

An elevated ‘Bubble’ at Shanghai’s New International Cruise Terminal

Tian-Fang JING*, Andrzej BRZOZOWSKI^a

*Principal

375 Hudson Street, New York, New York 10014, U. S. A.

jing@wai.com

^aSenior Associate

Abstract

This paper presents innovative structural engineering solutions developed in the design and construction of Shanghai's New International Cruise Terminal Observation Building. A steel framed roof system was designed to meet unique geometric shape and glass panel installation requirements.

Keywords: Terminal, observation building, glass-faceted façade, steel framed roof structure, wind tunnel, progressive collapse, seismic forces, buckling capacity, erection tolerance.

1. Introduction

The new International Cruise Terminal at Gaoyang Pier of Shanghai was opened for international passenger liners in August, 2008. It is the first underground cruise terminal built worldwide. Straddling the underground terminal is a stylish water-bubble-shaped Observation Building, which houses a variety of multi-use spaces and provides direct access to the terminal underneath. Adjacent to the Observation Building is a public park which covers the whole underground terminal. A pedestrian bridge in the park rises above the expansive terminal skylines and helps to merge the above-ground and below-ground areas (Figure 1).



Figure 1: Front view of Shanghai's New International Cruise Terminal

2. Design Concept

As part of the cruise terminal complex, the Observation Building is a three-level, 4,100 m² structure elevated on columns and elevator/stair core supports that rise 10 m above-grade, with glass-faceted façade profile suggesting an elongated bubble. The irregularly shaped bubble façade is supported on a steel framed roof structure, approximately 80 m long, 35 m wide and rising 20 m above an elevated steel framed transfer platform structure.

One of the key design challenges was to develop the steel framed roof geometry form to meet both the space function and the glass panel manufacture requirements. The curvature of this unique shaped roof structure changes in height in both directions, creating an asymmetric dynamic internal space. A variety of options were thoroughly studied to harmonize the steel roof framing with the glass façade layout. Only certain geometries produce the cost effective rectangular and trapezoidal flat panels layout. Special attention was paid to the two ends of the roof, which can become too densely packed with structural members as the roof grid converges (Figure 2).



Figure 2: Back view of observation building

After a value engineering study, the design team selected a conceptual geometry in which all the main roof frame elements are a series of vertical arches radially located along the longitudinal axis of the roof structure and the secondary roof frame elements are placed parallel with the ground along the height of the roof, connecting to the main vertical arches to transfer the loads and also provide lateral stability.

A rigid steel platform 1.2 m deep forms the first floor of the Observation Building. The steel roof framing is mainly supported on the perimeter of the platform and by a series of interior tree columns supporting the upper portion of the roof in order to minimize the deflections. The roof framing takes the form of interconnected steel pipes whose diameter range from 203mm to 254 mm for the main arches. All the secondary members are pipes with 152 mm diameter.

3. Several Key Design Issues

3.1. Lateral Load Design

During the preliminary design phase, it has been recognized that one of the important design issues of this structure is related to the lateral load effects due to wind and earthquake. To determine the wind loads, the Building Code was helpful in the preliminary design, but typically it did not provide the detailed input required to permit an optimized wind design for this special shaped structure. Therefore, a decision was made to perform a wind tunnel study to determine more accurate design wind loads. Wind tests were conducted in a boundary layer wind tunnel by Tongji University of Shanghai on a scale of 1:100 model under conditions simulating the surrounding environment. The model was placed at the center of the testing turntable and different wind directions were performed by

rotating the turntable (Figure 3). A total of 36 wind directions were tested by rotating the turntable at 10-degree increments. There were 372 pressure taps installed on the model. The testing results provided the mean and peak pressures acting on the building for the design of both the overall structural framing system and the glass cladding system. Dynamic analysis of the building was conducted prior to the wind testing using SAP 2000 (a structural analysis and design program) to determine the first 20 modes and their corresponding frequencies. The first three vibration modes with frequencies of 0.53, 0.85 and 0.93 Hz were determined by the analysis results. The first two modes were translational and the third mode was torsional.

