Nagano Olympic Memorial Arena: design and construction

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Summary

The Nagano Olympic Memorial Arena, located in Nagano-City, Japan is where the 18th winter Olympic games will be held in February 1998. It is one of the world's largest speed skating arenas, covering an 80m x 216m free space containing a 400m speed skate oval and seating for about 10,000 spectators.
One of the main features of the structure is the 30cm thick, 80m long semi-rigid hybrid suspended roof. Each hanging member is composed of two glued laminated timbers (glulams) sandwiching a steel plate. Hanging structures generally incorporate bracing members to increase roof stability and to resist wind up-lift and lateral load. This structure instead utilizes the bending stiffness of glulams and the in-plane stiffness of plywood panels attached to roofing members.
This paper describes the structural system and design, and its construction method.

1. Structural concept

A new type of hanging roof structure covering an 80 m x 216 m free space has been developed, designed and constructed. As shown in Photo.1, it comprises a series of suspended roof elements inspired by the peaks of the Japan Alps. It creates a new and fresh impression, contrasting the more traditional round dome configuration. This shape also decreases the total volume of the inner space. The most distinctive characteristic of the structure is its semi-rigid hanging roof spanning 80m. It's thickness is only 30cm. The structure consists of fifteen hanging roof panels, each composed of composite hanging beams with plywood fixed to them. Each composite hanging beam is composed of two glulam beams sandwiching a steel plate.
In general , one way hanging roof structures deform easily under up-lift and lateral wind loads. Therefore, this kind of hanging structure is usually designed with bracing and/or suppressing members to resist up-lift and lateral movements. However, the semi-rigid hanging roof structure here was required by its architectural design to have no bracing and suppressing members. Instead, it utilizes the bending stiffness of the composite beams (glulams) resisting the up-lift load and the shearing stiffness of the plywood panels resisting the lateral load.

2. Outline of structural system and design

The structural system and design of this speed skate ovals is outlined in Fig.1. As shown, the overall structure consists of fifteen structural units. Each unit has two reinforced concrete counterweights, two leaning walls, and a hanging roof panel pin connected to the top edge of the leaning walls. The center roof unit is the highest , and roof unit height reduces in 3-meter gaps toward the outside units. The configuration of the hanging roof portion is the same for all units,

and is as follows: span, 80 meters; sag, 5 meters; and width, 18 meters.
According to the Japanese Building Code, snow load is assumed to be $160kg/m^2$ and wind load is assumed to be $185kg/m^2$. The up-lift wind load coefficient is assumed to be 0.7 according to the results of wind tunnel tests. The basic load bearing mechanism of each roof unit is shown in Fig.2. The details of each structural portion are summarized in follows.

