Title: **Case Study: Marina Bay Sands, Singapore**

Author: Moshe Safdie, Principal, Safdie Architects

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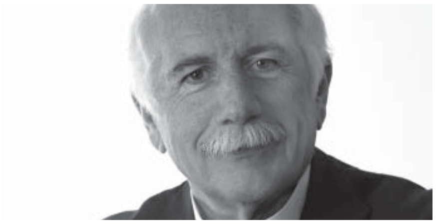

Moshe Safdie

Author

Moshe Safdie

Safdie Architects
100 Properzi Way
Somerville, MA 02143
USA

t: +1 617 629 2100
f: +1 617 629 2406
www.msafdie.com

Moshe Safdie
Moshe Safdie is a leading architect, urban planner, educator, theorist, and author. Embracing a comprehensive and humane design philosophy, Safdie has been a visionary force in architecture and urban planning for over forty years. Safdie is committed to architecture that supports and enhances a project's program; that is informed by the geographic, social, and cultural elements that define a place; and that responds to human needs and aspirations. Completing a wide range of projects, such as cultural, educational, and civic institutions; neighborhoods and public parks; mixed-use urban centers and airports; and master plans for existing communities and entirely new cities, Safdie has made lasting contributions to the quality of life in cities and neighborhoods around the world.

...link

"Today, we design tall buildings as mixed-use communities, and we link them to transit and parks. The way that we conceive tall buildings is an important part of contributing to urban vitality and reducing sprawl."

Peter Weingarten, Gensler, on how to make supertall buildings more sustainable. From "Can Super Tall be Super Green?," www.gensleron.com/cities, November 16, 2010

"While a skyscraper can be defined as a tower that primarily stands out for being tall, Marina Bay Sands is an example of a new and yet nameless type of tall building. The building has broke away from the conventional model of a mega-hotel and integrated resort and in doing so, defined both a new typology and a new icon for Singapore."

Marina Bay Sands is a 929,000-square meter (10 million-square foot), high-density and mixed-use integrated resort complex that brings together a 2,560-room hotel, a 120,000-square meter (1,292,000-square foot) convention center, a shopping mall, an Art & Science museum, two Sands Theatres, six restaurants, and a casino. It is located in Marina South, a peninsula of land reclaimed from the sea in the late 1970s across the bay from Singapore's Central Business District. Conceived as not just a mere building project, but as a city microcosm rooted in Singapore's culture, climate, and contemporary life, the project anchors Singapore's waterfront, creating a gateway to Singapore, and providing a dynamic setting for vibrant public life (see Figure 1).

Figure 1. Marina Bay Sands in the context of the bay

The Emergence of the Urban Window

With a program of nearly 2,600 hotel rooms, the most efficient massing would have resulted in a monolithic and wall-like building. Due to its prominent location within Marina Bay in Singapore, it was decided that three towers would be created instead of one. Each concrete tower hotel is designed at a height of 55 stories. Spanning across the top of the three towers is a 1.2-hectare (3-acre) SkyPark, a new type of public space, framing large "urban windows" between the towers. From the downtown area, framed views of the sea are created, and from the sea, a new city gateway is viewed.

At 200 meters (656 feet) above the sea, the SkyPark spans from tower to tower and on one side cantilevers 66.5 meters (218 feet)

