New Terminal 3 for Shenzhen Bao’an Airport: a 1250m long structure

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Summary

The new Terminal 3 at Bao’an International Airport in Shenzhen is an architecturally and technically outstanding building. The free-formed spatial steel framework for the concourse and terminal superstructure is based on a successful competition entry by the team of Massimiliano and Doriana Fuksas Architects, Rome and Knippers Helbig Advanced Engineering, Stuttgart/New York. The 1250m long steel structure is designed to cope with extreme wind and seismic loads and also acts as a perforated screen.

Keywords: airports; special steel frame; conceptual design; seismic loads.

1. Introduction

Shenzhen is located in the south of Southern China’s Province Guangdong, neighboring Hong Kong to the south and Guangzhou to the north. Since 1980, when Shenzhen was established as the first of five Special Economic Zones in China, the original population of 300,000 ballooned to about 13,000,000 in 2011.

Today Shenzhen is one of the largest cities in the Pearl River Delta region, one of the economic powerhouses of China. Shenzhen, with its strategic advantageous position, is a major transportation hub for the export-oriented industry. It is the third-busiest container port in China and Shenzhen’s Airport is the fourth-busiest cargo airport in China, handling ca. 26.8 million passengers in 2010.

Shenzhen Bao’an international airport is currently undergoing a major expansion with a second runway and a new terminal. In 2008 the Shenzhen Airport Group held an international design competition for the new-to-be-built Terminal 3, which is to serve international destinations. Massimiliano and Doriana Fuksas Architects, Rome supported by Knippers Helbig Advanced Engineering, Stuttgart won the competition with their approach of an organic shaped sculpture.

\textit{Figure 1: Rendering competition stage (© Fuksas)}
The New Terminal 3, which is planned to be opened at the end of 2012, is intended to help meet Shenzhen’s forecasted capacity of 45 million passengers by 2020.

2. Architectural approach

Fuksas’ architectural approach considers the roof of the terminal and concourses as a free-formed envelope and perforated screen to provide a pleasant atmosphere to travelers. The undulated shape creates a diverse and interesting airy impression for passengers as well as spacious and comfortable areas for dining, shopping and resting. For visitors arriving at Shenzhen by air, the organic-shaped body, which is illuminated by its interior lighting, is an iconic landmark of the young and modern city possessing a high recognition value.

Due to the adjusted configuration of two layers of partially opaque and translucent honeycomb-shaped elements, both on the inside and outside of the roof structure, natural light is filtered to provide areas of different brightness. The roof structure is wrapped by and integrated in the outer and inner skin but stays present and visible. Thus the structure is an integral part of the multi-layered and multi-functional building envelope.

![Figure 2: Photo section model](image)

3. Design concept

Because of the geometrical complexity and restraints, and due to the short time design and construction schedule, all structural components of the roof were proposed to be a steel structure. Furthermore, the project benefits enormously from the wide experience gained by the Chinese steel industry in more complex projects such as the Bird’s Nest and Watercube in Beijing and from the central axis roof constructed for the ‘Expo Boulevard’ in Shanghai [1].

The roof structure basically consists of a spatial framework with a varying height between the lower and upper chord level. Truss members are mainly tubular hollow sections and the tube diameter varies from 3 to 8 meters. In particular areas rectangular hollow sections were used. These profile sections are composed of flanges and webs with a plate thickness adjusted to the local structural requirements.
3.1 Segmentation/Basic Concept

The total size of the roof structure is approximately 1250 meters long and 642 meters wide.

In a close collaboration with the local engineering partner BIAD, the supporting concrete main structure and steel roof structure were divided into segments by expansion joints (Figure 3).

**Figure 3: Subdivision of roof structure [m]**

Terminal

The structural system of the mainly flat terminal roof has been developed as a truss girder grid based on a regular support interval of 36m. The supporting pendulum columns are up to 25 meters long. Since the structure is located up to 20 meters above floor level, horizontal support is therefore provided by strengthened elevator shafts.

Concourse

The concourse part of the structure extends over a total length of about 1,350 meters. Basically the structural system is generated by the extrusion of an arch-shaped truss with a maximum distance of 3 to 6 meters between upper and lower chord level. The two-hinged arch configuration rests on the outer perimeter line of the supporting main concrete structure at regular intervals of 18 meters. This support corresponds to the architecturally shaped massive walls which stabilize the concourse slabs. Longitudinal support is provided by an integrated and adjusted spring system at the bearing points.
3.2 Architectural intention and structural efficiency

The architect’s idea is to provide a double-layered screen perforated by honeycomb-shaped openings which allow an unblocked view to the outside for transiting passengers. This design intention does not initially correspond to a super-efficient structural system which would follow the direct load path by using the shortest span between the supports. So the basic trapezoidal grid has been adjusted to the architecturally set honeycomb. But the orientation of the so generated space-frame is sub-optimal since it does not provide sufficient stiffness in transverse direction.