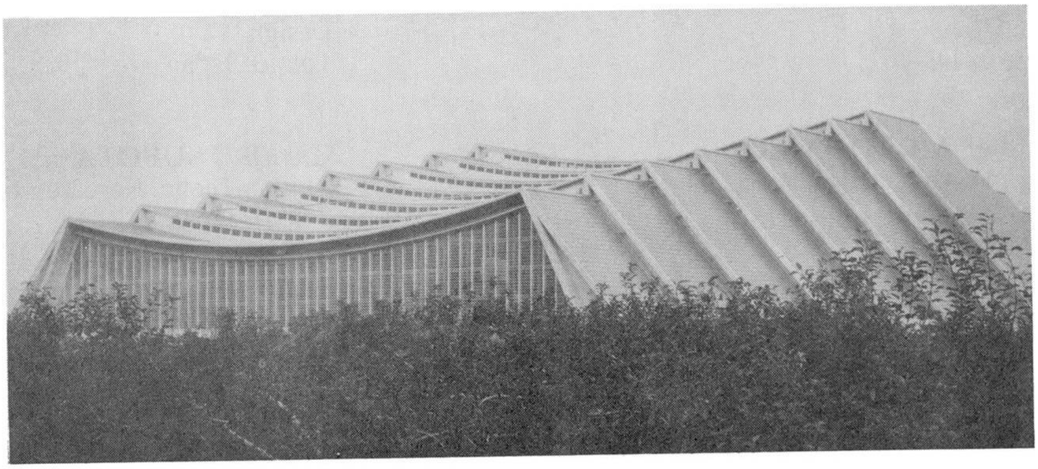

Photo. 1 General View

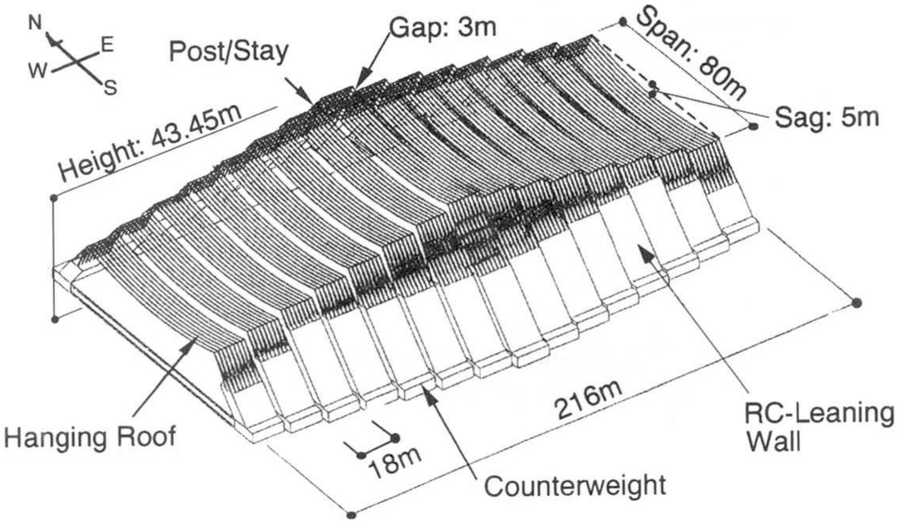

Fig.1 Outline of the Structure

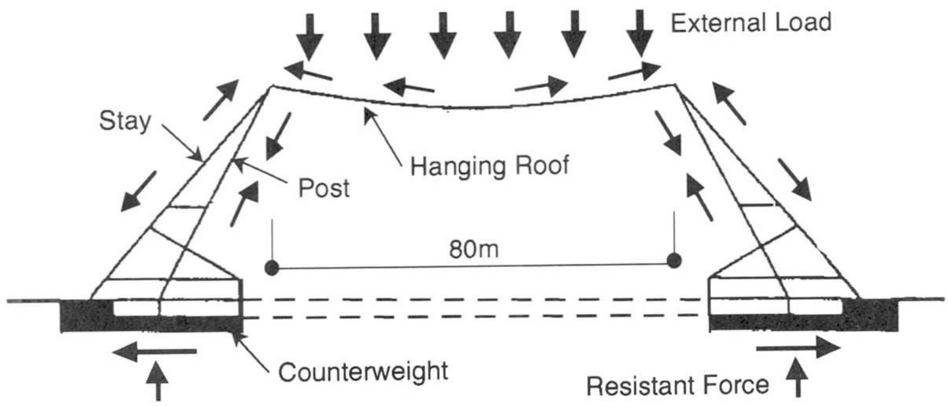

Fig.2 Basic Load Bearing Mechanism

2.1 Hanging roof

A section of the roof panel is shown in Fig.3. Each main beam is a composite member composed of glulams and a steel plate. Two glulam beams (300mm x 125mm x 2) sandwich a steel plate (200mm x 12mm) and they are connected to each other with steel bolts at 2m pitch. In the design of this composite member, the axial force and the bending moment are sustained by glulams and steel plate corresponding to their stiffness*1. Because of the feature of the structural system, the axial tensile force is dominant and the bending moment is rather small.
The most important thing in stabilizing this hanging roof under wind load is to maintain the tensile force in the composite member. This is assured by the three-dimensional wind-induced response analysis considering geometric non-linearity*2. Furthermore dynamic tests were conducted on a 1/4 scale hanging roof model*3 and an actual hanging roof*4 to confirm its dynamic characteristics.
The beams are spaced at 600mm. Thus, one roof panel consists of thirty main beams pin supported at the ends of the steel plate, and connected to each other at 10m intervals by steel tie plates.
Plywood panels 12mm thick are nailed to the top surface of the glulams. The panels work not only as sheeting roof boards, but also as structural members to increase the in-plane stiffness of the roof panels.