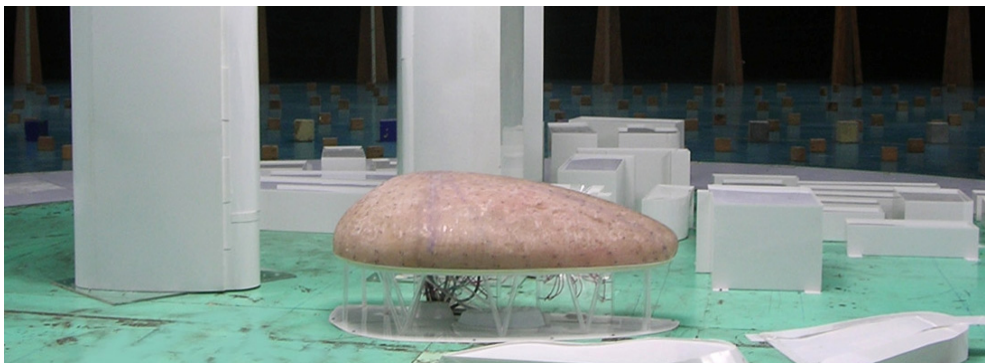


Figure 3: Wind tunnel model

Seismic design was performed in accordance with Shanghai Seismic Code requirements. The maximum ground acceleration of 35cm/s^2 was used in the analysis and design. Since this structure has many irregularities in comparison to standard buildings, a special seismic design submission and review process was performed. Three different seismic design analysis procedures: a) static equivalent method, b) response spectrum method and c) time history method were performed in order to define the most critical design forces. The results indicated that forces developed during the response spectrum analysis control the seismic design for strengths and serviceability requirements.

3.2. Progressive Collapse Study

The lateral load analysis and design were performed on the finalized 3D model using SAP 2000 Program (Figure 4). A detailed progressive collapse study was performed to determine the structural redundancy for this elevated structure by removing any base single column or base V-column to determine displacements and stresses in the platform framing and the remaining base columns.

The study indicated that this structure is designed to sustain local damage within the structural system but as a whole remaining stable. In case of local damage to a single

column or V-column, the structural system transfers load from the damaged region to adjacent regions capable of resisting those loads without collapse.