In a close collaboration between design architect and structural engineer several options of different strengthening strategies were investigated. The final design option follows a basically straightforward structural strategy of implementing effective bracing elements in the architecturally set trapezoidal configuration (Figure 6). Following the geometrical basic units bracing distances of 72, 36, 18 and 9 meters were investigated (Figure 5).

Geometrical conditions in longitudinal direction allow for reasonable space-frame trusses to span between the bracings of up to 36 meters. The global transversal stiffness had to be adjusted to cope with extreme wind loads resulting from hurricanes. This was achieved by comparing an analysis of inherent eigenfrequencies and a regular bracing distance of 18 meters was established.

![Investigation on different bracing distances](image)

To adjust the arrangement of the structurally efficient arch-framework to the hexagonal window arrangement the beam has been split into two halves. As a result a central unblocked window of about 2 metres which provides the intended clarity.

The two framework segments are connected at the base to form the supports. Due to the high repetition number these special elements are developed as cast iron steel elements. At the time the
so-called twin bracing support elements were considered one of the largest cast iron elements ever fabricated in China so far. The bracing connectors rest on a central pin which transfers vertical and horizontal loads but allows for longitudinal movement.

![Figure 6: Bracing at 18m interval (left) / Elevation base point (right)](image)

3.3 Optimization of support conditions

In order to reduce the number of technically complex and expensive expansion joints, long structure segments with a length of up to 200m have been chosen. As a result, another optimization aspect, namely the limitation of longitudinal reaction forces due to seismic effects or thermal expansion, becomes important. To let thermal expansion occur without restraint, usually one pair of fixed bearings is chosen at a central position while all others are sliding.

A disadvantage of such a bearing situation is that the seismic force (or other longitudinal forces) has to be transferred locally via one single pair of bearings. Also, the structure needs to be strengthened near to the fixed bearing point.

Such a local strengthening of the concrete substructure below the steel roof would have had a visible impact on the global architectural design which was not intended. In order to avoid this, spring bearings were chosen to optimize between these two controversial load scenarios and to equalize the total bearing reaction forces.
The figures show a simplified structural system as a continuous beam on five supports. For the different bearing situations that have been chosen, the differences of the results are shown qualitatively. The first two situations are extreme ones, showing a good behavior for only one of the load cases. In (a) thermal expansion does not lead to reaction forces and in (b) seismic loads are equally distributed. For the other load case high reaction forces occur. The third situation uses varying spring stiffness along the structure decreasing towards the borders. One can see from (c) that reaction forces resulting from an earthquake can be equalized at the intermediate bearing points. However, no important thermal constraints occur at the borders.

In a similar way, optimized spring configurations can be found for each concourse part when taking into account its individual length, seismic mass and friction force. The chosen spring type for the Shenzhen International Airport Terminal 3 is a disc spring positioned between the bearing strap and the strap of the main bracing structure. These springs can simply be mounted on the bearing shaft.

An advantage of the disc spring is the small width and the simple way of combining several disc springs together to produce higher or lower spring stiffness. This can be achieved by grouping several discs in the same or opposite direction to one another. The chosen package of disk springs for each bearing point has been arranged on both sides of the strap so that all load directions, as well as thermal expansion and contraction, can be transferred with the same properties.
Additional optimizing options can be created by using non-linear spring characteristics in either digressive or progressive course (see curve 1 and 2). Putting digressive spring characteristics into the central part and progressive characteristics into the borders can help to avoid too high forces in the central part.

In the case of high seismic forces the spring movement $u$ increases disproportionally high (curve 2) at the central part which leads to force redistribution to the border regions where the force increases disproportionally high (curve 1). On the other hand, the progressive characteristics at the borders have to keep the range of thermal expansion free of high reaction forces.

![Figure 9: Bracing (left) / Construction terminal and concourses (right)](image)

4. Conclusion

The structural design of Terminal 3 at Shenzhen’s Bao’an International Airport was strongly influenced by the coincidental necessity of coordinating architectural intensions and structural performance. Interdisciplinary design strategies were developed to segment and support a 1250m long structure. In a close collaboration with the design architect an efficient and well-integrated structure for the free-formed building envelope has been developed.

5. References