Figure 2. Hotel Lobby

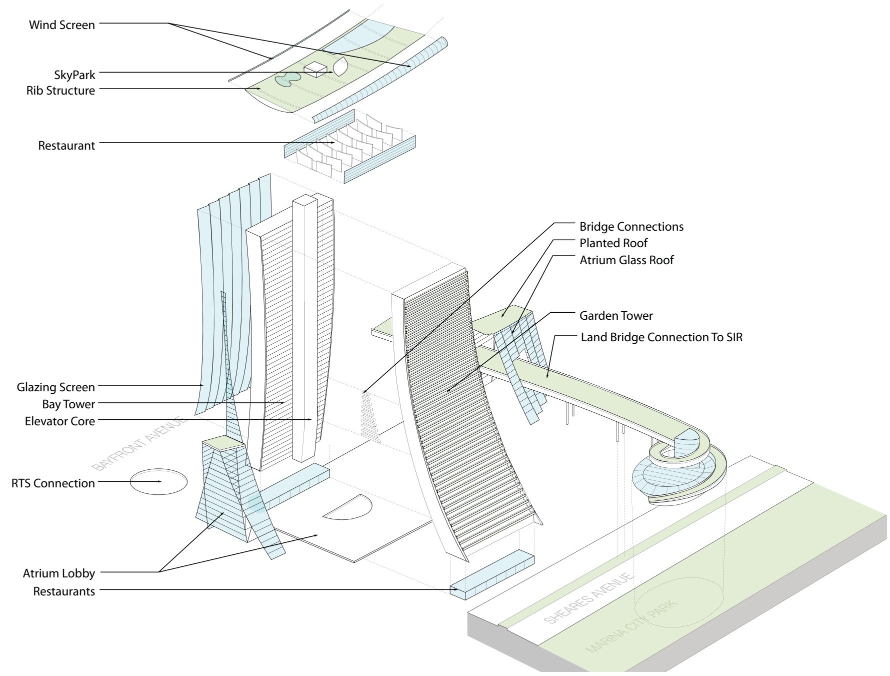

Figure 3. Diagram of Hotel Components

beyond. Longer than the Eiffel Tower is tall, and long enough to park four and a-half A380 jumbo jets, the SkyPark accommodates a public observatory, garden spaces, a 150-meter (495-foot) long infinity swimming pool, restaurants, jogging paths and offers sweeping panoramic views – a formidable resource in a dense city like Singapore. Lavishly planted with trees, the SkyPark celebrates the notion of the Garden City that has been the underpinning of Singapore's urban design strategy.

Design Concept

Conceptually, each tower is composed of two slabs of east and west-facing rooms. The double-loaded towers spread at the base forming a giant atrium at the lower levels, and converge as they rise (see Figure 2). The tower slabs also give further character to the massing and relate to the site context: the glazed west side faces the city center while the east side is planted with lush bougainvilleas facing the botanical gardens and ocean beyond. In plan, as the parcel varies in width, the cross section is decreased from one tower to the next. The three void spaces are connected by one continuous and conditioned glazed atrium, filling the space between the towers with restaurants, retail spaces, and a public thoroughfare. Each tower slab form is also twisted slightly in relation to its pair, creating a dance-like relationship between the two parts and accentuating the slenderness of the buildings, resulting in the appearance of six towers, rather than three (see Figure 3).

Façades

As the largest amount of heat gain occurs on the west façade, it was of paramount importance that an innovative solution be developed to maintain energy efficiency, without limiting the view from the hotel rooms to Singapore's downtown.

The design solution proposed and implemented was a custom double-glazed unitized curtain wall. The energy efficient double-glazed units rest in a frame suspended from the edge of the slab. Perpendicular to the façade, glass fins were installed to provide shading. The outer skin follows the natural curved shape of the buildings, and the use of reflective glass creates a taught mirrored façade. One of the keys to achieving this aesthetic was a minimal spandrel panel at the floor slabs (350 millimeters/13.8 inches), with a continuous double-glazed unit spanning the full 3 meters (10 feet) floor to floor. The glass fins are suspended out of the horizontal stack joint in order to allow them to radiate out in elevation. They are supported by a 3-sided aluminum frame, with the forward edge exposed, which catches the light of the sun, as well as reflections of the façade, to create a unique effect. The fins use a 30% reflective glass and are responsible for shading the façade for up to 20% of all solar gain (see Figure 4).

The east façade handles heat gain differently, utilizing deep planted terraces which follow the sloping radial geometry of the building's profile. The planters help to create microclimate cooling, and the deep overhangs of the balconies naturally shade the hotel rooms from direct sun. Each planter, filled with bougainvilleas, will in time cover the majority of this eastern façade.

The SkyPark

In addition to the 0.9 million square meters (9.6 million square feet) of built space, the project program also called for the development of extensive exterior gardens with

Figure 4. Glass Façade

swimming pools, jogging paths, and public spaces. As one of the aims of the project had been to minimize the height of the podium buildings, seeking to reference Singapore's pastoral hills more than its urban core, the problem emerged that the complex program left no vacant land suitable for these amenities. Creating gardens on top of the roof of the casino and the convention center was studied, however these vast spaces lacked views, overshadowed and overpowered by the adjacent hotel towers. The idea emerged to bridge between the three towers in order to reclaim exterior garden space and create a 2.5-acre park in the sky (see Figure 5 and 6).

The Belly

Another façade of the project which required careful consideration was thus the "belly" of the SkyPark (see Figure 7). Made of more than 9,000 silver-painted metal-composite panels, this skin encloses the mega trusses which bridge the buildings at level 55, as well as a multitude of back of house spaces (i.e., large mechanical rooms with water tanks supporting the pools and a network of corridors and offices for hotel operations staff). The geometry of the SkyPark began with a platonic toroid form, which was then further shaped to streamline the cross sections of the building. The resulting surface was then regularized and panelized using a computer script, triangulating the façade into simple shapes. The shapes were water-jet cut from flat sheet panels and shipped to the building site in containers pre-designed to be lifted to the top levels of the building.

