The Marina Bay Sands Complex in Singapore: A Modern Marvel of Structure and Technology

Jerzy Szolomicki 1, Hanna Golasz-Szolomicka 1

1 Wroclaw University of Science and Technology, Wyb. Wyspianskiego 27, 50-370 Wroclaw, Poland

Abstract. The paper presents architectural and structural analysis of the Marina Bay Sands complex in Singapore, which consists of a hotel, an exhibition and convention center with shopping centers, two theatres and Art-Science museum. The Moshe Safdie Architects architectural studio created an unusual complex that shows Singapore as a center of innovation, culture and entertainment. This complex fits perfectly into the architecture of Singapore, which is full of ecological solutions and surrounded by vegetation that is dominated by orchids (the national flower of Singapore). Hotel Marina Bay Sands is the main building of the complex. The hotel complex consists of three 55-storey towers and is situated on the axes of two streets. The spectacular design, which is now the island's hallmark, required many complicated structural solutions that can be considered as a modern marvel of structure and technology. The design of the hotel building, the co-contractor of which was Arup Company, due to its geometry and location on the reclaimed land of Marina Bay was recognized as the most difficult architectural task in the world. The important aim in the design of the whole complex was to ensure perfect sound and thermal insulation inside the buildings while using natural elements. In the Art-Science Museum, as well as in the two theatres, a façade cladding system consisting of blocks of mineral wool was used, which significantly increases the evacuation time in the event of a fire. The complex, which is characterized by high strength buildings, good acoustics and high fire safety, was created thanks to multi-sector cooperation. Marina Bay Sands complex have played important role in development of technological and structural solutions for such type of structures.

1. Introduction
Singapore's architecture is the result of a variety of influences due to its strong cultural and ethnic diversity. Its development was intrinsically linked with its colonial history. The first urban master plan was made in 1822 by Philip Jackson [1]. The plan imposed a regulated spatial system by segregating social layers. It served as a reference for the development of Singapore at the beginning of its history, and the impact of the overall layout of the plan is visible to this day. All government buildings were built according to British colonial style, and the almost entire architectural scene was dominated by British architects.

The breaking point in the history of Singapore's architecture was the creation of the Singapore Society of Architects in 1923. Its task was to create a city design with a modern architectural appearance. After the war, local architects that were educated abroad also appeared. Ng Kheng Siang became the first Singaporean admitted to the Royal Institute of British Architects.
In the 1950s, the island underwent a very complex decolonization process. Singapore gained independence on August 9, 1965. In a short period of time, a high number of important public projects, such as the industrial estate in Jurong, were built. During this period, experimental work of Japanese metabolism architects (Kiyonori Kikutake, Kisho Murokawa, Arata Isozaki and Kenzo Tange), as well as brutalists from Great Britain (Denys Lasdun, James Stirling, Peer and Alison Smithson) had a significant impact on the shaping of architecture by native architectural companies. One of the most interesting examples of this type of architecture is the design of the shopping and housing of the People's Park Complex, which was created by the Design Partnership studio (William Lim, Tay Kheng Soon, Koh Seow Chuan).

In 1972, Singapore's Foreign Minister Sinnathamba Rajaratnam initiated an action in which the main idea was for Singapore to become a global city. This idea was supported by the conceptual urban plan from 1971. From 1975 to 1990, the shiny façades of skyscrapers designed by foreign architects began to dominate Singapore’s landscape. In the second half of the 1990s, information technology and globalization developed rapidly. The idea of green city was developed in the residential complex of the five skyscrapers Skyterrace @ Dawson (2015). The development of this type of architecture had contributed to defining Singapore as the greenest and most ecological and sustainable city in the world. However, the most popular was Singapore's expansion of its downtown in accordance with the urban master plan of 2003, which later developed into today's Marina Bay Sands complex. This main Singapore's architectural attraction was designed by Israeli architect Moshe Safdie for the Las Vegas Sands Corporation. Its facilities, with an area of 845,000 m², form a gateway to the city and are characterized by high density and multi-functionality for public places.

2. The Marina Bay Sands complex
Marina Bay and the lower section of the Singapore River, together with the surrounding buildings, is the historic center of Singapore. This center is situated on the southern shore of the island. On one side, Marina Bay is surrounded by a financial center with high-rise buildings. On the opposite shore of the bay in relation to this center, the Marina Bay Sands complex was created, which includes the dominant hotel building, shops, restaurants, two ice rinks, a lotus flower-inspired art-science museum, two theaters, a casino, an exhibition center, and two floating steel and glass pavilions located on the river (figure 1). The complex of buildings around Marina Bay makes it the central water square of Singapore.

