The Marina Bay Sands Special Issue

Issue 1 2012

The Arup Journal

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Marina Bay Sands, Singapore

Conceived by architect Moshe Safdie and engineered by Arup, Singapore's new waterfront resort includes: three 55-storey hotel towers topped by the 1ha SkyPark; South East Asia's leading MICE (meetings, incentives, conferences and exhibitions) hub; two theatres, a casino, shops, two Crystal Pavilions and promenades; and the unique lotus-shaped ArtScience Museum.

Singapore's vision for Marina Bay

Author
Jenny Lie

The centrepiece of our redevelopment of the city is Marina Bay ... It will be a city in our image, a sparkling jewel, a home for all of us to be proud of, a home that will belong to all of us.

Lee Hsien Loong, Singapore Prime Minister, 2005

Singapore and urban renewal

Singapore has been engaged in urban renewal since the mid-1950s, with the formulation of its masterplan from 1952-55 and approval by government in 1958. The subsequent establishment of the Urban Redevelopment Authority (URA)[1] in 1974 was a key milestone in focusing efforts to maximise land usage in this small, densely packed country. The masterplan has since undergone eight reviews, and defines five Regions: the West, North, North-East, East, and Central. Within the Central Region is Central Area, which embraces Marina Bay.

The Marina Bay vision thus began some 40 years ago. Located at Singapore's southern tip, this 360ha development was designed to seamlessly extend the downtown district and further support the city-state's continuing growth as a major business and financial hub in Asia[2]. It is an artificial bay, and groundwork for its transformation into a waterfront business district was laid as long ago as the late 1960s, with land reclaimed in phases between 1969 and 1992.

With Singapore's signature city skyline as a backdrop, Marina Bay is envisioned as a Garden City by the Bay, a 24/7 destination presenting an exciting array of opportunities for people to explore new living and lifestyle options, exchange new ideas and information for business, and be entertained by rich leisure and cultural experiences in a distinctive environment.

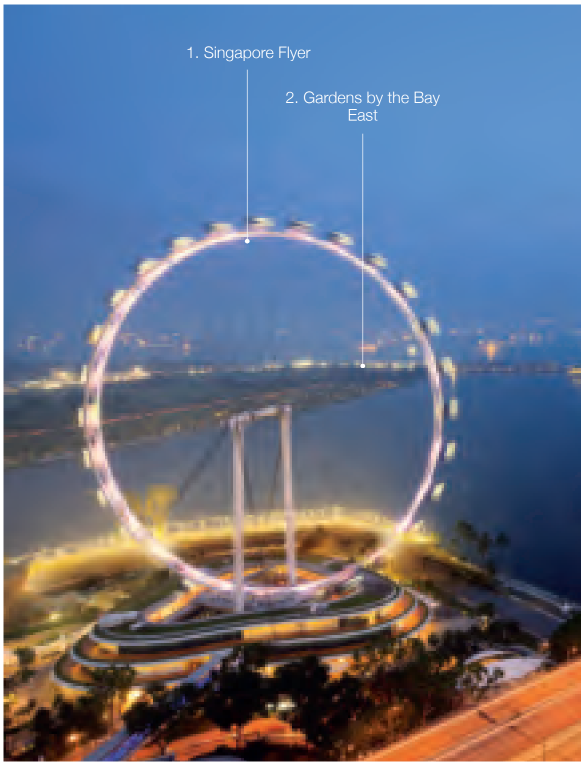
Creating value

In planning Marina Bay, specific attention was paid to creating value. The masterplan focuses on encouraging a mix of uses (commercial, residential, hotel and entertainment) to ensure that the area remains vibrant around the clock. Along the waterfront and fronting key open spaces, building heights are kept low, maximising views to and from individual developments further away from the waterfront, enhancing their attractiveness, and creating a dynamic "stepped-up" skyline profile as well as more pedestrian-scaled areas. The development of Marina Bay is supported by state-of-the-art infrastructure worth more than $4.5bn.

Marina Bay features:

- over 400 000m^2 of Grade A office space
- 101ha of Gardens by the Bay
- a common services tunnel housing data and telecommunications cables, sewers and services
- a 5.5km long promenade linking all the major attractions around Marina Bay
- the iconic Helix Bridge and a separate vehicular bridge linking Marina South and Marina Centre
- extension of roads linking directly to the city and airport
- five new underground MRT stations
- the new Marina Barrage, making the Bay a 182ha haven for motorised and non-motorised recreational activities.

This was the background against which, in May 2006 after a highly competitive bidding process, Las Vegas Sands was declared winner with its design by Safdie Architects for Marina Bay Sands, a business-oriented integrated resort on the east side of Marina Bay.



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Evaluation of Marina Bay Sands design

In the design evaluation portion of the tender, a panel of local and international architects commended the MBS design as superior to other bids in terms of pedestrian circulation and layout, as well as best fit with the Marina Bay landscape. They liked the hotel towers being set back from the waterfront to open up expansive views of the city and the entire Marina Bay, making the skyline more attractive and distinctive, but the MBS trump card was its promise to bring convention visitors to Singapore with 110 000m^2 devoted to this – half of what Singapore had earmarked for the whole downtown business district.

This pledge, plus the inclusion of the ArtScience Museum, two performing theatres and no less than six celebrity chefs, gave it top marks in tourism appeal, a category comprising 40% of the total score.

Singapore aims to double tourist arrivals to 17M and triple tourism receipts to $30bn by 2015. The completion of Marina Bay Sands is expected to make this happen – an extra $2.7bn, or 0.8%, will mark its contribution to the Singapore economy by 2015.

References
(1) www.ura.gov.sg
(2) www.marina-bay.sg

Arup involvement in Marina Bay

1. Singapore Flyer
Building on experience gained from the London Eye, Arup's award-winning design resulted in a revolving structure that is resilient, comfortable for passengers and aesthetically unique. (*C, E, F, G, M, S, T*)

2. Gardens by the Bay East
Arup looked to nature for inspiration and designed a water management strategy that uses Marina Bay as a reservoir to supply the garden's water features and themed areas. (*B, E, G, M, Mr, S, T, W*)

3. Gardens by the Bay South
This 54ha garden features Singapore's first conservatories, housed in two large biomes. Arup designed a natural smoke venting system and an innovative glass façade system that supports the conservatories' microclimates. (*F, Fc*)

4. The Helix Bridge
5. Bayfront Bridge
These new bridges provide pedestrian and vehicular connections between the old and new precincts of Singapore. Intricate and lightweight, the Helix is a world first for this type of design. (*C, E, G, L, M, Mr, S*)

6. MARINA BAY SANDS
(*A, AV, BI, C, F, Fc, G, I, R, S, Se, T***)**

7. Downtown Line (underground)
This 40km project required Arup to design a floating retaining wall system in soft marine clay ground conditions, and in close proximity to an existing line. (*C, E, En, G, M, S, T, Tn*)

8. Common services tunnel (230KV/22KV electrical substation and tunnel)
Arup allowed for the construction of this 3km underground common services tunnel that houses a comprehensive range of telecommunication and utilities networks with the capacity for expansion to meet changing utility needs. (*Fc, G, R*)

9. Marina Bay Waterfront Promenade
By creating a range of street furniture that doubles as environmental intervention and as a near-zero energy city gallery, Arup helped enhance this waterfront promenade as a comfortable outdoor space for viewing the Singapore skyline. (*C, E, Es, G, L, M, Mr, S*)

10. Marina Bay Financial Centre
Arup's innovative fire engineering approach scored several firsts in Singapore and raised the bar for local fire engineering standards.
This includes the use of the cabin concept as a smoke hazard management strategy for a retail outfit, total internal discharge for core staircases, and a space-efficient vertical protection design for a high-rise residential tower. (*F*)

11. One Marina Boulevard
Compared to a code-compliant solution, Arup's fire engineering design allowed this building to be constructed substantially closer to its neighbours, thereby maximising the use of limited land space in the heart of the CBD. (*F*)

12. UOB Plaza
At 280m, UOB Plaza 1 is one of the tallest buildings in Singapore with three levels of basement carpark.
Arup designed large steel trusses to create a 50m x 50m column-free space within the podium, and introduced a permanent underslab drainage system to limit uplift water pressures under the basement. (*C, Fc, G, S*)

13. OCBC Centre
Arup's innovative construction method for Singapore's first modern skyscraper allowed for simultaneous construction of the bank's floors, leading to a 35% reduction in construction time. (*C, G, S*)

Key to Arup disciplines

A	Acoustics
AV	Audiovisual
B	Blast engineering
BI	Building information modelling
C	Civil engineering
E	Electrical engineering
En	Environmental consulting
Es	Environmental sustainability design
F	Fire engineering
Fc	Façade engineering
G	Geotechnical engineering
I	Infrastructure
L	Lighting
M	Mechanical engineering
Mr	Maritime engineering
R	Risk consulting
S	Structural engineering
Se	Security consulting
T	Transport planning
Tn	Tunnel design
W	Water engineering

Introduction to Marina Bay Sands

Author
Va-Chan Cheong

Overview

Early in 2005, Arup was engaged by the resort developer Las Vegas Sands Corporation (LVS) to work on the planned integrated resort development at Marina Bay, Singapore, branded as Asia's most exciting urban lifestyle hub-to-be and the centrepiece of Singapore's redevelopment. With other elements then completed, under construction or planned – Marina Bay Financial Centre, various residential premises, the floating platform, and the Singapore Flyer[1], plus the existing Esplanade Theatres on the Bay – the Marina Bay Sands integrated resort (MBS) was to complete the "necklace" of tourism attractions in the Marina Bay area.

This crowning jewel would energise and activate the whole waterfront through its connections to other leisure and entertainment destinations, such as the Marina Barrage and the future Gardens by the Bay. It would also be one of the area's significant visual markers, together with the Esplanade, the signature Merlion sculpture, the Flyer, and the city skyline itself.

The new pedestrian Helix Bridge, completed in 2010, continues the link along the Marina Bay promenade, putting MBS within a seven-minute walk (500m) of the Singapore Flyer, the Gardens by the Bay and Marina Centre, and 12 minutes (800m) to the Esplanade Theatres, the Merlion, and the existing central business district (CBD).

As described in the previous article, the whole development is envisaged as Singapore's new downtown, its facilities both boosting tourism and making it South East Asia's leading MICE hub (meetings, incentives, conferences and exhibitions). The lotus-like ArtScience Museum and unique cantilevered SkyPark observation platform are already icons as identifiable with Singapore as Sydney Opera House is for its home city and Australia.

1.

Origins

Conceived by Singapore's Urban Redevelopment Authority and Tourism Board, the resort was envisaged as including hotel space, landscaped sky terraces, convention/exhibition areas, entertainment, recreation, public attraction, lifestyle, retail, and dining facilities, casino, links to the existing infrastructure network, an observation deck, night lighting, public art, etc. The design competition parameters were expressed as EXPLORE (new living and lifestyle options), EXCHANGE (new business ideas, and information) and ENTERTAIN (rich cultural experiences, fun and beautiful surroundings.)

In early 2005 the architect Paul Steelman Design Group, in association with Arup Hong Kong and other consultants, helped LVS in the RFC (request for concept) stage of the development competition, to a shortlist by the Tourism Board for the RFP (request for proposals) stage. From then on, Arup worked successively on the RFP, schematic and detailed designs. The Boston-based Safdie Architects was engaged by LVS for the RFP competition, and in May 2006, the Tourism Board announced that the development rights had been awarded to LVS in preference to the Malaysian casino operator Genting and two Las Vegas rivals: MGM Mirage, teamed with local developer CapitaLand, and Harrah's, which had joined with another local company, Keppel Land.

Arup's contribution

For this mega-project Arup provided a one-stop design service to its client, including advance works, infrastructure, structural, civil, and geotechnical engineering, and traffic, acoustic, façade, fire and risk consulting. Design team members came from many offices including Boston, Brisbane, Melbourne, Hong Kong, Shenzhen, and Singapore.

For its work on the scheme design, the Boston office had the advantage of being close to Safdie Architects. Arup Singapore was involved in the advance works, foundations, and substructure, as well as the fire and façade engineering designs. Arup Australia worked on the traffic consultancy and the dynamic behaviour of the structures, notably the SkyPark.

Hong Kong was responsible for Arup's overall performance and for the civil works design, while the detailed superstructure design was a collaboration between Singapore, Shenzhen and Hong Kong. Arup Singapore, with representatives from Hong Kong, was responsible for day-to-day liaison with the client and contractors to ensure proper implementation of the designs.

This project demonstrates how Arup's global resources respond to project design and management challenges, eg in this instance the architect being in the US and the client and building site in Singapore.

The firm deployed expertise across four continents, and made a virtue of the different time zones to overcome geographical restraints and facilitate continuous design development through real-time co-ordination between the parties. Alongside its comprehensive civil and structural engineering experience, Arup also deployed its expertise in fields such as materials, dynamics, risk engineering, bridge engineering, and frequently involved the range of skills within its Advanced Technology Group.

Each principal element in MBS is a major project and a significant building in its own right. MBS was technically challenging right from the enabling works, foundations and basement construction at the outset, to the geometrically complex ArtScience Museum and the extraordinary 66.5m cantilevered SkyPark 200m above ground.

Construction sequencing was another big challenge; it included both top-down and bottom-up methods. Since the works involved many different disciplines and trades, the procurement packaging and interfacing between them required serious consideration so as to achieve and complete the works within the constrained time-frame.

Arup's cross-continental collaboration contributed significantly to the project's success, overcoming challenges related not only to construction issues but also the severe global financial crisis that happened during construction.

Originally scheduled for 2009, the official opening of Marina Bay Sands took place on 23 June 2010 at 3.18pm, after a partial opening that included the casino on 27 April 2010. The SkyPark opened a day later, on 24 June. The theatres were completed in time for the first performance by "Riverdance" on 30 November 2010, followed by the ArtScience Museum in February 2011 and the Crystal Pavilions in September 2011.

Reference

(1) ALLSOP, A, *et al.* The Singapore Flyer. *The Arup Journal*, *43*(2), pp2-14, 2/2008.

A continuing client relationship

Author: Va-Chan Cheong

The relationship between Arup and LVS originally began in August 2002. George Chan, a former Director of Arup in Hong Kong, was invited by Phil Kim, Senior Partner and Managing Director for Asia at the Jerde Partnership architectural practice, to join a meeting with the executives of LVS to discuss the strategy for developing a casino project in Macao. (Phil Kim and George Chan had successfully collaborated recently on the Langham Place Mall project in Hong Kong.)

Chan's innovative ideas and appreciation of the need for timely completion of the project impressed LVS, and in September 2002 Arup was appointed as engineering consultant for the Venetian Sands Macao. Piling began in December 2002 and within 18 months, the 15 330m^2 casino was completed and opened to public, on May 18 2004.

After completion of this project, Arup's relationship with the client continued on to the Cotai Macao Parcel 1, an integrated resort development with a gross floor area of 975 000m^2 on newly reclaimed land between Coloane and Taipa. Parcel 1 started in June 2004 and opened in August 2007.

Then, while construction at Cotai was in full swing, the Singapore Tourism Board announced on 26 May 2006 that LVS had won the bid and was to be awarded the license to build Singapore's first casino at Marina Bay. The LVS proposal best met the city-state's economic and tourism objectives, and would significantly strengthen Singapore's position as a leading destination for conventions and exhibitions. The proposal also possessed unique design elements, developed by Safdie and Arup, that would give Marina Bay a memorable profile.

Arup's relationship with LVS thus continued when the firm was appointed for this project in July 2006. The schematic design by Arup's Boston office and Safdie, also based in Boston, was completed in December 2006, and the whole design package was transferred from Boston to Singapore in January 2007. With the joint efforts of Arup Hong Kong and Arup Singapore, the ground-breaking (in every sense) project at Marina Bay started in January 2007. The first phase was completed in April 2010.

Now, following Marina Bay Sands, Arup is again working with LVS for Parcel 5 and 6 in Cotai, Macao, another integrated resort. This is anticipated to be completed in early 2012.

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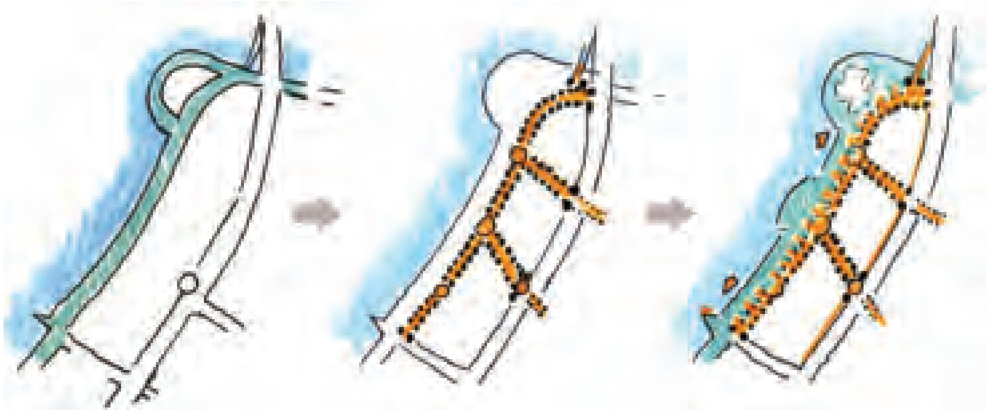
1. Location plan and site plan.

2. Architectural rendering of Marina Bay Sands from the south-west.

Designing Marina Bay Sands

Author
Moshe Safdie, Safdie Architects



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The vision
The 1Mm^2 mixed-use complex of Marina Bay Sands should not be considered as a building, but as an urban sector. From the outset we recognised Marina Bay's potential to demonstrate our capacity to create a new kind of urban centre for the 21st century: vital, connected with nature, interactive, of a humane scale, and climatically sustainable, its enormous complexity and size notwithstanding. Thus the first strategic move was to look into urban design traditions in search of an appropriate organising structure. Traditional cities, particularly those of the Greco-Roman period, were always designed around major spines, the criss-crossing *Cardo Maximus* (north-south) and *Decamanus* (east-west), along which all the major public structures, temples, palaces and agoras were organised.

Singapore's Urban Redevelopment Authority conceived the Bay frontage as a segment of the continuum of promenades that surround the Bay and extend up the Singapore River. The landfill that provided the site for Marina Bay was itself intended to create an enclosed bay, helping to complete the loop and, through the construction of a dam, convert the Bay into a freshwater reservoir.

We seized on the promenade concept as the opportunity to create an even more powerful spine – an indoor/outdoor *Cardo Maximus* extending along the waterfront and cutting inland in two perpendicular cross-spines connecting to the hotel and to the subway along Bay Boulevard (Fig 1). Having determined the fundamental structure of public place, we aligned by shops providing access to the larger program components: the convention centre, casino, two theatres, and three hotel towers along them. Everything fell into place.

Hotel complex and ArtScience Museum
Having conceived what came to be known as the "podium building", we turned to the other two major pieces: the hotel complex and the ArtScience Museum. For the promontory, the site programme called for a major cultural building, an icon for Singapore. We decided on a museum of ArtScience as best representing the spirit of Singapore and evolved a design of below-grade galleries as well as a floating structure reaching tall with skylights, to serve as this icon. Now dubbed "the hand of welcome" by some and "the lotus" by others, it is the centrepiece of the promenade experience surrounding the Bay.

A major planning decision was to set the hotel back east of the Bay Boulevard, so as not to encumber the pedestrian scale of the podium building. As all three other competitors placed the hotel close to the water's edge, this proved to be a significant move. Though it might have been more efficient to place the approximately 3000 modules in a single hotel tower (as in Las Vegas' Sands), we recognised that such a building would form a wall-like barrier between the downtown and the sea across to the east. Seen from incoming cruise liners, a single tower would also have blocked the view of the city, so we decided to split the hotel into three towers, with the emphasis on achieving a delicate and dynamic scale for them (Fig 2). Since each tower comprises two paralleled stretches of rooms straddling a corridor, we decided to give individual identity to each of the half slabs, slipping them in section so as to read independently of each other, and spreading them at the base to form a continuous series of atria. As the site tapered, the spread at the base varied from tower to tower.

Next came the question of providing an appropriate network of parks, gardens and swimming pools appropriate to an urban resort of this scale. With land all used up and the decision that we best not place these atop the long-span casino and convention centre, we invented the concept of the SkyPark, a 1.24ha network of gardens bridging the three towers and cantilevering 66.5m towards the north, forming a public observatory overlooking the city on the 57th floor.

3.

4.

1. Development of the architectural spine concept.

2. Sketch by Moshe Safdie of the hotel towers and ArtScience Museum from the Bay.

3. Architectural rendering of Marina Bay Sands looking south-east.

4. The SkyPark from above, looking south-west.

Challenges to the design team
Each of these strategies presented a series of structural, mechanical, and construction logistics challenges of the highest order.

A major challenge to the structural and architectural team working together was that the entire concept (including its presentation) occurred within four months. This was the result of the client LVS deciding to turn to Safdie Architects only four months before the submission deadline. Since it can be seen that the concept as presented and selected by the Singapore government was almost identical with what was built four years later, the initial concept held up to the test of later development. Indeed it was the Arup team's work with our team in Boston, with the support of Aedas, the client's design and construction team, over four months that became reality four years later.

Given the four-year schedule for design and construction, formidable organisational moves occurred. The team expanded exponentially to embrace Aedas and Arup offices across the globe including those in the region, as well as engineering teams in the other disciplines and all the specialist consultants including landscape, lighting, etc. Indeed, two comprehensive teams of stateside (USA) consultants and their counterpart Singapore consultants were formed as work slowly shifted from Boston to Singapore. The hallmark for the process was the workshops that occurred every three weeks, where architecture and engineering teams, specialist consultants, and client representatives from Las Vegas and Asia gathered in Boston for two to three days at a time to evolve the design and make the required decisions.

As this progressed, sub-teams were formed to deal with each component: the Spine which included the retail, the MICE convention centre, the casino, the theatres, the ArtScience Museum, the Crystal Pavilions, and the hotel. Each presented a complex project of its own, involving hundreds of millions of dollars' worth of construction.

Further considerable challenges had to be overcome, eg excavating six levels into the water table in what was highly unstable landfill, and retaining the water and soil pressure while foundation and basement levels were constructed. Construction sequences and, in particular, temporary supports for the construction of the hotel towers and their atria, the ArtScience Museum, and the long-span spaces in the podium, proved to be as challenging as the final design was set in place.

Unified language and co-operation
The major task, however, was to develop an architectural-engineering language for the project that would unify the parts, a system of detailing, cladding, and connectivity that would allow each individual element its uniqueness while at the same time making it cohesive as the whole. Working with the Arup façade team, developing for example the cladding systems for the podium and for cladding the SkyPark belly, each and every part required a unique solution while at the same time being part of the family of details.

In my 47 years of practice, I have never seen such a formidable team effort, fundamentally harmonious in its character, encompassing five continents, interacting with contractors and suppliers from across the world, co-ordinating through meetings, "see-and-share" sessions and every other device invented in our computer era, with such a singularity of purpose moved by an ambition for excellence.

Collaboration with Safdie Architects

Authors
Daniel Brodkin Patrick McCafferty

Competition design
Building on a long relationship of collaborative design, Moshe Safdie invited the Boston and New York offices of Arup to join the team comprising Safdie Architects, Aedas, and Las Vegas Sands Corporation to participate in the MBS competition. The competition, which ran from January through March, 2006, culminated in a design that featured bold geometric forms, including the sweeping hotel towers and the iconic ArtScience Museum.

The towers rise from their base in two halves before merging some 20 storeys above and then reaching up to over 50 storeys in total. Spanning the top floors is the SkyPark, an expansive structure in its own right that bridges the towers and culminates in its 66.5m cantilever beyond the northernmost tower. The Museum's form, in turn, highlights the galleries within and anchors the north end of the resort along a promontory on the bay.

The government of Singapore announced the team as winners in June 2006, but the schedule left little time to celebrate. With a piling tender package due that September, the design team began to mobilise quickly. The Arup team rapidly grew internationally, and put the latest telecommunications and 3-D documentation tools to work so as to co-ordinate design efforts across multiple continents simultaneously. In addition, Arup appointed one of its Principals to a leadership co-ordination role, travelling extensively to calibrate the efforts of each team in person.

Structural concept for hotel towers
Safdie's design of the hotel towers, with their independent "legs" at the lower levels, creates a dynamic form while defining space for a contiguous connecting lobby uninterrupted by hotel structures. While this arrangement implied "A-frame" structural action, it also posed significant technical challenges for the Arup team (Fig 1).

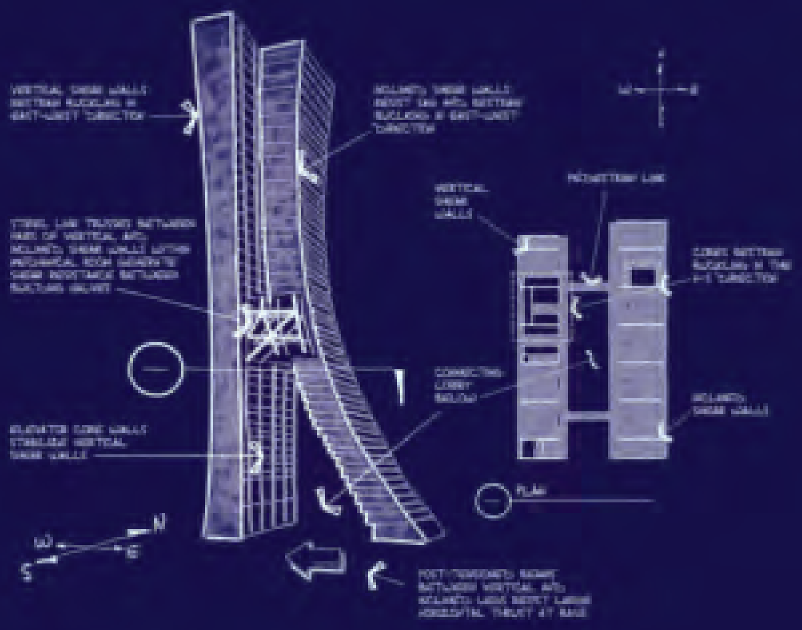
The team therefore developed a shear link using steel trusses just above the lobby to ensure positive engagement of the two halves, with a system of post-tensioned beams to resist tie forces at the base. Each leg, only half the building width and carrying substantial load, required detailed analysis for lateral buckling. Indeed, a system of parallel shear walls coupled with transverse cores in each half was carefully designed to resist this effect (Fig 2).

Finally, recognising the challenge of constructing the inclined legs, Arup's engineers developed a shoring strategy and a staged construction analysis as early as the schematic stage to ensure that the towers could be constructed without compromise to the completed building.

Structural concept for the Museum
Safdie's form for the ArtScience Museum responds to the galleries within. Two floors occupy each of the museum's "fingers" to create distinct galleries arrayed around a central atrium (Figs 3, 4). This arrangement called for a screen around the atrium to create a sense of enclosure to each gallery while still encouraging views between them. In keeping with the design goals, it was agreed that this screen should serve a structural function to reinforce its integrity, and Arup's strategy took the form of a cylindrical diagrid (Fig 5).

The overall structure is configured to focus horizontal forces caused by wind, earthquake, and unbalanced gravity loads on a tension ring at the top of the diagrid, demands for which this form is particularly efficient. A spiralling compression ring and a colonnade of "mega-columns" work together to protect the diagrid from the gravity loads and horizontal thrusts generated along the bottoms of the cantilevered galleries.

1. Structural design of hotel towers.
2. Buckling analysis for hotel towers.
3. Cross-section through the ArtScience Museum.
4. Plan of the ArtScience Museum.
5. Structural diagrid for the ArtScence Museum.
6. Safdie's design for the ArtScience Museum.



