism of Damper



PARTS NO	NAME OF PARTS
1	Piston Rod
2	Piston
3	Inner Cylinder
4	Outer Cylinder
5	Return Spring
6	Suction Valve (A)
7	Suction Valve Spring (A)
8	Relief Valve (A)
9	Relief Valve Spring (B)
10	Suction Valve (B)
11	Suction Valve Spring (B)
12	Valve
13	Valve Spring
14	Bearing
15	Oil Seal
16	Ring Key
17	Flange
18	Nut
19	Oil Gage
20	Fitting Pin
21	Nut
22	Spherical Bearing
23	Bracket
24	Damper Oil

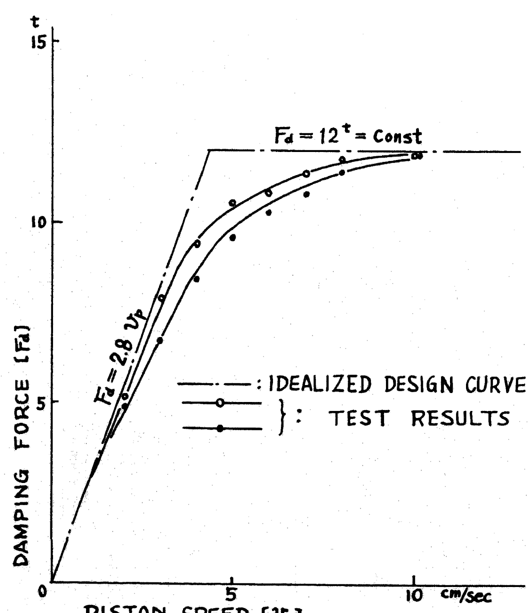


fig. 8 Characteristic Curves of Dampers