Once on top of the building, the panels were installed via temporary aluminum frame underslung mobile gantries which traveled on a permanent track of steel rails. The gantry system track serves double duty as a Building Maintenance Unit, therefore the track was designed to be hidden within the reveal pattern of the façade panels.

Engineering

One of the primary design issues tackled by the architects and engineers was building movement. The unique design of three buildings connected by a SkyPark called for many engineering innovations.

The dynamic properties of a tall building structure are particularly hard to predict as many elements contribute to the building movement. The wind engineers carried out extensive wind testing on the towers and SkyPark to provide the design team with the data necessary to develop the design approach. In addition to determining the loads for each tower in isolation, it was necessary to predict the behavior and movement of each tower relative to the others. This allowed for strategies to be developed for the steel-spanned SkyPark, as well as to determine appropriate measures to guarantee the safety and comfort of the building users.

The site and surrounding buildings were modeled at a scale of 1:400 and tested in a wind simulator. Mean and gust wind speed ratios were measured at 28 locations on the SkyPark model. The measured wind speed ratios were then combined with a statistical model of the local wind climate to determine the predicted pedestrian comfort in and around the development.

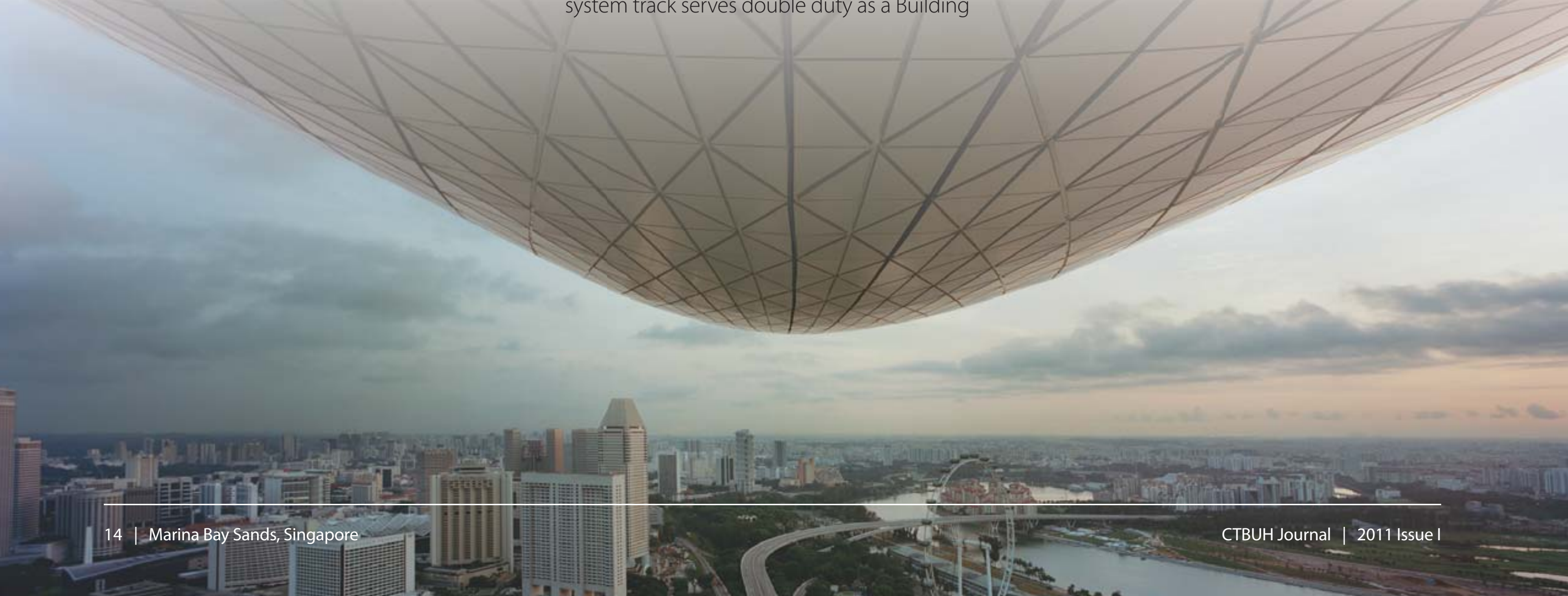

Figure 5. Skypark View

The studies also showed that each tower could sway as much as 250 millimeters (9.8 inches) from center. To deal with the differential building sway, the engineers developed a series of aluminum and stainless steel plates, and multi-directional bearings, located at the bridge spans between towers, which act as sliding components and allow for the natural and individual movement of each tower.