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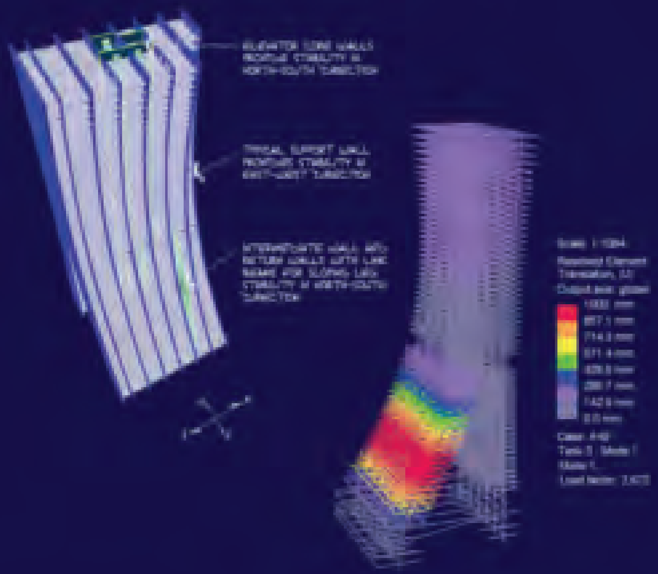

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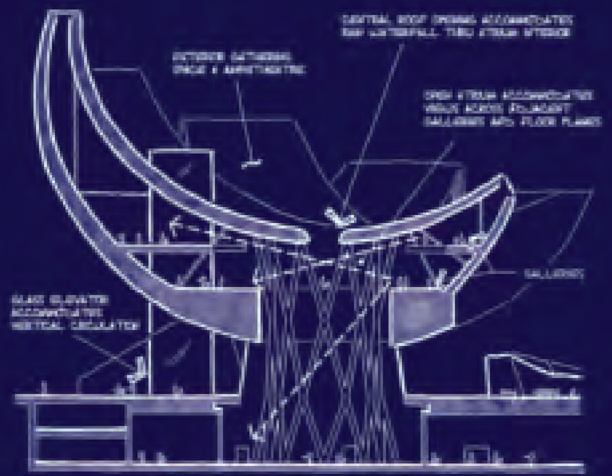

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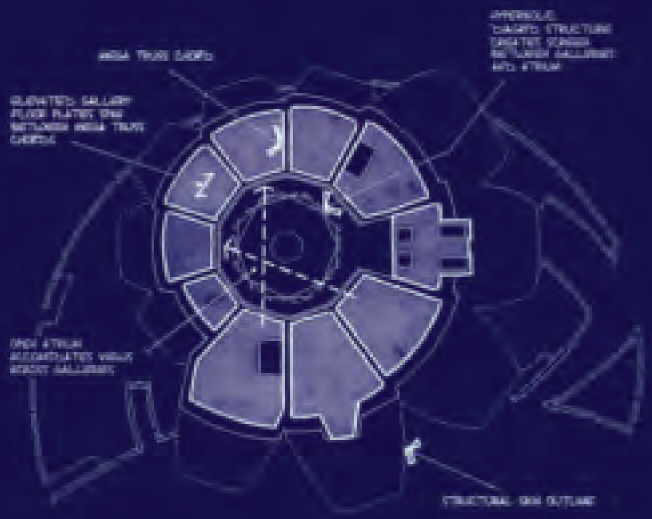

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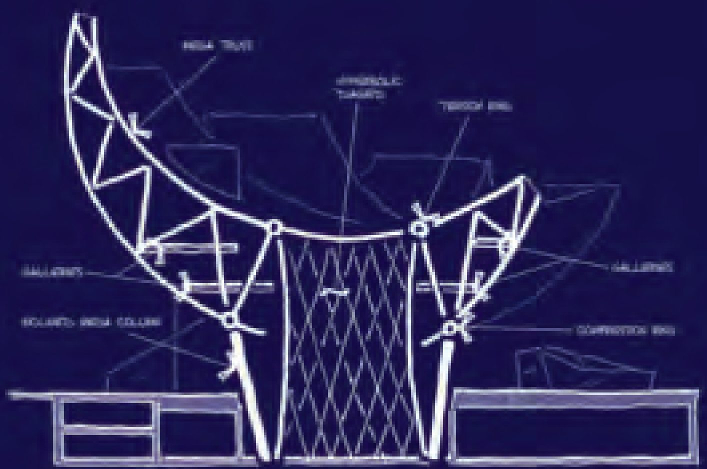

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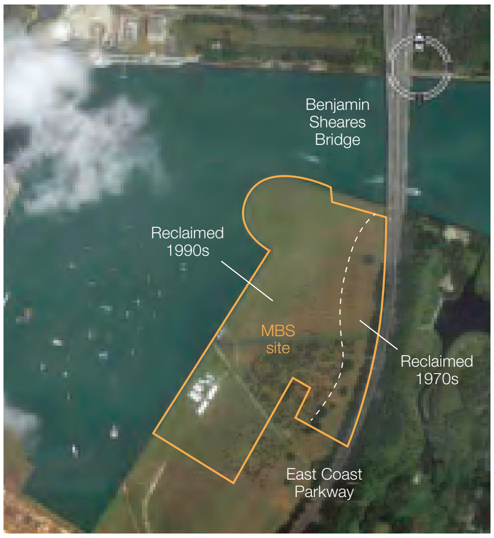

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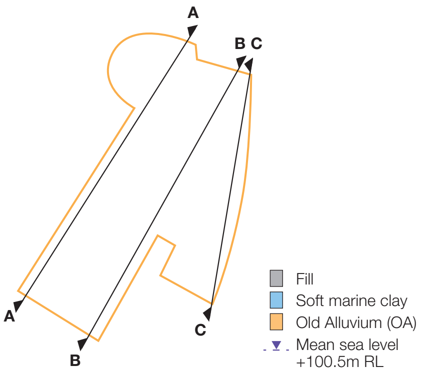

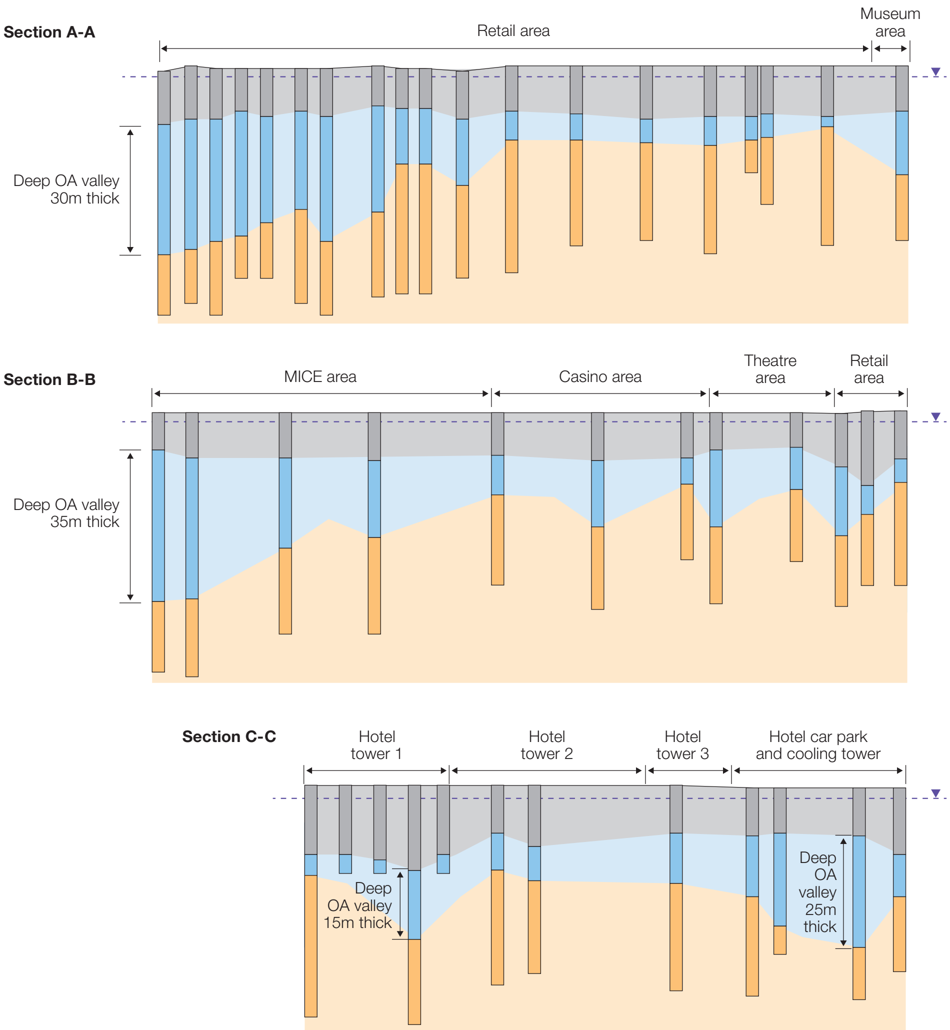

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1. Aerial view of the MBS site before development.

2. Geological sections.

Geotechnics and foundation design

Authors
Philip Iskandar Leong Wing Kai
Jack Pappin

Introduction

Marina Bay Sands is on reclaimed land, comprising sand infill overlying deep soft clay marine deposits, above an underlying very stiff-to-hard Old Alluvium (OA) layer. This soft marine clay, coupled with the proximity of the East Coast Parkway highway and the Benjamin Sheares Bridge, posed significant challenges to the design of the excavation works.

The 15.5ha MBS development is founded on the underlying very stiff-to-hard OA layer using a forest of barrettes and 1m-3m diameter bored piles. The average basement excavation depth was around 20m, and with over 40% of the concrete construction occurring 18m-35m underground, the required timetable was only made possible by Arup's innovative approach to excavation in the first year. Overall, some 2.8Mm^3 of fill and marine clay was taken from the site, ie about 800 trucks a day for two years! The development also required Arup to engineer a 35m deep cut-and-cover tunnel for the Downtown Line 1 (DTL1) extension to Singapore Mass Rapid Transit rail next to the Benjamin Sheares Bridge, which links the island's east and west coasts and had to remain operational throughout construction.

Site geology

The Marina Bay area has had several phases of reclamation, the latest completed in the mid-1990s. Most of the MBS development sits on this latest reclamation zone (Phase VIII), while the eastern side is located within the Phase VB reclamation zone, completed in the late 1970s (Fig 1). Ground level across the site is generally flat at about +103m to +103.5m, with the recorded groundwater table at approximately +100.5m.

The subsoil conditions typically comprise a 12m-15m thick layer of reclamation fill overlying 5m-35m of Kallang Formation soils, underlain by the stiff-to-hard OA. The Kallang Formation is predominantly soft marine clay, with some interbedded firm clay and medium dense sand of fluvial origin.

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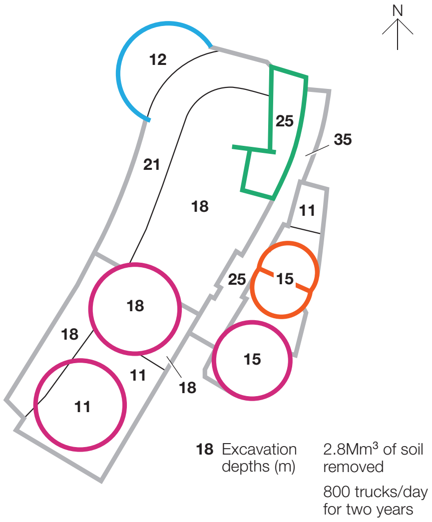

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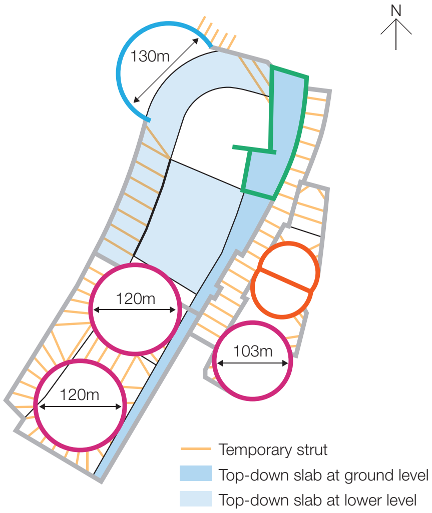

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Under the main podium area, covering the Sands Expo and Convention Center (MICE), casino, retail, theatres and ArtScience Museum, there is a marine clay deposit, up to 35m thick at the southern end, which thins toward the north (Fig 2, A-A, B-B). On the eastern side, where the hotel, district cooling system, and DTL1 extension are located, the soft marine deposit is some 10m thick, except at the northern and southern end where deep valleys in the OA are encountered (Fig 2, C-C).

Circular diaphragm walls for minimum strutting

To overcome the challenges of the bulk excavation and minimise shoring in the difficult soil environments, Arup's excavation design included five huge reinforced concrete cofferdams:

- two circular, 120m diameter, in the MICE area
- one circular, 103m diameter, and one twin-celled and peanut-shaped, 75m diameter, in the hotel area
- one semi-circular, 65m radius, in the ArtScience Museum area.

Each circular cofferdam was a dry enclosure, within which excavation and subsequent construction could be carried out without the need for conventional temporary support. The only constraint was that excavation within a cofferdam must take place before excavation outside (Figs 3-5).

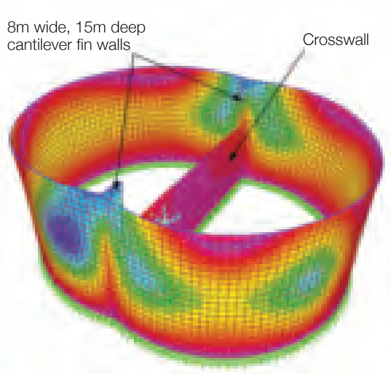
The 120m diameter cofferdams were among the largest ever deployed both by Arup and in Singapore generally, and notable for their excavation depth – down to 18m below ground (Fig 6). They allowed work to progress across the site simultaneously. The design of the north cofferdam in conjunction with a steel truss system to the perimeter diaphragm walls at the MICE area allowed independent excavation between there and the casino and theatre areas to the north. The single-layer steel truss/strut system enabled the 11m deep excavation to be completed outside the two cofferdams in the MICE area.

3. Aerial view of MBS site showing positions of cofferdams.

4. Excavation depths.

5. Minimal strutting.

6. Excavation in 120m diameter circular cofferdam.



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7. Model for hotel twin-cell cofferdam (“peanut”) in the *SAP2000* program.

8. Diaphragm walls removed to excavation level.

9. Excavation in semi-circular cofferdam.

10. Excavation sequence in casino and retail areas.

Due to the vicinity of the East Coast Parkway, innovative use of the peanut-shaped diaphragm wall, without any crosswall above excavation level, enabled unhindered bulk excavation of the breakwater mole that had been buried during previous reclamation (Fig 7).

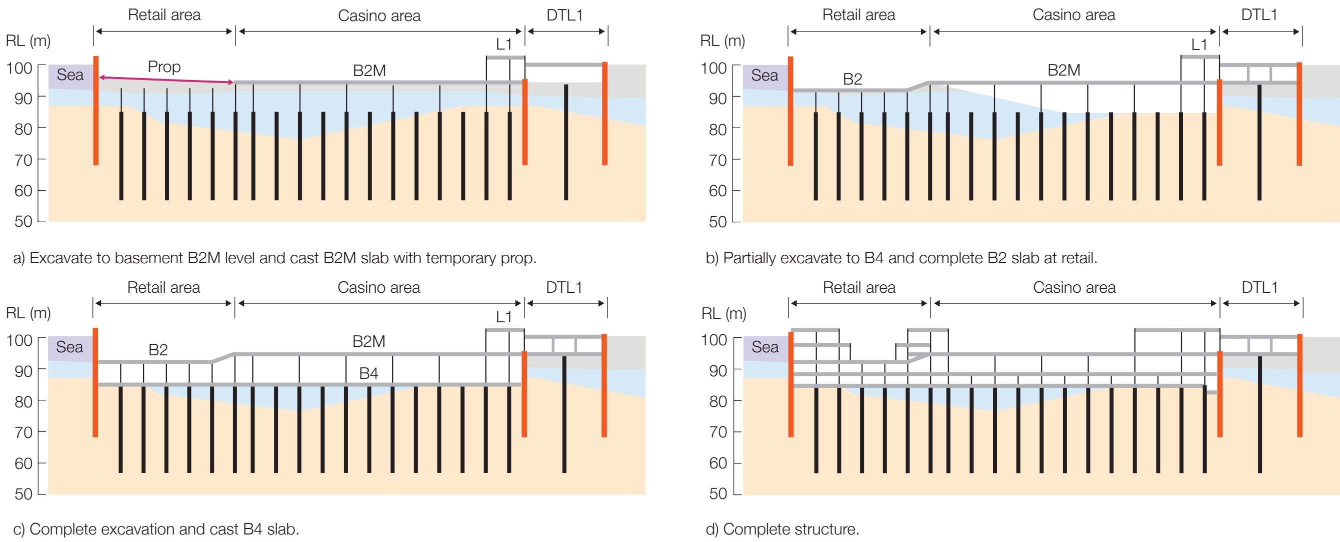
Parts of the diaphragm walls of the two hotel cofferdams doubled as permanent hotel basement walls and loadbearing elements for the hotel towers. The remaining parts of these walls, and both the 120m diameter cofferdam diaphragm walls, had to be removed down to the excavation level by “wire cutting” them into liftable blocks before removal (Fig 8).

Top-down construction in the casino area
As the layer of soft marine clay is generally thinner in the northern part of the site, to create the four-level basement in the casino area a top-down excavation method with minimum temporary props was used, in conjunction with a simultaneous top-down excavation in the adjacent DTL1 tunnel area.

After various considerations, it was decided that the practical way forward was to design the B2 slab to act as a continuous support between the two retaining walls on the west and east sides, which then allowed excavation to B4 and construction of the substructure and superstructure above B2 to proceed concurrently. These two activities proceeding simultaneously gave considerable time savings (Figs 10a-d).

Continuously reinforced diaphragm wall for DCS box
For energy efficiency, the Singapore Government required MBS to incorporate a district cooling system (DCS), its plant housed in a deep reinforced box east of the theatre area (Fig 11). Shear walls constructed with the DCS box enabled unhindered bulk excavation across the theatre area to the west. Within the DCS box, the team used partial “top-down” excavation within minimum temporary strutting. The DCS box also doubled as a retaining structure for the deepest excavation in the DTL1 tunnel where a deep valley of soft marine clay is present. As the theatre structures are isolated from the rest of the development, the DCS box has to permanently support the lateral loads from the ground to the east of the DTL1 tunnel.

The large shear forces to be transferred into the underlying OA needed continuously reinforced diaphragm walls, and to achieve this support, three east-west shear walls were constructed (Fig 12). Each is 1.5m thick and about 50m long, and comprises a series of “male” (6.4m) and “female” panels (3.0m). To ensure continuity, the shorter female



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11. Construction in the theatre area, showing the adjacent DCS box.

12. Locations of shear walls.

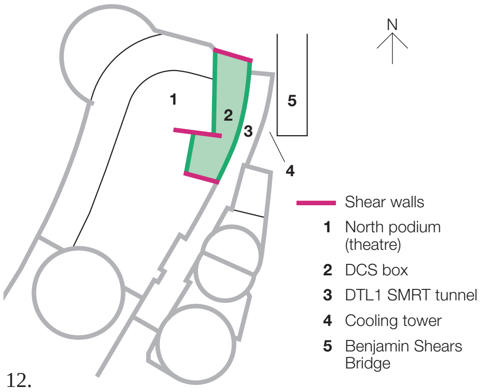
13. Construction of shear wall.

14. Elevation of south end of Benjamin Sheares Bridge.

15. Method of allowing articulation between pier and deck.

16. 1.8m high adjustable shear pin.

17. Section on plan of adjustable shear pin.



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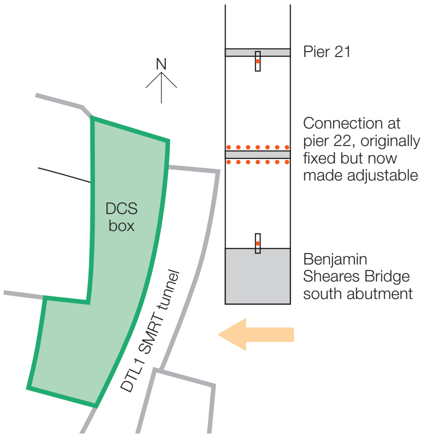
panels are cast with steel end plates on both ends, leaving about 1.5m of reinforcement bars unconcreted at each end for future lapping with the subsequent male panel reinforcement (Fig 13). While this type of wall is relatively common in Taiwan, this was Arup's first experience with it elsewhere.

Managing the impact of excavation on the Benjamin Sheares Bridge

Excavation within the deeper end of the DTL1 tunnel adjacent to the Benjamin Sheares Bridge (Fig 14) was carried out using a stiff temporary strutted T-shape diaphragm wall and the DCS box. Inevitably, lateral ground movement would affect the bridge and calculations showed that this would overstress the shear connections between piers and deck. The existing fixed shear pins between the deck and the southernmost pier (22) were therefore replaced by fewer, but adjustable, pins (Figs 15-17). Periodic adjustment of these enabled the last section of the bridge deck to articulate in plan and rendered the whole bridge tolerant of the ground movement inevitably caused by the deep excavation for MBS and the DTL1 tunnel.

Conclusion

The basement structure was completed in 2009. Arup's innovative approach to the excavation design in these difficult site and time constraints set a benchmark for future large-scale excavations both within Singapore and elsewhere.



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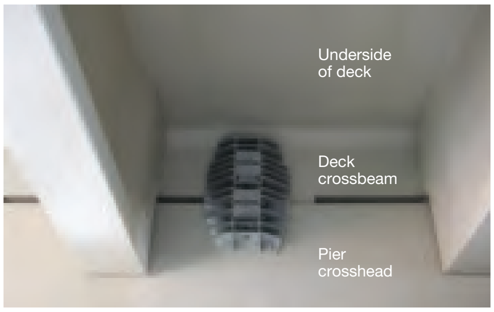

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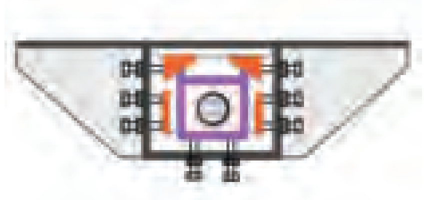

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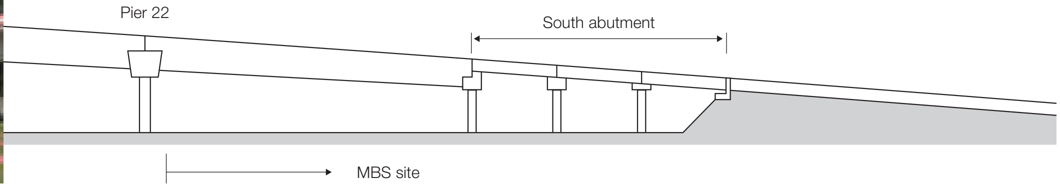

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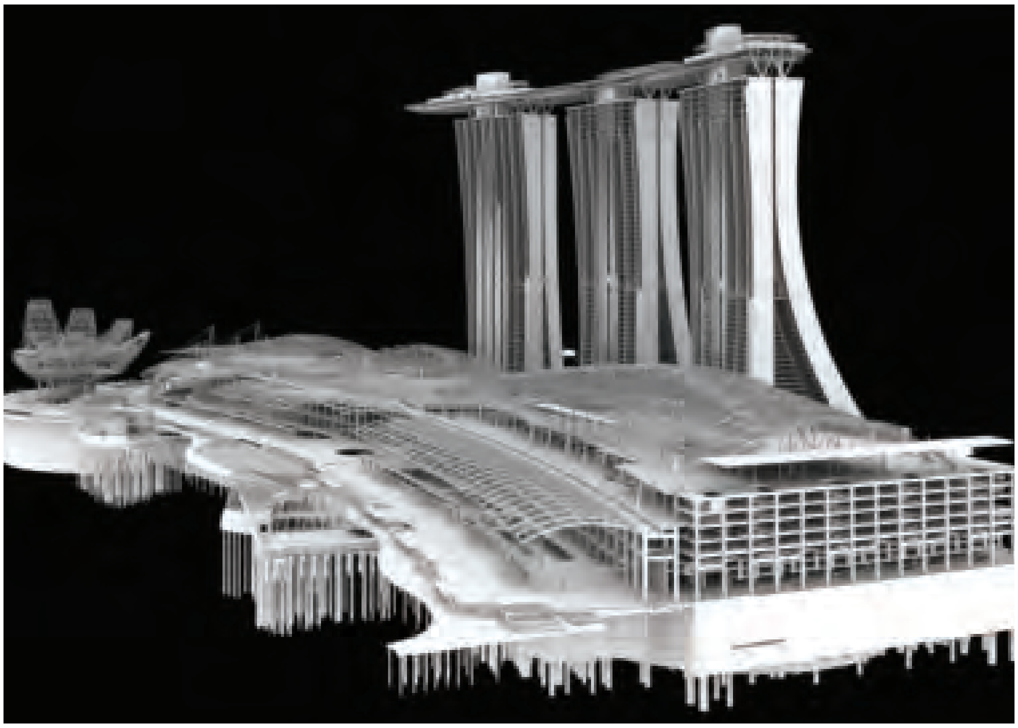
The Sands Hotel and Sands SkyPark



2.

The hotel towers

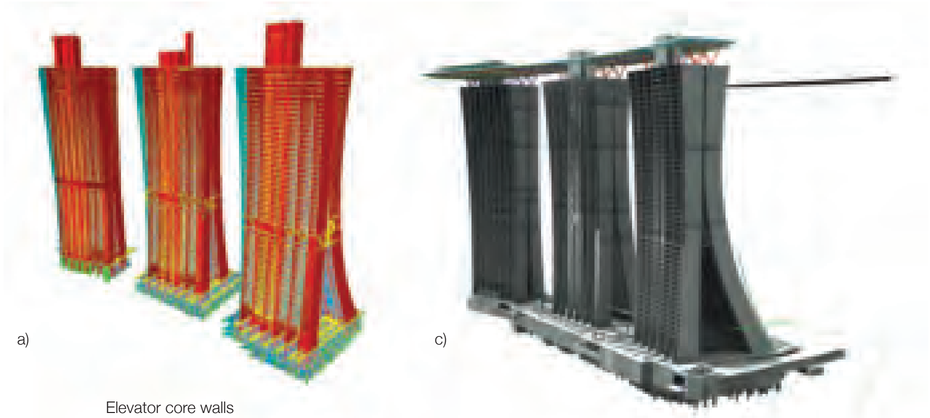
Authors
Rudi Lioe Wijaya Wong

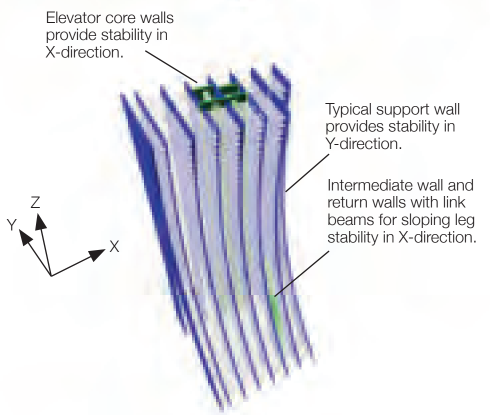
Unique and complex geometries
Each of the three 55-storey hotel towers has its unique geometry, with varying curvatures on their east sides. The combination of these curvatures and the buildings' verticality on the west side creates an open continuous space within that links all three towers, forming a grand atrium at ground level.

It was essential to create a realistic 3-D analysis model that was capable of representing the towers' complex behaviour, including deformation, wind-induced movement, and stresses between elements, and so the design team used building information modelling (BIM) extensively to resolve the many co-ordination and documentation issues that arose from the unique and complex geometries (Fig 2).

Loading
Unlike most high-rise towers, the primary lateral stability demands on the MBS hotel towers 1 and 2 are induced by gravity loads. The dramatic curve of the eastern halves creates overturning forces due to gravity loads in the short direction that overshadow those due to wind or notional loads.
The assumed material properties had to be given particular attention, since these lateral loads are permanent, not transient as is usually the case with wind loads.

The primary lateral system in the towers consists of the reinforced concrete shear walls between the rooms and the concrete cores around the elevators. The walls and cores provide stiffness in the short direction, while the cores and sway action between walls and slabs supply longitudinal resistance (Fig 3).





3.

2. CAD model of complete MBS structural framing.

3. 3-D analysis models and structural system:
a) *ETABS* models for checking the overall stability of the hotel towers at early stages of design;
b) *GSA* model for checking overall stability of hotel tower, at transfer of design from Arup Boston to Arup Singapore;
c) CAD model of an early design stage for the SkyPark (truss system).

