Opera House, Copenhagen: Outstanding Roof Structure

Hans Exner, Senior Chief Consultant, Rambøll Denmark A/S, Virum, Denmark. Contact: HE@ramboll.dk

Introduction

The Opera House (*Fig. 1*) in Copenhagen has received the 2008 International Association for Bridge & Structural Engineering's Outstanding Structure Award, principally in recognition of the innovative design of its roof. "This award is the big one in our world of structures."

The roof of the Opera House is one of the largest canopy roof structures in the world, with horizontal dimensions of 158 m × 90 m—about the size of three football pitches. An innovative design was developed for the roof to ensure the necessary strength, stability and dynamic response, whilst at the same time appearing light and slender. The main construction concept for the roof structure is taken directly from modern steel bridge design.

Keywords: Opera House; Copenhagen; Ostrac; roof; cantilevered.

Fig. 1: Opera House, Copenhagen

Architectural Requirements

The roof has been erected as two separate roof structures—the east roof and the west roof. The architects required that the west roof should include a large cantilevered roof, sized 78 m × 90 m (*Fig. 2*). The canopy roof should only be supported on ten foyer columns, located around the curved foyer, and on four supports located on the interior concrete walls along the fly tower. This leads to the roof being cantilevered on three sides—32 m to the west and 21 m to the north and the south. The maximum cantilever length is 43 m from the corner foyer column to the outer roof corner.

Furthermore, the architects have decided the structure should have a smooth outer surface and the smallest possible depth. Normally, the depth of a cantilevered structure will be one-tenth of the maximum cantilever span, but the roof of this building is 30% less than this with a maximum depth of 3 m.

Technical Challenges

When the depth is decreased by 30%, the stiffness of the structure is reduced substantially. However, by constructing the cantilever roof as a closed steel box, the flexural as well as the torsional rigidity is significantly higher compared with that of a traditional lattice roof structure. It is the same technique as used in steel bridge designs, where the large torsional stiffness is used, for example, in cable-stayed bridges with a central cable plane.

The plate thickness is very thin in relation to typical bridge design, being limited to 6 mm in the main part of the cantilevered structure and only increased to 15 mm in the region near the foyer columns.

The roof structure (*Fig. 3*) could not be designed as a closed box over the total area because of differential temperatures, but it was divided into a section made as a box and the remaining section made of a number of girders.

The outer ring beam forms the inner closure of the box, and the radial beams are designed so that the flaring of the beams can absorb the horizontal axial stress from the box structure. The foyer balconies are supported by vertical hangers, which are anchored in transverse beams spanning between the radial beams.

Outside the box structures along the three edges of the roof, truss girders are arranged to support the outer roof. This solution is advantageous in that it can accommodate the building tolerances in bolted connections between the box structure and the girders.

Static Analysis

The roof was designed for wind, snow and dead loads, as well as stresses from temperature and settlements of the foyer columns. The wind load was based on results from wind tunnel tests.

In the design of a cantilevered roof, it is certainly of high importance to minimize the steel weight, which leads to the adoption of a hollow box structure. The plate thickness of 6 mm, evaluated as a minimum from a fabrication point of view, is extremely thin for such a large structure. Hence, in order to provide sufficient strength and stiffness to the roof structure, a slenderness ratio b/t of approximately 70 was required, which determined the distance between the troughs. To analyze stability problems in the slender plates, it was necessary to develop new comprehensive formulas for biaxial stress combinations,

