Introduction: Recent Structures in India

In anticipation of the forthcoming IABSE Symposium in Kolkata in September 2013, this special issue of Structural Engineering International presents a series of projects in or related to India. As varied as the country itself, the following eight technical papers present structures ranging from an underground cavern to a research station in Antarctica.

In the first paper—and highlighted on the front cover—the new terminal building of the Mumbai airport is described, including the elaborate roof and wall system. This is followed by two projects in and around New Delhi: a new signature cable-stayed bridge with its backwardly inclined pylon and the addition of a cable roof system for the retrofit of a stadium. A brief history of landmark bridges constructed over major rivers in India and the challenges faced in their construction is then elaborated. Next, the construction of one of the world's deepest caverns for the storage of liquefied petroleum gas in Visakhapatnam is detailed, followed by a description of the new Indian research station on the world's southern-most continent, Antarctica. Back on the Indian subcontinent and aboveground, the last two papers present a light-weight, double layered cable-net roof system for the retrofit of a swimming facility, as well as a 10 km-long infrastructure project in the technology hub of Bangalore.

The Indian Group of IABSE is looking forward to welcoming delegates to the 36th IABSE Symposium, in Kolkata from 24 to 27 September 2013 entitled "Long Span Bridges and Roofs—Development, Design and Implementation". More information on this symposium, as well as other upcoming IABSE events can be found on the IABSE website under www.iabse.org/Events.

B. C. Roy, Vice-President of IABSE, Chair of Scientific Committee of 2013 IABSE Symposium in Kolkata

Ann Schumacher, Editorial Board, Structural Engineering International

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Chhatrapati Shivaji International Airport—Integrated Terminal Building

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Abstract

The new Integrated Terminal Building at Mumbai's Chhatrapati Shivaji International Airport combines international and domestic operations at one of the busiest airports in India. The 410 000 m^2 building, being constructed at the site of the existing terminal, will achieve a capacity of 40 million passengers per annum upon completion in 2014.

The primary design feature of the building is a long-span roof covering a total of 70 000 m^2 over various functional requirements, making it one of the largest roofs in the world without an expansion joint. The Headhouse Roof, supported by only 30 columns spaced at 64 m in the North–South direction and at 34 m in the East–West direction, produces a large column-free space ideal for an airport. By increasing the depth of the trusses near the columns and running trusses in both an orthogonal grid and a 45° grid, large spacing and cantilevers of 40 m along the perimeter are achieved with an overall truss depth of only 4 m. In response to site constraints and proximity of the existing operational terminal building, the mega-columns are also designed to serve as hoist mechanisms such that the entire roof can be constructed without tower cranes. The Terminal Building also includes the largest and longest cable wall system in the world. The structural studies completed include solid finite element analysis of connections to optimize material efficiency. Furthermore, the structural design prioritizes modular construction for economy and facilitation of an accelerated construction schedule.

Keywords: airport terminal; long-span roof; unidirectional cable wall; structural efficiency; phased construction.

Introduction

Mumbai International Airport Limited, owner-operator of Chhatrapati Shivaji International Airport at Mumbai, is currently building a new Integrated Terminal Building that combines international and domestic operations at one of the busiest airports in India in order to achieve 24-h utilization. This 410 000 m^2 terminal building is being constructed at the location of the existing terminal with minimal disruption to its operations. An international consultant with vast experience in designing airport terminals around the globe was chosen as the principal architect and engineer for the new building. One of the largest construction firms in India was chosen as the local designer and general contractor for the project. The Terminal Building is being constructed in phases where Phase 1 includes construction of the western pier, and Phase 2 includes construction of the Headhouse zone. Upon completion of Phases 1 and 2, the building will become operational and Phase 3 will commence, which consists of the demolition of the existing terminal building and the construction of the eastern pier. Following the completion of Phase 3 in 2014, the new terminal, shown in *Fig. 1*, will serve approximately 40 million passengers annually.

Fig. 1: Architectural renderings (clockwise from top left) plan view of integrated terminal building; approach roadway at departure level; check-in concourse; aerial view of integrated terminal building

Owing to the scale and project occupancy, the client directive was to meet the requirements of the Indian codes as well as satisfy requirements of the International and American codes. This was achieved by evaluation of the most stringent conditions at all stages of design and analysis. Early in the design process, an evaluation of local construction techniques, available construction materials and availability of skilled labor played an important role in the choice of the building materials. Concrete was selected as the primary building material for the base building, while steel was used for the structural framing of the roof in order to achieve a lightweight system with large column-free spaces. The construction site of the new terminal building is located within close proximity of the existing terminal that had to remain operational during construction, which resulted in an elongated X-shaped plan utilizing repetitive, modular designs that accommodate construction phasing and permit rapid construction.