1.

In each tower, the link trusses on level 23, which accommodates the plantroom, fulfil a vital role (Fig 4). Without them, the two walls would act independently and significant differential displacement would occur across the corridor at the upper levels. This would have resulted in unacceptable cracking and out-of-level floors. The use of embedded steel sections with shear studs enables the forces to be effectively transferred from the external braces to the wall elements. The sectional geometries of the truss elements were also sized to fit within the wall thickness.

As self-weight was the factor driving the lateral demands on the structures, it was prudent to adopt a floor system that offered the lightest overall structural weight. The floors were therefore designed in post-tensioned concrete with a maximum span of 10m. This arrangement eliminated the need for internal columns and provided the lightest combination of horizontal and vertical structure.

Movements

The asymmetrical geometry meant that lateral movement is induced not only by lateral load but also by gravity load. As this behaviour was critical both during construction and after completion, the following tower movements were observed and carefully studied:

- angular rotation at the tops
- maximum deflection on elevations (vertical and lateral)
- differential settlement between straight and sloping walls
- differential settlement between adjacent wall bays
- differential movement between the towers, which would affect the behaviour of the SkyPark.

4.

5.

4. Tower 1 link trusses.

5. Tower 1 link trusses under construction.

Short-term movements due to self-weight were offset by applying precamber during construction. As the completed towers are expected to continue deforming sideways due to their geometry, concrete creep, and shrinkage effects before converging in 30 years' time, this was factored into the early design of the various building services such as the vertical transportation system, building enclosure, MEP services, etc.

Detailed analysis provided an estimate of the short-term and long-term movements of the towers, and a corresponding specification was prepared to assist contractors in the selection and detailed design of the affected finishes and services (Figs 6-8).

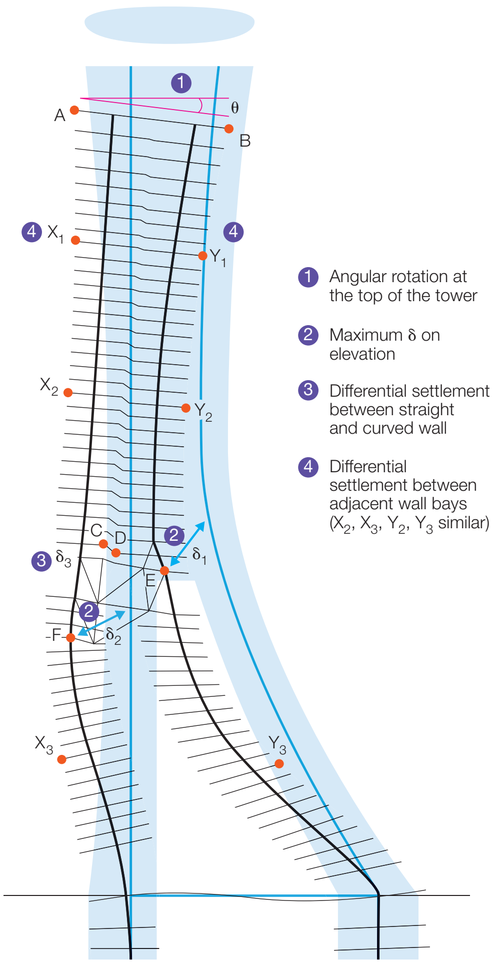
Construction

Building the very inclined towers 1 and 2 proved to be another challenge, as this was impossible without massive temporary works. Rigorous studies early in the design stage to assess the available construction options concluded that it would be very costly, if not practically impossible, to construct the towers without introducing lock-in stresses on the structures, and so reasonable lock-in stresses were considered in the designs of the key structural elements.

Subsequently, a performance-based specification was prepared to give tenderers the flexibility to provide their preferred temporary works system while limiting the lock-in stresses in the key elements.

For towers 1 and 2, the main contractor and specialist advisor together devised a temporary works system combining post-tensioned and steel strutting systems. The latter were installed to prop the sloping walls against the straight walls so as to limit movement, while a series of vertical post-tensioned tendons were provided in the walls to control the lock-in stresses (Figs 9-11). As tower 3 had an almost vertical geometry, it could be constructed without any temporary works.

At the various construction stages, further thorough analysis was performed to estimate the stresses and movements, to ensure compliance with the design intent. A real-time monitoring system was implemented during construction to monitor the actual stress level and movement. If this differed from what was predicted, a back-analysis was carried out.



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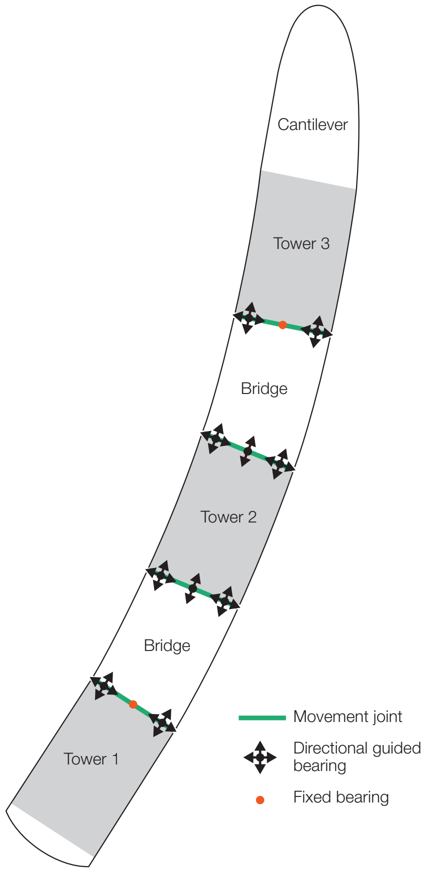

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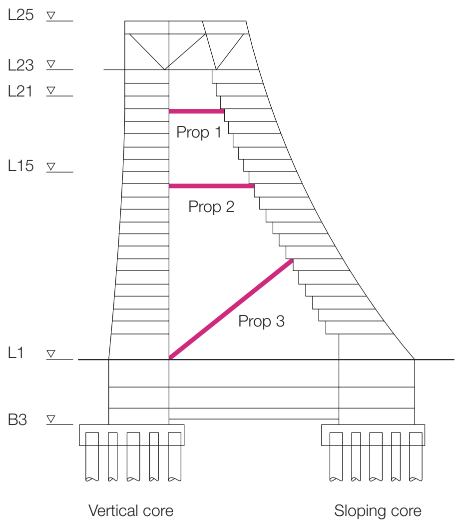

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6. Deflection stage of tower 1.

7. Angular rotation at top of tower.

8. Movement joints between towers and SkyPark.

9. Wall post-tensioned tendons.

10. Cross-section through lower part of tower 1 showing temporary strutting.

11. Tower 1 under construction.

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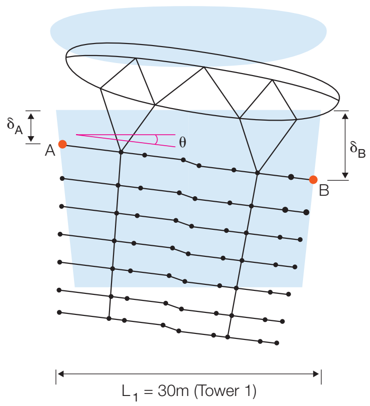

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1.

1. The Sands Hotel atrium, looking north from the main entrance.

2. Atrium walls extending from tower 1, each side of the main entrance.

3. Wind arbors designed by Ned Kahn on west atrium wall.

2.

3.

Hotel atrium walls

Authors
Brendon McNiven Xiaofeng Wu

Introduction

The unique and complex geometry by which all three 55-storey hotel towers splay out towards their bases creates an equally unique set of open spaces between them, with the walls on the inner sides of the towers linking these open spaces to form the grand Sands Hotel atrium (Fig 1). This begins at a height of approximately 20 storeys at tower 1 (south end), and angles down to around six storeys at tower 3. Its width also decreases, from approximately 40m in tower 1 to 20m in tower 2 to 10m in tower 3.
The integrated design of the atrium was aimed at ensuring the highest standards of safety and comfort as well as a remarkable aesthetic experience for guests of the Sands Hotel. This article mainly focuses on the structural design of the atrium walls.

Natural light is brought in through the roofed glass atrium walls between the towers, while inside, air-conditioning creates thermal comfort. In elevation, the tallest atrium walls extend out of tower 1 at the southernmost end (Fig 2), with the top lines sloping down to the walls between towers 2 and 3. Following the towers' body surfaces, the profile of the linking atrium walls integrates visually with them. The west side vertical atrium walls are also externally decorated with wind arbors designed by Ned Khan[1] (Fig 3), the constant movement of which furnishes a special visual experience.

Structure

The atrium walls (Figs 4, 6) are framed with aesthetic and structurally efficient steel trusses connected by horizontal transoms, with rectangular hollow sections used as the main structural members. The layout of the trusses was arranged to achieve modulation with the glass panels, so as to enable economical and fast construction.

Except for the atrium walls on the south side of tower 1, which extend out from the tower shear walls suspended from the roof above (Figs 2, 6C), the other walls between the three tower blocks span vertically from ground level to the steel truss roofs above (Figs 6A, B, D, E). The maximum span is 47m in the wall trusses between towers 1 and 2 (Figs 6B, E), with a minimum span of 27m between towers 2 and 3 (Figs 6A, D).

The trusses are pin-connected at the bottom by cast-in base plates, and vertical slot holes are provided at the connections between the roof trusses to allow relative vertical movements. The glass panels are supported by T-shaped transoms which are tied by double stainless steel rods to the primary horizontal RHS transoms.

Besides carrying loading from the glazing, the horizontal RHS transoms play an essential role as the lateral stability system of the wall trusses. In the west side vertical walls (Figs 6A, B), the horizontal RHS transoms are pin-connected on the south side to the tower shear walls.

Horizontal slot holes are provided on the north side connections with the tower shear walls to allow relative lateral movement of the towers as well as movement of the walls due to thermal effects. The boundary conditions are the same in the east side walls (Figs 6D, E), but the mechanism is different due to the inclined architectural layout. Horizontal RHS transoms act with CHS braces to form closed triangular load paths as the lateral stability system.

The glass panels and the primary and secondary steel elements were produced in factories and transported to site for erection. The base plates at ground level and the tower shear walls were cast in situ. The modulation of supply and design of the glass panels and trusses facilitated a speedy, efficient and economic construction of the atrium walls.

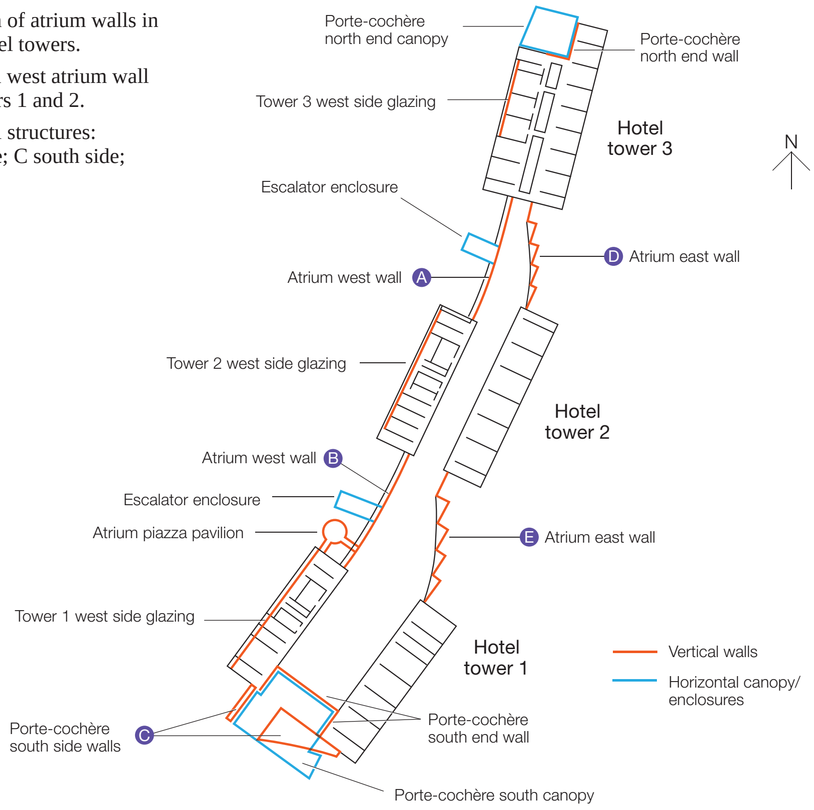
Reference

(1) http://nedkahn.com

4. Layout plan of atrium walls in relation to hotel towers.

5. The vertical west atrium wall between towers 1 and 2.

6. Atrium wall structures: A, B west side; C south side; D, E east side.



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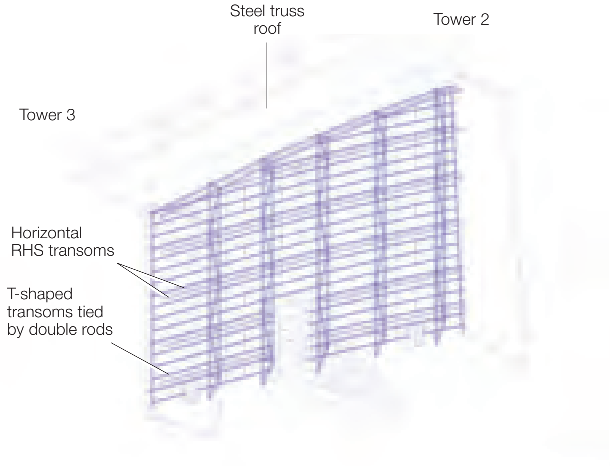
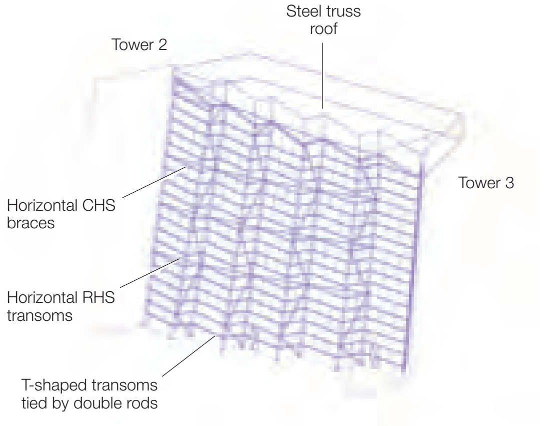
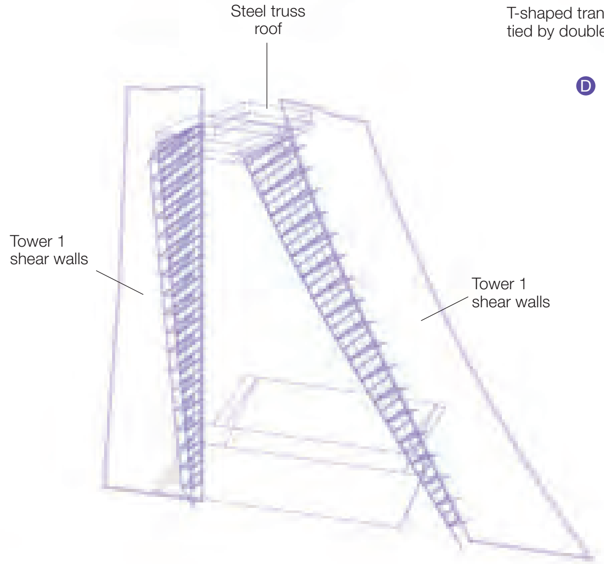


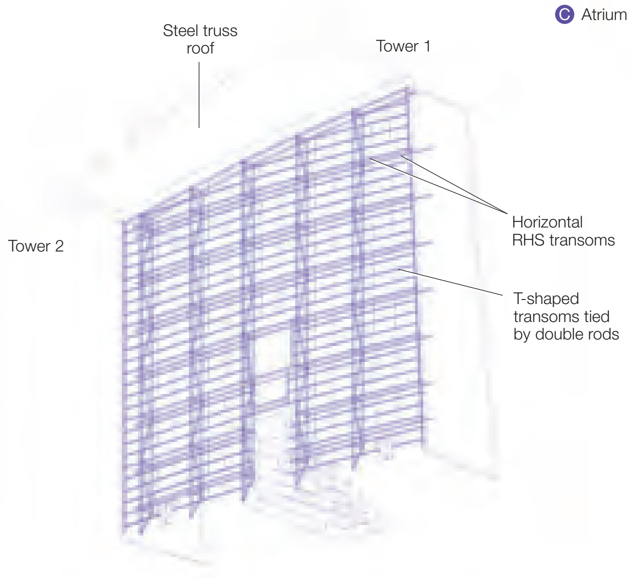
A Atrium wall between towers 2 and 3 (west side).



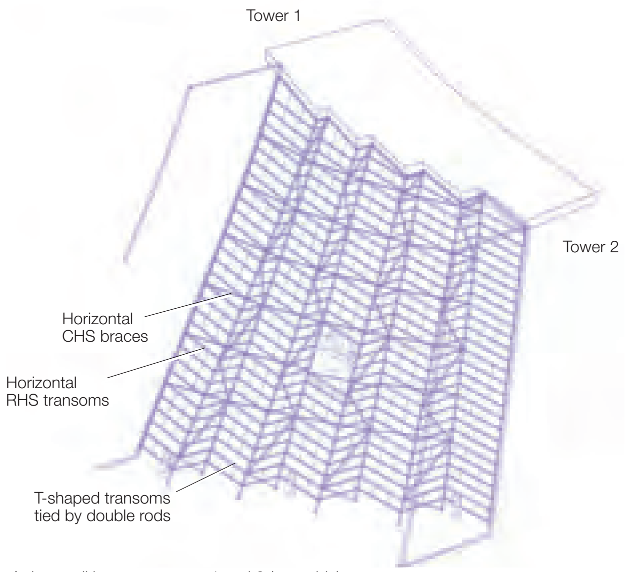
D Atrium wall between towers 2 and 3 (east side).



C Atrium wall extending out from tower 1 (south side).



B Atrium wall between towers 1 and 2 (west side).



E Atrium wall between towers 1 and 2 (east side).

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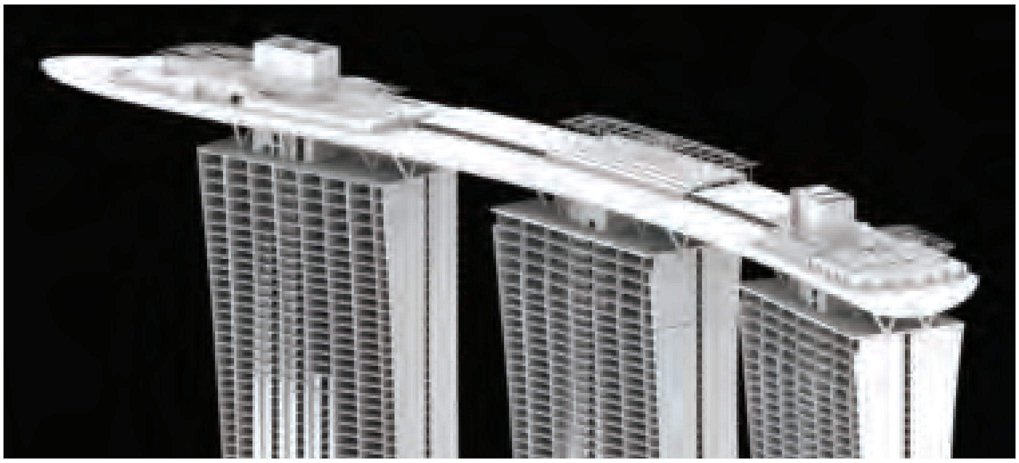

2.

The Sands SkyPark

Authors
Brian Mak Brendon McNiven
Wijaya Wong

1. The completed Sands SkyPark.
2. CAD model of SkyPark.
3. Infinity pool.
4. Underside of the completed SkyPark between hotel towers.
5. Structural layout of SkyPark, showing movement joints.

Introduction

The 38m wide and 340m long Sands SkyPark (Figs 1, 2) is the world's longest habitable cantilevered observation deck, and has now become a symbolic icon for Singapore. Covering more than 1ha and as long as four and a half Airbus A380s, the SkyPark sits atop the three 55-storey towers of the Sands Hotel and includes facilities such as landscaped gardens, signature restaurants, an infinity pool (ie where the water appears to have no boundary) covering nearly 1400m^2 and containing 1.4M litres of water (Fig 3), and a 66.5m cantilevered viewing platform that offers visitors a 360˚ view of the city. Over 7000 tonnes of steel was used in the SkyPark's construction.

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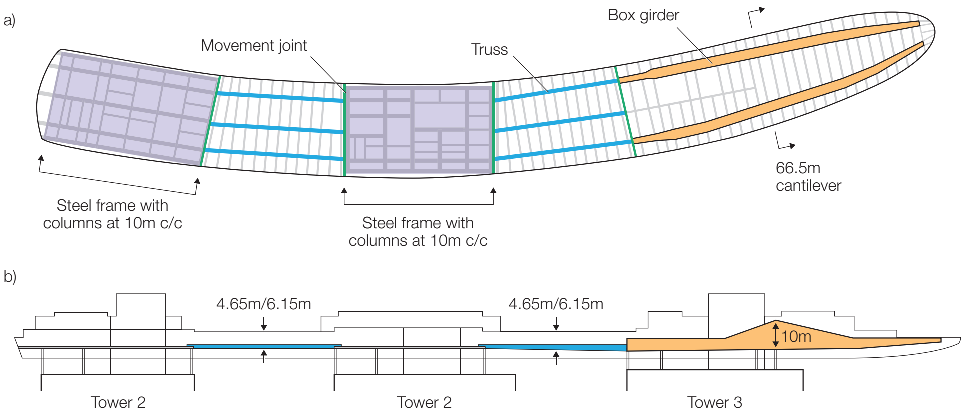

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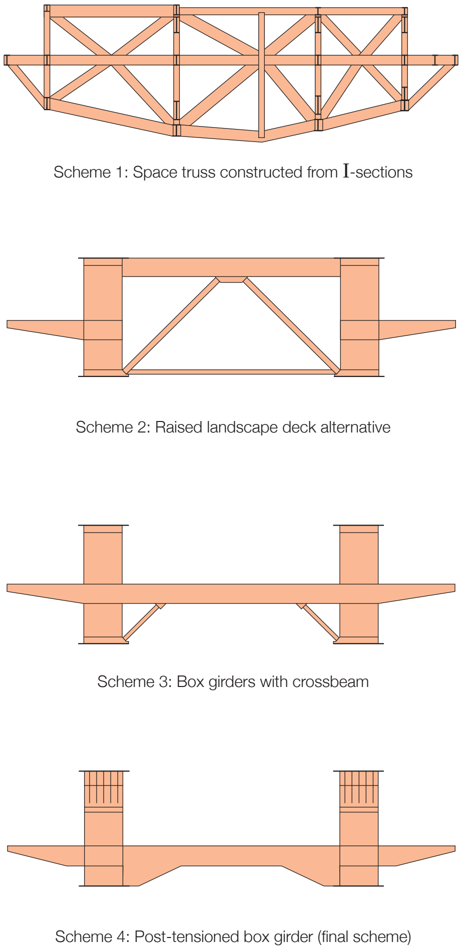
Structural design
The SkyPark consists of a steel frame with composite slab for flooring above towers 1 and 2 (Fig 5). The bridge sections, spanning over 50m between the towers, each comprise three longitudinal steel trusses, with cross-girder beams supporting the composite deck at approximately 4m centres. The central lift cores of each hotel tower penetrate through the SkyPark to provide – in addition to access for users – comprehensive lateral restraint through their connection to the steel structure combined with the diaphragm action of the composite slab.

A major challenge was to cater for the natural movements of the towers upon which the SkyPark was to be supported, and this was met through the design and construction of five distinct joined plates.

The movement joint strategy (Fig 5) was to split the SkyPark into three zones that correspond to the hotel towers, and isolate each portion laterally. The SkyPark elements are fully articulated to allow for differential movement of the towers under gravity, wind and seismic loads, and form the bridge trusses already noted between the towers. While simply supported, the bridge bearings are provided with special ties to hold each deck in place in the event of an earthquake.

Another significant challenge was to formulate a design that allowed for safe and easy erection so high above the ground, and this was achieved through a combination of bridge and building technology. Though the structural form of the SkyPark has more in common with typical bridge structures than with buildings, it was designed to *BS5950*[1] as implemented in Singapore. However, *BS5950* does not include clauses to cover all of the relevant structural checks which had to be carried out. Specifically, it requires that reference be made to *BS5400*: *Part 3*[2] for the design of longitudinally stiffened webs and compression elements, and so the design is referenced to *BS5400-3*.

Additionally, *BS5950* is not expected to cover adequately restraint of compression flanges by U-frame action and design of box girder support diaphragms. To achieve a safe and efficient design, verification of the steel box girder thus follows *BS5400-3* as implemented in Singapore, with modifications of the partial safety factor on design load (γ_{fL}) to *BS5950* and the safety factor on design resistance (γ_m) to *BS5400*.



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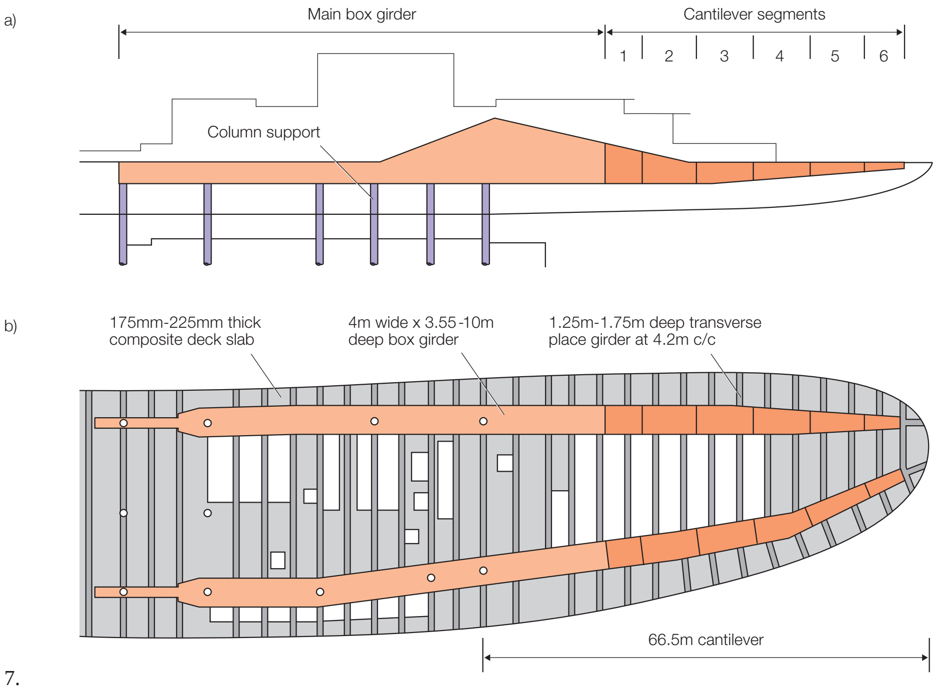

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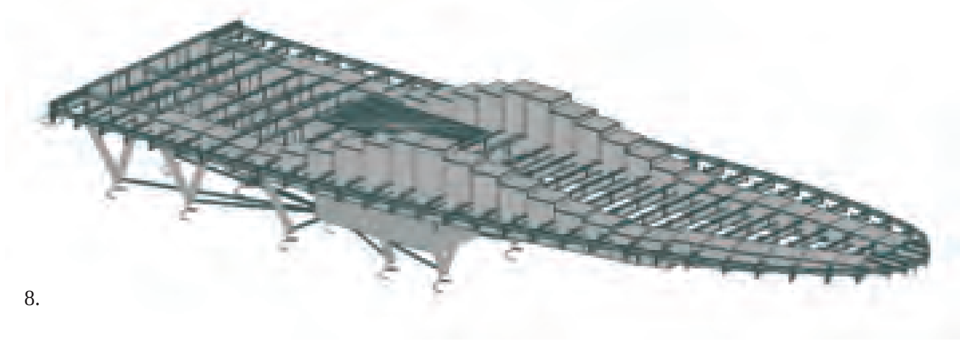

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The cantilever structure
The most challenging aspect to the design team was the cantilever that extends 66.5m and 200m above the ground from tower 3, and much time and analytical effort was spent by Arup's bridge and dynamics specialists to understand its complex behaviour under wind and human excitation (dancing, etc).

