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Design of a Long-Span Prestressed Concrete Spherical Shell Roof

Projet d'une coupole sphérique de grande portée, en béton précontraint

Entwurf eines weitgespannten Kuppelschalendaches

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SUMMARY

This paper deals with the structural design of a large-span reinforced and prestressed concrete dome shell, which will be constructed underground in a park and will support large loads including soil. The structure of 110 m in diameter and 16 m in rise has a roof of an arena of an underground gymnasium facility, and supports all the loads (about 5 tons/m2) on the roof. Its tension ring is made of prestressed concrete, while the shell is a composite structure consisting of precast prestressed concrete beams and slabs, as well as cast-in-place concrete.

RÉSUMÉ

Les auteurs présentent l'étude d'une coupole de grande portée, en béton armé et précontraint, destinée à recouvrir une salle de sport souterraine. D'un diamètre de 110 m et présentant une flèche de 16 m, elle a été conçue pour supporter de fortes charges (y compris la couverture de terre), à savoir 5 t/m2. L'anneau tendu est réalisé en béton précontraint, tandis que la coque se compose de poutres et de dalles précontraintes préfabriquées, complétées par du béton coulé sur place.

ZUSAMMENFASSUNG

Der Beitrag beschreibt den Entwurf einer weitgespannten Stahlbeton-/Spannbetonkuppel, die in einem Park eine unterirdische Sportstätte überspannen wird. Mit 110 m Durchmesser und 16 m Stich ist sie für grosse Lasten (einschliesslich Ueberschüttung) von 5 t/m2 ausgelegt. Für den Zugring wird Spannbeton verwendet, während die Schale aus vorgefertigten Trägern und vorgespannten Platten mit ergänzendem Ortbeton besteht.

1. INTRODUCTION

The building introduced in this paper is a city gymnasium intended to serve as the core of various sports facilities in the city of Osaka, Japan. The building now under construction comprises two circular arenas, one large and one small, and is planned to have most parts located underground. The project is quite unique in that it intends to integrate a large-scale structure with a green-rich park in an urban area of one of Japan's large cities, which have a green-area deficiency problem.

The aforesaid large and small arenas were planned so that their roofs would support soil fill planted with trees and vegetative cover to form a part of the park's landscape while creating large-scale spaces under these roofs. The main arena and the sub-arena have diameters of 110m and 52m respectively.

To cover these two arenas, spherical concrete shell roofs provided with prestressed tension rings at the perimeters were proposed and adopted. The present paper introduces some structural design features of the spherical prestressed concrete shell roof that covers the main arena.

2. BUILDING OUTLINE

- Primary intended use : Gymnasium
- Owner : The City of Osaka
- Site area : 123,986m^2
- Total floor area : 38,425m^2
- No. of floors : 3 floors underground
- Height : Building - 30m above the datum G.L
- Foundation : - 11.5m below the datum G.L.