Figure 1. The Marina Bay Sands complex (developed by authors on the basis of [2])
Marina Bay's architectural vision was created about 40 years ago. This 360 ha project was created to expand the downtown area, which is the main business and financial center in Asia. Marina Bay Sands consists of a layer filled with sand covering a deep layer of soft sea clay, below which there is a very rigid layer of alluvium. Occupying an area of 15.5 ha, Marina Bay Sands is founded on a very rigid alluvial layer using barrettes and bored piles with a diameter of 1 to 3 m. Arup Company designed five huge reinforced concrete cofferdams [3]. The implementation of this system, together with a system of peripheral steel diaphragm walls, enabled independent excavations between the theater, casino, and the exhibition and convention centre. Some cofferdams of the diaphragm walls that were made in the hotel area have double thickness of the walls below ground level and the bearing elements of the hotel towers, while the other parts were removed.

Arup's innovative approach used in the excavation project in such difficult geological conditions is a turning point for the future of large-scale excavation work, not only in Singapore, but also all over the world.

2.1 Marina Bay Sands Hotel
Marina Bay Sands Hotel is a high-rise building with a steel-concrete structure, figure 2. The building consists of three towers of 193.9 m in height, and contains 57 floors above-ground and 3 floors underground (2561 rooms), figure 3. The hotel was designed by the Moshe Safdie and Associates architectural studio. The entire building is topped with a large roof, on which was designed "Sky Park", which includes an observatory, jogging paths, gardens, restaurants, lounges and a swimming pool. Sky Park, with 250 trees and 650 plants, fits perfectly into the concept of a garden city, which was the basis of Singapore's urban strategy [4]. Each of the three towers consists of two legs [5], which have different curvature on the east side and are vertical on the west side. The open continuous space connecting the three towers creates a large atrium at ground level. The height of the atrium is differentiated; in the first tower it is about 20 floors, and in the third tower it is 6 floors. The same applies to the width of the buildings. It changes from 40 m in the first tower, to 20 m in the second tower, and it finally reaches 10 m in the third tower. In the façade, the highest walls of the atrium come out of the first tower and descend between the second and third towers. The western glass façade faces the city center, while the eastern one filled with vegetation overlooks the Gardens By The Bay and the ocean. The western façade uses a double glazed unit, consisting of panels that are 3 m high and 35 cm deep, and in which glass triangles installed in aluminum frames with 30% reflective glass provide shading. In the eastern façade, the terraces create natural air conditioning, and the deep overhangs of the balconies shade the hotel rooms from direct sunlight. The Sky Park façade is made of 9,000 silver-painted metal-composite panels.

Figure 2. The Marina Bay Sands Hotel (photo by authors)
Due to the fact that gravitational loads play an important part in the stability of the structure, the designers used the lightest possible structural system in which internal columns were eliminated. The walls of the atrium are framed by steel trusses connected by horizontal spandrel beams with rectangular hollow tubes. The layout of the trusses is strictly related to the modules of the glass panels in order to ensure their quick assembly. With the exception of the atrium wall on the south side of tower 1, which comes out of the shear wall, the other walls between the three towers rise vertically from ground level to a steel roof truss, the span of which between tower 1 and 2 is 47 m, and between tower 2 and 3 is 27 m.

On the 23rd floor in each of the towers, where the MEP room is located, a truss of one floor high, which connects both legs of these towers, was designed. Thanks to this structural design, the walls in both legs cannot work independently, which would cause their uneven displacement on the upper floors. The truss geometry was precisely adapted to the wall thickness. Due to the extreme extension of the tower legs, opposite shear walls tended to bend and move sideways during their construction. Therefore, it was important that the project contained an analysis of the order of individual stages of construction. The first task during the construction of this building was to protect the excavation of the building's outline. The whole complex is located on land filled with sand on deep layers of sea clay [7]. Marina Bay is a former salt-water outlet that is now a reservoir of fresh water. The foundation of the building is situated in an excavation protected by a diaphragm wall 150 cm thick that reaches a depth of 50 m [8]. The building is founded on a raft foundation, which cooperates with piles and barrettes. Unlike most high-rise buildings, the main requirements for the lateral stability of the hotel result from the occurrence of constant overturning forces due to gravitational loads from the asymmetrical geometry of the building. The structural system consists of reinforced concrete shear walls and cores that are located around elevators. These walls have different thickness from 71 cm in the base to 51 cm on the upper floors. They constitute the main vertical and transverse structural system of all three towers. Moreover, the reinforced concrete walls of the core in both legs of each building protect the hotel in the longitudinal direction, counteracting plane buckling. Prestressed floor slabs with a height of 20 cm and a maximum span of 10 m are located between the sheared walls [9]. This system creates a simple floor slab solution that allows for its quick construction.