The team considered several options for its design (Fig 6), and finally chose a post-tensioned box girder solution. As a result, the cantilever's structure comprises a pair of variable depth box girders with longitudinal stiffeners in both flanges and webs, and intermediate transverse web stiffeners. The maximum depth of the box girders is 10m at the end support from tower 3; otherwise the box girders are generally 3.55m deep (Fig 7).

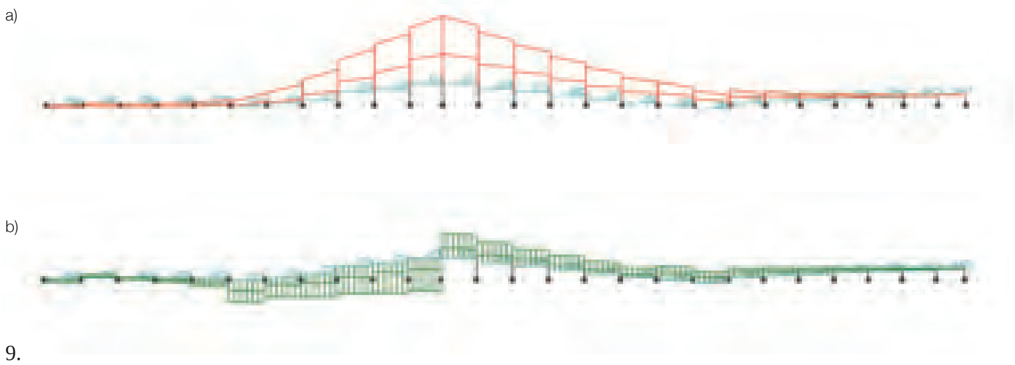
A 3-D analysis model was created in the OASYS *GSA v8.2* program[3] to model the main steel structures over tower 3 and the cantilever (Fig 8), beam elements being used to model the steel girders and the cross-members. For the longitudinal prestressed box girder, the element centre is offset to the centroid of the section such that the bending due to prestress eccentricity is incorporated.

Since a movement joint separates this structure from the bridge section between towers 2 and 3, the bridge section was modelled separately and the reaction force from it put back to this model for further analysis. For simplicity, the upper deck structure also was not included in this model (loading from the upper deck structure is applied as a grid area load on this model for analysis).

To account for the flexibility of the shear wall supporting the SkyPark columns, their supports were modelled as a spring with vertical stiffness equal to that of the shear wall below.

A local finite element model using 2-D plate elements was created using *Strand7* software[4] to determine the load path and local stress at the diaphragm and adjacent web/flange panels (Figs 9, 10).

Crossbeams and transverse stiffeners were also included in this model, while translation and rotation restraints were calibrated with the global *GSA* model. Tendons with prestressed forces were modelled using beam elements and offset from the top flange, and loading at the crossbeams and ends of the cantilever beam were extracted from the global *GSA* model and applied at the corresponding location.



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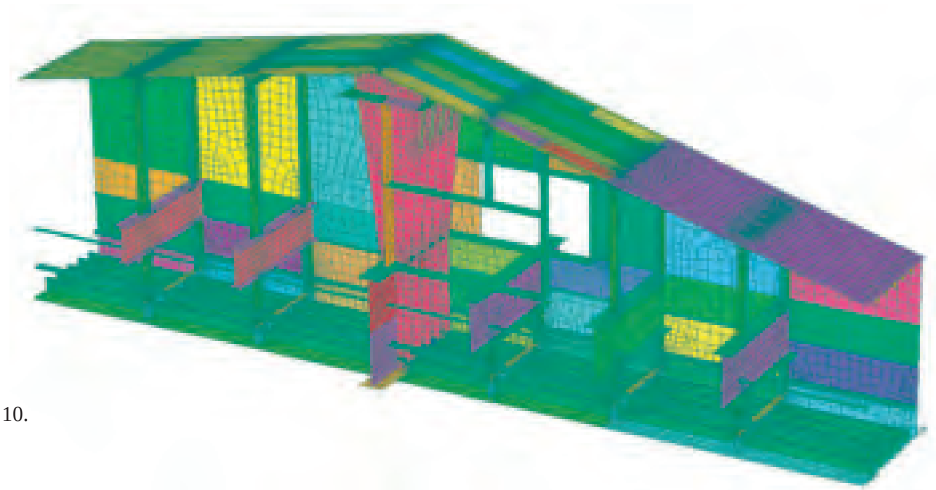

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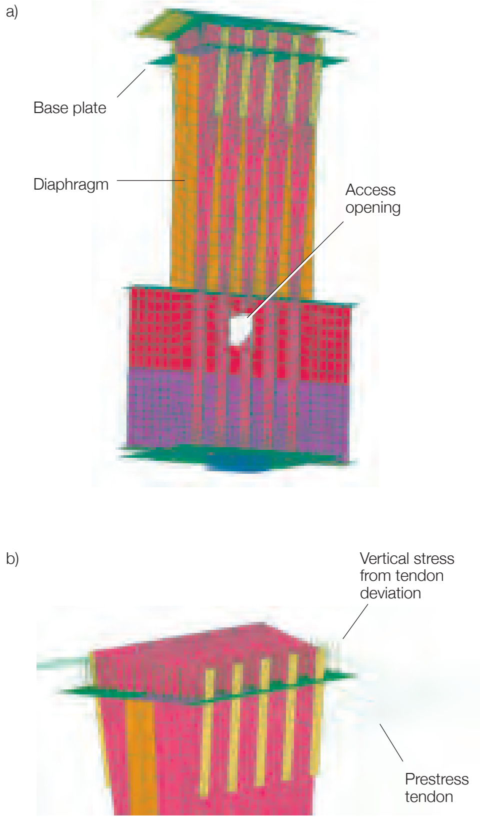

11.

6. Design evolution of cantilever section.

7. Cantilever elevation a) and plan b).

8. *GSA* global model.

9. Ultimate limit state moment envelope in east girder a); shear envelope in east girder b).

10. Isometric of support diaphragm finite element model (near-side web plate not shown).

11. Support diaphragm: Checking of support diaphragm with opening a); relationship between support diaphragm and tendon b).

Dynamic behaviour

A fourth challenge was, as already noted, the dynamics of the SkyPark in response to strong winds and vibration caused by people movement. The structure's dynamic properties were particularly hard to predict as the SkyPark incorporates so many structural elements and architectural finishes, all of which make their contribution. Large tuned mass dampers, acting in a similar manner to shock absorbers, were incorporated within the structure's belly, and large-scale vibration tests were conducted to verify the design.

Using linear dynamic analysis in the *Strand7* program, the team investigated in detail the cantilever's behaviour when subjected to dynamic loads from human activities and wind loads. This finite element model was based on the static analysis model, but incorporated several changes so as to correctly model the structure's dynamic behaviour. To improve the response of the cantilever under dancing crowds, the box girder taper near the tip was reduced, thereby stiffening the second bending mode of the structure. This modification gave a significant improvement in performance for dancing crowds and some reduction in wind load response. The team also advised the client that management control is required for "vandal load" (a small group of highly co-ordinated and vigorous dancers).

The design predictions for the SkyPark's dynamic performance were based on various assumptions in terms of structural properties, the forces applied by people, and the effect of a crowd on the structure. To confirm the performance of the completed cantilever,

12.

13.

14.

a) Bridge trusses.

c) Cantilever sections.

15.

a programme of dynamic tests was carried out on 24-27 May 2010. This included measuring the modal properties of the structure in addition to vibration response measurements of individuals and groups walking, jumping, and dancing (Figs 12-14).

These tests were also intended to give the MBS Operations and other stakeholders the opportunity to experience the vibration levels and comment on their acceptability. All were deemed positive and acceptable, but it was recommended that use of the SkyPark cantilever for dancing events be carefully managed to ensure adequate comfort levels.

Fabrication

Steel plates varying in thickness from 6mm to 150mm were used for the structure. For the cantilever support, 1.2m diameter columns with various wall thicknesses – 30mm, 40mm, 50mm, and 63mm – were purpose-designed. Normalised plates were bent with longitudinal welds to form the column geometry, and were subsequently stress-relieved to meet the design requirements. To pre-empt possible logistical issues, typical segments of approximately 50 tonnes each were fabricated and delivered to site for assembly, and trial assembly of steel girders was carried out to confirm their configuration and geometry.

Erection

Erection of the steelwork for the SkyPark was completed at the end of December 2009. To meet the challenge of the vertical lift, Arup bridge engineering experts contributed ideas from the conceptual design stage onwards. At workshops attended by the design and construction teams, team members comprehensively discussed the method and lifting procedure, along with numerous reviews of the method statement and proposal to ensure safe construction of the SkyPark.

The six bridge trusses (each weighing approximately 400 tonnes), two box girders (each approximately 700 tonnes) and the cantilevered parts (six sections, each approximately 200 tonnes) were all assembled at ground level prior to the lift. Once assembled, each of these 14 major sections was then raised a few hundred millimetres above ground for monitoring purposes, and then the main lift to the top of the tower began the following day. Once it was fully raised, the section was slid into the designated position for final fixing.

At the rate of 15m per hour for each lift, it took almost a whole day for each section to be lifted and placed in position. After each segment was lifted, a five-day interval ensued for fixings between the components, measurements, tightening bolts, touching up paintwork, etc, before the process began all over again with the next.

Special arrangements were required for the main box girders, as the lift was paused at 60m above ground so as to align the eastern box girder to the final orientation. This was due to the shape of the base of tower 3. A movable lifting gantry was fixed at the secondary beams between the main box girders, a method that is normally used in bridge construction for lifting cantilevered elements.

Including temporary steelwork, over 7000 tonnes was hoisted 200m above ground in 13 weeks, a great achievement for both the design and construction teams.

16.

17.

18.

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12-14. Around 120 people at the tip of the cantilever for dynamic testing.

15. Erection sequence of the 14 major sections.

16. Erection of bridge truss.

17. Erection of box girders.

18. Cantilever under construction.

19. Completed Sands SkyPark (overleaf).

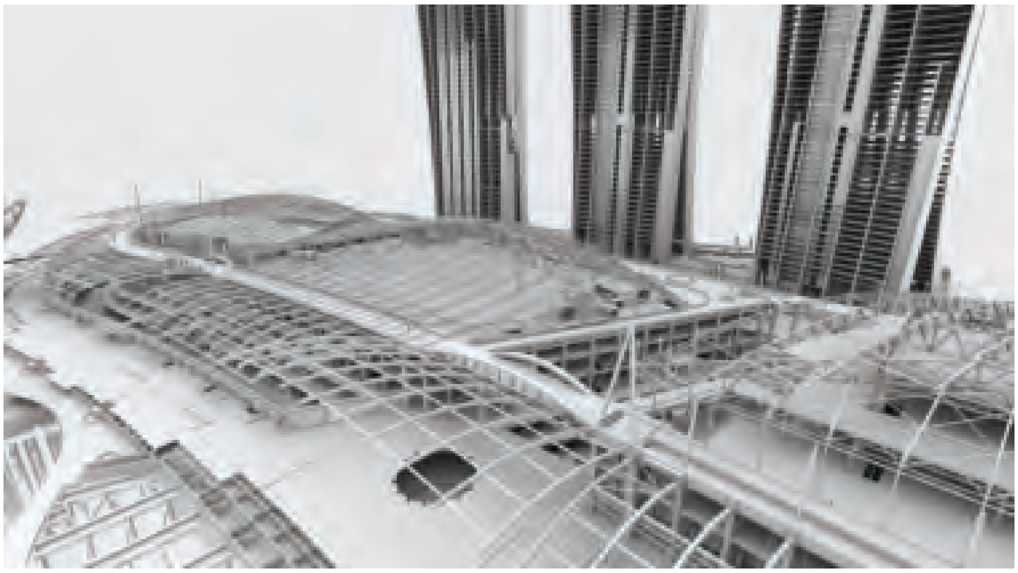
Sands SkyPark facts:

- 340m long from the northern tip to the south end
- maximum width: 40m
- 66.5m long cantilever (application to Guinness World Records in process)
- public observation deck at RL 295, 191m above ground level
- highest public area at RL 299, 195m above ground level
- 7692 tonnes of permanent steelwork
- 4413 tons of temporary steelwork used in construction
- 146m long infinity edge to swimming pool
- three pools containing 1.42M litres of water
- 500 trees up to 8m tall, selected for hardiness and suitability for the constant breeze at the SkyPark elevation
- 2200m^3 of soil, weighing 3300 tonnes
- estimated weight of aluminium hull cladding: 350 tonnes
- total weight of lifted sections for cantilever: 2600 tons
- heavy lifting gantries: 1905 tons
- length of strand cable used in strand jacking operations: 77km
- heavy lifting of 14 segments completed in just under 13 weeks
- approximately 200 tons of bolts used in steelwork.

19.

The podium

1.



2.

The podium roofs

Author
Juan Maier Brendon McNiven

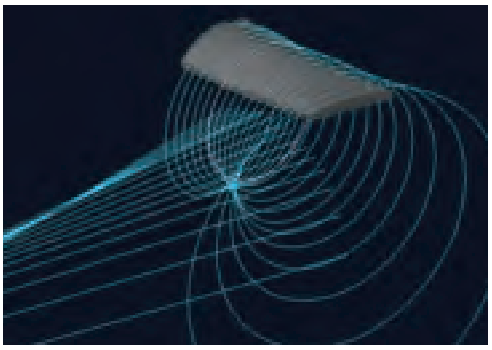
Introduction
Technically challenging like every part of the Marina Bay Sands development, three separate long-span roofs enclose the podium buildings: the casino, the theatres, and the state-of-the-art Sands Expo and Convention Center (MICE facility) (Figs 1, 2).

The roofs span up to 120m and have highly individual, stepped, wave-form surfaces. In addition, the retail arcade that extends along the western side of the podium is sheltered by lightweight steel canopy structures, cable-stayed back to the concrete podium. Erection of the roof steelwork commenced in April 2009 and was completed by the end of that year.

Design of the podium roofs
The podium roofs have highly complex geometries, the fundamental elements of their form and shape being based on Euclidean geometry, such as how arcs are derived from toroidal surfaces. The architect cleverly pushed and pulled these seemingly independent geometries together into an overall form that appears to be vastly more complex than the sum of its original components (Fig 3). The concept of using developable geometry was very important to the design team, not only for enhancing understanding of the structure, but also to help its constructability.

Supporting the greatest surface area of each of the three roof structures is a spine truss, curved in elevation and in plan. Over long spans, the latter can induce large overturning moments, but this effect is efficiently combated by the rotational stiffness of the secondary roof trusses connected either side.

These are 2-D planar in nature and, with spans of 120m maximum, vary in depth from 4m at the springing points to 8m at their centres. The span lengths were finely balanced between the architect’s desire to



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1. Plan showing those elements of Marina Bay Sands that are covered by the podium roofs and canopies.

2. Structure of the roofs and canopies.

3. Roof geometry developed from surfaces of a torus.

4. Stability of spine truss.

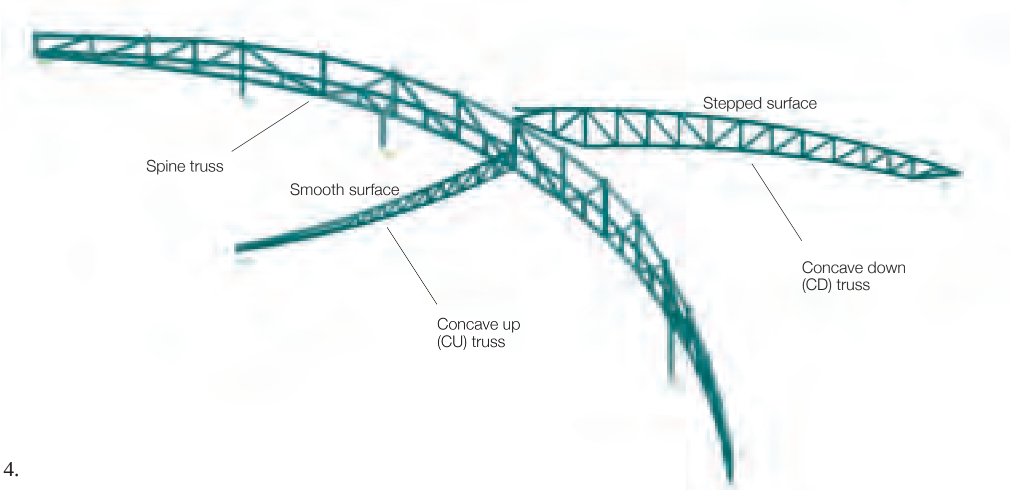
5. MICE facility roof under construction.

maximise clear span openings and the need to maintain an efficient structure. To match the building form, all the roof trusses are curved in elevation, "concave up" (CU) to the west of the spine truss, and "concave down" (CD) to the east (Fig 4).

Lateral stability is maintained by forming a continuous diaphragm plane of cross-bracing along the CU side. On the CD side, which features the stepping wave form surface, a continuous line of bracing could not be established, so various patterns were investigated for optimal lateral stability. Since the continuous diaphragm on the CU side provides most of the roof's lateral stability, an efficient bracing pattern for the CD side could be achieved by limiting the bracing to every second bay with only discreet fly-bracing members stabilising the unbraced bays back to the braced bays.

Steel section sizing was rigorously optimised, with the aim of minimising the roofs' total self-weight and thus the total cost of structural steel, while still complying with *BS5950*. This was accomplished by writing customised software, linked directly with Arup's in-house structural analysis platform *GSA*, that firstly read the forces and moments of every element in the analysis model, then calculated the utilisation ratio of the elements, and finally evaluated the element's utilisation ratio based on predefined acceptance criteria. If the element did not fall within the acceptance range, the program selected a new section size for it from a predefined pool of section sizes.

This process was reiterated until all the elements fell within the acceptance range. Using this program had the added benefit of helping to automate the analysis and design. For example, the 10 000+ elements of the MICE roof analysis model would have been close to impossible to design using traditional methods.



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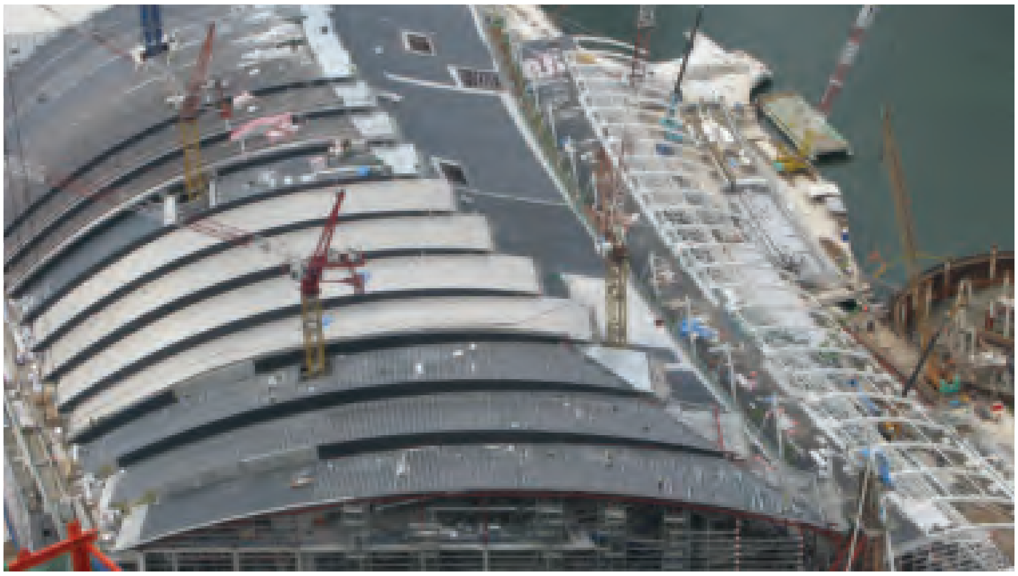

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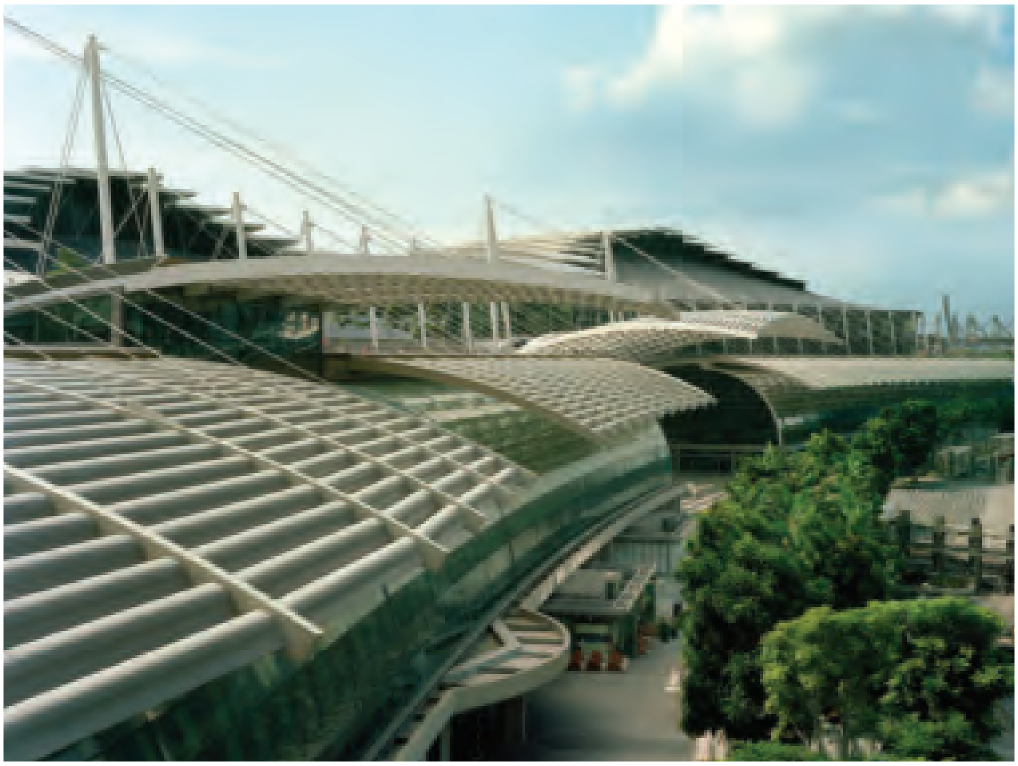

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The canopies
The lightweight, tension-stayed canopies (Fig 6) are also geometrically complex and doubly curved. Fabricated steel box rafters, up to 1m deep, form their ribs, with RHS cross-members running transversely to provide lateral stability through moment-frame action. The rafters are in turn supported by tension stays from a system of *Macalloy* bars and carefully placed tall tubular masts. The largest canopy is nearly as large as a soccer pitch, measuring 45m x 90m in plan.

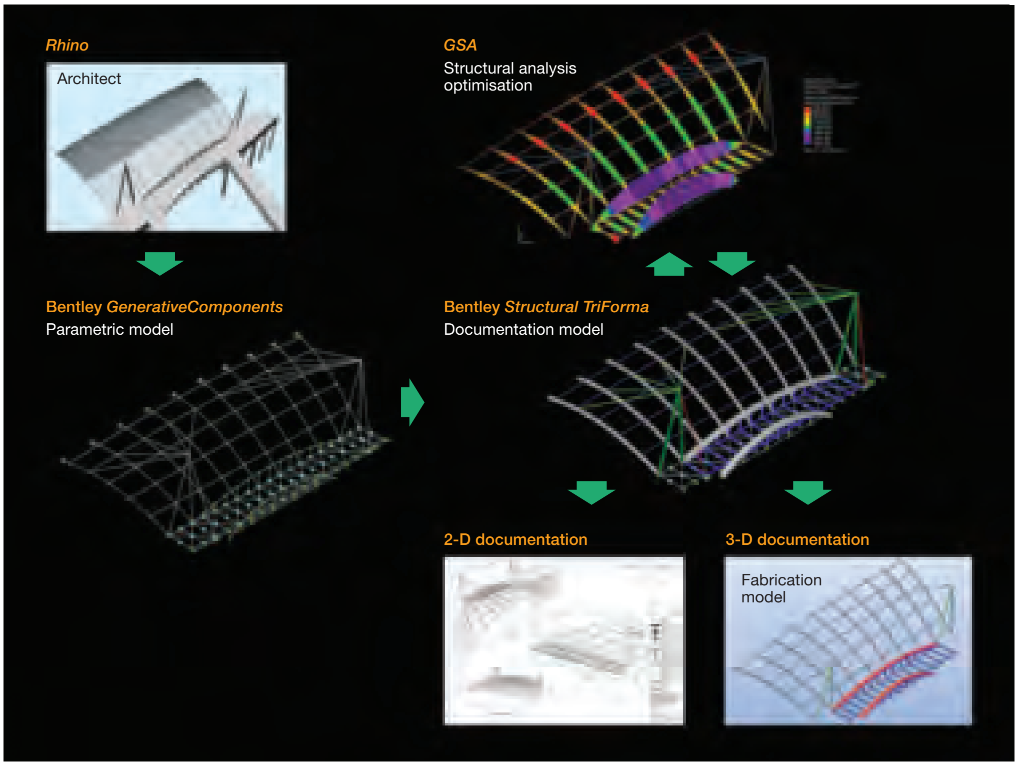
At three locations along the retail promenade, the canopies are linked by pedestrian footbridges of varying lengths. These are double tied arches, spanning up to 70m over the concrete podium structure. Their design was complicated by being curved in plan; the tied arches on either side of each bridge have different spans, thus creating differential stiffness across the deck.

Since the canopies are extremely light and flexible, they tend to exhibit non-linear behaviour, so elaborate analyses were carried out. First, a full second-order non-linear analysis of the structure was undertaken, and then used in combination with a custom-built software program, written specifically for these canopies. It iteratively determined the required pre-tensioning level of the *Macalloy* bars so that under full dead and superimposed dead load, there would be no net downward deflection at the points where the tension stays connect to the rafters. The non-linear analysis model also considered slenderness effects, and adjusted the elements' stiffness in the model based on the axial loads they attracted, thus permitting elastic buckling behaviour to be observed.

Secondly, the team undertook a full buckling analysis of all the critical load cases to determine the buckling load factors and corresponding buckling mode shapes. These shapes could then be correlated to a set of initial imperfections in the canopy structure so as to determine moment amplification factors and apply them to the results of the earlier non-linear analysis, so as to evaluate the structure's susceptibility to buckling. The amplification factors used were inversely proportional to the buckling load factors and directly related to the magnitude of initial imperfection represented by the buckled mode shapes.

3-D integrated design and documentation
An innovative aspect of this project was the integrated use of 3-D modelling in all facets of design, analysis and documentation. Early in the design, Arup began an open dialogue with shop detailing firms and fabricators to obtain best practice advice on preferred detailing and fabrication processes. The team produced full 3-D models of the steel structures as a basis to beginning a shop drawing model that would later be issued as part of a construction set of documents to the appointed fabricator/contractor. This same model was used for the analysis, design and documentation of 2-D drawings, and for co-ordination and collaboration with the architect and other consultants. All this was critical, as it would have been nearly impossible to develop, analyse/design or build structures with this level of complexity with only 2-D documentation (Fig 7).

Parametric modelling was also used to great advantage, especially during design development. Software such as Bentley's *GenerativeComponents* enabled the roof structures to be modelled with predefined variables to allow for future modifications where necessary. This parametric model could then be integrated into the 3-D design and documentation to permit rapid modification of the geometry. With the parametric relationships already set up, the new geometry could be easily incorporated into the existing structural analysis model. Any resulting changes in member section sizes, along with the new geometry, were



7.

directly translated into 2-D and 3-D documentation. This innovative workflow saved much time in redrawing the model each time a modification, either small or large, was made.