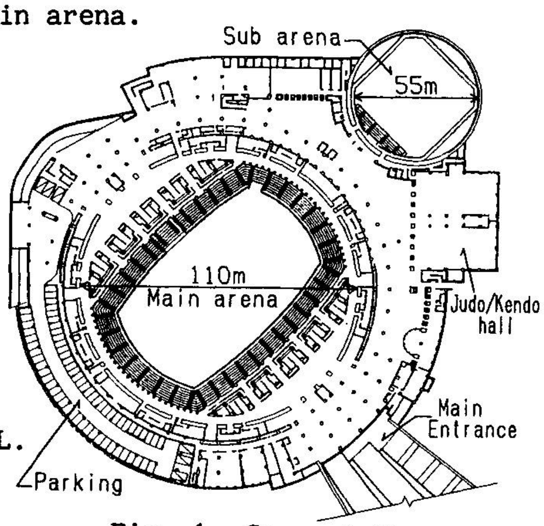

Fig. 1 General Plan

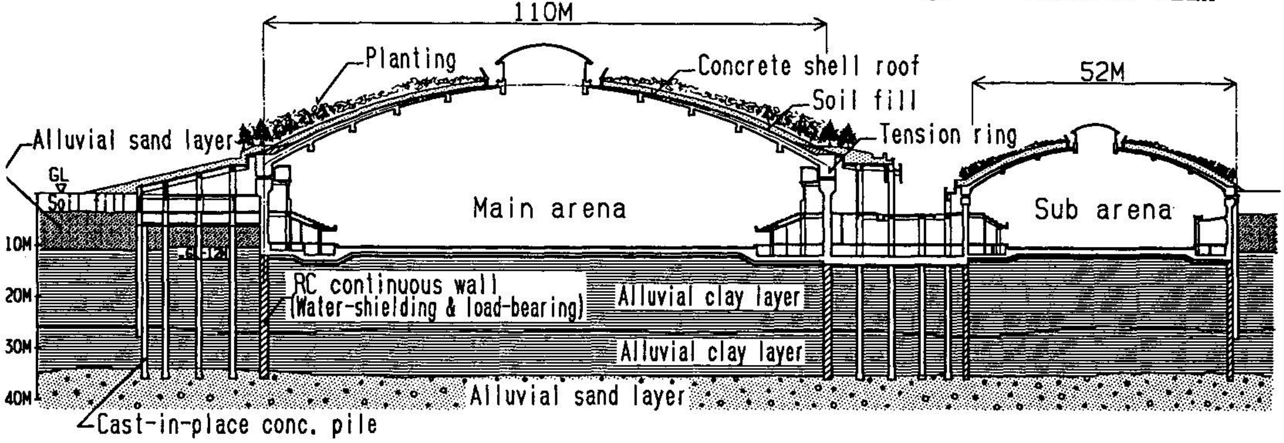

Fig. 2 Structural Cross-Section

3. STRUCTURAL DESIGN

3.1 Structural Design of Spherical Shell

(1) Structural Features of Spherical Shell

The prestressed concrete spherical shell used for the roof of the main arena of this project has the following structural characteristics.

1) The spherical shell roof of the main arena is a long-span structure having a diameter of 110m and a rise of 16m.
2) As has been mentioned, the shell forms the roof of a large-size gymnasium located underground in a city park and is overlain by soil fill of about 1.0m in average depth (0.6 - 1.5m). Thus, the roof must support a total load of about 5 - 6 tons/m^2.
3) Reinforced concrete is used for the main part of the shell structure with cast-in-place prestressed concrete (PC) used to form the perimeter tension ring into which tensile force of about 20,000 tons is to be introduced.
4) To facilitate construction and in the interest of economy, composite construction using precast PC slabs and beams and cast-in-place concrete elements was adopted for the shell portion (see Fig. 4).

(2) Structural Design of Spherical Shell

Fig. 3 shows a conceptual drawing indicating the flow of force in the spherical shell. As shown in the drawing, when a vertical load is applied to the shell, compressive force is produced in the radial (radius) direction of the shell. This compressive force is transmitted to the tension ring and causes a tensile force which tends to expand the tension ring and the shell perimeter. This tensile force is countered by the prestressing force introduced in the circumferential direction of the tension ring. In view of this, it was decided that this portion would be designed to form a prestressed concrete structure in which compressive force is pre-applied to concrete by way of prestressing strands which are located in the concrete along the shell circumference.

Where a long-span roof structure must support a heavy load, as is the case with this project, the use of a spherical shell made of concrete that has high compressive strength provides a highly economical and rational solution because in such a shell, most loads imposed on it would be supported as if they were compressive loads. By introducing prestresses into the tension ring, the low tensile strength which is a disadvantage of concrete can be compensated for and this makes it possible to utilize concrete in compression effectively over the full sectional area. If, for instance, a similar shell roof is designed using structural steel, the steel members will have to be designed for extremely high stresses. This will result in an uneconomical structure which is also subject to large deformation. Further, the present roof structure has an additional advantage because it enables prestresses to be introduced stage by stage during construction as concrete placement and soil filling progresses and this makes it possible to control stresses in the concrete and to minimize deformation at each stage of construction.