Long-Span Structural Steel Headhouse Roof

The primary design feature of the Terminal Building is a long-span roof covering the departures roadway, check-in hall, security, and passport control functions. The architectural cladding of the roof and ceiling features a molded surface and skylights over the column locations and throughout the terminal ceiling, allowing natural light to flood into the main hall. The Headhouse Roof, covering 70 000 m^2 and spanning over seven individual concrete base structures, is supported by only 30 composite mega-columns. Beyond typical gravity and seismic loads on the roof, special loading considerations were taken for the cable wall which applies a significant wind load to the roof structure and whose cables are pre-stressed against the roof trusses at the northern end of the terminal. The wind loading also presented challenges as a significant portion of the Headhouse Roof is open to the outdoors and behaves as a canopy.

In order to create one of the largest roofs in the world without an expansion joint, the roof mega-columns and steel roof structure were kept completely independent from the base concrete structures below. Large openings in the concrete base structure allow the mega-columns to pass through as well as create architectural design features. This allows the Headhouse Roof structure to move independently in response to loads, particularly expansion and contraction caused by temperature variation. This thermal gradient is applied to the steel in the structural analysis model and accounted for in the design of the roof members.

In response to the functional requirement of the space below the roof, the entire Headhouse Roof is supported on just 30 composite mega-columns. Following requests from the client, the design team sought to minimize the number of columns in the departure halls. However, the final design surpassed this constraint and resulted in a departure hall entirely free of columns through the use of composite mega-columns spaced 64 m in one direction and 34 m in the perpendicular direction. The structural system for the Headhouse Roof is akin to a two-way flat slab system. Increasing the depth of the trusses near the columns and running trusses in an orthogonal grid as well as along a 45° grid results in an overall truss depth of 4 m for the roof system. The greater truss depths near the columns create "column pod" areas which seamlessly integrate into the pyramidal skylights that serve as major architectural features. All of these aspects of the Headhouse Roof can be seen in the structural model in *Fig. 2* as well as in the construction photographs of *Fig. 4.*

The lateral system for the Headhouse Roof comprises steel moment-resisting frames consisting of composite mega-columns and long-span steel roof trusses. Frame action is achieved between the primary roof trusses and the composite mega-columns in the North–South direction and between the secondary roof trusses and the composite mega-columns in the East–West direction. Additional trusses running at 45° to the orthogonal grid provide additional stability and diaphragm stiffness. The weaving of the orthogonal and diagonal trusses, in addition to ensuring diaphragm action of the roof, was also extremely useful