Fabrication
In addition to the head start the fabricators gained in their shop drawing workflow process from the 3-D models, Arup also prepared a schedule of both open and closed section profiles for each of the members in the podium roof structures (ie I-section vs circular hollow section profiles). Fabricators could then choose the best profile type to maximise cost-effectiveness, procurement strategy, lead time, and fabrication process. For the complex doubly-curved spine trusses, the fabricators preferred hollow section profiles to open I-sections. Conversely, for the planar 2-D CU and CD trusses that only curved in one direction, they favoured open I-section profiles as being less expensive and having shorter lead times than hollow sections.

Given the extremely complex 3-D geometry, innovative custom jigs were needed to properly and accurately fabricate the components. For the canopy structures, the masts required precise setting out so as to accurately define the 3-D location of their top and bottom points. A vertical custom jig permitted fit-up welds to align the masts, followed by sequence welding to complete the sections. Additionally, the complex geometry also required special compound and profile cutting of sections, heavy bending of tapered or curved members, and implementation of cross stiffener plates through boxed up sections.

To meet the fast-track construction programme, 24-hour/day fabrication was implemented, with continuous shifts of dedicated fabrication manpower. These included engineers, supervisors, fitters, welders, grinders, and QA/QC, NDT (non-destructive test) and ITA (independent inspection and testing agency) personnel. All of this helped to achieve the highest possible quality in the final product.

Erection
The fabricators spent much time pre-planning every work phase, so that the segments comprising the structure were as easy as possible to handle, store, transport, and install. They studied all possible site access, storage space and cranage capacity before deciding how the segments would be sized, and transport companies were consulted over delivery routes that might limit their dimensions. All were trial-fitted at the factory, as well as any adjustments or modifications so as to save time during erection and installation. The cranes' size and capacity were predetermined, and checks made on crane parking locations to ensure adequate capacity during lifting. Lifting lugs were pre-welded to segments in the factory after determining the lifting points from the segment's centre of gravity.

This greatly saved time during erection as it avoided the need to find the centre of gravity by trial and error on site. Erection clips, to ensure the segments were aligned and fitted precisely together, were also pre-welded on to reduce erection time, and bolted connections were used wherever possible. Where welding was required, it was greatly speeded up through the use of FCAW (flux-cored arc welding). This needs only limited protection in windy environments – a major concern at locations near the sea.

6. Completed canopies.
7. 3-D design process.
8. Tubular mast being fabricated.


8.

On repetitive areas of steelwork like the canopy structures, custom assembly jigs were used to temporarily support the rafters and masts (Fig 10). These enabled the structure to be assembled, fitted up, bolted and welded into position. On de-propping, they were shifted to the next location.

Careful alignment of the canopy structures was also required. As these are highly flexible, the length of the tension stays had to be precisely calculated so that during erection the canopies could be installed (unloaded) to a level higher than their final level. Later, they would deflect with the added weight of roof cladding and finishes, and the whole structure settled into its final position. Canopy levels were adjusted through detailed survey and use of tension stay turn-buckles.

In addition to cranes, electric winches were also used to speed up work. These are light and easy to handle, and can lift up to 2 tonnes. This greatly reduced erection time, alleviating the need for constant reliance on cranage.

Work safety and health officers and safety co-ordinators were deployed throughout the site to ensure a safe working environment. Risk assessments were carried out before work began, as well as safe work procedures and safety management systems.

Temporary works design was also carefully reviewed and endorsed by qualified Professional Engineers. Strict and close supervision throughout construction ensured safe completion of the works.

9. Canopy in front of The Shoppes arcade.

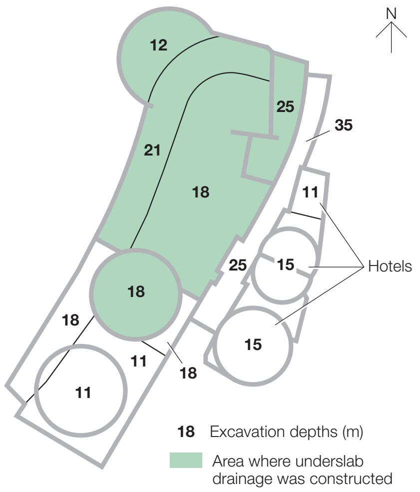
10. Temporary jig supporting canopy rafters.

10.

9.

Podium underslab drainage system

Authors
Otto Lai Wing-Kai Leong



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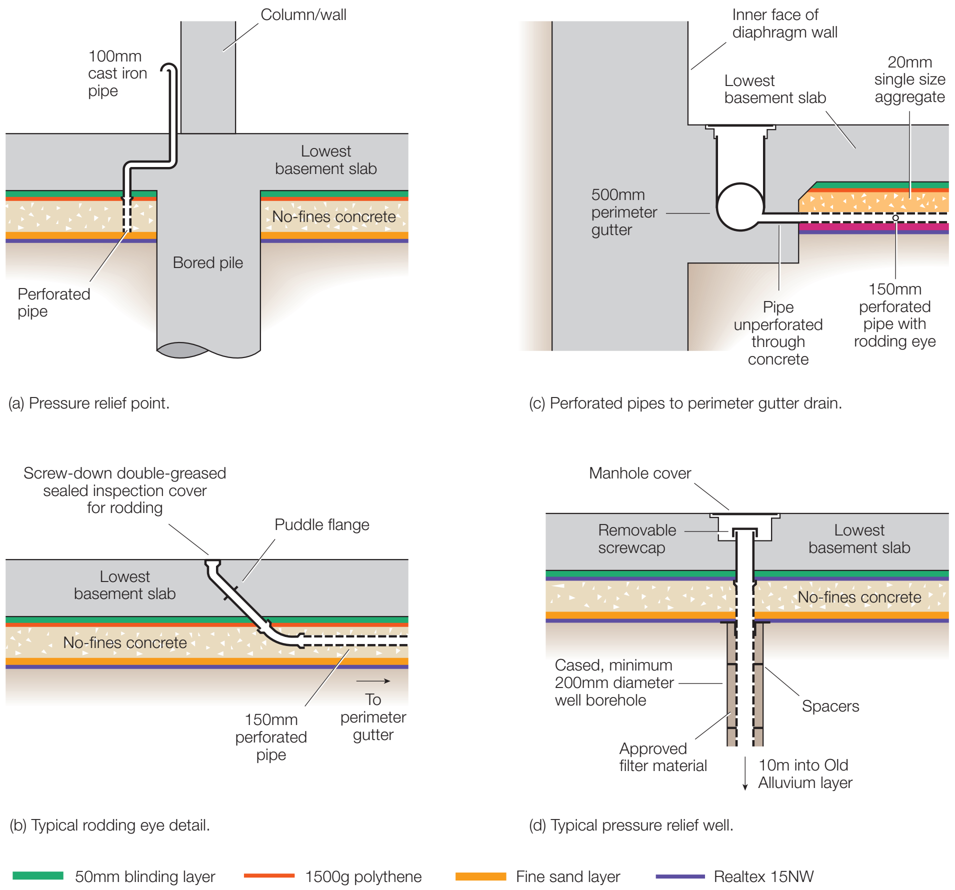

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1. Underslab drainage location plan.

2. Sub-systems forming the underslab drainage system.

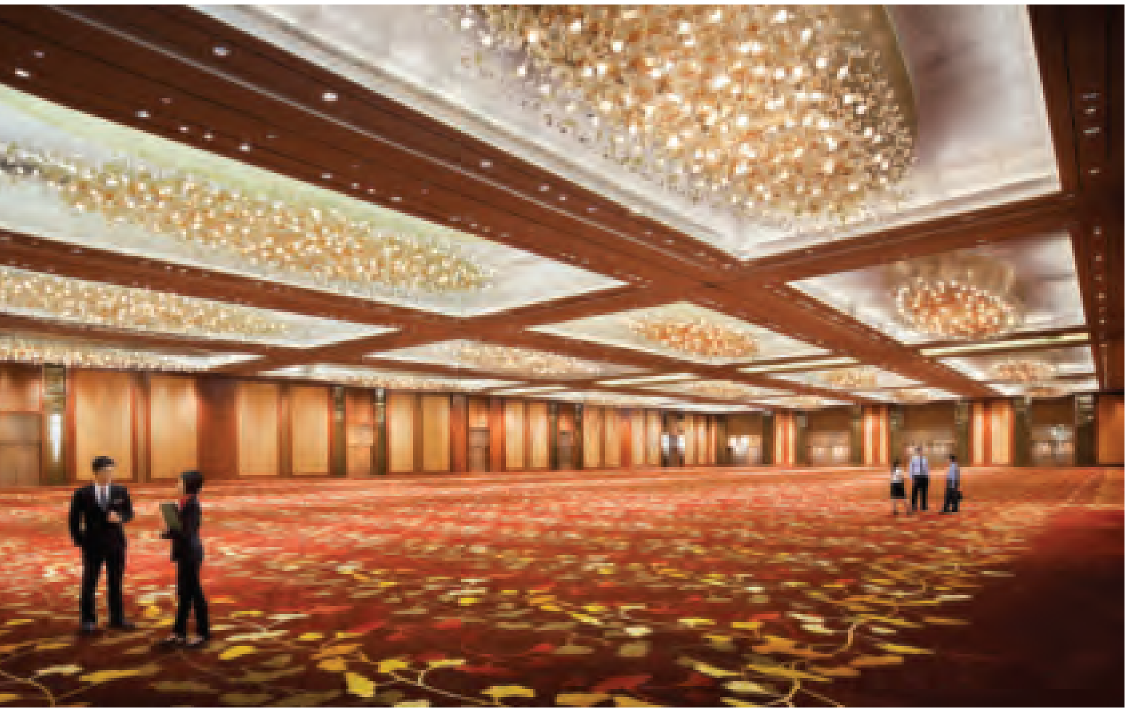
The underslab drainage system was designed to relieve the lowest basement slabs of uplift water pressure, and thereby negate the need for hold-down tension piles. The system was installed in part of the south podium (the north donut beneath some of the MICE facilities), the north podium, the ArtScience Museum, and the DCS (district cooling system) area (Fig 1). The differences in excavation depth are due to the range of basement levels across the site. The MBS drainage system as constructed is the largest of its type in Singapore.

The system typically comprises a drainage blanket formed of 20mm single-size aggregate, perforated pipes, perimeter gutter drains, piezometers, sump pumps, and pressure relief wells (Fig 2). The seepage groundwater collected by the system is discharged into the public drainage system outside the site.

Normal maintenance is expected to keep the system in full working order. Should part of the underslab drainage system malfunction, however, the pressure relief points (Fig 2a) local to the affected area will automatically overflow, alerting the owner to the problem before any structural damage occurs. Flushing of the system by way of the rodding eyes and the pressure relief wells would be carried out to restore the system its full capacity. In the worst case scenario, localised remedial works may be required.

Sands Expo and Convention Center

Authors
Don Ho Otto Lai



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Background

The Sands Expo and Convention Center is the southernmost element of the whole Marina Bay Sands development.

More commonly known to the design team as the meetings, incentives, conference and exhibitions (MICE) facility, it can host up to 45 000 convention delegates in total, its space able to accommodate a maximum of 2000 exhibition booths and 250 meeting rooms. It can thus handle events of any size, from an intimate meeting for 10 persons to lavish presentations for up to 11 000 people. The largest and most flexible meeting and exhibition venue in Singapore, it contains south-east Asia's biggest ballroom (Fig 1)*.

The gross area of 120 000m^2 is spread across five floors plus mezzanines, all of which sit atop five more basement levels. The gigantic footprint, 240m x 140m, makes it the most extensive single building of the entire MBS development in terms of land area occupied.

Timing

Fronting the coastal area of the development, MICE was required to be one of the first MBS facilities to become operational, despite being one of its largest. The stipulated schedule for opening Phase 1 meant a very limited construction time, beginning in early 2008 and extending to the end of 2009 in time for the opening.

The main floors were therefore designed with composite slabs on long-span steel frames, the use of this "propless" scheme allowing construction work on several floors to be carried out in parallel (Fig 2). This design also minimised the manpower needed on site. This was an important consideration, as on-site manpower requirement is a major factor in a country like Singapore which imports a lot of foreign labour to service its construction industry.

* The original competition entry scheme promised the largest ballroom in Asia. Part-way through the design, a bigger one previously overlooked was discovered elsewhere. The plans for the new ballroom were promptly updated and enlarged to ensure that the development delivered on its earlier competition-winning promises!

Foreign labour content is managed by the government through the enforcement of strict quotas on construction sites.

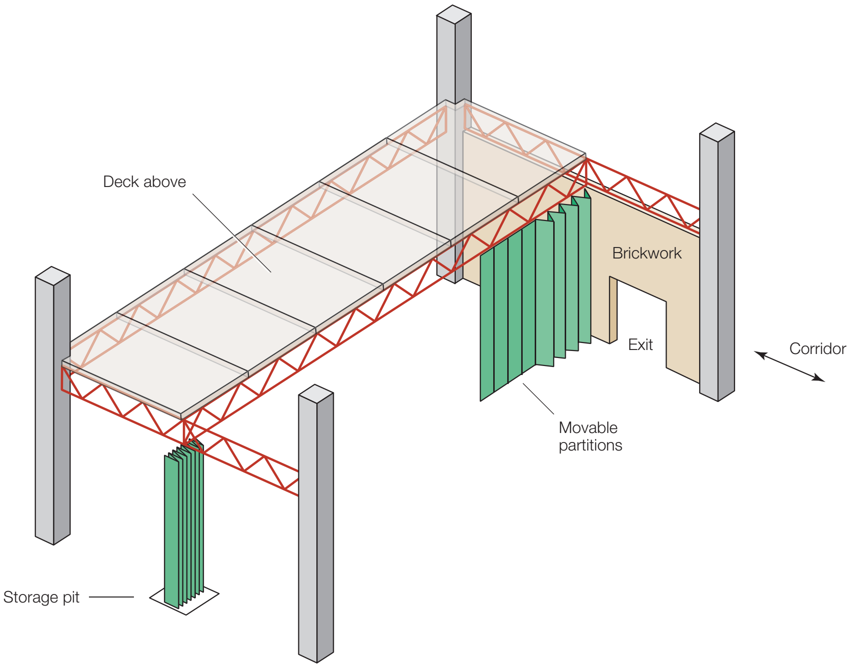
Necessarily, design time was also limited, extending from the outset of the project to mid-2009, but by running the design and construction phases in parallel, the Arup team innovatively re-engineered the conventional design cycle. This enabled the principal structural elements to be put in place when only the preliminary architectural design was ready, as one of the major uncertainties during the structural design phase was the placement of the massive moving partitions for the convertible meeting rooms.

Instead of applying an unnecessarily conservative design load, the Arup team recommended the architect to orient the opening directions of the movable partitions to the gravity load paths of the structures, with each partition's storage pit located on a main truss spanning between columns (Fig 3). This arrangement allows for a high degree of flexibility, yet ensures that the designed condition with distributed wall loading is the most critical loading condition among the numerous operational combinations.

Efficiency

As it was such a major element in the whole MBS project, MICE naturally contributed a very considerable portion of the total cost. This being the case, only a slight variant in the efficiency of the MICE structural design could have significantly affected the overall budget.

So as to make the best use of materials, the team carried out an advanced, non-linear, elastoplastic, large displacement analysis with consideration of the static construction sequence. This analysis reflected the most realistic structural response by considering the lock-in stresses from construction and the redistribution of forces through yielding and buckling (Fig 5). Fig 6 shows the formation of plastic hinges in a typical bay under the designed ultimate loading.



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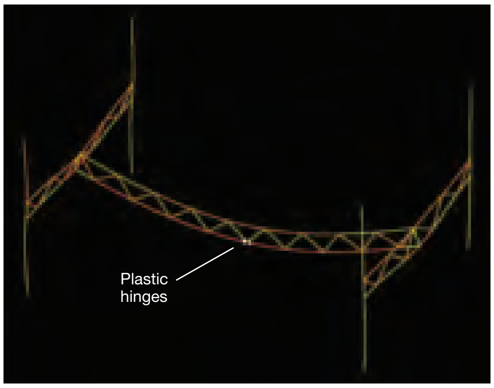

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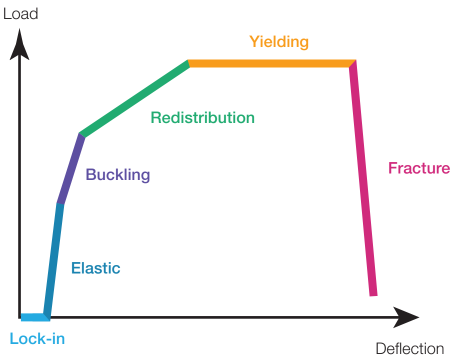

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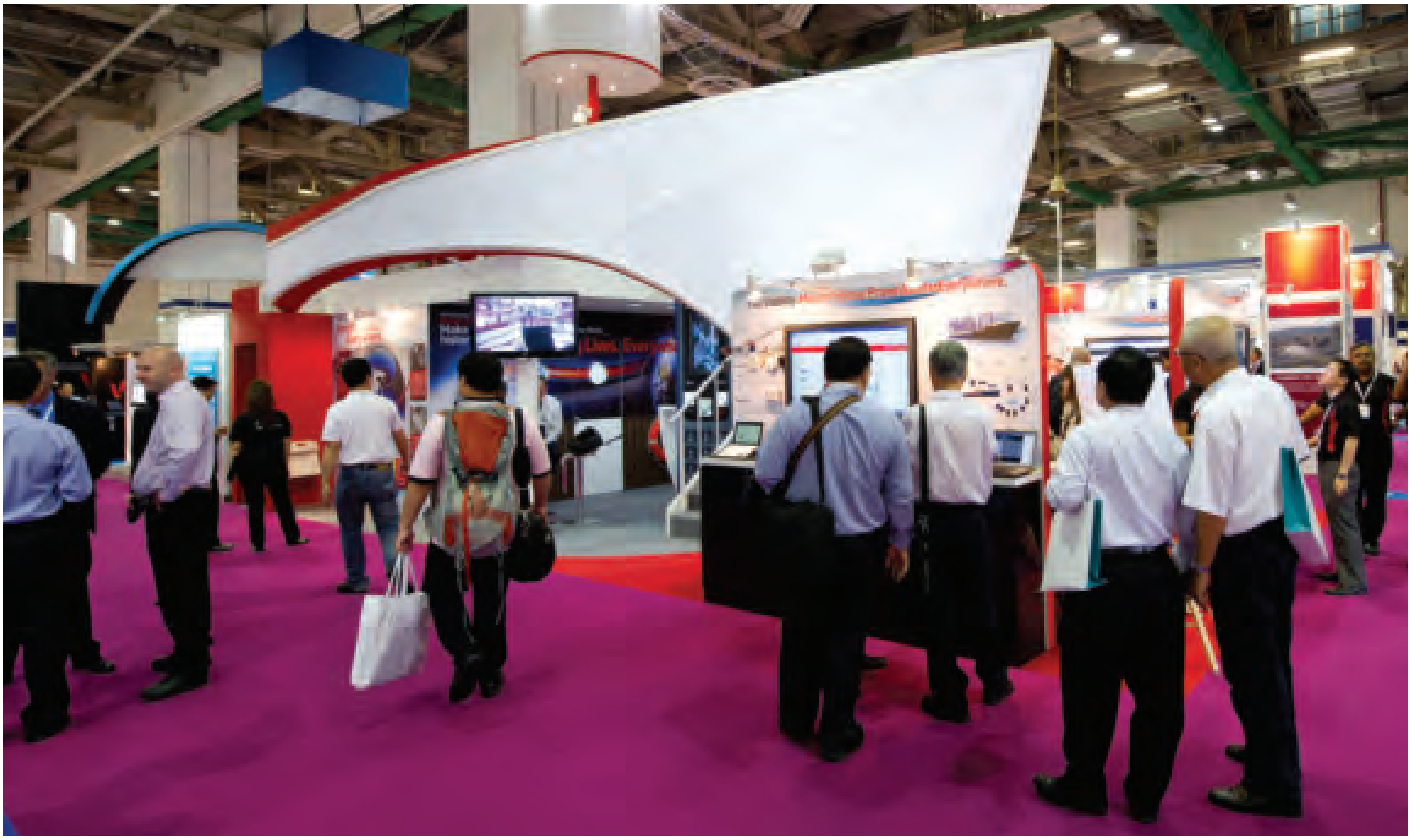
1. The main ballroom.
2. Construction work for MICE under way in late spring 2009.
3. Typical framing.
4. Pre-function area.
5. Illustration of typical load-deflection relationship.
6. Formation of plastic hinges.



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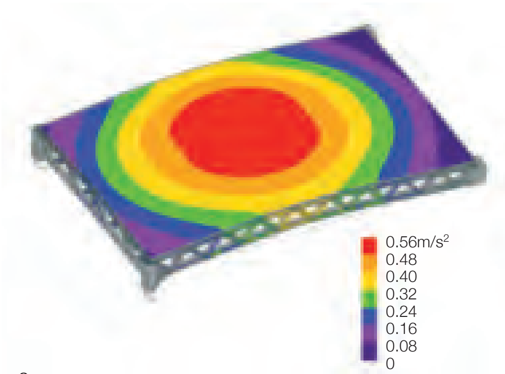

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7. Trade show in progress at the Sands Expo.

8. Peak acceleration of typical bay under extreme “social dance” conditions.

Comfort

Vibration is inevitable in flexible, long-span structures if they are to be economically feasible. To ensure that MICE is a first-class conference facility, the Arup team had to carefully study the structural factors involved in ensuring occupant comfort under human-induced vibrations.

Conventional footfall vibrations resulting from individual unco-ordinated actions contribute hardly any significant movement to such a massive long-span structure, but the size of the grand ballroom meant that slab movement caused by the synchronised actions of large groups of dancers could cause concern. Factors like crowd patterns, dance styles, music rhythms, and the effects from transfer structures were all studied.

Fig 8 shows the typical vibration response of the ballroom floor under an extreme event of 500 people doing synchronised dancing at the critical frequency in a typical 33m x 18m structural bay. The predicted dynamic performance was verified by direct site measurements, together with feedback from participants.

This analysis convinced the Arup team that the structure would perform appropriately for the nature of the facility, with very limited noticeable effects on occupants from structural vibration.

The team also gave recommendations to the client on precautions for possible comfort concerns if the facilities were used for any unusual events.

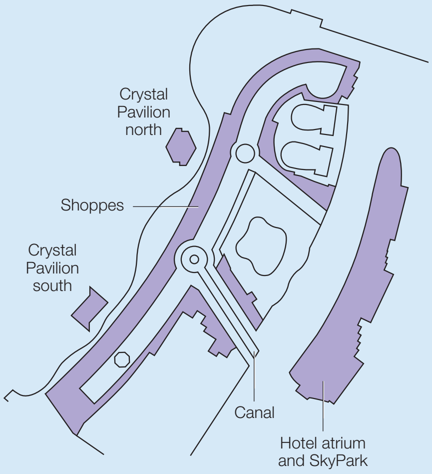
Conclusion

Given the scale of the MICE facility within the whole development, the Arup team applied best practices to enable such a demanding megastructure to be constructed within the tightest time-frame and to the most stringent budget.

Through close co-operation between designers from different offices and disciplines, the whole team put forward its utmost efforts for the successful completion on time of this world-class conference and exhibition venue, which forms an vital component in the grand development of Marina Bay Sands.

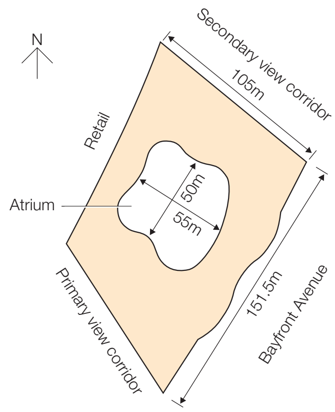
Retail areas

Most of the MBS buildings include retail areas. The largest of these – “The Shoppes at Marina Bay Sands” – includes over 300 stores plus food and beverage outlets along the whole north-south length of the podium. A canal runs through the Shoppes, similar in style to the one at the Las Vegas *Venetian*, with sampan rides for guests corresponding to the gondola rides at the *Venetian*. As well as the retail areas, the development has many places to eat and drink, including several celebrity chef restaurants, some located in the Sands Hotel atrium and the SkyPark. Two internationally-renowned nightclubs and a flagship store for Louis Vuitton are housed in the Crystal Pavilions.



The casino

Authors
Otto Lai Patrick McCafferty



1.

Overview
The casino is housed in the middle of the three major buildings on the podium, lying between the MICE facility to the south and the theatres to the north. Its four-storey reinforced concrete structure is supported by diaphragm walls and bored piles, and the building also includes five levels of basement. The casino is immediately bordered by retail areas to the west, by the primary and secondary view corridors on the south and north sides respectively, and by Bayfront Avenue to the east (Fig 1).

Lateral stability is provided by frame action between the columns and beams; this enabled large open spaces and flexible space usage without having to change the positions of walls when programming the use of the spaces. The large atrium in the middle of the casino required floor openings up through four levels, and this continuous large vertical void in the floor diaphragm had to be taken into account when designing for lateral stability (Fig 2).

The floor-to-floor heights in the casino itself were different from those in the immediately adjacent structures, due to the need for higher headrooms there, and so the B2M level was introduced as the main gaming level with most of the level B1 in the ancillary areas being deleted. This, however, made connections into the adjacent structures difficult and also created headroom issues. Beam depths had to be co-ordinated carefully so as to fulfil the headroom requirements, with atypical connection detailing being needed.

The amount of light emanating from above alone would have been inadequate for the large B2M gaming area below the atrium, so individual trellises, designed by Arup, were provided at each gaming table, containing surveillance cameras and loudspeakers in addition to local lighting (Fig 3).

Level 4 at the top of the building houses the mechanical systems for the entire casino, while levels B3 and B4 are used for vehicle parking as well as to house the tanks for potable water and for fire-fighting (another part of Arup's commission was the fire engineering design – escape, smoke control and fire compartmentation: see also the article on the fire engineering, pp68-71).

Construction
The original proposed construction sequence was top down from level B2M, enabling the basement levels to be built at the same time as the superstructure. Foundation construction began in 2007 and was completed in 2008, with "plunge in" columns cast into bored piles that extend 40m into the Old Alluvium layer.

After level B2M was cast, however, the construction sequence was changed so as to expedite the reinforced concrete works. The top-down construction below level B2M was revised to allow for excavation to level B4/B5 and level B3 constructed later.

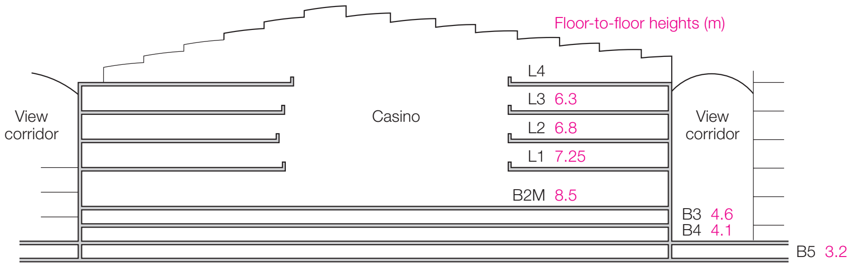
Deviation of the "plunge in" columns had to be initially considered on level B2M, and consequently at level B4 once excavation had reached that level, and again at level B3 after formwork was carried out to that level. Pile deviation was considered at level B4, once piles were exposed and cut to correct cut-off levels.

Also, to increase speed of construction, single and double T-section precast units were employed for the flooring. The building had to be completed in time for the planned "soft" opening on 27 April 2010.

The casino chandelier
Composed of an intricate weave of high strength cables suspended from an undulating perimeter steel compression ring, the feature chandelier high above the main gaming room of the casino supports a network of 16 500 LED lights and over 130 000 precision-cut *Swarovski* crystals. With a footprint of 520m^2 and measuring approximately 24.4m across and over 6m deep, this signature piece is one of the largest installations of its kind anywhere in the world, nestled snugly between the finished ceiling above and a series of decorative ceiling ribs below (Fig 3).

Given the compressed construction schedule of the project, the casino roof was erected and the ceiling ribs were being fabricated before the final configuration of the chandelier had been established by the architect. Arup was thus tasked with form-finding the fabrication geometry of the chandelier cable net and of analysing the complex buckling behaviour of the chandelier's compression ring to within extremely tight tolerances.