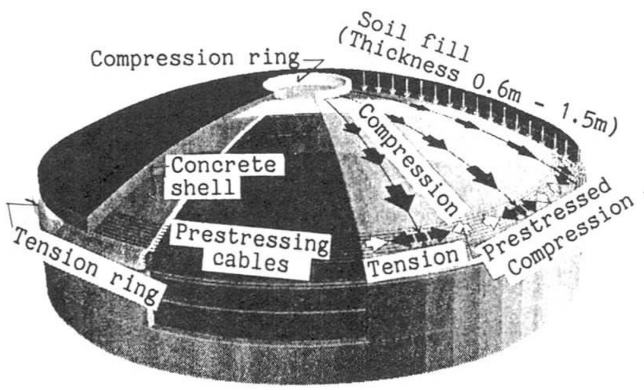

Fig. 3 Conceptual Drawing Indicating Flow of Forces in the Shell

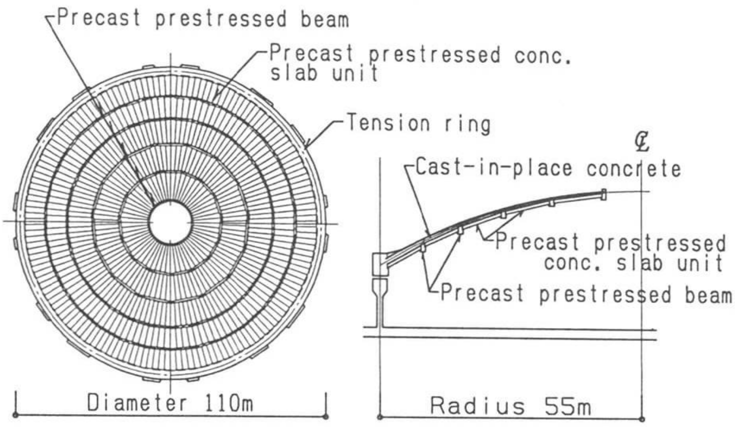

Fig. 4 Simplified Drawing of Main Arena's Shell Roof

The roof of the main arena is composed of a spherical shell portion which varies in thickness from 480 - 1200mm, a tension ring beam (a cast-in-place concrete rectangular beam 4.8m in depth by 3.0m in width), and a compression ring (a precast PC beam 16m in diameter) located at the crown of the shell. As shown in Fig. 4, the spherical shell portion is of a composite construction consisting of five precast PC ring beams all concentrically related to the perimeter tension ring, precast PC slab units (DT slab units) laid between the aforesaid ring beams, cast-in-place concrete elements.

The reasons for using precast prestressed slab units and beams in this structure are as follows: Precast concrete slab units serve as formwork for cast-in-place concrete; hence, scaffolding work and formwork can be almost entirely eliminated. This also enable precast PC units to be used more effectively for structural purposes. Moreover, since these precast units are supported by precast PC beams which have high rigidity, supporting elements may be concentrated at the support points at the ends of these precast beams. Further, because the deflection of these precast beams is small, the support points may be widely spaced.

Fig. 5 shows the detail of the support points near the tension ring of the main arena. As shown, rubber elements are used at the perimeter tension ring of this spherical shell to enable the shell to deform in the direction of the radius. These rubber elements are used to relieve the spherical shell of lateral deformation and long-lasting deformation due to creep that are likely to occur when a vertical load is imposed on the shell or a tensioning force is introduced into the prestressing strands.

3.2 Planning for Construction of the Spherical Shell

Fig. 6 shows the construction sequence for the spherical shell roof of the main arena. The work performed at each stage in this sequence is as follows.

(1) Install rubber supports, place steel reinforcements, and then pour concrete. When concrete has cured well, tension three cables that correspond to about 10% of all the cables. (Primary tensioning)

(2) Erect props to support precast PC beams and place the PC beams (about 7.6 - 9.4m long) on the props in the direction of the radius. Then, lay precast PC slabs units between the PC beams.

