Engineering an Icon

The Marina Bay Sands® Integrated Resort – Part 2

By Patrick McCafferty, P.E., Daniel Brodkin, P.E., David Farnsworth, P.E. and David Scott, P.E.

Figure 1: The Marina Bay Sands® Integrated Resort. Courtesy of Timothy Hursley.

The Marina Bay Sands® Integrated Resort, part of a bold new development initiative within Singapore's Marina Bay district, encompasses nearly 10 million square feet of mixed-use development and features three 55-story luxury hotel towers housing 2,560 rooms and topped by the 2.5 acre landscaped rooftop SkyPark®. The resort also boasts an iconic museum, two steel and glass pavilions within the Bay itself and accessible by underwater tunnels, a 1.3 million square foot convention center, two 2,000 seat performance theatres, and over 1 million square feet of casino, retail, and restaurant space (*Figure 1*).

This is the second of two articles discussing the structural engineering design of the Marina Bay Sands Integrated Resort. The first article (STRUCTURE® June 2011) presented the structural engineering behind the Hotel and SkyPark building components; this article will discuss the engineering design of the other structures throughout the site.

Difficult Soil Conditions

The complex sits upon more than 6 million square feet of reclaimed land comprised of deep, soft marine clay deposits, making the excavation extremely difficult. With an average excavated depth of approximately 65 feet, the 38 acre waterfront development involved some of the largest marine clay excavation anywhere in Singapore. The complexity of these earthworks was exacerbated by the need to construct a 115-foot deep "cut-and-cover" tunnel within the site and adjacent to the Benjamin Sheares Bridge, Singapore's longest bridge.

To overcome the challenges of the bulk excavation and to minimize shoring in this particularly difficult soil environment, Arup set about designing:

- two 400-foot diameter circular cofferdams within the podium zones
- a 330-foot diameter donut and a twin-cell 250-foot diameter cofferdam without cross walls within the hotel zone
- a 200-foot radius semi-circular cofferdam within the museum zone

This approach drastically reduced the quantity of steel struts required to prop the excavation walls, which in turn reduced congestion and enabled the site work to advance as quickly as possible. Within just the first six months of the design process, an army of diaphragm wall and piling equipment had been mobilized and construction of the project was well underway (*Figure 2*).

ArtScience Museum

The 161,500-square-foot ArtScience Museum anchors the northern end of the resort promontory extending along Marina Bay. As the most geometrically complex building of the development, the museum resembles a lotus flower with its ten asymmetric petals radiating from a central atrium (*Figure 3*). Gallery floors within each petal encircle the atrium and actively relate to the overall form. Conceived as an open air gathering space, the roof of the museum accommodates live performances and offers commanding views of the neighboring bay. A wide opening centered at the low point of the curved roof allows rainwater into the interior of the central atrium to create a dramatic waterfall through the heart of the museum. This configuration called for a perimeter screen around the atrium to environmentally enclose each gallery while accommodating views across the atrium among the galleries.

Figure 2: The site was quickly engulfed by a sea of cranes in order to achieve the very aggressive construction schedule. Courtesy of Arup.

Figure 3: Resembling an open palm of welcome, the lotus-shaped ArtScience Museum houses multi-storey gallery space within each of its ten radial petals. Courtesy of David S. Robins.

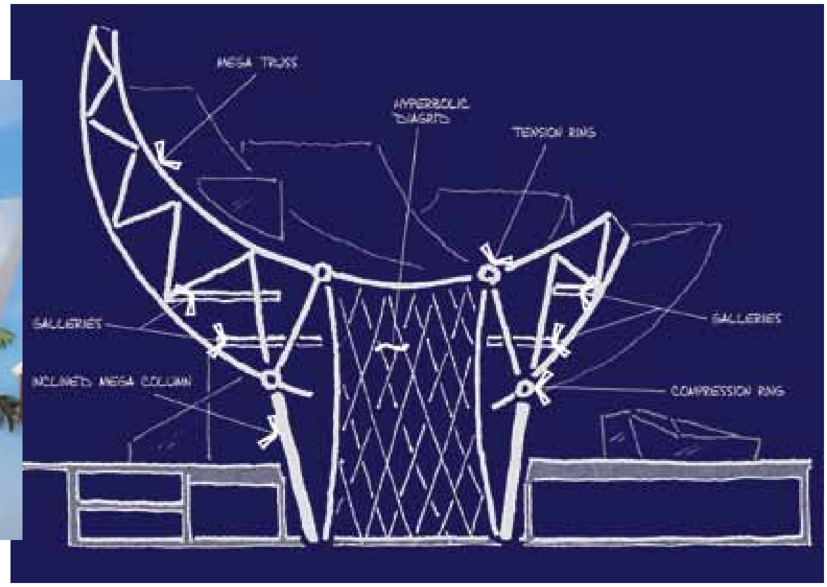

Figure 4: Tension and compression rings resist the push-pull action of the cantilevering mega trusses which support the elevated galleries of the ArtScience Museum. The hyperbolic diagrid provides primary lateral stability to the entire system. Courtesy of Patrick S. McCafferty.