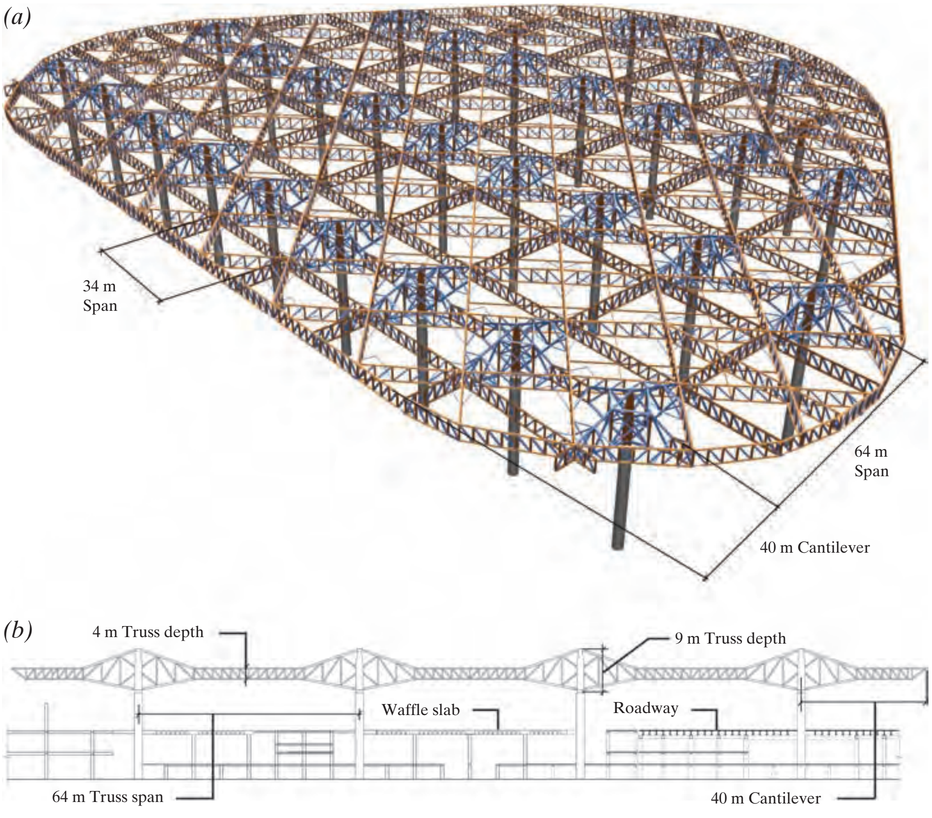

Fig. 2: (a) Three-dimensional structural model of Headhouse Roof framing; (b) section through Headhouse Roof

in reducing the system depth for the entirely cantilevered perimeter zone of the Headhouse Roof. This resulted in up to 40 m cantilevers at certain locations with a truss depth of only 4 m.

The orientation of the steel wide-flange members of the trusses along the orthogonal grid were rotated 90° such that flanges were aligned vertically, while the steel members of the trusses along the diagonal grid were aligned with the flanges horizontally for simplification of connections with multiple trusses. Nonlinear, solid finite element analysis was carried out for the design of major connections for optimum use of materials. The meshed three-dimensional geometry of the connections (*Fig. 3a*) was loaded at the connection work point with forces directly obtained from the overall Headhouse Roof analysis model. Rigid link elements from the work point transfer the load to the connection end faces (where the steel members are attached to columns, beams, etc.), and von Mises stress gradients were obtained and studied to verify that no part of the connection exceeded the steel yield stress (*Fig. 3b*).

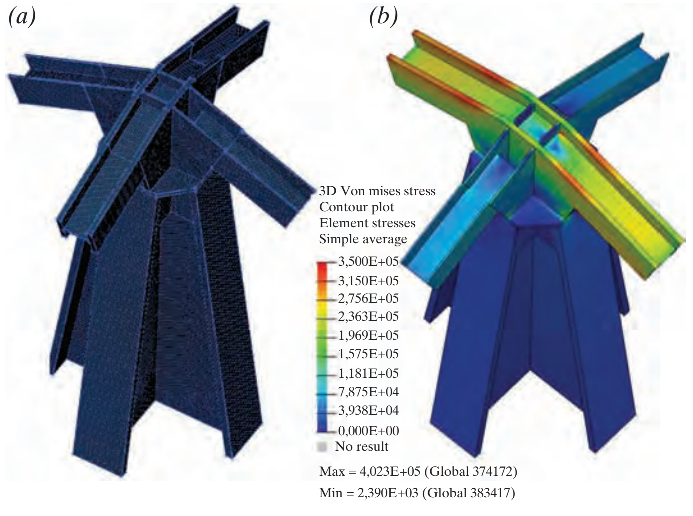

Fig. 3: Three-dimensional solid finite element analysis model of column pod top node connection: (a) three-dimensional finite element mesh of column pod top node; (b) finite element von Mises stress results of column pod top node (N/m^2)

The behavior of the 40 m tall cantilevered composite mega-columns was studied using nonlinear buckling analyses for each individual mega-column. The composite mega-columns consist of a built-up steel cruciform shape encased in 2,7 m diameter of concrete for the majority of its height. Once the column reaches the height of the column pod bottom chord connection, it transforms into a bare steel cruciform shape and tapers to the column pod top chord connection (*Fig. 4*). The P–M (axial-moment) interaction curve and stability analysis was performed for each segment of the column as well as for the overall stability of the complete mega-column system. These analyses were deemed necessary, because the code-prescribed design methods do not accurately correspond to the behavior of these columns.