Arup's in-house non-linear structural analysis solver, Oasys *GSA GSRelax*, was employed for the many hundreds of millions of non-linear analysis iterations required to establish a fabricated geometry that, once installed, would drape to within exacting tolerances between the finished ceiling above and the decorative ribs below.
Once an acceptable geometry was thus determined, a suite of non-linear buckling analyses of the perimeter compression ring were then conducted to investigate the ring's robustness against buckling forces induced by the cable net, establish an appropriate system of lateral restraint from the casino roof to the ring, and enable final design and detailing of the ring and its support system.



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1. Plan of the casino building, enclosing the irregularly shaped atrium.

2. North/south cross-section through casino showing levels.

3. Casino interior, showing the chandelier centrally placed to illuminate the atrium gaming area.

3.

1.

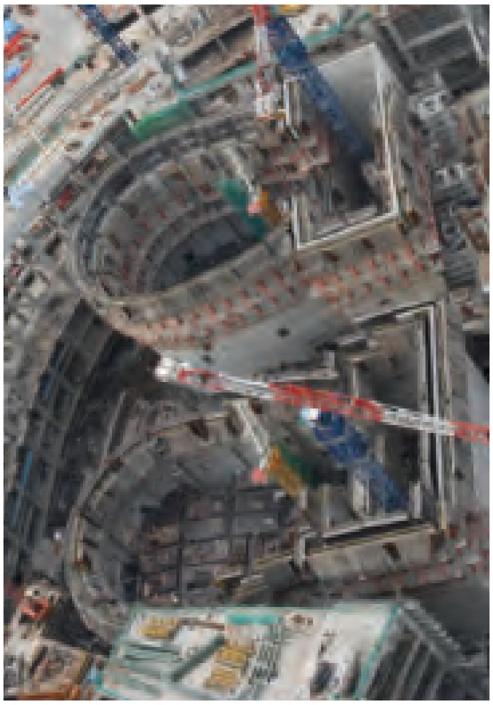
Theatre structures

Authors
Otto Lai Brian Mak

Introduction
The Marina Bay Sands development includes two fully-equipped proscenium theatres. The Grand Theater has a seating capacity of 2139, and is designed for show-based entertainment ranging from popular acts and concerts to special touring events. The slightly smaller Sands Theater (Fig 1), seating 1679, offers a different kind of theatrical experience, where Broadway-type shows are performed.

The two theatres are located side-by-side in the north-east area of MBS (Fig 2). They have two entrances, one facing the grand arcade node and the other Bayfront Avenue, and they share a lobby, which provides for easy flow of pedestrian traffic before and after performances as people move to the ArtScience Museum, the grand arcade and waterfront promenade, as well as to the casino and the hotel.

"Box-in-box" structures
Arup's design for the structure of the theatres was basically a conventional "box-in-box" reinforced concrete frame, so as to provide the greatest flexibility for construction (Fig 3). The external box is formed by the podium structures and the basement walls, which provide overall



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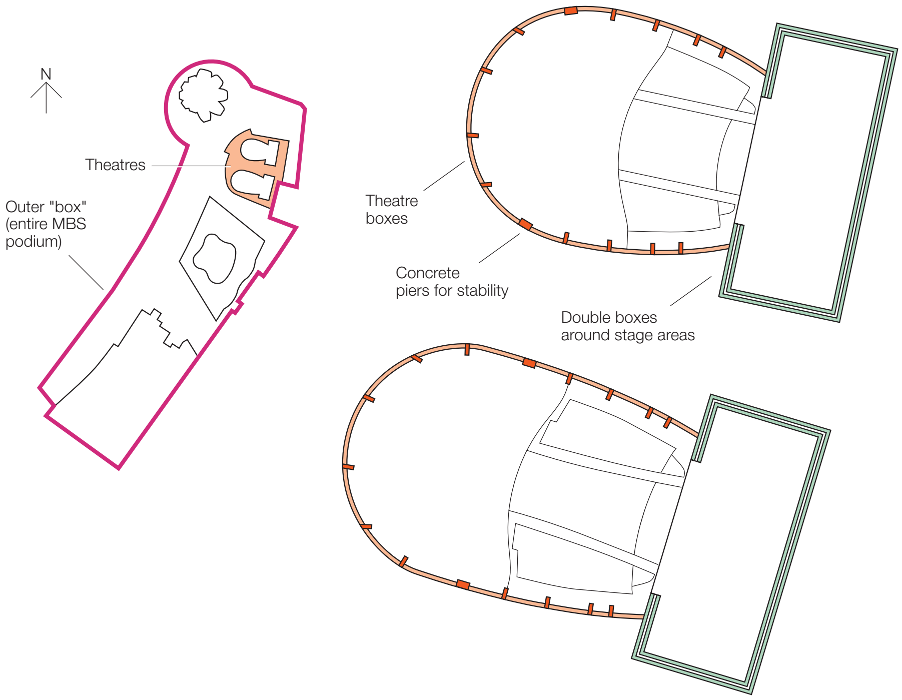

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1. Interior of the completed Sands Theater.

2. Theatre shells under construction. The structures were built between April and December 2009.

3. The "box-in-box" structural arrangement, showing the additional double box surrounding each stage area and the positions of the concrete piers.

4. Cantilevered steel balcony.

5. Concrete piers for temporary stability.

4.

5.

stability for the theatres against soil load. The internal box is a reinforced concrete shell for each theatre defining its shape. The internal box transfers all gravity loads from the theatre to the ground, so that any modifications to the internal theatre layout involved only checking gravity load, and did not affect the external podium structures and basement walls.

The acoustic benefits of box-in-box construction are significant. One is that a decoupled inner and outer structure reduces the transmission of vibrational energy that could reradiate inside the theatre as airborne noise. Another is that the resilient air space between boxes greatly improves sound isolation from exterior noise. So as to limit transmission of outside noise and vibration into the theatres, and of internal noise and vibration from them into surrounding areas, additional double structures with a minimum 50mm cavity between them were provided at the interface between theatre stage and surrounding structure (Fig 3).

Theatre construction

Internally the Grand Theater and the Sands Theater are very similar, each containing a partially raked auditorium floor and one balcony. The balconies are steel cantilevered frames (Fig 4) with concrete decks for the seating, while at the top of each building beneath the curving roof (see pp32-36) is the 150mm thick composite slab that comprises each theatre's level 4. This accommodates the MEP plant room, and is supported by 3.5m deep steel trusses.

Construction of the theatres was undertaken "outside-in", the concrete shells being completed before the steel balconies were begun. The shells were slender cantilevered structures with concrete piers integrated into them to provide temporary stability (Fig 5). The verticality of the theatre shell walls was stringently controlled so as to minimize any adverse impacts from construction tolerance on the subsequent steel balcony truss installation.

A similar procedure was adopted for the Cirque du Soleil theatre at the Venetian Macau (also an Arup project), and it proved to be very effective and efficient in terms of time and construction logistics.

The event plaza

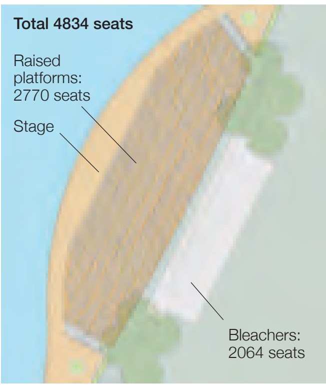
Authors
Va-Chan Cheong Franky Lo

1.

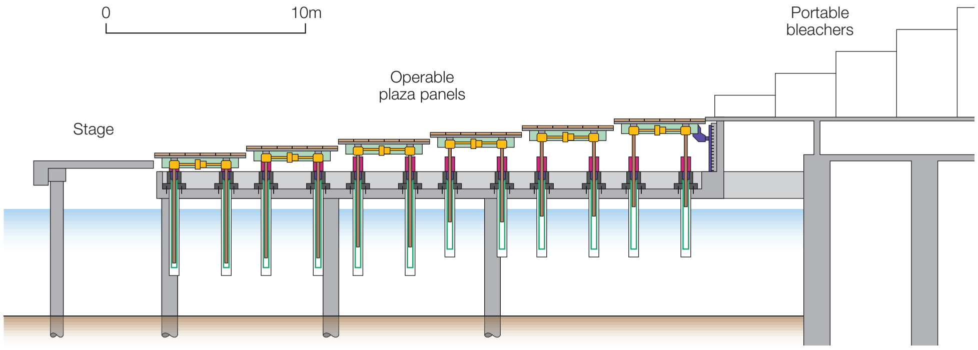
Introduction

Located along the marine deck between the North and South Crystal Pavilions, this moving platform connects the upper and lower promenades (Fig 1). It can be used to host various events itself, or to provide 2770 seats for events either at the lower promenade waterfront or on the stage at the upper promenade (Fig 2).

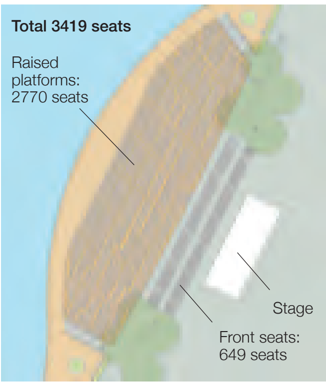
With a total area of about 2300m^2, the platform is divided into series of steps supported by a mechanical system that operates vertically to position the steps in different configurations for events, depending on whether they are on the lower or upper promenade, or at the platform itself. The platform can be raised to a maximum 3.7m from its lowest operating level. Removable steps, and handrails for access and prevention against falling, are variously provided to suit the different platform profiles.



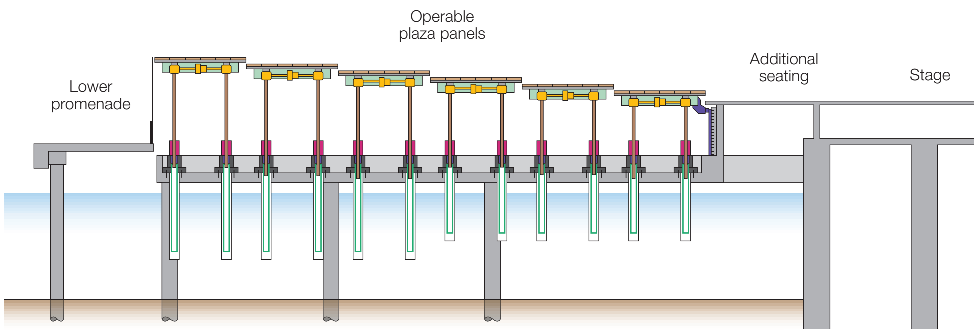
a) Plan for lower promenade event.



b) Elevation for lower promenade event.



c) Plan for upper promenade event.



d) Elevation for upper promenade event.

2.

Structure

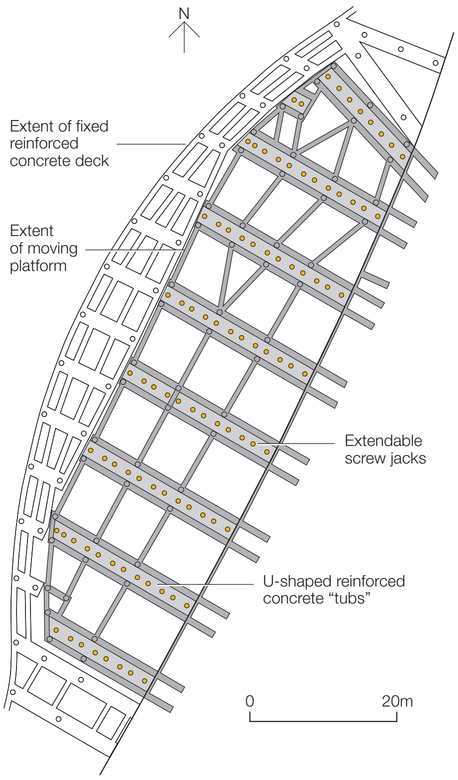
The main structure of the event plaza comprises reinforced concrete U-shaped "tubs" under the platform spanning over the water on marine piles. The platform itself is formed of a composite deck with profiled steel sheeting resting on steel beams.
The design live load is 7.5kPa to cater for public crowds as well as for its use as a stage for hosting events, and detailed considerations regarding vibration induced by activities on the deck were made in the design to avoid discomfort being caused to users from any excessive vibration.

The tubs are mostly in parallel layout at approximately 12m spacing, and interconnected with tie beams (Fig 3). Nine series of extendable screw jacks are installed along the centres of the tubs at about 2.2m spacing to provide vertical support to the platform deck (Fig 4).
At the eastern edge of the platform, adjacent to the main podium structure, a continuous reinforced concrete wall with a buttress houses the guide rails that provide lateral restrain to the platform. To facilitate its rapid erection under the tight programme, the reinforced concrete tubs were precast, while the main parts of the platform decks were shop-prefabricated in advance.

Moving the platform

At each jack position in the tubs, a sleeve opening is provided for the screw rod to pass through when the platform is lowered. At the undersides of the tubs, waterproof sockets connecting to the sleeve openings prevent potential corrosion of the screw rods from contact with water (Fig 5). The platform loading is transmitted through the screw rods to the concrete structure by nut casing units bolt-anchored to the tubs.

Capped on each pair of screw rods, a jack casing formed by a grid of steel beams houses the geared motor, the shafts, and the jack at top of each rod. The motor provides power for the rotary action of the screw rod, causing it to rise or descend and thus raise or lower the platform to the desired level. All the motors are controlled by a central system that synchronises the level of each platform step to provide different platform topographies, including flatted profiles as the stage for hosting events, or in stepped configuration to provide seating for events in the upper and lower promenades.



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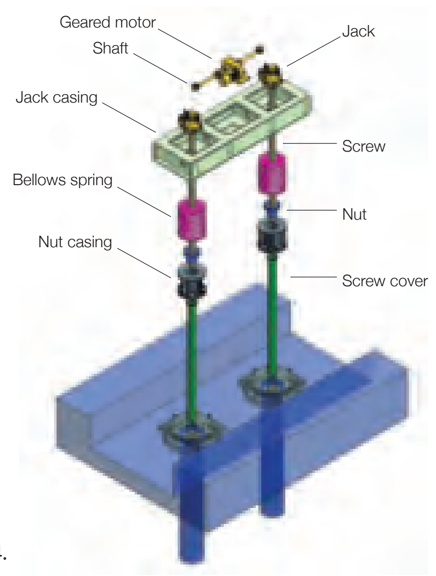


4.

a) Underside of platform supported by screw jacks.

b) Installation of nut casting on reinforced concrete tub.

c) Jack casing on top of screw jack.

d) General view of platform in construction.

5.

1. Architect's impression of the event plaza alongside the marine deck.
2. Configurations of the platform for events on the upper and lower promenades.
3. General arrangement of event plaza reinforced concrete structure.
4. Exploded view of screw jack and jack casing.
5. Building the moving platform.

1.

2.

The ArtScience Museum

Authors
Dan Birch Joe Lam Mac Tan

Introduction
Designed by Moshe Safdie Architects as a symbolic gesture of welcome to guests from across the globe, the lotus-shaped ArtScience Museum (ASM) is situated at the north-west extremity of the MBS site, on a promontory overlooking Marina Bay (Fig 1).

Following its opening on 17 February 2011 by Singapore's Prime Minister Lee Hsien Loong, the museum has become a premier destination for major international touring exhibitions from the most renowned collections in the world, with initial attractions ranging from artefacts from the *Titanic* to a comprehensive survey of Salvador Dalí's art (Figs 15-16, p53).

This unique structure features over 5500m^2 of galleries housing the permanent and touring exhibitions, and embraces a spectrum of influences from the relationship between art and science, to media and technology, to design and architecture. Visitors appreciate not only the building's iconic form and the world-class exhibits within, but also the virtuosity of its innovative roof, which channels rainwater through the central atrium (Fig 2).

The lotus form
Approximately the same size as Bilbao's Guggenheim, Singapore's new Museum seems to float above its surrounding reflective pool, almost as if it were upside down. The overall structure comprises two levels of concrete basement below ground level plus the sculptural steel frame of the lotus itself, containing a further two floors of gallery space and a plant level (Fig 3). The lotus form is approximately 62m high above grade and has 11m of vertical support below grade. The roof is 80m across at its

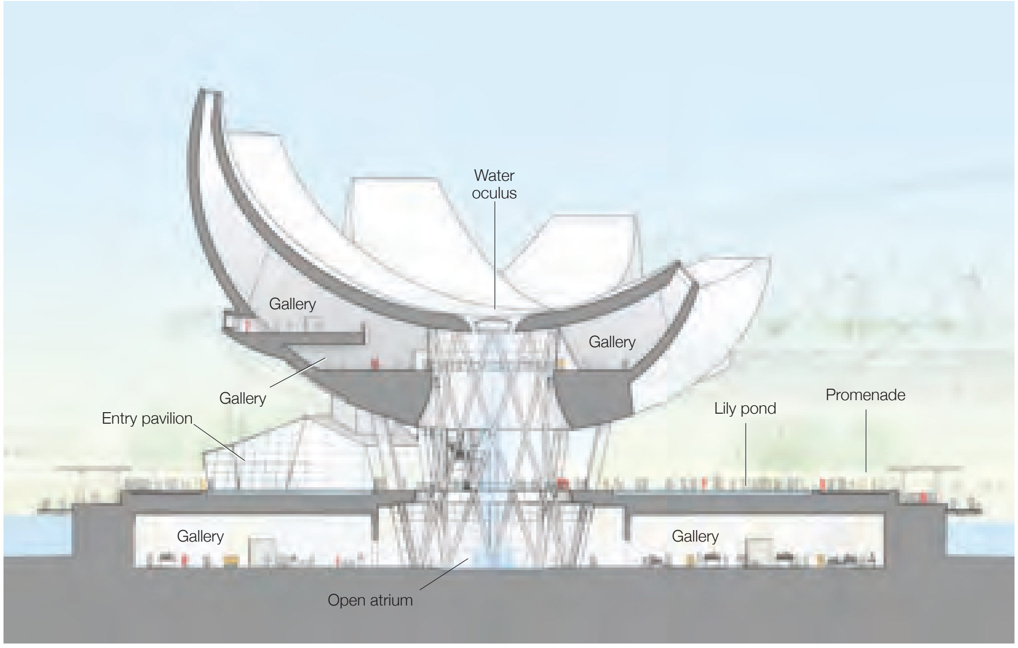
widest point. The highly complex geometry required Arup to adopt innovative 3-D parametric modelling technologies, the use of which gave a significant reduction in modelling time, better co-ordination, visualisation of the complex steelwork, and improved communication with the client.

The lotus form comprises 10 petals of varying height and width on a radial axis and spaced evenly at 36˚. The "petals" were rationalised from the free-form geometry developed by Safdie Architects at the competition stage, and the top, bottom and side surfaces of each were defined by flattened spheres or spheroids (Fig 4). This led to a series of doubly curved surfaces, each with constant radius on plan and variable radius vertically.

Structural scheme (see also pp10-11)
Each petal is formed by secondary members spanning onto primary girders, which load side trusses that bend downwards in cantilever action. The side trusses of adjacent petals meet at waler beams which resist out-of-plane forces caused by the steps in the roof between each petal. Loads from the side trusses are resolved at the waler beams and transferred to the radial mega-trusses (Fig 5).

These act as cantilevers, taking the museum loads to the vertical supports which consist of a central diagrid structure and a series of 10 mega-columns, inclined outwards. Tensile loads in the top chords are resolved into the tension ring which connects to the top of the diagrid, while the compressive loads are resolved into the compression ring below. The vertical loads are carried by the inclined mega-columns (Fig 6).

The architectural vision inspired a building shape that resulted in an eccentric structure. The overturning forces thereby generated, together with wind loads, are resisted by the diagrid acting as a vertical cantilever in conjunction with the inclined mega-columns.



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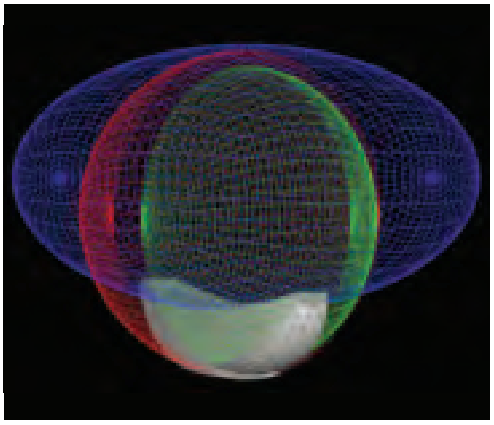
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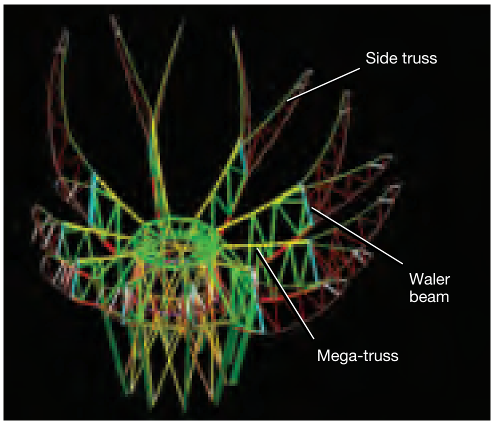

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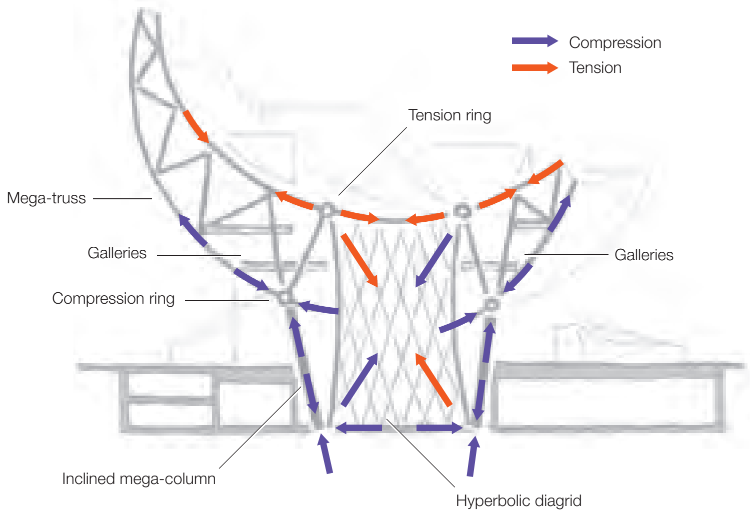


6.

1. The ArtScience Museum nearing completion.

2. Water feature in the central atrium, showing the diagrid structure.

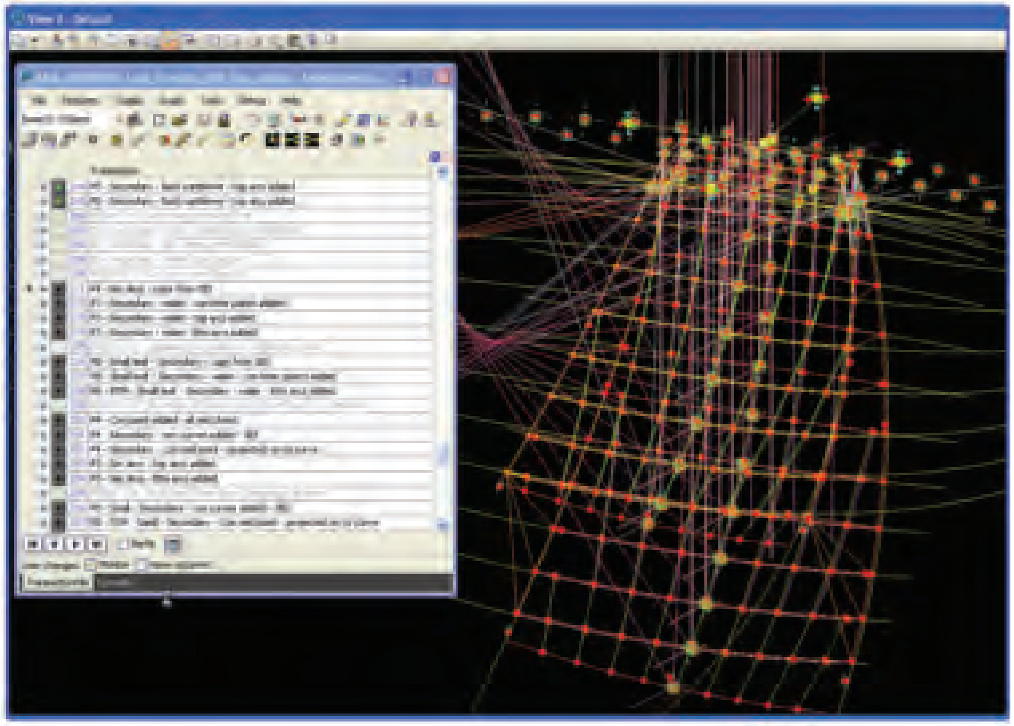
3. Architectural cross-section.

4. Spheroid geometry of the petals in *Rhino*.

5. The primary structure in *Microstation Triforma*.

6. The structural scheme.

7.



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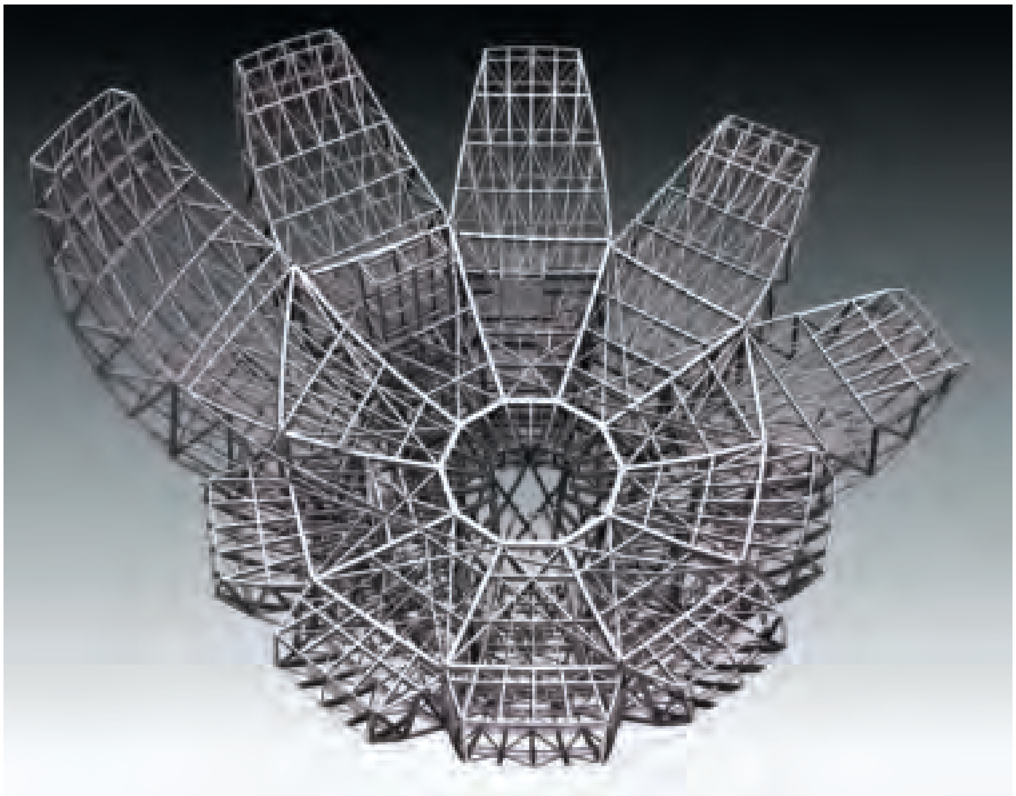

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3-D modelling and coordination

The highly complex geometry of the lotus shape led the design team to use parametric modelling techniques for the structural steel skeleton. Initially MSA developed a *Rhino* model (Fig 7) to generate the surface profiles, and then Arup used these surfaces to develop a parametric model of the steelwork centrelines using Bentley's *GenerativeComponents* software.

For the steelwork of one petal, a parametric model was developed with the use of *GenerativeComponents* (Fig 8), so that Arup could then automatically develop the centreline model for the other petals' varying geometry.

The centreline model was then exported to generate a spaceframe analysis model of the roof in Arup's own *GSA* program, and following analysis and section size definition, the *GSA* analysis model was imported into Bentley *MicroStation Triforma* to accurately model all the steel sections for both size and location. On completion of the 3-D drafting, the model was exported to *Tekla* (Fig 9) and issued to the steelwork contractor as the basis for their fabrication model. The *MicroStation* model was also used to generate a record set of 2-D drawings for the project.

