Realization of a space for prayer with 3D free-form surface roof in harmony with the surrounding environment

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Abstract

A religious building containing a space for prayer has been constructed in Ōta City, Gunma Prefecture, which is noted for its heat in summer due to the foehn phenomenon and its cold in winter due to downdraft winds from the mountains. The site is in a quiet residential area on a gentle slope from the mountain towards the urban area, so the building has a gently sloping large roof to minimize the impact on the surroundings. The large roof has a special form with a 3-dimensional free-form surface. The large roof is supported by a reinforced concrete wall structure.

Keywords: 3-dimensional free-form surface; single-layer latticed frame; low rise/span ratio; shape optimization program; thrust processing; analysis during construction

1. Outline and Issues of the Building

The major features of this building are the heavy double skin large roof made from concrete and metal sheet in order to reduce the environmental load, and the extremely low rise to span ratio with a span of 24 m and a rise of 1.8 m, giving rise/span = 0.075. Therefore the issues were dealing with the thrust generated at the ends of the roof in order to resolve the instability of the shape, and realizing the shape in construction with high accuracy.

Fig. 1: External view

2. Large Roof Structural System

As a result of the comparison study, a structural steel single-layer latticed frame that can be made shallow and having a rectangular grid that could be easily made to conform to an irregular plan shape was adopted as the structure of the large roof. Fig. 2 shows the structural system.

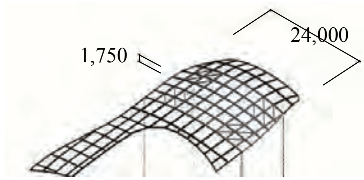

Fig. 2: Structural system

3. Design of Members and Connections

Low cost H-shaped steel was adopted for the members. Because the grid is rectangular 4 members are connected at each connection. Stiff connections can be achieved by in-situ welding of the flanges of the connections and HTB connection of the webs, to ensure a high resistance to overall buckling. In order to ensure quality of the flange in-situ welding, at the design stage it was confirmed using 3D-CAD that the tolerances at the flanges in all the connections could be maintained within the allowable values (Fig. 3).

Fig. 3: Connection using H-shaped steel

4. Determining the Form by Optimization

In order to optimize the structural scheme while satisfying the requirements of the construction scheme, a shape and cross-section optimization program was adopted for the free-form curved surface structure. This program is applicable to allowable stress design of steel structures, and determines the structural form and member cross-sections to minimize the mass of the structural steel under constraints of stress, displacements, and cross-sectional dimensions, etc. In this scheme, the major factor determining the member cross-sections was the fact that the rise/span ratio was very small. Also, because the rise/span ratio was very small, the thrust pushing the tops of the walls out of plane was large, which is disadvantageous in terms of the structural scheme. Therefore, the relationship between the form (rise) and the required quantity of steel was calculated by the optimization program, and an increase in the rise by 750 mm from the initial scheme (1,000mm → 1,750 mm) was agreed between the client and the architect. As a result the roof thrust force was reduced by 30% and the structural steel quantity by 20%.

5. Method of Dealing with the Thrust

Openings were provided at random in the RC walls supporting the large roof. Also, because the roof was heavy the thrust force was also large (200 kNm/m), causing out of plane deformation of the walls. In the long term the out of plane deformation will increase further due to creep. If the large thrust was not properly dealt with, there was a possibility of occurrence of snap through buckling of the roof (overall buckling by out of plane reversal). Therefore, a scheme was adopted in which the axial forces of the structural steel beams with large span and thrust were transferred as in-plane forces using roof in-plane horizontal braces to large beams with small span that were supported by internal walls (Fig. 4).

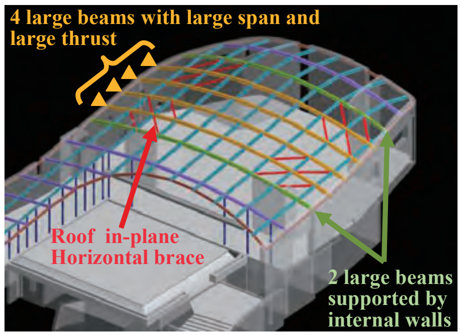

Fig. 4: Method of Dealing with the Thrust

6. Verification

In order to check the validity of the axial force values produced in the roof horizontal braces, the brace axial forces were calculated using strain gauges attached to the braces, and compared with the analysis values. The axial forces in the horizontal braces corresponded extremely well to the analysis values within factors ranging from 0.83 to 1.03, which confirmed that the required axial force was introduced into the braces, and that the thrust was being properly transferred within the plane of the roof (Fig. 5).

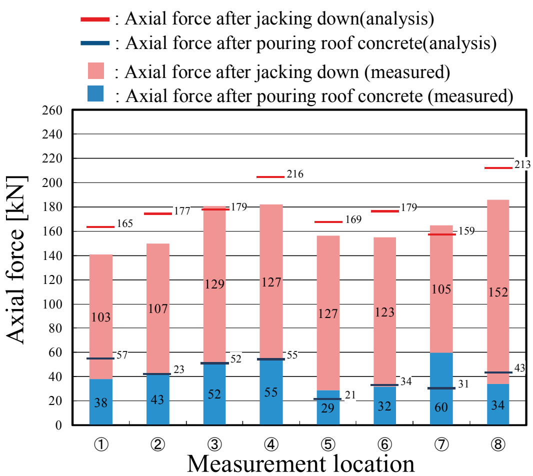

Fig. 5: Verification of the Structural Scheme

7. Conclusions

A church with a peaceful prayer space in harmony with the local community in severe climate conditions has been realized by overcoming the increase in mass due to the large span and low rise double skin roof.