The top of the hotel is finished with the construction of “Sky Park”, which consists of 14 prefabricated steel segments connecting the three towers [10]. These segments consist of steel bridge girders that are 10 m deep and 3.60 m wide with 3.5 cm sidewalls and a 6 cm flange. They form the basis of the structural system of the cantilever segment and the segments between the hotel towers [11]. This structure is supported on steel V-shaped struts coming out of the hotel roof directly above the concrete shear walls. The Sky Park hotel terrace is the longest and highest (198,11 m) residential terrace in the world with a length of 340 m, a width of 40 m, and a cantilever of 64,92 m.

As for all tall buildings, the basic design problem was the ensuring of the stability of the building, which is subjected to dynamic wind loads. Therefore, a model of a scale of 1-400 was tested in a wind tunnel. The tests showed that each tower inclines up to 250 mm from the vertical. In order to counteract different building deflections, a series of aluminum and stainless steel plates and multi-
directional bearings, as well as a set of lifting cylinders, were installed under the pool. In addition, a 5-ton tuned mass damper was introduced in the cantilever section to counteract vibration.

2.2 Art-Science Museum
The Art-Science Museum is located along the Marina Bay Sands waterfront and contains exhibits that connect the relationship between art and science, figure 4. The idea of creating this museum was based on drawing attention to the similarities of these two disciplines that have an impact on the different stages in the history of mankind. The author of the design is Moshe Safdi, who modeled the body of the building in a form that resembles an open hand or lotus flower. The museum building consists of two main parts:

- the base, which is embedded in the ground and is surrounded by a lily pond
- the steel structure, which consists of 10 petals covered with stainless steel panels [12].

Figure 4. Art-Science Museum: a) front façade (photo by authors); b) floor plan (developed by authors)

The two main exhibition spaces in the museum are designed around a central atrium. The entrance to the museum leads through a free-standing glass pavilion. Elevators and escalators provide communication to three levels of the gallery, which has a total area of 6,000 square meters. The upper galleries of the museum are organized into 10 rooms that vary in height and length. To increase the visual effect, the shape of the gallery inside reflects the external form of the museum.

The main load-bearing structure of the museum consists of 10 steel columns, and in its middle part it is made of a steel diagrid structure, which carries the asymmetrical forces generated by the building. This type of construction results in an optimal distribution of forces, what is evidenced by the lightness of the building. The asymmetrical structure of the museum has maximum height of 60 meters and its skeleton is a complex steel truss structure. The structure was designed and made by Yongnam Engineering and Construction using Tekla BIM software. It is shaped by spheroids of various radii and apparently hovers above the base of the pond. The petal-shaped shell elements of the structure rise up and reach different heights. Each element is topped with a skylight, which results in daylight penetrating the base and illuminating the galleries located in it.

The geometrical form of the roof resembles a vessel that collects rainwater. The accumulated water is drained through the oculus 35 meters down into the atrium, creating a waterfall in the central part that feeds the internal pond. One of the proof of the technological innovation of the project is the use of a double-curved FRP polymer layer in the building's façade, usually used in the construction of boats and yachts. The use of FRP made it possible to obtain a smooth seamless surface, which in turn gave the building a visual lightness thanks to shiny petals. Similarly, to other buildings in the Marina Bay Sands complex, designers strive to achieve the highest level of sustainable development [13].
2.3 MasterCard Theatres

In the northeastern part of the Marina Bay Sands complex there are two Mastercard Theaters, figure 5. The Grand Theater has a capacity of 2139 people, and the second smaller Sands Theater has a capacity of 1679 (figure 6). Both theaters have two entrances, one from the Grand Arcade and the other from Bayfront Avenue. They have a one lobby that ensures easy communication between the complex's facilities. The Arup Company applied a traditional reinforced concrete outer and inner frame construction, which is used for "box in box" theaters.

![Figure 5. MasterCard Theatres (photo by authors)](image)

![Figure 6. MasterCard Theatres: floor plan (developed by authors on the basis of[14])](image)

The external structure includes the construction of the podium and walls below ground level, which ensure the stability of the building's under-ground load. The internal reinforced concrete shell structure shapes the body of the theaters. This structure carries all the gravity loads on the foundation so that each modification of the internal configuration of the theater does not affect the outer structure. This
type of system has significant acoustic advantages, which is due to the separation of the external and internal construction. Another significant advantage is the air space between the partitions, which substantially improves the acoustics of the building. Both theaters have a similar structure inside. The theater stage is made of a concrete slab with a central area filled with platforms in an arrangement of 4 m x 8 m [3]. Each building has a partially inclined auditorium and a one-level balcony. The balconies have the structure of steel cantilever frames with a concrete plate under the seat. At level 4 under a roof, a composite floor slab 15 cm in height was designed. At this level there is a MEP room that is supported on a steel truss with a depth of 3.5 m.