It was critical to get a steelwork contractor on board early and producing fabrication drawings, and the direct issue of the 3-D steelwork model in this way proved invaluable in co-ordinating the complex geometry, reducing requests from the steelwork contractor for information, and vastly speeding up production of the fabrication information.

Using such advanced programs for documentation enabled better communication and reduced the time taken to produce shop drawings, as they provided geometrically correct design models to the fabricator. They also enabled real-time interchange between analysis software and documentation modelling packages. Since the 3-D models were co-ordinated among the consulting team members, this minimised the likelihood of further co-ordination being needed after the shop drawings were produced, and speeded up the progress of fabrication and the reviewing process. A draftsman from the steelwork fabricator noted that Arup issuing the 3-D model for the steelwork directly to them saved them three months in drafting time.

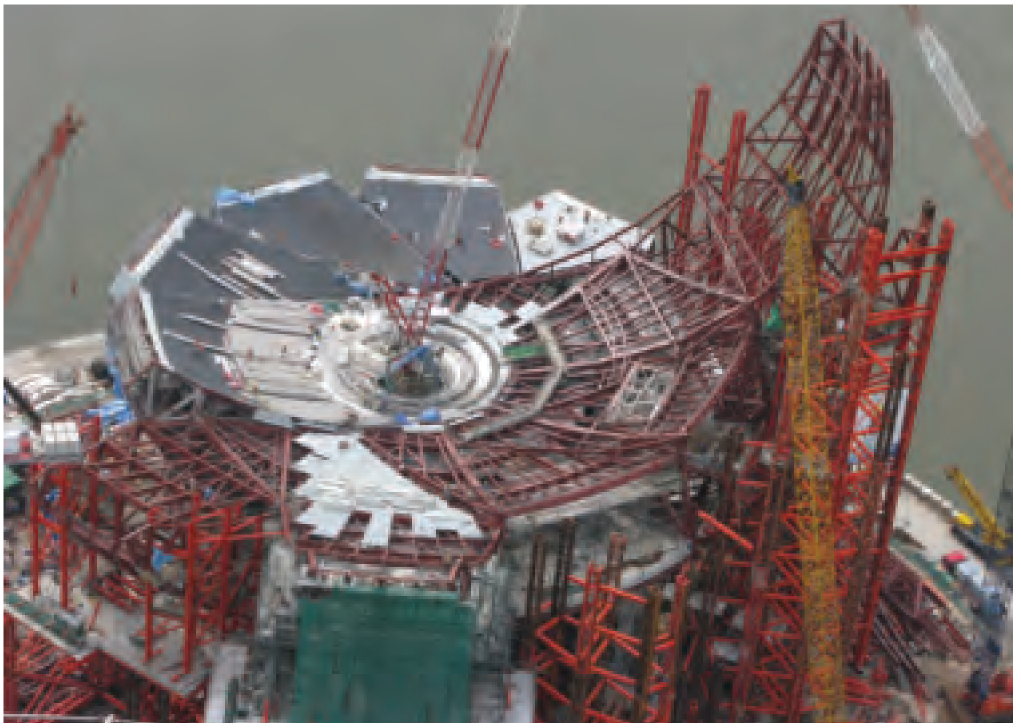
The substructure

As described in the earlier article on the MBS excavation and foundation design (pp12-15), huge cofferdams were used on much of the site to facilitate bulk excavation and minimise shoring in the difficult soil environments. Among these was the 130m diameter semi-circular cofferdam for the ASM (Fig 11).

This cofferdam was supported primarily by the permanent basement retaining walls and temporary ground anchors to its west and east respectively, enabling the 12m deep bulk excavation to proceed unsupported and unhindered. Ring action was used to take the water pressure, the reaction forces of the ring being restrained by ground anchors at the north side and the contiguous bored pile wall at the south side of the diaphragm wall. This allowed excavation without the need for shoring and thus saved overall construction time.

Building such a very large reinforced concrete structure close to the harbour waters created some challenges, exacerbated in this instance by time constraints (as already indicated, a key program driver had been the complexity of the steelwork). Critical was the construction of the ring beams and radial beams at the oculus area to support the mega-columns and diagrid, after which the central core of the steel structure was installed concurrently with the remainder of the substructure. Levels B1 and L01 were constructed in parallel with the programme to install the fingers and radial trusses, as the L01 structure was used as a temporary working platform.

The ring beams and radial beams at the oculus area link with the large 1.8m-3.0m diameter piles under the mega-columns; these piles were designed to resist the large lateral forces from the mega-columns. This enabled the construction of the substructure and installation of the steel structure at same time.



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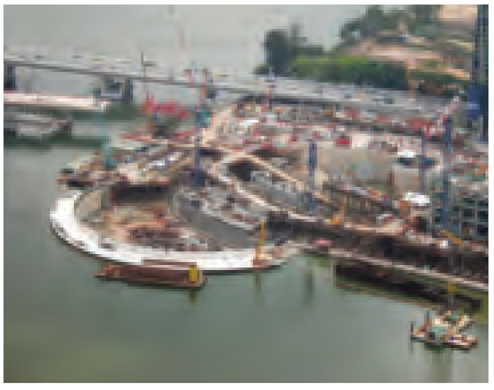

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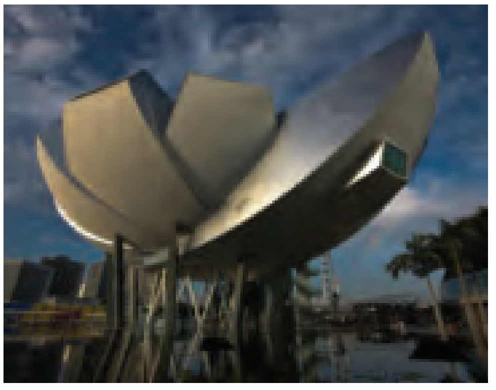

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7. Architectural *Rhino* model.

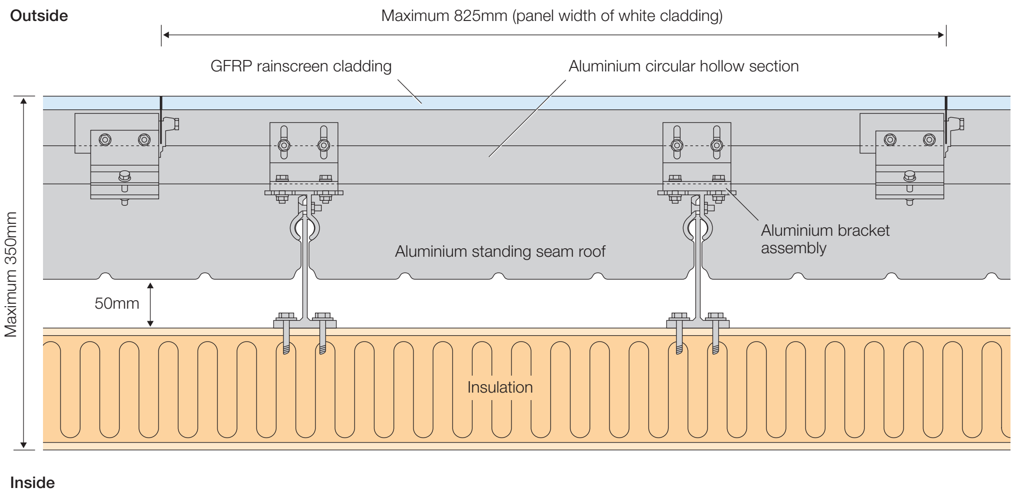
8. *GenerativeComponents* parametric model of a petal.

9. *Tekla* model.

10. Structural steel skeleton under construction.

11. Excavation within coffer dam for the ASM.

12. The completed Museum.



13.

13. Typical section of cladding build-up.

14. The egg-shell skin of the completed ArtScience Museum.

15, 16. The 2011 exhibition "Dalí: Mind of a Genius".

The skin

A fundamental aspect of the façade design was the need for a smooth seamless, egg-shell skin, and extensive studies were made to determine how this could be formed. A heavy site-finished concrete shell was quickly dismissed due to structural concerns, and the search for a solution focused on the concept of a cladding skin sitting above and below an inner standing seam roof.

A standing seam is a very robust and practical system for this application. It creates a continuous weather line and allows for a rainscreen cladding of choice to be attached to the seams without the need for support penetrations, thus reducing the risk of leaks and failures (Fig 13).

A greater challenge, though was to develop an over-cladding that had the eggshell finish. A wide range of locally-sourced materials was considered and reviewed against several criteria (Table 1).

Based on the findings, fibre-reinforced polymer (FRP) was chosen for the skin. Typically used in high-performance racing yachts, this use of 12 500m^2 of FRP was a first in terms of its scale and highly visible application for a Singapore project. The doubly-curved FRP skin made jointless construction possible, resulting in a seamless and continuous surface (Fig 14).

Table 1

Material	Eggshell appearance	Double-curved	Factory-applied finish	Monolithic joint	Light weight
Prefinished compressed fibre cement	✓✓✓	✓	✓✓✓	✓	✓
Glassfibre reinforced concrete	✓✓✓	✓✓✓	✓✓✓	✓	✓
Solid aluminium panel	✓✓✓	✓✓	✓✓✓	✓	✓✓
Filled resin	✓✓	✓✓✓	✓✓✓	✓✓	✓✓✓
High-pressure laminates	✓✓	✓✓	✓✓✓	✓	✓✓
Fibre-reinforce polymer	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓

The use of this new material posed several challenges, not least among them being the identification of a grade of FRP that would provide excellent fire resistance and performance. Testing was a critical part of obtaining approval from Singapore's Fire Safety and Shelter Department for its use. Mock-ups and other tests were also completed by the sub-contractors to demonstrate that they could achieve the appearance and structural performance.

FRP is factory fabricated into moulded panels which, though they can be large in size, still have to be joined together on site to achieve a monolithic skin. The sub-contractor, DK Composites, developed a method of bonding adjoining panels with seamless joints so that the skin moves and responds monolithically, with provisions made at the perimeter and in the intermediate supports for expansion and contraction.

Conclusion

Integrating the engineering and architectural design of the ASM was perhaps Singapore's most sophisticated building undertaking yet. As with Sydney Opera House, another waterfront icon with which Arup is historically linked, the ASM profile is a bold new visual identifier for Singapore.

In addition, the finished building reflects Moshe Safdie's intention:

"From the inside out, every element in the design of the ArtScience Museum reinforces the institution's philosophy of creating a bridge between the arts and sciences. The building combines the aesthetic and functional, the visual and the technological, and for me, really represents the forward looking spirit of Singapore."

14.

15.

16.

The Crystal Pavilions

Authors
Don Ho Joe Lam Brian Mak

1. Completed South Pavilion.

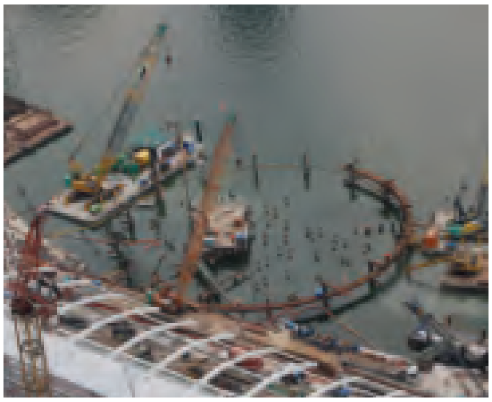
2. Completed North Pavilion.

3. Dewatering at the South Pavilion after installation of tubular piles and cofferdam.

4. Excavation within cofferdam for the North Pavilion.

1.


2.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4.

Introduction

The North and South Crystal Pavilions are two glowing “jewels” for resort visitors to explore, and seem to float in Marina Bay west of the MBS podium. In fact they are securely founded in the Bay strata, and linked to the podium by cast in situ submarine tunnels, which bring visitors from the basement retail area to enjoy the contrasting sense of open water. The North Pavilion houses a flagship store for Louis Vuitton (Arup’s client for the fitout), while the other enables visitors to dine on the water. Two slender steel bridges provide alternative access to the Pavilions.

Geotechnical challenges

The geology here generally comprises an approximately 15m-25m thick band of soft-to-firm marine/fluvial clay layer overlaying the Old Alluvium (OA) formation (see also pp12-15). Another consideration in the Pavilions’ location and founding was water level; following completion in 2008 of the Marina Barrage across the Marina Channel that feeds Marina Bay, the highest level in this reservoir area was 2.5m above mean sea level.

The Pavilions and their connecting structures are founded primarily on the underlying OA layer using open-ended driven tubular steel piles. It was anticipated that the foundations would be subject to compression loads during construction but to permanent uplift forces during operation, so at areas where higher uplift forces were expected, mini-piles were constructed at the toes of the tubular piles to increase tension capacity. Due to the tight construction programme, the foundations were subjected to the full uplift forces prior to completion of the Pavilion superstructures.

The constructed foundations were compression load tested using the *Statnamic* method, which involves launching a reaction mass that weighs about 5% of the weight required for a conventional static load test. Conventional tension load testing was carried out on the tubular piles and mini-piles.

The Pavilion basements and connecting submerged tunnels were constructed in the dry. For both Pavilions, dewatering to the seabed plus about 2m depth of bulk excavation was carried out within circular and adjoining linear cofferdams (Figs 3, 4). The latter extend from both Pavilions to the basement retail areas in the podium, and house the cast in situ access tunnels.

The circular cofferdams were extended through the soft marine clay to found on the underlying alluvial sand, with radial lateral restraint provided by circular steel section waler beams installed prior to the dewatering. After dewatering, bulk excavation towards the centre of the circular cofferdams was carried out. Allowance was made in their design for anticipated closing in during initial dewatering, to bear against the restraining ring waler beams.

The foundation and excavation works were successfully completed in early 2010, and the general sequence of works may be summarised as follows:

- pile installation and testing of pile foundations
- circular cofferdam installation
- dewatering within circular cofferdam
- linear cofferdam installation and excavation within circular cofferdam
- dewatering and excavation within linear cofferdam
- construction of basement structure within circular and linear cofferdams
- forming of opening in circular cofferdam to enable structural connection of the access tunnels and Pavilion basements
- basement construction completion and temporary works removal.

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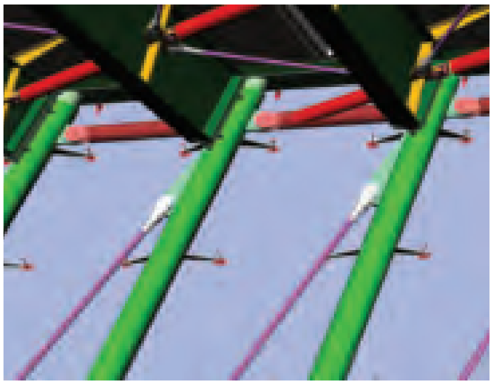

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5. Detail of the North Pavilion nearing completion.

6. 3-D model of the connections and façade fin.

7. Connections and façade fin as built.

8. GSA model of North Pavilion.

9. Construction progress for both Pavilions, July and September 2010.

Pavilion roofs

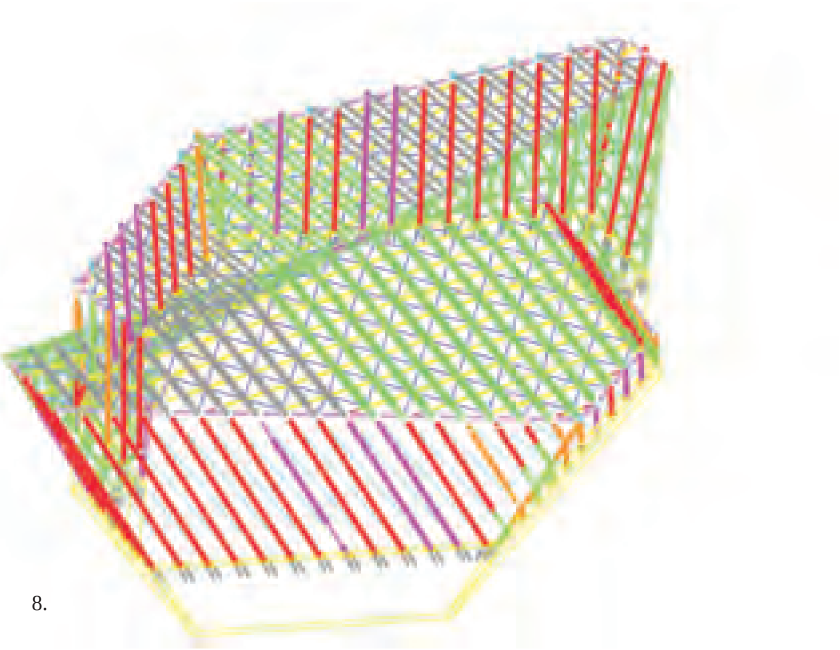
With the Pavilion façades tilting 20° from the vertical in different directions, and the two roofs on each Pavilion having completely different gradients, the structures have an inevitable tendency to lateral movement. This imposed big design and construction challenges, even taking into account the effect of self-weight. To achieve the high transparency that the name “Crystal Pavilion” implies, the Arup team decided to support the decorative outer frames with lightweight steelwork (Fig 5), and provide the lateral stability with prestressed *Macalloy* ties.

Since the prestressing system could only provide full stability for the roofs when they were prestressed to the design load, maintaining stability during construction was a critical factor. The Arup team indicated clearly in the tender drawings the structural requirements during construction, and the contractor’s construction sequence analysis was carefully reviewed before approval, well before any steelwork was delivered to site. To avoid unbalanced forces or local overstress of members, the ties were prestressed in stages, one-by-one around the roof. The prestress force in each was increased by a small percentage until every tie was prestressed to its full design load.

As the connections and members are exposed, structural detailing was of major architectural importance, so the architect asked Arup to develop and document all the connection detail in 3-D, for which Bentley *Structure* was used (Figs 6, 7). All the connections were sketched out and designed early in the process, and then reviewed through local workshops in Singapore and See and Share sessions between the Hong Kong and US offices until the connection detailing was as the architect wanted. All of the team then worked together to draw up every typical and non-typical connection detail in 3-D.

This not only showed the architect how the final details would appear but also identified all the geometrically complex connections, which were analysed and adjusted to make them aesthetically acceptable to the architect before being passed for construction.
The 3-D model (Fig 8) was issued to the contractor as a reference and used as a base for overlaying with the contractor's submitted 3-D model. This revealed any clashes, reducing by over 50% subsequent requests for information (RFI).

So as to provide extra flexibility for the floor arrangement, the conventional reinforced concrete structures are separated from the Pavilions' steel roofs. However, as the outer frame can move relative to the inner core under the designed lateral load, the potential drift was carefully calculated and numerous sections cut from the 3-D model, to ensure that every edge of the concrete core is sufficiently distant from the outer frame.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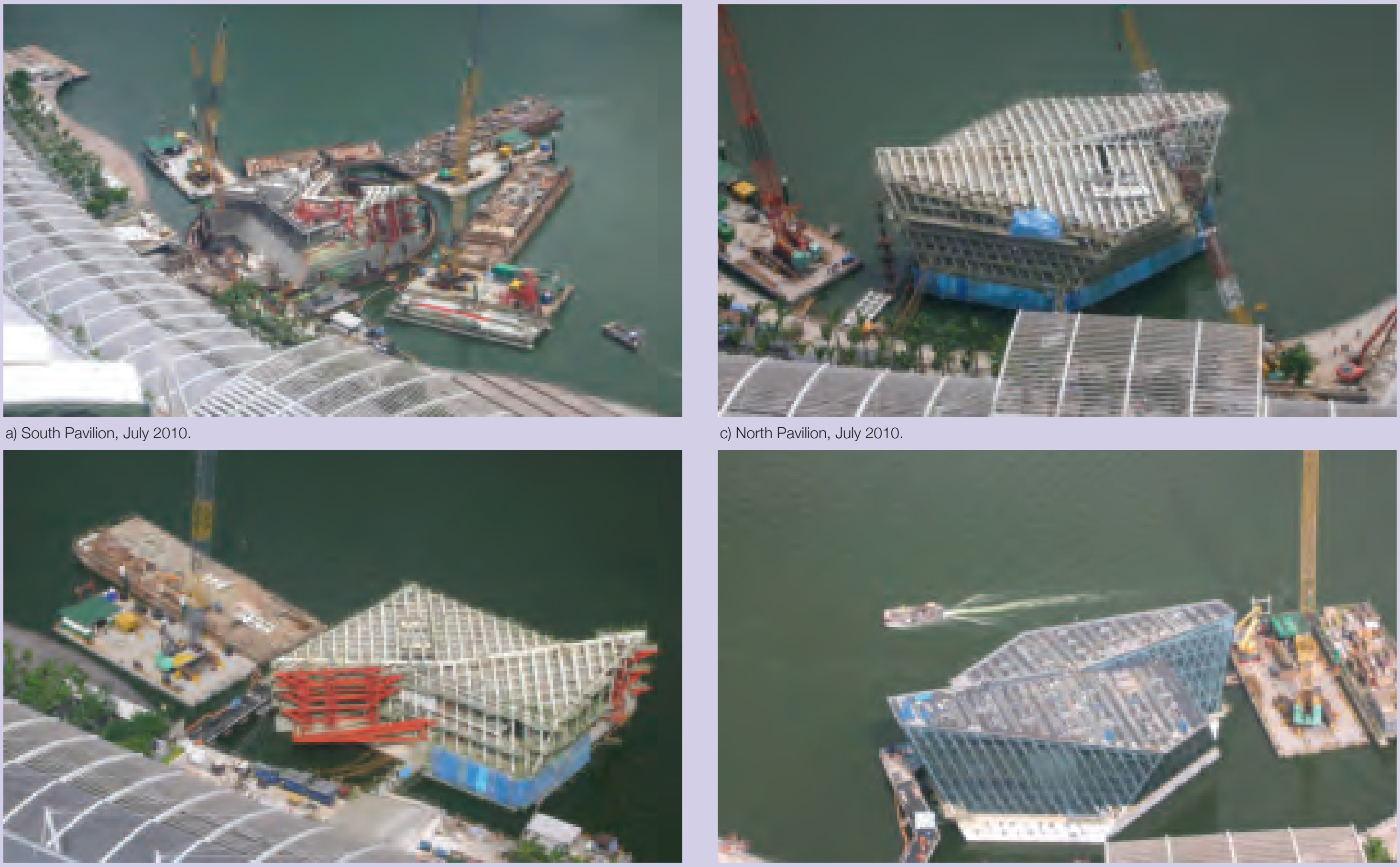
a) South Pavilion, July 2010.

c) North Pavilion, July 2010.

b) South Pavilion, September 2010.

d) North Pavilion, September 2010.

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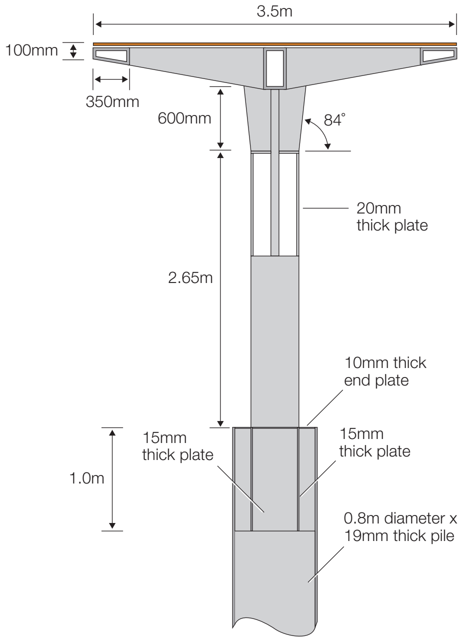

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Integrated design to achieve architectural intent

Transparent glass roofs need to be as devoid of services as possible. To avoid air ducts at roof level, an underfloor supply system was selected, but the consequent need for openings around the edge of the floor plate made for some structural challenges.
The Level 1 floor acts to prop the top of the slanted basement wall (Fig 10), and considerable forces were thereby induced in the Level 1 floor both from keeping the slanted basement wall in position and from the slanted steel roof columns on the top of the wall. The Level 1 floor structure had to be analysed in great detail, and the floor openings positioned in consultation with the building services engineer so that they were feasible in both structural and mechanical engineering terms.

Unlike other types of buildings where façade supports are normally concealed or clad, the façade support structures for the Crystal Pavilions are architectural features, and had to be carefully engineered by the Arup façade team. The main beam-to-façade fin detail is designed to avoid any unwanted stiffeners, and the final product has the very clean detail required by the architect.

The footbridges

During the design stage, the local authority informed the team that a footbridge to each Pavilion was required for alternative access, as well as means of escape in case of fire. They extend some 40m and 50m to the North and South Pavilions respectively, each supported by 10 slender piers.

With the design of the Pavilions already established, these bridges had to be complementary – elegant and transparent, with very slender profiles, and a minimum number of piers extending as deep into the water as possible before connecting to the piles. This was because the Marina Barrage effectively fences the Bay off from the sea, so that by the time MBS opened, the Bay's fresh water would be clean enough to make the seabed clearly visible.

In addition to these aesthetic requirements, there were site constraints. Because raking piles from the main Pavilion structures already extended into the bridge areas, each bridge could only be supported by a single central line of piers, rather than also be stabilized by raking piles.

The slender bridge columns and piles resulted in an undesired cantilever mode shape being dominant (Figs 11, 12).
The effective cantilever length of the column + pile element is very critical in affecting the frequency of this mode (Fig 13), so in the human-induced vibration (footfall) analysis model (Fig 14), the team used a lower bound soil stiffness in estimating the fixity point of the pile (the depth at which the soil acts as a lateral restraint to it). This lower bound assumption was to ensure that any secondary effects were not underestimated.

For strength checking, another computer model was built, the main difference from the footfall model being that full-length piles with closely-spaced soil springs were included. As the team was more confident about the magnitude of lateral loading from wind and wave action, this gave a clearer indication of the soil/structure interaction.

Reactions from each soil spring were checked to make sure they were within acceptable limits. Where soil springs were overstressed, they were removed and the computer model rerun iteratively until all were are within the allowance load. It was later determined that the structural size was mainly dictated by human-induced vibration, not design strength.

Conclusion

Despite the difficult environment and the range of design challenges that it generated, the design team successfully realised the Pavilions' unique and complex design with high precision and quality. They were the final elements of MBS to open to the public, in September 2011.

10. The South Pavilion complete.

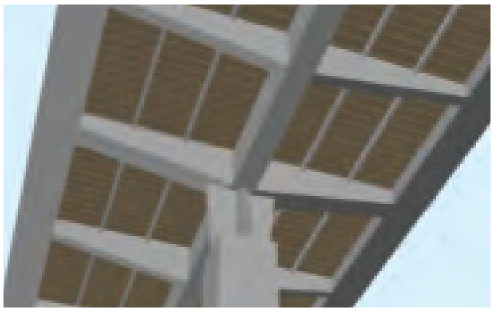
11. Cross-section through bridge/pier/pile structure.

12. 3-D model of bridge structure.

13. First mode behaviour of bridge.

14. Human-induced vibration (footfall) model for the South Pavilion footbridge.

15. Completed footbridge to the North Pavilion.



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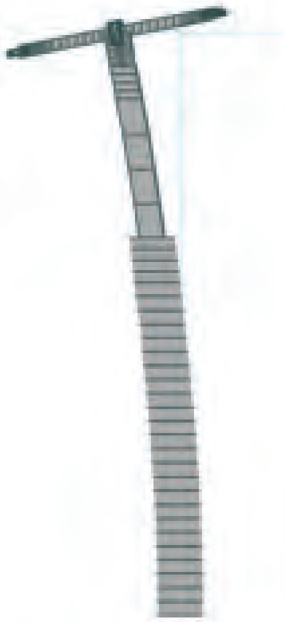

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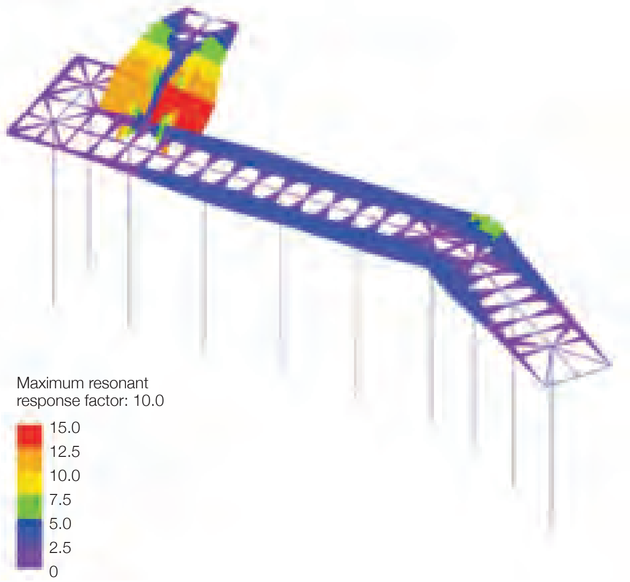

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Bayfront Avenue and Downtown Line 1

Author
Brian Mak

Bayfront Avenue runs through the heart of MBS, separating the hotel towers and podium structures (Figs 1, 4). The Avenue links the new resort not only with its immediate surroundings, but also with other developments like Gardens by the Bay and the Marina Bay Financial Centre, forming a further element in the Marina South area's complete road network.