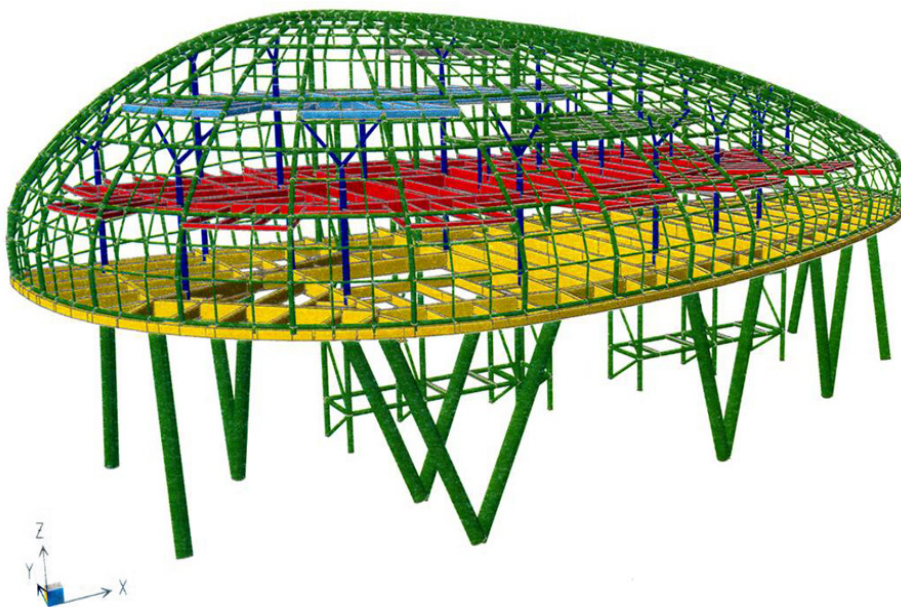


Figure 4: 3D analysis and design model

$$BL_{cr} = (BSF) \times (SW + SDL + 0.5LL) \quad (1)$$

BL_{cr} = Critical Buckling Load

SW = Selfweight of Structure

SDL = Superimposed Dead Load

LL = Live Load

BSF = Buckling Scale Factor

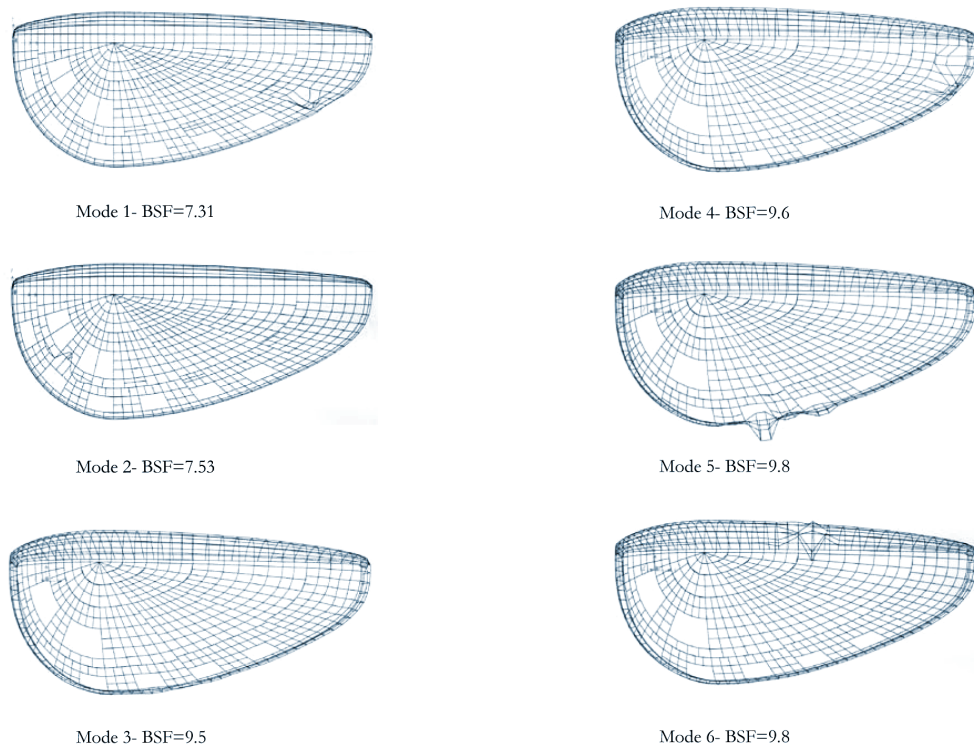


Figure 5: The first six roof buckling modes

4. Detailing and Construction

Once the structural system of the Observation Building was developed, the next issue was to detail this complicated structure.

The steel roof geometry was fully defined in dimensions and curvatures. All roof framing joints are welded type connections, either shop or field welded, depending on erection procedures. Bridge sliding detailing was introduced at the bases of main columns supporting the bubble's transfer platform.

The maximum erection tolerance established for the roof structure was 10 mm, which was extremely tight for steel construction industry standards due to glass installation requirements. The steel construction sequence was developed in order to meet the erection tolerance requirements (Figure 6).

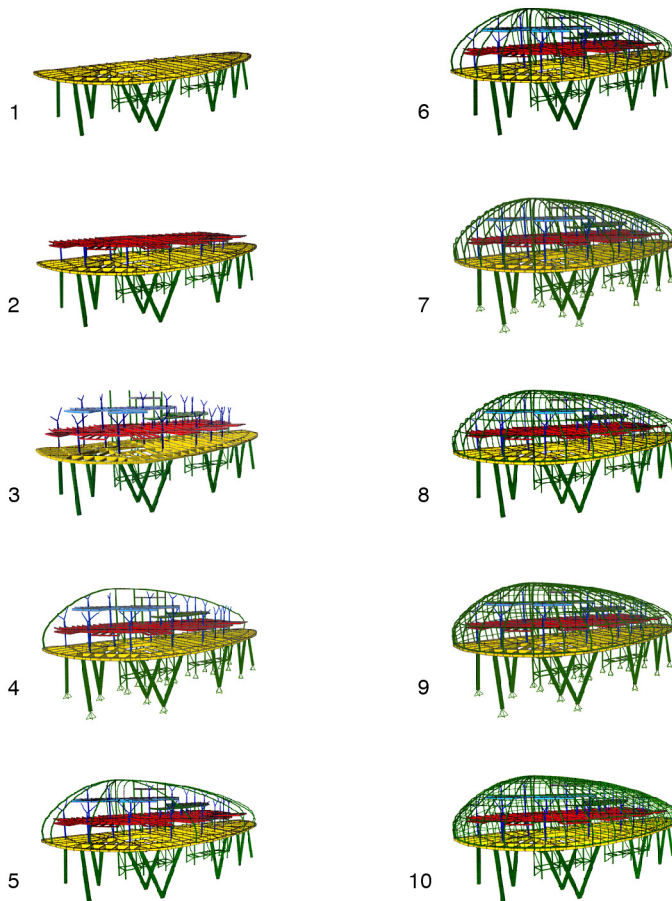


Figure 6: Steel erection sequence (total 10 stages)

The steel erection was divided into two phases. Phase One was the erection of the platform and interior floor framing structure (Figure 7). Phase Two was the installation of steel framed roof structure (Figure 8).



Figure 7: Steel platform and floors erection



Figure 8: Steel framed roof installation

The erection of the Observation Building was completed in 5 months, meeting the construction schedule.

5. Final Remarks

The architectural design of this unique Observation Building has many variable features contributing to the complexity of the structure. The structural solution developed in the design and construction of the steel frame system represents creative engineering innovations.