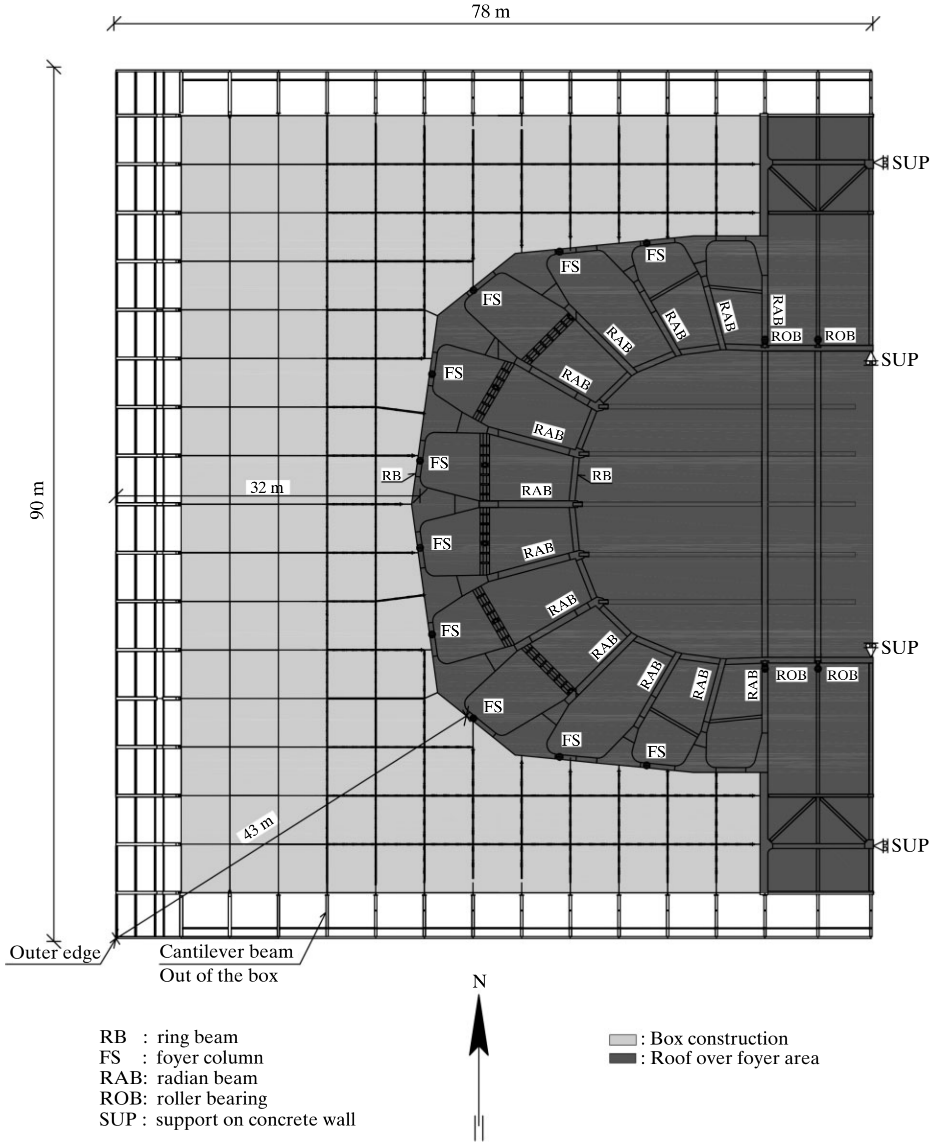

Fig. 2: Plan of the cantilevered roof

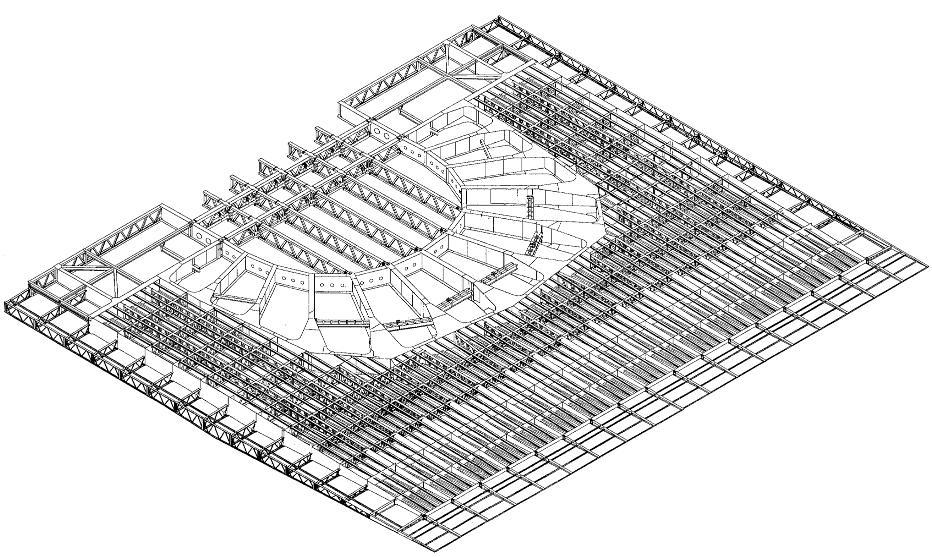

Fig. 3: Roof structure

including post-critical stresses and not only initial buckling stresses. The formulas have led to significantly lower plate thicknesses of the cantilevered roof. The box solution proved to be an optimal solution, because of the use of stress in both directions of the plates in combination with the shear stresses from the large torsional moments in the structure.

In order to perform the complex static analysis, two different three-dimensional (3D) structural analysis programmes were used, including a third programme to cope with the geometry (see *Fig. 3*). This is an early example of the now more common use of detailed 3D analysis in building design.

Dynamic Behaviour

The increase in torsional stiffness of a box section compared with truss girders is beneficial for the dynamic behaviour of the structure, and thereby for the limitation of the dynamic amplification of the vertical wind loads.

For large structures with predominant mode shapes involving global deflections, it is important to consider the cross-correlation of the wind when calculating the dynamic response. The cross-correlation takes into account that the wind is not acting with the same pressure all over the structure at any given time. A wind tunnel test was carried out, and it showed that constructing the cantilever roof as a closed box girder reduced the dynamic wind load to an acceptable level, and therefore damping devices were not required.