2.4 Casino
The casino building is located between the MasterCard Theaters, and Convention Centre, in northern and southern part of complex respectively (figure 7). The casino is connected to a shopping center in the western part of the complex through the main and side corridors. In 2010, Marina Bay Sands Casino was recognized as the world's most expensive casino, and at the same time the largest. The building has a reinforced concrete structure and contains 4 above-ground floors and 5 floors underground. The foundation of the building is in an excavation protected by a diaphragm wall. The building is founded on bored piles [3]. Lateral stability is achieved by the column-beam structure. A large atrium was designed inside the casino, which required holes in the floor slabs on four levels. The height of the storey in the casino is different in relation to the height of the adjacent structure. At the highest level 4, there are mechanical systems for the entire casino, while on the underground levels B3 and B4 there is a parking lot, as well as a tank with drinking water and fire protection installations.

A very effective load bearing structure in the form of high-strength cables is the suspension system of a huge chandelier, located in the main game room and composed of 130,000 precisely cut Svarovski crystals. The roof of the building consists of aluminum roof panels attached to a pre-mounted aluminum sub frame attached to the Kalzip roof cladding.

Figure 7. Casino (photo by authors)

2.5 Sands Expo and Convention Centre
The Sands Expo and Convention Centre building is located furthest south of the Marina Bay Sands complex and has a capacity of 45,000 people and 2,000 exhibition stands, figure 8. The building contains 4 above-ground floors (L1, L3, L4, L5), one floor underground, and a mezzanine. It is designed on a rectangular plan with dimensions of 240 m x 120 m. The building has the largest ballroom in Southeast Asia with a capacity of 8,000 people. The exhibition halls on levels L1 and B2 offer over 30,000 square meters of flexible exhibition space. The height of the storey is 9.45 m, and the movable walls allow the space at each level to be divided into separate rooms. Reinforced concrete columns are designed on a regular modular mesh with dimensions of 33 m x 18 m [3]. There are ballrooms and conference rooms on levels L3, L4 and L5.
Due to assumption of short time of assembly, the main floors were made of composite panels on steel frames with large spans. This solution allowed work to be performed on several levels simultaneously.

2.6 The Shoppes
Most of the Marina Bay Sands buildings contain retail space. The Shoppes are located along the entire length of the podium in a north-south direction and include over 300 stores and food outlets. Just like in shopping centers in Las Vegas and Doha, there is a Venetian canal with a gondola to cross. In addition, two crystal pavilions - North and South (South is under construction) - are located on the bay, and they house world-famous nightclubs and Louis Vuitton's flagship store.

2.7 Louis Vuitton Cristal Pavilion
The north crystal pavilion is situated opposite the Marina Bay Sands promenade. This original pavilion is designed on islands that can be reached from the main shopping area using an underwater tunnel or steel footbridge, figure 9. A 40 m long footbridge, which leads to the pavilion, is supported on 10 slender columns. The characteristic geometric form in the shape of a prism enlivens the view from the promenade, the glass façade of which reflects the image of the sky, city and water during the day and transforms into a glowing lantern at night. The North Pavilion is the newest luxury Louis Vuitton store in Singapore.
The pavilion’s façade is inclined 20 degrees from the vertical. The interior was designed by architect Peter Marino. The design reflects the sailing theme, consistent with both the location and the historical relationship of the Louis Vuitton brand with travel. The main challenge for the design team of Peter Marino and FTL Design Engineering Studio was managing the level of light in the entire glass pavilion and protecting luxury goods from UV radiation. The solution was to use over 300 unique frame panels with a UV-resistant coating in order to achieve the effect of transparency on the walls and ceilings. The interior design uses two different materials: PTFE (Polytetrafluoroethylene) and the other of fiberglass with polymer coatings. The extremely durable and easy to clean panels provide consistent diffused light and are arranged so that visitors do not obstruct the spectacular views of Marina Bay. Due to the complex geometry of the building, Eventscape Company made a 3D model. Floor panels are designed with hinges and a pull mechanism to allow access during its maintenance to the skylights located above.