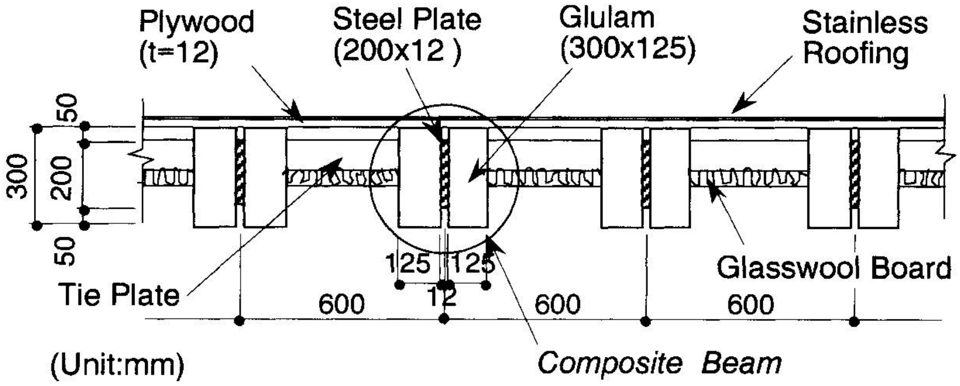

Fig.3 Section of Hanging Roof

2.2 Leaning wall

The leaning walls transmit loads from the hanging roofs to the foundation. Their upper portions are composed of steel posts and stays, forming a triangle. The posts resist compression and the stays resist tension. The lower portions of the walls are made of reinforced concrete. Pre-stressed steel rods are added to the outer portion of the wall to resist the tensile force, which is caused by the hanging roof, from steel stays. The center triangle is the highest, and the height reduces in 3-meter gaps toward the outer units.

2.3 Foundation

Reinforced concrete counterweights, which resist tensile forces from the hanging roofs, are located under the leaning walls. Pre-stressed steel rods are fixed into this counterweight. All of these structures are supported by pre-stressed concrete piles, 600mm in diameter and 10 - 12m long, founded on a sand gravel layer.

3. Construction

One of the most important problems was how to construct these flexible hanging roofs. Unlike conventional rigid roofs, the 80-m-span hanging roofs are stabilized by introducing the necessary tension into structural elements, even in the construction stage. Furthermore, there was no available construction record on such large flexible hanging roofs. Therefore, a rational and new construction method have to be developed. Various construction methods were proposed and investigated. Finally, a new lift-up construction method was devised and actually employed.

3.1 Construction Method

The newly developed construction method is illustrated in Fig.4. The outline of the construction sequence is summarized as follows.

First, six composite hanging members composed of glulams and a steel plate were assembled into one lift-up unit (80m long and 3.6m wide) on the ground level. Next, both ends of the lift-up unit were temporarily fixed to lift-up racks. At this point, the necessary tension was introduced into the lift-up unit. The lift-up racks were then raised gradually with winches along vertical guide frames by wires hanging at the four corners of the lift-up unit. Hydraulic jacks were installed on the lift-up racks. When the lift-up unit rose to the specified level, the hydraulic jacks were used to adjust its horizontal position for inserting pins into shoes of steel posts. At this stage, the lift-up unit is completely pin-connected to the steel post. Then, the lift-up racks were returned to ground level and moved horizontally along the rails. One hanging roof was completed by repeating this procedure five times.

With this method, the necessary tension was introduced into the flexible 80-m-span lift-up units, and were stable even under strong wind during construction. Furthermore, this method reduced the work load at high levels, maintained safety and shortened construction time.