Differential Temperatures

"The committee made special mention of the fact that the structure moves in response to internal and external temperatures, which is very innovative."

One of the main challenges in the construction of the large roof was to accommodate the differences in temperature between the cantilevered roof portion and the portion of the roof over the foyer. The maximum temperature difference occurs during wintertime, with the cantilevered roof portion subjected to ambient external temperatures and the foyer roof subjected to heated internal temperatures. Such large differential temperatures are not typical for bridge structures.

In a continuous plate, temperature differences of this magnitude will lead to normal stresses in the thin plates of the same order of magnitude as the critical stresses. Therefore, it was necessary to integrate the box structure with a system of truss girders over the foyer area. The cantilevered part of the roof forms a horseshoe around the foyer area, and in winter, this horseshoe will contract and therefore compress the structure over the foyer from the outside. The approach was to locate as few girders as possible in the North–South direction and place roller bearings between the cantilevered box portion and the foyer girder portion of the roof. The roller bearings can release the differential horizontal deformations in the North–South direction and can transfer compression/tension forces in the vertical direction.

The result of the temperature load case is that the structure over the foyer will be squeezed in the North–South direction, the girders will deflect horizontally and the entire foyer roof structure will move towards the east.

Surface Treatment

The closed steel box is protected against corrosion by an internal air dehumidification system, eliminating the need to paint the internal surfaces of the hollow box section. This principle of corrosion protection has been used successfully on steel bridges for more than 35 years. To our knowledge, the Opera House represents the first application of this principle to a building structure (*Fig. 4*).

Facts

The Opera House in Copenhagen was opened on 15 January 2005. It was designed and built within a very short time schedule of four years. The Opera has a total area of 41 000 m^2, of which 7000 m^2 is accessible to the public. It comprises one main auditorium for 1500 people, a foyer, the stage plus five side and rear stages, a small stage for 200 people, six major rehearsal rooms, individual rehearsal rooms, dressing rooms, offices, workshops, a canteen, archives, stores and technical plant rooms.

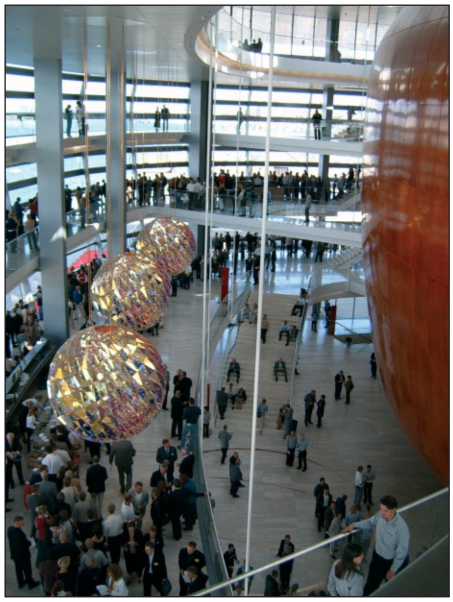

Fig. 4: Opera interior

Conclusion

The Opera in Copenhagen owes its iconic shape to the cantilevered roof, greeting and protecting everybody arriving at the building. The roof has an extraordinary span and slenderness. Its elegance was enabled by its structural principles founded on the following principal means:

- The main box steel structure has high bending and torsional strength and thereby reaches out to its far corners, with an economical use of material.
- The stiffness of the box structure ensures against wind-induced vibrations as well as visible deflections.
- The arrangement of the box in the outdoor and the truss beams in the indoor parts of the roof ensure unconstrained movements with low stresses at varying outdoor temperatures.
- The design and corrosion protection brings ideas and skills of steel bridge construction into building design - to be adapted to the different geometrical and functional constraints of the building deviating from those of a bridge.
- The innovative unification of bridge and building principles has not been realized before on a similar scale.

SEI Data Block

Client, donor and builder:
A. P. Moller and C. McKinney Moller Foundation, Copenhagen, Denmark

Owner:
Danish National Theatre

Architect:
Henning Larsen Architects, Copenhagen, Denmark

Structural Design:
Ramboll Denmark, Virum, Denmark

Main Contractors:
E. Pihl & Son A/S, Copenhagen, Denmark

Structural Steel *(t)*:	
Auditorium	350
Foyer	1000
East roof structure	1200
West roof structure	1800
Fly tower	1000
Miscellaneous	1500
Concrete (m^3):	
Cast in place	26 000
Precast elements (2500 pieces)	9000
Total cost (USD million):	More than 400
Service date:	January 2005

Note: This structure was featured in SEI Feb. 2005 issue (Pg. 16-20) where a more detailed description of some aspects can be found.