(3) Place steel reinforcements in the upper surface portion of the shell

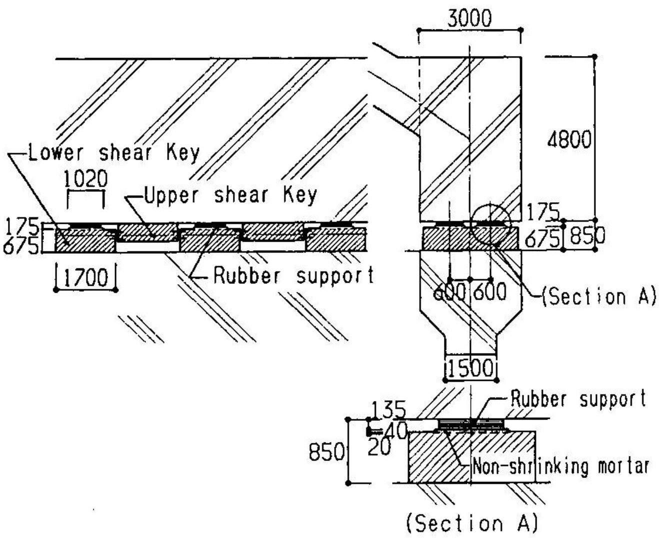

Fig. 5 Detail of Support Points

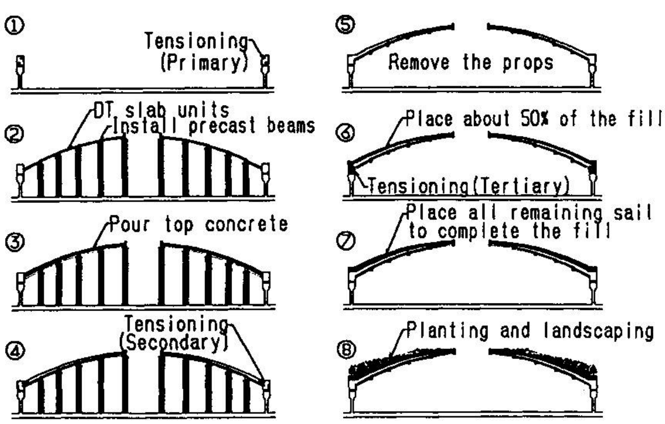

Fig. 6 Construction Sequence

where concrete is to be poured in place. Pour concrete and let it cure. Start pouring of concrete at the lower edge near the tension ring and proceed gradually to the crown of the shell.

(4) Perform secondary tensioning of the tension ring PC cables. Tension about 50% of all the PC cables at this stage.

(5) Jack down the props supporting the precast PC beams and remove the props.

(6) Waterproof the spherical shell, place soil to a depth equal to about 50% of the total fill depth, and then perform tertiary tensioning of the tension ring PC cables (i.e., tension all the cables not tensioned in the primary and secondary stages).

(7) Place all remaining soil to complete the fill.

(8) Perform planting and landscaping to finish the work.

3.3 Spherical Shell Design Principle

(1) Principle for Dealing with Stresses due to Long-Term Loads

The cast-in-place portion of the shell was designed so that it would be subject to compressive stresses of about 20 - 40kg/cm^2 and no tensile stresses would be produced in it. In particular, the tension ring was designed to be prestressed so that compressive stresses produced in it would be about 20kg/cm^2.

Further, based on the concept of limit-state design, the sectional area was designed so that the compressive stress developed in the shell concrete by a loading equal to 1.7 times the long-term loading would not exceed the short-term allowable compressive stress (Fc x 2/3) as prescribed in the applicable structural standard of the Architectural Institute of Japan and the tensile stress would not exceed the crack-causing tensile stress (Fc/10).

(2) Studies on Stresses due to Seismic Loads

The shell was designed in such a way that the long-term allowable compressive stresses developed by the design seismic load (horizontal seismic coefficient K=0.3) would not exceed the long-term allowable compressive stress (Fc x 1/3) with no tensile stresses developed by the seismic load. Further, in terms of limit-state design, the shell was designed so that the compressive stress developed in it by a load equal to 1.5 times the design seismic load would not exceed the short-term allowable compressive stress used for the shell design and so that such a load would not produce any tensile stress in the shell greater than the crack-causing tensile stresses.

In addition, analyses were conducted to verify the shell's hysteretic response to earthquake motions and it was found the aforesaid limit-state principle would be satisfied when the shell was subjected to severe earthquake motions.