Structural System

Cantilevered gallery trusses with 24-inch by 24-inch box section chords were employed to carry the galleries. However, these posed a significant challenge as their large reactions demanded resolution where they met the atrium, precisely where the architectural form was intended to run unencumbered. In response, Arup devised a system of tension and compression rings encircling a central hyperbolic diagrid of straight 20-inch diameter circular hollow steel sections. The gallery trusses are configured to deliver the large horizontal forces from their top chords into the 30-inch by 30-inch steel tension ring, built up from 2-inch thick steel plates along the top of the diagrid. Any net horizontal forces on the tension ring, whether caused by wind, earthquake, or unbalanced gravity loads, are carried to the ground through the diagrid via shear and overturning action. Forces from the diagonals and the bottom chords are carried by a spiraling 35-inch square compression ring built from 2-inch plates and by an inclined colonnade of 71-inch by 30-inch built-up steel box mega-columns welded from $1\frac{9}{16}$-inch steel plate. The compression ring encircles but does not touch the diagrid, thereby protecting the diagrid from the large horizontal thrusts generated along bottom chords of the gallery trusses (*Figure 4*).

The diagrid also provides a necessary screen between the galleries and the atrium, creating a sense of enclosure to each gallery while still encouraging views among the spaces. In this way, the diagrid serves to differentiate the interior spaces of the museum while also providing overall stability to the structure. Such duality of purpose underscores the overall design principles of the museum.

Arup employed a suite of design and modeling programs including X-Steel, Rhino, MicroStation Triforma, and Oasys GSA to create three-dimensional engineering models of all buildings within the development. Once created, these were then cross-checked against the architectural models (*Figure 5*). By utilizing these tools early and regularly throughout the design process, the team was able to evaluate, modify, and re-analyze a wide range of design options for the irregular and complex form of the museum. Once the design was complete, Arup provided the fabricator with geometrically accurate design models to facilitate the production of shop drawings. In this way, the architectural team, the engineering team, and the fabricator were necessarily working from a common geometry. This approach eased coordination and accelerated the shop drawing review process considerably.

Crystal Pavilions

Conceived as shards of ice floating within the Bay and physically disconnected from the rest of the development, the two Crystal Pavilion buildings represent a sleek, angular departure from the otherwise curvilinear forms of the resort. Both pavilions house high-end retail space and are accessible via underwater tunnels and bridges (*Figure 6, page 32*).

Each pavilion is founded within the Bay on a concrete plinth which contains occupiable floor space both above and below the surface of the water. The folded perimeter surfaces of each structure stabilize themselves, avoiding the need for braced frames or cores extending to the roof. Individual facets within each pavilion are structured from parallel but inclined 12-inch diameter by 1-inch thick circular hollow steel sections that are braced in-plane via 2½-inch diameter steel Macalloy bars. The steel struts of a given facet are likewise capable of transferring all out-of-plane loads through flexure to the plane's perimeter. In this way, every facet becomes a stiff diaphragm, each bearing against its neighbor to stabilize and stiffen the entire arrangement.

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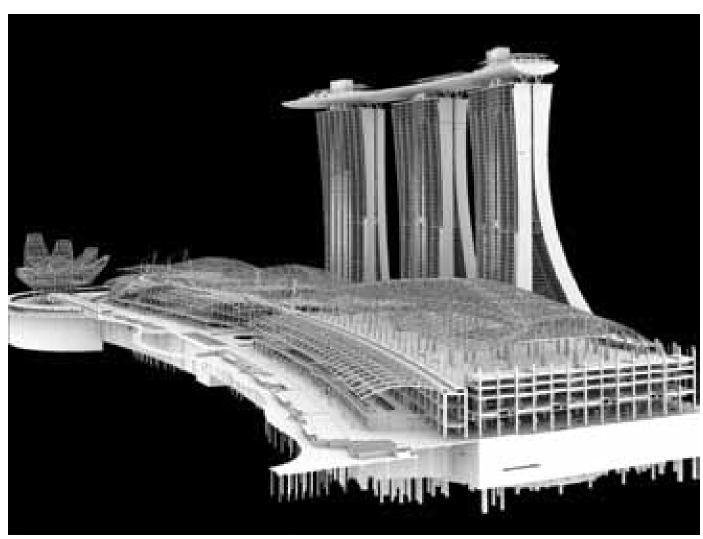