Unidirectional Cable Wall System

Another unique feature of this project is the cable wall exterior cladding system. The Terminal Building features two separate cable wall systems totaling over 1 km in length and 11 000 m^2 in area, making it the longest and largest cable wall in the world. It includes a number of unique features that create various challenges in the design and detailing of the structure. Both cable walls comprise unidirectional cables spanning vertically between two levels of the terminal structure. At the Departure Level, the use of unidirectional cables was necessitated by the fact that the cable roof completely envelops the terminal Headhouse, eliminating the possibility of any horizontal anchorage points. In addition, as the cable wall circles the Headhouse, it crosses four independent base structures and reduces in height from 15 to 6 m. Expansion joints were installed in locations where the cable wall crossed separate structures to allow individual segments of the wall to move independently. On the east and west sides, the cable wall spans to the cantilevered edge of the Headhouse Roof, up to 40 m from the nearest mega-column. The large cantilevers result in significant deflection at the roof edge, which proved to be a challenging situation. With

Fig. 4: Headhouse Roof construction photographs: top, terminal building panorama; Headhouse roof to left, May 2012; middle, Headhouse Roof over departure level roadway, February 2012; bottom, stages of column pod installation

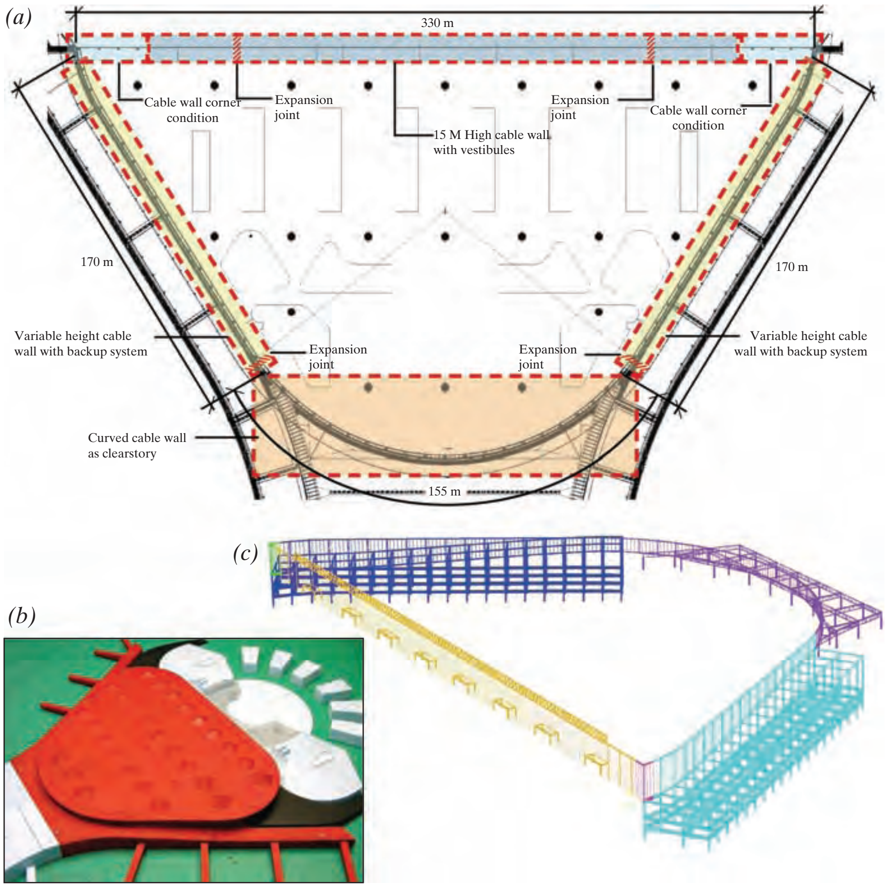

Fig. 5: (a) Cable wall plan and support conditions; (b) Headhouse Roof and cable wall wind tunnel study model; (c) cable wall structural analysis model with back-up systems

the cables anchored to the roof, large roof deflections would cause a loss of pretension in the cables and failure of the system. As a result, a back-up system has been introduced consisting of composite columns cantilevered from the base structure below and interconnected with structural steel girders at the top and bottom of the wall. The cables span between these girders, and the top of the back-up system is laterally supported by the Headhouse Roof above with dampers at composite column locations. This system allows for differential movements between the edge of the Headhouse Roof and the base structure without the loss of cable pretension. The various cable support conditions are highlighted in *Fig. 5a* and can be seen in the construction photographs in *Fig. 6*.