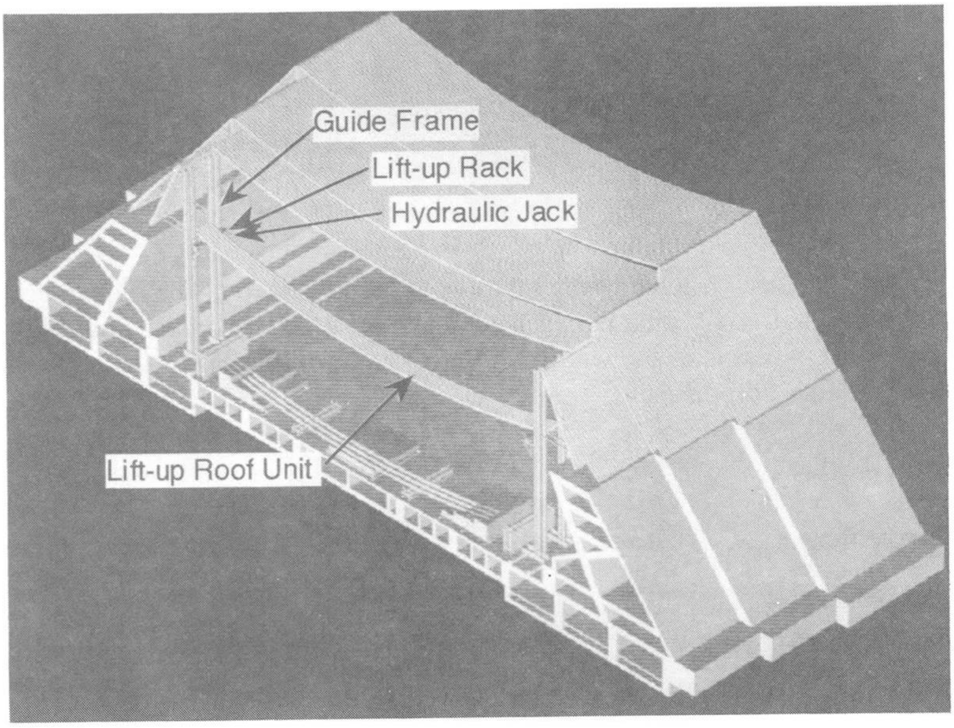

Fig. 4 Lift-Up Construction Method

3.2 Scale-model test for construction

Prior to actual construction, a scale-model test was carried out to confirm the feasibility, safety and workability of this lift-up method. The test specimen was a 1/4-scale hanging roof panel model, with 20m span and 4.5m width. As shown in Photo.2, the same equipment, i.e. a lift-up racks, wires, winches and hydraulic jacks were installed to this model, and one lift-up unit was raised. During the test, strains in the hanging members, tension in the hanging wires, forces in the hydraulic jacks, lift-up height and configuration of the model were measured. In the test, in addition to the normal lift-up procedure without error or accident, abnormal procedures which correspond to strong wind conditions and/or unbalanced lift-up state assumed in the actual construction were tested.

This scale-model test confirmed the feasibility of the proposed lift-up method. The measured stresses of the lift-up unit during the lift-up state were within the allowable range, and the structural safety during construction was confirmed. Furthermore, the stresses and configurations under the abnormal lift-up procedure were grasped, and the tolerance construction errors in the actual construction were quantitatively evaluated. Finally, these data obtained from the scale-model test were fed back to the actual construction .