The pavilion is set on an old alluvial layer and steel bored piles. Its construction has a tendency to lateral movement, even if only due to its self-weight. Unlike other types of buildings where the façade supports are hidden, the supporting structure of the façade of the Crystal Pavilion is an architectural element. To achieve high transparency, the Arup designers used a light steel structure to support the outer decorative frame, which ensures lateral stability using Maccaloy steel tension bars. Because the tension bar system could provide roof stability for the load designed during the operating phase, maintaining stability during construction was a key problem to solve. To counteract the appearance of unbalanced forces, the tension bars were pre-compressed in stages, one after the other, during the roof construction. In order to achieve a flexibility of shaping the floor layout, conventional reinforced concrete structures are separated from the steel roof. However, the outer frame has the possibility of minimal displacement for the designed lateral load. To avoid creating air channels at the roof level, a ceiling supply system was used, which required making holes around the edge of the floor slab.

3. Conclusions

Contemporary Singapore is an important center for investment and construction projects. Numerous original buildings with complex structures and infrastructure are being implemented for the needs of the constantly developing economy. Marina Bay Sands is a contemporary showcase of Singapore, which impresses in its size and design vision. Searching for the architectural symbol of Asia, one of the first places that should be mentioned is the complex of Marina Bay Sands, which is the central square of the metropolis. It includes, in addition to hotel, casino, Convention Centre and two theatres, a shopping center, restaurants, the Museum of Arts and Science, and two floating pavilions. This complex was created in order to form the Singapore gambling and tourism capital of the region. With the investor Las Vegas Sands Corp., Marina Bay Sands is compared to the MGM City Center in Las Vegas in terms of the scale and cost of the investment.

The most spectacular building of the complex is the design of the Marina Bay Sands hotel, which faced several major challenges for builders. Thanks to a multi-sector cooperation, a building that provides strength and good acoustics of internal spaces and high fire safety was created. Creating a building with such a complex structure required special precision, deep knowledge of modern materials, and advanced structural techniques. In the near future the hotel complex will be expanded by a fourth tower, on which a terrace referring to the original structure will also be built. To conclude, the Marina Bay Sands complex is a modern marvel of architectural design, technology and science.

References
[1] R. Kam, “Singapore Identity and Architecture”, History Thesis, pp. 1-67, 2015, Available online: https://www.academia.edu/18082626/Singapore_Identit_and_Architecture (Accessed on 5 May 2019).
[2] Marina Bay Sands Singapore. “Sands Expo & Convention Centre Floor plan”, Available online: http://www.marinabaysands.com/ (Accessed on 31 May 2019)
[3] Marina Bay Sands, The Arup Journal, Issue 1, pp. 1-83, 2012.
[4] K. Pieskaczyńska, “Singapore – City of Friendly Space” (In Polish), Poznan University of the Arts, pp. 1-169, 2013.

[5] M. Safdie, “Case Study: Marina Bay Sands, Singapore”, CTBUCH Research Paper, Issue I, pp. 12-17, 2011.

[6] Marina Bay Sands – Hotel and SkyPark, Available online: https://www.safdiearchitects.com/projects/marina-bay-sands-hotel-and-skypark (Accessed on 10 May 2019)

[7] R. L. Reid, “Towering Imagination”, Civil Engineering, pp. 51-59, August 2011.

[8] W. F. Knight, F. Johari, “Singapore’s Marina Bay Sands Development”, Foundation Drilling, pp. 16-25, June/July 2012.

[9] P. McCafferty, P. Brodkin, D. Farnsworth, D. Scott, “Engineering an Icon. The Marina Bay Sands Integrated resort”, Structure Magazine, pp. 29-33, June 2011.

[10] Y. Miwa, ,“SkyPark – A Huge Rooftop, Steel Structure Spanning Three High-rise Towers”, Steel Construction Today & Tomorrow, No 34, pp. 4-7, 2011.

[11] R. Liew, “Advances in Steel Concrete Composite and Hybrid Structures”, National University of Singapore, pp. 1-191.

[12] L. Kuo, “The Singapore ArtScience Museum: a modern marvel of science, technology and art”, Available online: http://www.asbmb.org/asbmbtoday/asbmbtoday_article.aspx?id=13700 (Accessed on 1 December 2015).

[13] L. Kong, “Making Sustainable Creative/Cultural Space in Shanghai and Singapore”, Singapore Management University, pp. 1-30, 2009.

[14] A. Pang, “Emergency Preparedness. Marina Bay Sands”, Available online: http://www.nfec.org.sg/downloads/fire_safety_seminar/2017/Emergency%20Preparedness%20in%20Marina%20Bay%20by%20MBS.pdf (Accessed on 10 June 2019).