The continuous 150-meter (492-foot) long infinity edge pool was also a challenge, and underwater movement joints were designed with interconnecting three distinct 50-meter (164-foot) stainless steel pool enclosures into a flexible singular whole. In order to test the design, a full scale mock-up of the design solution was built and tested under movement conditions (see Figure 8). In addition to building sway, the pool design also accommodates building settlement, and is built upon adjustable steel jacks, which ensure the infinity edge will maintain its horizontal level over time (see Figure 9).

Another significant challenge facing the design team was the 66.5-meter (218-foot) long SkyPark cantilever that overhangs the northernmost tower. Much time and analytical effort was invested by Arup's bridge and dynamic specialists to ensure that the

Figure 6. Marina Bay Sands SkyPark is longer than the Eiffel Tower is tall

Figure 7. View looking up at the "Belly"

Figure 8. The pool's full scale mock-up for movement test

Figure 9. The pool's adjustable steel jacks

complex behavior of wind and human movement on the structure was understood. The cantilever has a large number of low frequency vertical modes that are susceptible to resonant dynamic response due to synchronized crowd activities, such as dancing. Through the construction phases, two improvements in structural design were made in relation to the dynamic performance of the building. First, the taper of the main supporting box girders was reduced to improve the response of the cantilever under human excitation. Second, a 4.5-metric ton (5-ton) tuned mass damper was introduced

Figure 10. Temporary steel struts for the sloping towers

and located at the tip of the cantilever, hidden within the belly of the architectural form, and aimed to add an additional percentage of damping to the structure. The damper was suspended from transverse girders and accessed via catwalks already present for the inspection and maintenance of the box girders.

The design was verified prior to building opening by carrying out large-scale vibration simulations, testing key excitation modes.

Construction Challenges

Once the project was awarded, teams were on the ground immediately to begin the fast tracking of the construction. The first and most critical task was to secure the building footprint. The entire complex sits on 0.56 million square meters (6 million square feet) of reclaimed land – sand infill on deep soft marine clay deposits. Marina Bay is a former salt water estuary that is now a fresh water reserve. Prior to excavation, the site needed to be reinforced. In order to do this, 1.5 meter thick (5 feet) steel-reinforced concrete diaphragm walls (coffer dams of up to 120 meters or 394 feet in diameter) were extended 50 meters (164 feet) into the ground providing an enclosure for excavation.

The key challenge of building the hotel towers was the construction of the part of the towers that slope at an incline. Unsupported, they could buckle under their own weight. The sloping leg induces an enormous external force onto the structure, which needed to be addressed during construction.

The structural engineer conceived of an approach to build large temporary struts of structural steel to prop up the sloping towers as they rise (see Figure 10). Like a suspension bridge, high-tensile steel tendons give an added layer of support inside the walls. Both the struts and the tension cables were designed as temporary supports and planned to be removed once the giant linked trusses that connect the towers on the 23rd floor were installed. However during the construction process it was decided that the cables would become permanent.

The most practical method of erecting the SkyPark was to prefabricate each of the 14 main steel segments off-site, truck them to the site, lift them into place and assemble them on top of the tower. Taking a cue from bridge building, the design team engaged Swiss/French company VSL to assist with the complicated lifting. VSL employed a strand jacking process (the largest and longest of its kind), utilizing hydraulic jacks to lift the box girders to the top of the towers and slide them into place. The two largest sections to be lifted were the 80-meter (262-foot) long, 1,270-metric ton (1,400-ton) pair of box girders that would form the cantilever. At a lifting speed of 14 meters (46 feet) per hour, it took over 16 hours to lift the girders and slide them into place (see Figure 11).