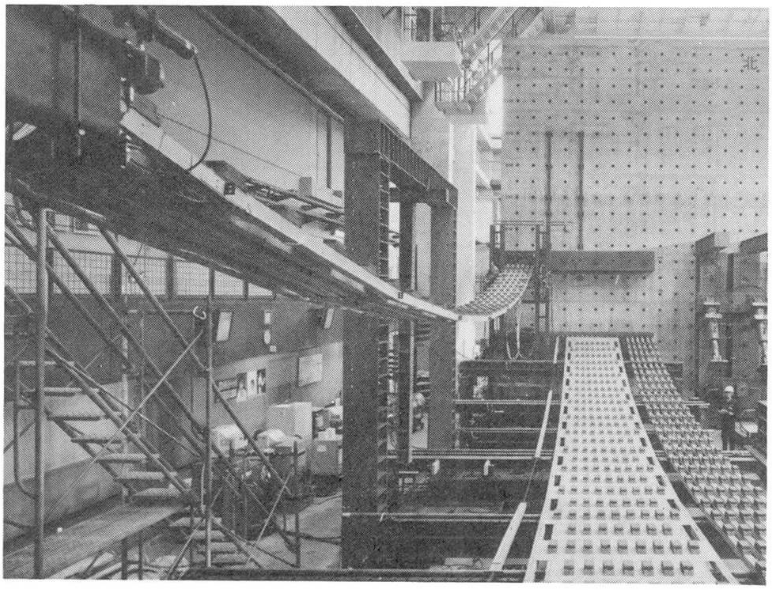

Photo. 2 Overview of the Scale-Model Test for Construction

3.3 Actual construction

The set of equipment consisting of lift-up racks, guide frames and hydraulic jacks, employed in the actual construction is shown in Photo.3 and Photo.4, and the actual lift-up state is shown in Photo.5. During the actual lift-up procedure, the stresses in the lift-up unit and supporting steel frames were measured to reconfirm the structural safety of the hanging roof panels during construction. Furthermore, its final configuration after raising procedure was also measured to examine the construction accuracy.

The measured stresses were within the allowable range predicted in the scale-model test, and its final configuration was almost same as that specified in the design. Therefore, these measurements confirmed that the proposed construction method was rational and safe.

In the actual construction, two of lift-up systems were employed, and three lift-up units were raised per two days. As a result, it took about two months to raise the all hanging roofs. This construction period was very short compared with conventional erection methods, and the construction time was significantly reduced.

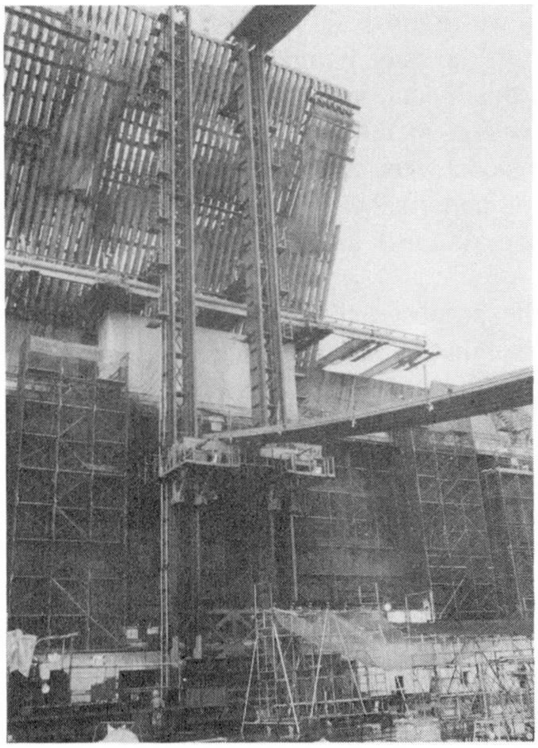

Photo. 3 Lift-Up Equipment (Start)

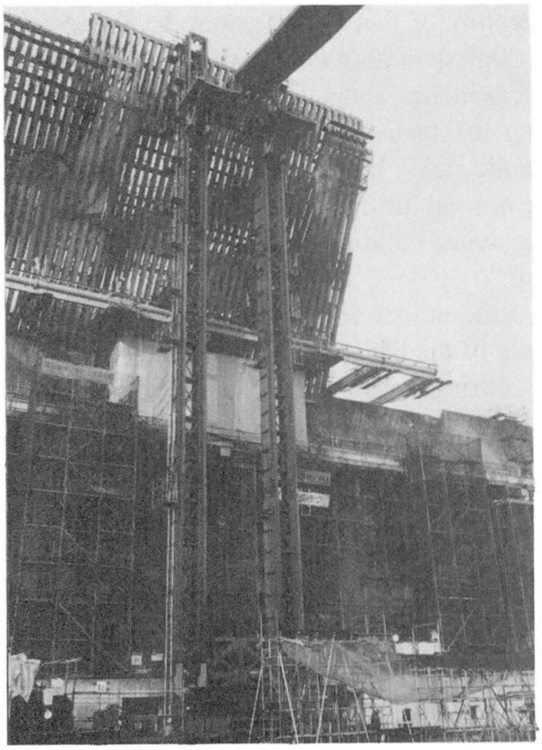

Photo. 4 Lift-Up Equipment (Top portion)

Photo. 5 Overview of the Actual Lift-Up State

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