In addition to its size and length, the cable wall includes a number of features rarely seen in cable wall structures. A large portion of the wall follows the curvature of the plan of the Headhouse Roof, a feature only achievable because the cable wall consists solely of vertical cables. At the two ends of the north portion of the wall, there are absolute corners. The allowable deflection typical of cable walls would have caused the two portions of the walls to collide at this location. To prevent this from occurring, the corner cables are reinforced with horizontal stiffener plates connected between the cable and the corner column of the back-up system. Variations in height, changes in anchoring conditions, and the inclusion of corners, curves, and entrance vestibules all worked to necessitate a very precise design of cable pretension. Owing to the shape and scale of the Headhouse Roof and the cable wall, a wind tunnel study (*Fig. 5b*) was carried out to accurately determine the cable wall cladding pressures as well as the structural roof loads for the Headhouse Roof. After establishing the appropriate gravity and wind loads, a finite element analysis model, as shown in *Fig. 5c*, was built including the cables and support structure. Through a geometrically nonlinear static analysis, the deflection and axial force of each cable was determined. In locations where deflections exceeded L/50, the pretension force in the cable was increased, and cable diameters were selected to meet the axial force demands. A primary concern during the design of the cable wall was preventing warping of the cable wall insulated glass units (IGUs). Warping

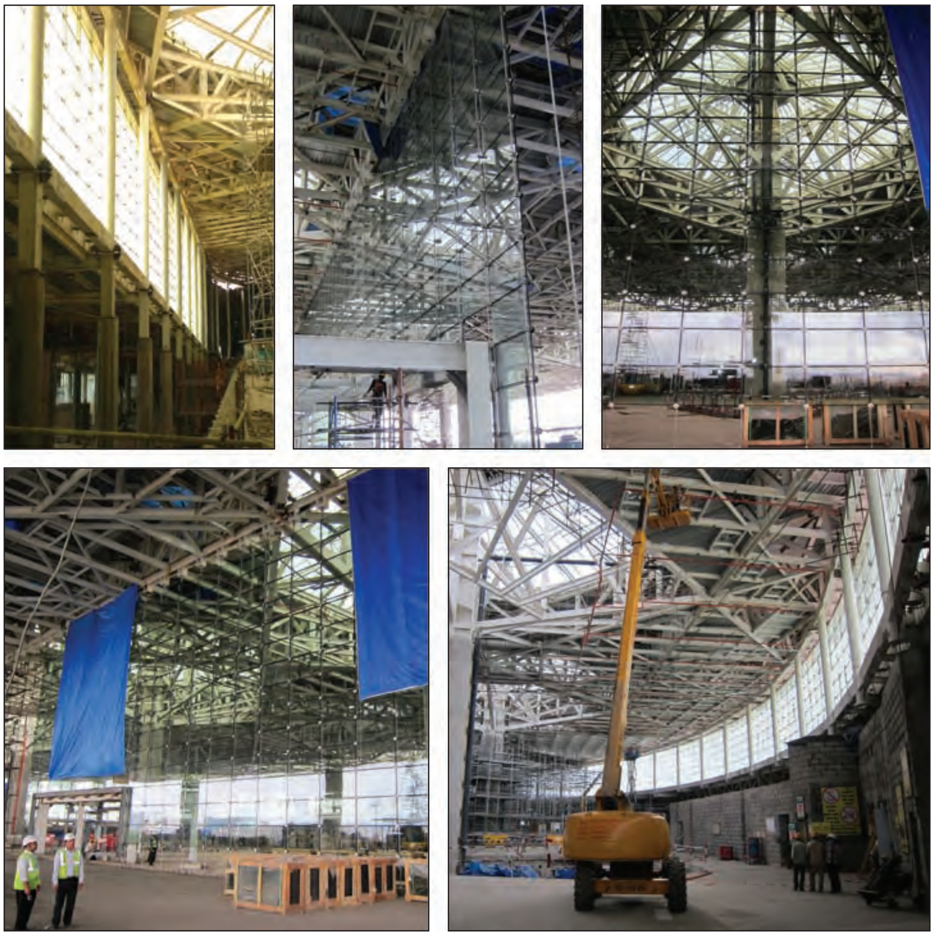

Fig. 6: Cable wall construction photographs (clockwise from top left) varying-height cable wall with steel column back-up system; cable wall at entrance vestibule; departure level cable wall with column pod beyond; curved cable wall along clerestory zone; departure level cable wall connected directly to Headhouse Roof

occurs when the four joints of the rectangular glass units do not lie in the same plane, and it can cause the seal between IGUs to break. Based on the allowable shear deformation of the IGUs, the out-of-plane deflection was limited to $L/100$, where L is the shorter length of the rectangular unit. To prevent warping of the IGUs, the largest values of pretension are required in areas with sharp geometric changes, such as the vestibules and at the wall corners. Based on these conditions, cable diameters vary from 25 to 37 mm and pretension values range from 150 to 400 kN.