Figure 5: Arup utilized a suite of engineering design and computer modeling programs to create three-dimensional models of the entire complex. Courtesy of Arup.

Figure 6: One of the two Crystal Pavilions emerges from Marina Bay as an angular counterpoint to the curved form of the ArtScience Museum beyond. Courtesy of David S. Robins.

Long-span Podium Roofs

The three primary podium buildings of the complex extend the western edge of the site along the Bay. Rising as a stepped waveform over each building are their long-span roofs that serve as the foreground to the hotel, which rises from behind. From north to south, these three buildings comprise the theaters, casino, and convention center. While each houses a different program with distinct requirements, Arup devised a common structural system for the design of all three roofs.

The program of each building demanded a different structural grid below the eastern and western halves of the roofs, posing a significant design challenge. As such, the use of simple straight trusses to span the halls would have required substantial transfer trusses at either end, precisely where transparency was demanded. In response, Arup derived a system of trusses which spanned only half of the space and employed a central perpendicular spine truss to support them. This central truss resides behind the crest of the waves where the architectural form naturally offers added depth. In an effort to lighten the spine truss, the system was conceived as a three-hinged arch with the spine truss as the uppermost hinge, drawing load from it towards the supports. In response to the intended architectural form, the western half of each roof is comprised of a series of concave-up trusses spanning between the spine truss and the western perimeter, while the eastern halves are configured as a series of concave-down trusses. Three-hinged action of this system also mitigates the accumulation of large internal stresses under imposed building movements, foundation settlements, and thermal loading effects. Where feasible, relatively stiff reinforced concrete shear walls and braced frames were used to resist the large horizontal thrust forces generated along the edges of each building. Elsewhere, particularly along the western perimeter of all three buildings, colonnades of precast concrete moment frames are employed to help resist these thrusts (*Figure 7*).

The system of trusses, with depths ranging from 10 to 15 feet and spans between 200 to 300 feet, was structurally optimized within the geometric constraints of the intended architectural form. The resulting roof tonnage was approximately 20 pounds per square foot.

Challenges Met with Excellence

As a building project, the Marina Bay Sands Integrated Resort is unrivaled in scale, complexity, and speed of execution. The engineering design of the project was technically challenging in every way and was rife with firsts, not just for Singapore but for the construction industry as a whole. From its iconic and gravity-defying forms to its complex soil conditions and unrelenting construction schedule,

Figure 7: View from atop the hotel looking down upon the waveform casino roof and the dual theatre buildings still under construction at the time of this photo. The ArtScience Museum's hyperbolic diagrid is seen under construction at top right. Courtesy of Arup.

Figure 8: The Marina Bay Sands Integrated Resort has become a landmark feature along Singapore's glimmering skyline. Courtesy of Timothy Hursley.

everything about this project was demanding. These many challenges were met in equal measure by an uncompromising commitment to excellence, professionalism, and collaboration among the entire project team. This approach enabled an owner's vision, a design team's ingenuity, and a construction team's skill and dexterity to coalesce, culminating in the creation of an iconic new landmark for Singapore (*Figure 8*).▪

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Project Team

Structural, Civil, Geotechnical, Façade, Fire, Traffic, Acoustic and Audio Visual, Security and Risk Engineering, and 3D Building Modeling: Arup
Owner: Las Vegas Sands Corporation
Design Architect: Safdie Architects
Executive Architect: Aedas Ltd. Pte.
MEP Engineers (Design): R.G. Vanderweil, LLP
MEP Engineers (Production): Parsons Brinckerhoff
Landscape Architect (Design): Peter Walker & Partners
Landscape Architect (Production): Peridian International, Inc.
Contractors: Bachy Soletanche (Substructure, Foundations)
JFE Engineering Corporation (SkyPark)
Ssangyong Engineering & Construction (Hotel)
VSL Heavy Lifting (SkyPark)
Yongnam Holdings (Museum, SkyPark)