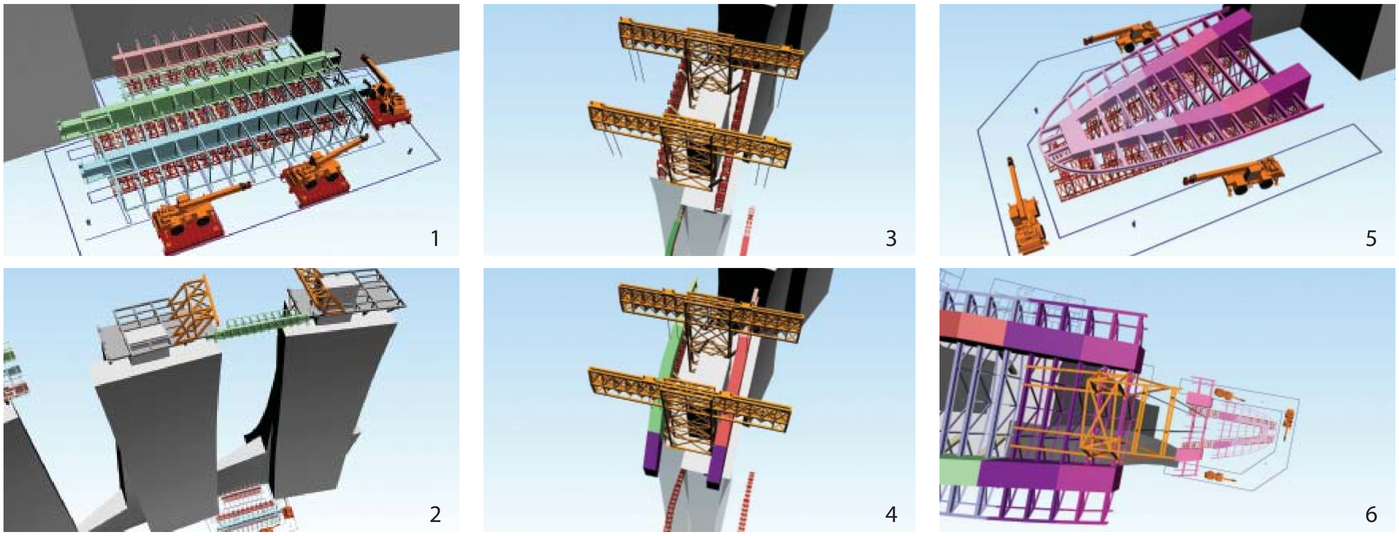

Figure 11. Diagramatic phasing of erecting the SkyPark

SkyPark Facts

- The 1.2-hectare (3-acre) structure is longer than the Eiffel Tower is tall and large enough to park four and a-half A380 jumbo jets. Designed to be a tropical oasis in the sky, it can host up to 3,900 people.
- It spans from tower to tower and cantilevers 66.5 meters (218 feet) beyond to form one of the world's largest public cantilevers.
- It is 340 meters (1,115 feet) long from the northern tip to the south end, and maximum width is 40 meters (131 feet).
- The SkyPark is designed for wind pressures of up to 2.5 kPa (250 kg/m^2 or 5,933 lbs/ft^2), and wind speeds of up to 32 m/s (105 ft/s).
- The 1,396-square meter (15,026-square foot) swimming pool, containing 1.424 million liters (376,200 US gallons) of water, is the largest outdoor pool at its height and has a 145-meter (475-foot) vanishing edge.
- Its lush gardens include 250 trees, up to 8 meters (26 feet) in height, and 650 plants, requiring in excess of 2,300 cubic meters (81,200 cubic feet) of soil. All of the trees have stainless steel cable restraints from the root balls to precast blocks to prevent toppling.
- The SkyPark contains 7,000 metric tons (7,692 tons) of permanent steelwork, and used 4,000 metric tons (4,413 tons) of temporary steelwork in the construction. The total length of strand cable used in the strand jacking operations is 77 kilometres (47.8 miles).

Conclusion

The principle challenge for the Marina Bay Sands project was the combination of complex design parameters matched with a very fast project schedule, from initial sketches to substantial completion within four years. This meant arranging close and intensive relationships between the engineering, construction management and design teams on site, such that coordinated solutions could be quickly negotiated as they arose.

The success of the project lies in the fact that the inventiveness of the design (the conception of the hotels and the SkyPark) was matched by an equally inventive and novel approach developed by the engineering and construction teams. ■

Project Data

Completion Date: June 2010
Height to Architectural Top: 207 m (679 ft)
Stories: 57
Area: 249,843 sq. m. (2,689,288 sq. ft.)
Primary Use: Hotel
Owner/Developer: Marina Bay Sands Pte. Ltd.
Design Architect: Safdie Architects
Associate Architects: Aedas Ltd.
Structural Engineer: Arup
MEP Engineer: R. G. Vanderweil, LLP
Main Contractor: Ssangyong
Other Consultants: CL3; CPP Wind Engineers; Hirsch Bender Associates; Howard Fields International; Natare Corporation; Parsons Brinckerhoff Pte. Ltd.; Peter Walker & Partners Landscape Architects

...ship

"Bringing the SkyPark into the sky – a floating ship-like structure that overlooks the sea – is a remarkable feat of engineering."

Ahmad Abdelrazaq, Samsung Corporation, on Marina Bay Sands Integrated Resort. From "Best Tall Building 2010, CTBUH International Award Winning Projects."