Multiple System Concrete Base Structure

The Terminal Building is divided into the Pier and Gate Zone, Retail Zone, Headhouse Roof Zone, and the Frontage Road Zone. Despite its immense size, the Terminal Building requires only two grid systems to cover the entire footprint of the building. An orthogonal $8{,}5 \times 8\ \text{m}^2$ grid was adopted for the entire central facility, which provided optimal use of space for the baggage handling facilities. Meanwhile, the grid utilized for the Gate Zone was a $9 \times 11\ \text{m}^2$ continuous linear and radial grid along the periphery of the building.

The concrete base structure of the Terminal Building employs three distinct structural floor systems in response to functional zones with varying optimal clear-span requirements. In the linear and radial Gate Zone, a regular, repetitive one-way concrete beam and slab system has been utilized. At locations which generate heavy passenger congestion such as the Baggage Claim Hall, functional requirements called for a relatively column-free space. This was achieved by placing columns within the baggage claim belts and having a clear span between belts resulting in structural framing bays of $17 \times 16\ \text{m}^2$ and employing a waffle slab system for the floor framing above. In the Retail Zone, where maximum flexibility for floor openings and future renovations was desired, the floor system utilizes steel framing with composite metal deck slabs in-filled between concrete moment frame systems. At all locations, the regular grid system has resulted in the repetitive use of concrete formwork and economy in construction.

Along the perimeter of the terminal, security requirements mandated certain clearances between the building and aircraft, as well as a vertical separation of departing and arriving passengers. To provide this separation at the terminal while maintaining a single point of aircraft entry, steel fixed bridges connect the terminal to the aerobridges. The fixed bridges utilize a truss system along the edges with a minimal number of touchdown locations to provide maximum flexibility below for airside traffic movement.

Owing to the constraints of the site, the layout of the Terminal Building is such that areas with internal functions occur in the levels below the departures roadways adjacent to the Arrivals Hall. The roadway system therefore had to be isolated from the Terminal Building structural framing below to minimize vibration and to maintain acceptable acoustic levels in the occupied spaces below. The structural system for the roadways consists of reinforced concrete moment-resisting frames of the base building below in conjunction with pre-stressed, pre-cast reinforced concrete long-span I-beams supported on isolation pads. A cast-in-place reinforced concrete slab interconnects the I-beams and acts as a diaphragm. Given that the roadway slab is exposed to the elements, it was designed to allow for movement due to temperature changes; the pre-cast I-beams are fixed at one end and free to slide at the other end. The roadway is exposed to the elements and large temperature changes, but with interior space below the roadway, expansion joints in the roadway slab had to be water-tight. To meet this requirement, these joints were located at 17 m intervals to minimize the width of the joint.

The design of the parking structure brought along a number of aesthetic and functional challenges. Designers did not want an imposing structure, but difficult geological conditions limited the depth of excavation. Working within these constraints, the parking structure utilizes a shallow floor framing system with two-way concrete flat plate with concrete shear walls for lateral support. The compact nine-level parking garage meets all of its parking requirements within the stipulated height so that its roof aligns with the Departure Level and serves as a green roof for the visitor area.

Concluding Remarks

The design of the Terminal Building placed a high priority on material efficiency and ease of construction. All parts of the building utilized repetitive, modular designs that accommodate construction phasing and permit rapid construction. Ensuring the stability of the individual portions of the Terminal Building throughout the phased construction was an important consideration in selecting the building's structural systems. Construction of Phase 1 began in 2008 and was completed in early 2012. By November 2013, both Phases 1 and 2 of the Terminal Building are expected to be fully operational, and at that time the remaining portion of the existing terminal is to be demolished and construction will begin on Phase 3, the gate areas on the eastern pier. Upon completion in 2014, the terminal will serve 40 million passengers per annum.

SEI Data Block

Owner and operator:
Mumbai International Airport Limited

Architect, structural engineer, and MEP engineer:
Skidmore, Owings & Merrill LLP

Local designer and general contractor:
Larson and Toubro Limited

Steel (t):	Approximately 22 000
Concrete (m^3):	Approximately 520 000
Estimated cost (USD million):	1200
Service date:	November 2013