3.4 Structural Analyses

(1) Stress and Deformation Analyses of the Spherical Shell

1) Analysis method

The static stress and deformation analyses of the shell as a whole were performed by conducting three-dimensional elastic analyses of quadrangular shell components by means of the finite element method.

2) Results of the analyses

The stress of the shell under long-term loading are as shown in Figs. 7 and 8. Fig. 7 shows the stresses in the shell due to the axial force; Fig. 8, the stresses due to the bending moment. In Figs. 7 and 8, the left half of each stress diagram show the stresses in the direction of the circumference (or the latitude) and the right half shows those in the direction of the radius (or the longitude). In Figs. 7 and 8, the top left diagrams indicate the stress state that would occur in an assumed case where the full vertical load was applied while the tension ring was not prestressed at all whereas the top right diagrams shows the stress state in an assumed case where the tension ring was fully prestressed with no vertical loading applied to the shell. At the bottom of each figure, these two types of diagrams are superimposed to indicate the actual state of stresses. (The diagrams were prepared by disregarding the effects of cracking of the concrete and assuming that the same degree of rigidity was maintained on the tension side as on the compression side.) It is known from the axial force diagram of the shell in Fig. 7 that if no prestressing force is introduced, particularly in the latitudinal direction, a large tensile force is developed near the tension ring. It also is known that a prestressing force introduced into the tension ring effectively counters such tensile force and in practice causes the compressive stresses to be dominant throughout the entire shell. Further, from the bending moment diagram in Fig. 8, it is known that the bending moment caused by vertical loading is offset by the bending moment generated by the prestressing and in consequence the shell is not actually subject to a large bending moment.

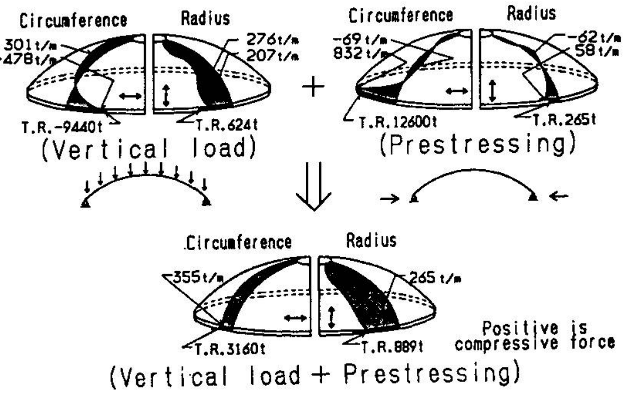

Fig. 7 Axial Forces in Shell

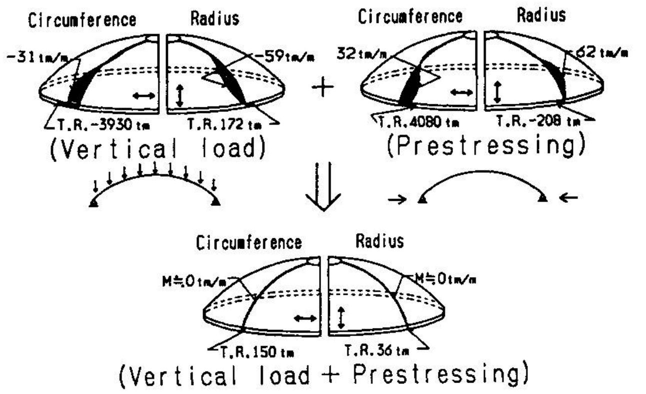

Fig. 8 Bending Moments in Shell

4. CONCLUSION

The construction of a gymnasium covered by the spherical shell roof described in this paper is now in progress with the completion slated for 1997. In the course of the spherical shell construction, further deformation and stress measurements at various locations are planned, which are expected to lead to still more interesting data. The authors wish to make a thorough study of the structural behaviors of this spherical shell by continuing on-site observation and data analyses on a comparative basis.

5. ACKNOWLEDGEMENTS

By taking this opportunity, the authors wish to express their cordial thanks to Professor Kazuo Suzuki of Osaka University for his cooperation and advice in designing the spherical shell.