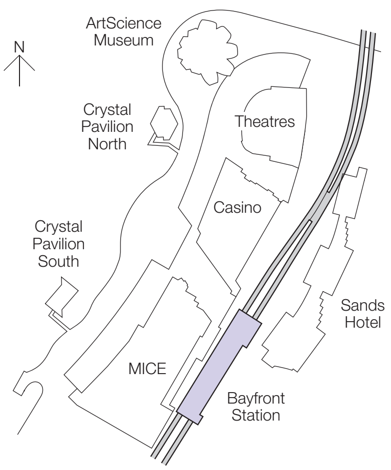
The new road opened to traffic on 25 April 2010, enabling bus, taxi and other vehicular access to the resort. An underground link to the SMRT network is also being added, with the inclusion of Bayfront Station as part of Singapore's Downtown Line 1 (DTL1) development, being constructed here beneath Bayfront Avenue (Figs 2, 3). This station, which opened on 14 January, 2012, now interfaces with the Shoppes, the Sands Expo and Convention Center, and the Sands Hotel, so as to provide even easier public access to and from the area (Fig 6 overleaf).

Bayfront Avenue was built by the top-down method (Fig 5 overleaf), and the structure played an important role in the early construction stages as it formed the heart and linkage for all the other areas. As well as enabling the movement of manpower and materials around the site, it also functioned as a working platform/temporary support for other areas, eg the SkyPark steelwork was assembled on top of it. The structure below, the future Bayfront Station, was then constructed after the ground slab was cast.

Parts of the DTL1 extension cut-and-cover tunnels were constructed by the bottom-up method. Soil is excavated to the required depth, and then casting of the concrete progresses upwards until the roof of the structure is completed.

Extensive co-ordination between the design team and the local authority was needed concerning the interface between Bayfront Station and MBS. Detailed structural analyses were performed to ensure that any deflections in the diaphragm walls would have no adverse effects on those parts of the DTL1 that were already constructed, and the planned excavation sequence was adhered to strictly to avoid any adverse impacts to either the resort or the station structure.

A major constraint on the tunnel construction was the existing Benjamin Sheares Bridge, which carries an eight-lane cross-Singapore arterial route that here runs adjacent to the



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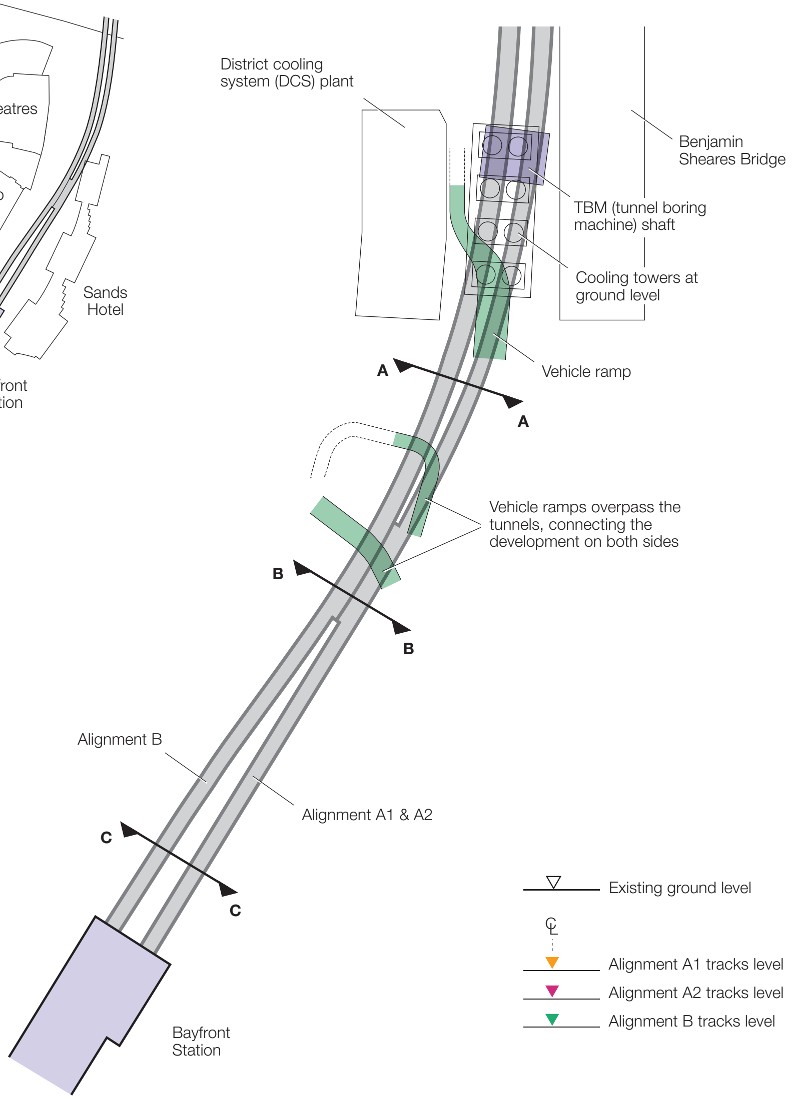

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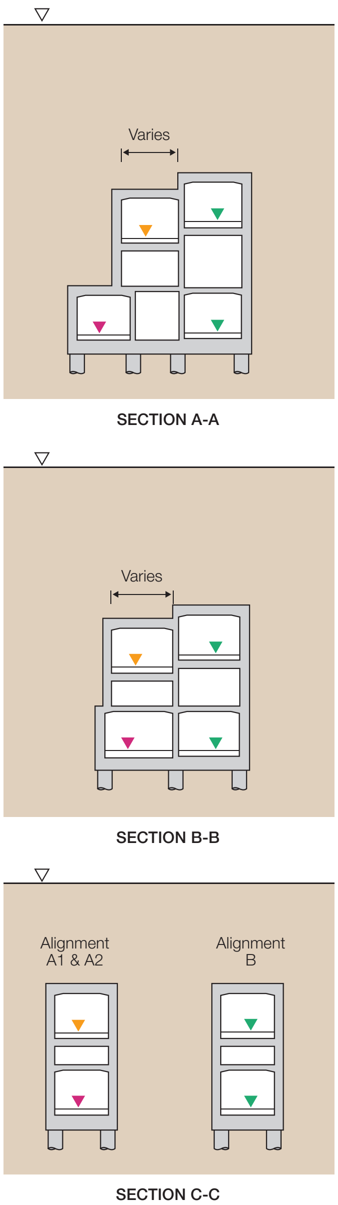

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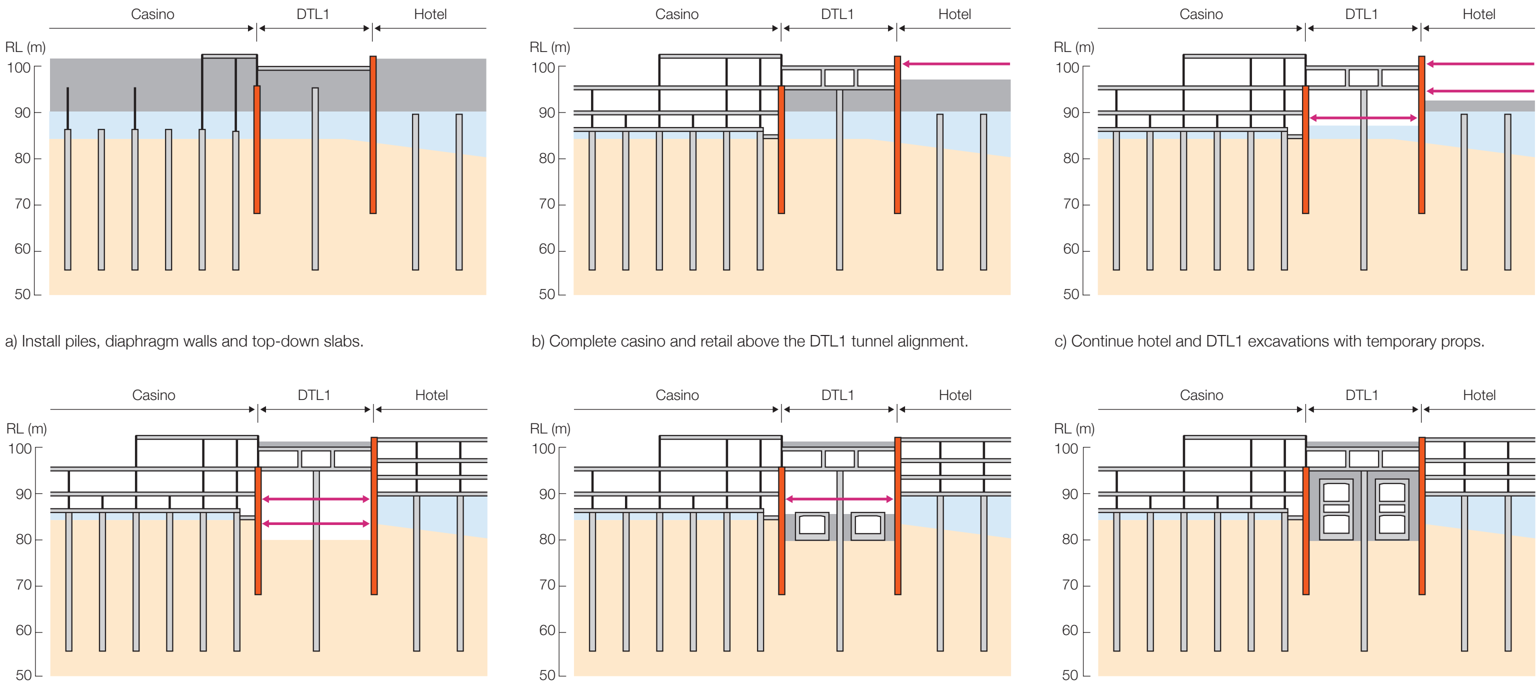
1. Bayfront Avenue alongside the hotel towers.

2. Alignment of DTL1 tunnels beneath Bayfront Avenue.

3. Plan and cross-sections of DTL1 tunnels at three locations on the route into Bayfront Station.

4. Bayfront Avenue seen from the ground level.



a) Install piles, diaphragm walls and top-down slabs.

b) Complete casino and retail above the DTL1 tunnel alignment.

c) Continue hotel and DTL1 excavations with temporary props.

d) Complete hotel basement and DTL1 excavation.

e) Commence DTL1 tunnel boxes bottom-up and backfill.

f) Complete DTL1 tunnel boxes.

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deepest part of the excavation in an area of deep soft clay. The Arup team calculated that the proposed works would cause the bridge to move laterally by 47mm. As the deck and piers were fixed together by pins that allowed little lateral movement, this would result in overstressing of the columns of the closest pier as well as damage to the pins. Arup's solution to modify the connections between the deck and the pier is described and illustrated in the article on the MBS geotechnics and foundation design (pp12-15).

Without this simple but effective modification to the bridge, the design of the excavation works would have been significantly complicated and taken much longer. Arup's solution allowed the project programme to be met while the bridge continued to operate as normal.

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5. Top-down construction sequence for Bayfront Avenue and the DTL1 tunnels.

6. Bayfront Station entrance.

Specialist skills

The façade systems

Authors
Russell Cole Mac Tan Alex Wong

Introduction

The building envelopes of Marina Bay Sands are a fundamental part of the project's architectural definition. Arup's façade team covered the entire development, ranging over several zones with multiple types of façade, and working with the architect, the other design disciplines, and the client project managers to develop and refine the design intent for these various façade types.

Arup subsequently provided engineered design intent drawings, and performance specifications for a design-and-build tender contract. This also covered design development and co-ordination with façade contractors, reviewing of all submissions, and other façade activities that stemmed from testing through fabrication to installation.

The façades were grouped into five broad packages – the hotel towers, the podium structures, the ArtScience Museum, the Crystal Pavilions, and "others" – but several key common factors ran throughout.

Common issues

Architectural intent

Safdie Architects had a clear vision for the form and appearance of MBS, and the façades were a critical aspect of this vision. However, the programme, budget, and many different performance requirements had to be met. This being the case it was crucial, given the scale of the project, that a pallet of materials and façade systems be developed that would impart a strong sense of cohesion and a consistent appearance, as well as simplify procurement and construction.

Transparency

In certain areas transparency was critical, and this need for unimpeded views implied maximising the glass area and minimising structure. These areas were:

- the east-west view corridors between the MICE, casino, and theatre blocks of the podium, to provide good views of the city
- the retail mall, giving views of the promenade as well as the city beyond
- the west-facing hotel rooms, again to give views of the city
- the atria between the hotel blocks, which needed to have a light and airy feel.

To enable these views, high light transmission was needed, with avoidance of tinted glass so as to give good colour rendition. This resulted in less areas for insulation which, coupled with the use of clear glass, implies the consumption of greater amounts of energy. Also, concerns had to be met about night-time views in these areas, especially concerning the rooms at the Sands Hotel.

Energy performance

Singapore has strict requirements on the amount of solar and ambient energy flowing into a building. The maximum amount of energy permitted is deemed to comprise the total of the thermal flows through the solid areas and the glazed areas, and the solar transmission through the vision areas. Normally this is calculated across the whole of a building, but in the present case MBS was considered as two buildings – the hotels and the podium block.

Highly transparent areas tend to let in more energy, even if high-performance solar coatings are used (the most advanced of which do have an impact on light transmission), so areas of high energy transmission had to be balanced with lower performance areas. These calculations were used throughout the design process to inform where transparency targets could be achieved. In the end, careful tuning of the glass selection cross-checked with the ETTV (envelope thermal transfer value) calculations.

Glass selection

A very detailed study of glass types was carried out, with regard for the different roles the glazing would have in the various areas of MBS. Factors that had to be taken into account in the selection process were architectural intent, expected transparency, energy requirements, safety regulations, and other requirements such as acoustic performance.

Glass sources from all around the world were considered, but as with all projects there were budget constraints, and eventually the many types of glass used were all sourced from Asian factories. During the study period and on into procurement and production, numerous inspections of glass factories were necessary, and as a result Arup is now very familiar with fabricators throughout Asia. In many parts of the building some of the latest high-performance glass was used. Other areas of high transparency required low iron glass – sand with low iron content avoids the tendency to a green tint of normal clear glass.

Hotel glass curtain walls and glass fin design

The west-facing orientation of the hotel towers created an issue of thermal comfort during afternoons. Safdie Architects' design incorporated vertical glass fins to express the building shape and complex curvature of the towers, with preference for frameless glass with exposed edges. Arup was tasked to design and achieve these aesthetic requirements, with the following challenges:

- Typically, vertical glass fins in façades align with the supporting mullions, but here the fins do not; this constraint forced the Arup design to provide support on the transoms (see also p22)
- The fins do not align consistently with any façade element, as the hotel towers taper in elevation. The fins are spaced every 6m from the top of the towers (level 55); this gap reduces down to 5m at level 5 (Fig 1).
- The architect's intention was for the glass fins to be supported only at the top and bottom, spanning the height from floor to floor.
- The architect wanted to express the curvature of the towers in the fins themselves, so that they would be 1200mm wide at the top and bottom of the buildings and gradually taper to 600mm in the middle.
- The fins had to be made more visible by using a more reflective glass than that used for the curtain wall glazing, thus forcing the glass for the fins to exceed Singapore statutory requirements.

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- Maintenance had to be considered.
- The slab structural design could not incorporate a top-fixed curtain wall bracket that would require notching on the existing slab.

Arup with the specialist sub-contractor developed several options, identifying the design and structural implications for each. Although the architect's intent to support the fins only at the top and bottom could be achieved, this would require the laminated glass to have three layers. This in turn would have major implications for the loads imposed on the curtain wall system, so the architect eventually accepted a system having each fin supported at the rear as well as the top and bottom, with the front edge left exposed to achieve the visual intent.

Since the glass fins were not in line with the curtain wall mullions, the only possible option was for them to be fixed to the horizontal curtain-wall transom and the stack joint, the horizontal connection between curtainwall panels (Fig 2). Considering the major loading implications, Arup designed the main support to be from the top frame of the curtain wall. This was considered to be the most efficient solution because it is the only frame member in the curtain wall system that takes no dead load from the glazing. As the curtain wall was designed as a hanging system to cater for additional loads arising from the fin design, this made the top transom the closest horizontal member to the dead load brackets; this approach minimised the loading implications on other elements of the curtain wall panel.

The fins were designed on the same principle as a unitised curtain wall. The three-sided support elements were factory prefabricated, where the fin brackets were also assembled together with the unitised curtain wall, so as to reduce the amount of on-site assembly and ensure high quality of work. Since the architect required the edge of the laminated glass to be exposed, Arup chose the *Sentry Glas*® system to reduce if not eliminate risk of delaminating. This system also adds structural integrity and safety.

1. Elevation of hotel tower 1, showing non-alignment of fins and mullions, and gradual reduction of spacing between fins down the tower.

2. Close-up of fins, showing connection and three-sided framing.

3. Spring system installed at SkyPark movement joints.

4. The nose of the SkyPark.

5. Underside of the SkyPark soffit cladding nose panel, showing welds and support framing.

6. Inspecting the nose panel.

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SkyPark soffit cladding

The design concept for the SkyPark included a smooth façade to its soffit. Aluminium composite cladding panels were chosen due to colour consistency and their ability to supply the colour tone that the architect preferred during the sample review. Gaps between panels of 100mm and 40mm were selected to help visually express how the panels form the shape of the soffit.

Another challenge was the SkyPark's movement joints. It includes what are essentially two bridge spans between the hotel towers, and so movement joints had to be incorporated (see also p25). The façade cladding had to accommodate this movement without there being any major aesthetic impact on the panel design and pattern.

A pantograph system – a mechanical linkage that includes an articulated assembly to provide a motion guide for contraction or expansion – was added in the original panel design to regulate the centre panel between those adjacent during any movement. This would ensure that the gaps at the movement joint would always be equal whatever the structural movement.

This was later developed by the sub-contractor, as well as an alternative spring system solution. In this – the concept that was the final choice for the actual installation – two equal-capacity springs acting in opposite directions keep the panel gaps equal during movement, achieving the same design intent and principle (Fig 3).

Thermal movement and expansion were also carefully reviewed to ensure that the panels will stay in place with large redundancy and safety factors.

The nose of the SkyPark cladding has a very small radius, forming a doubly-curved panel (Fig 4). The aluminium composite panels used elsewhere would not work here, so solid aluminium panels were used, formed in a similar way to the fabrication of aircraft parts. They were carefully beaten to into shape with computerised controls to ensure the correct formation. This method necessitated a minimum 5mm panel thickness to ensure that no imperfections were visible after finishing (Figs 5, 6).

Installing the SkyPark soffit cladding was a major challenge for the sub-contractor, with the short programme and the needs of safety in the process being the principal concerns.

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7. West-facing view corridor wall.

8. Cable anchorage detail at the west-facing view corridor wall.

9. Architect Moshe Safdie signing hotel glass samples before final procurement, September 2007.

A large gantry system on tracks ensured ease of installation access, at a fast rate that would meet the programme, and ensuring safety during the operation.

Balustrading for the SkyPark observation deck had of course to meet rigorous safety requirements, and to achieve this, heat-strengthened *Sentry Glas®* laminated glass was again used.

The Bayfront façade

A range of different façades and podium building entrances face Bayfront Avenue (Fig 4, p61). At the southern end the glazing forms the ground level colonnade to the exhibition spaces, which then transitions into the southern view corridor and the casino, and finally the northern view corridor and the theatres.

Here the simplest form of the horizontal glazing system is used, comprising horizontal steel T-sections with aluminium glazing adapters fixed to the front face. The double-glazed units are then clamped to the horizontal T-sections. There are no steel or aluminum glazing sections running vertically, with only a simple glass-to-glass seal. Stainless steel hanger bars stop the 9m steel horizontals from sagging.

Most of this elevations's many entrances have automated sliding doors.

View corridor walls

The conditions of the land sale included sightlines that needed to be maintained through the development. To this end the architect envisaged the creation of view corridors dividing the elements of the podium block, with highly transparent walls at the ends each view corridor arcades. These were achieved in two principal ways.

Firstly the façades team developed a lightweight structural support system that minimized the size and density of the structural elements. Secondly, highly transparent glass was specified. This area was given priority for the use of low iron glass that increased visible light transmission even though it meant a lower thermal insulation performance. To compensate, the double-glazing used in other areas of the podium has less transparency and better thermal performance.

In developing such a highly transparent structure the first objective was to use the largest spacing between supports: glass sheets 2.6m high x 3.7m wide with supports only along the horizontal edges. Small transoms were used to take the load to the major steel vertical elements at the ends of the glass panels.

The west-facing wall of the southern view corridor running between the MICE and casino blocks is oblique to the axis of the corridor and so is 52m wide. The wall sits between the promenade level and the bridge at the end of the 20m high view corridor. As this wall frames the view of the main CBD of Singapore from this focal point of the retail spaces, here again a particularly transparent structure was needed – a challenge, given the dimensions of the whole wall.

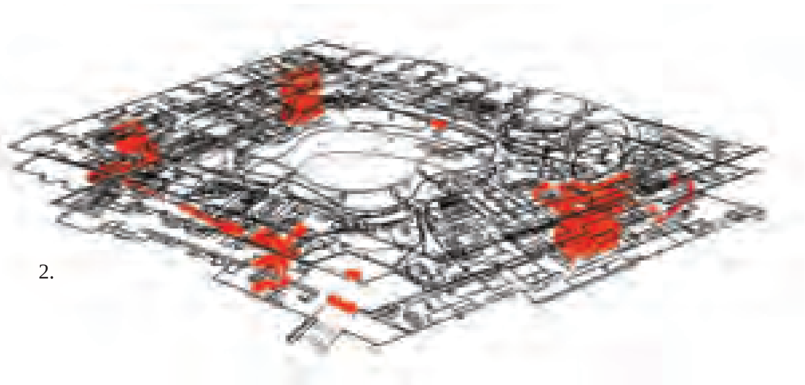
The final scheme uses a set of vertical steel mullions stabilised against the wind by a cable net (Figs 7-8). The inward wind pressures are resisted by a box cable behind the vertical mullion, whereas the outward suctions pull against two levels of horizontal cables that span the width of the wall and are anchored to the concrete structures of the MICE and casino blocks. Similar structural systems were used for the smaller view corridor walls facing Bayfront Avenue.

1.

Fire engineering

Authors
André Lovatt Ruth Wong

Introduction and design philosophy
Marina Bay Sands, with its iconic design, stature and location, inevitably posed a challenge in its fire and life safety design. The large populations in the casino and the Sands Expo and Convention Center, the multiple basement floors (down to a fourth level in places), and the compacted "jigsaw" of different components into a single building, all made MBS in fire engineering terms "an interesting building to work on".



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The fire safety strategy had to involve as stakeholders the parent company Las Vegas Sands (LVS) and its insurance brokers, as well as Singapore Civil Defence Force (SCDF) as the local authority having jurisdiction. As an international company with significant overseas presence, LVS has corporate guidelines for critical fire safety systems for all its properties, whether in the US, Macau, or Singapore. Insurance brokers similarly have their own standards relating to acceptable products and design standards to minimise risk and losses to insured businesses and properties. As for statutory approvals, the SCDF planning approvals department – the Fire Safety and Shelter Department (FSSD) – has jurisdiction and oversees fire and life safety compliance approvals.

It was determined fairly early on through close consultation with the FSSD that the Singapore *Code of Practice for Fire Precautions in Buildings* 2007[1] would form the basis for the MBS fire safety design.

This differed from other LVS properties in the US and Macau where the *International Building Code* (IBC)[2] was used. Where the development for design or construction reasons departed from the Singapore Fire Code 2007, it was agreed with the FSSD that a performance-based approach, as permitted under the Fire Safety Act, would be utilised for additional flexibility. Though the Singapore Fire Code 2007 would be the basis for design, many aspects of the IBC, eg the use of horizontal exits, and US National Fire Protection Association standards, eg *NFPA13*[3], were referenced in the final design.

Performance-based design and its application to MBS

The performance-based approach to fire safety design is not a new concept in Singapore, having been introduced there in 2004. The Singapore Fire Code 2007 has a subsection in front of each chapter, laying out the root and sub-objectives of the Code with regards to fire and life safety design.

In MBS, the performance-based approach contributed to the overarching intent to create an iconic design masterpiece on Singapore's waterfront district. The fire and life safety design had to incorporate seamlessly the requirements of all its relevant stakeholders, and to the advantage of the project.

In many instances, the risk management strategy employed by the insurance brokers corresponded with the fire safety measures. Such centred on the use of maximum foreseeable loss (MFL)* walls – with minimal two-hour fire resistance rating – to limit burnout or complete loss to a single MFL compartment. The MFL compartment also served as both the required separation between purpose groups (or classifications of use) where required under the Singapore Fire Code 2007, and as horizontal exit lines as part of the means of escape strategy.

Phased evacuation, horizontal exists, and the use of monumental exit stairs

Due to MBS's large interconnecting footprint, horizontal exiting was used in many parts, where people escape from a location exposed to fire, heat and smoke, to another relatively safe place separated by distance and fire-rated construction. In most cases, the horizontal exit line was designed to coincide with the MFL separation required for insurance purposes to limit damage in a fire incident.

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1. The Sands Theater in use. The theatres are provided with negative smoke pressurisation in accordance with *NFPA 92A*[5].

2. Evacuation modelling for simultaneous evacuation of the casino, using the STEPS program.

3. Sliding doors retracted in MICE ancillary areas.

4. Exit staircases at MICE.

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While referenced widely in US-originated codes such as IBC and *NFPA 101*[4], the use of horizontal exits is less common in Singapore. At MBS, however, horizontal exiting as a strategy has specific advantages in that it enables the controlled evacuation of people from one component/part of a building as part of an overall phased evacuation plan, and limits disruption to ongoing businesses and operations in the event of a false alarm (Fig 2).

The horizontal exits at the main entrances to the MICE and casino also used another US-originated product – horizontal sliding doors (Fig 3). Similar to horizontal fire shutters, such doors are permitted under the IBC to serve as part of the means of escape, and are equipped to be automatically operable for people to escape and then to close. When not in use, the doors are discreetly stored in pockets hidden at the sides.

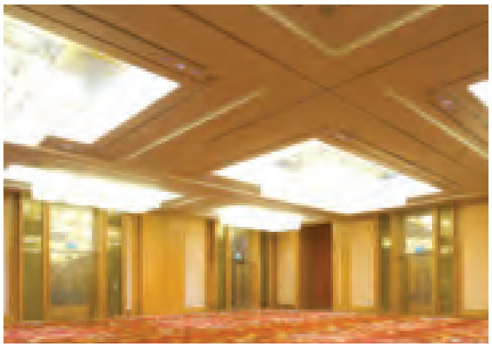
Another new concept was the use of monumental exit staircases within the high population areas (Fig 4). Exit staircases up to 4m wide in a scissor-stair arrangement were provided for both MICE and the casino so as to give sufficient capacity for the expected populations – in the order of thousands of people per floor. This differs from the stipulations in the Singapore Fire Code 2007, which only permits up to 2m of the exit stair width to be counted as capacity, regardless of its total width.

* An insurance industry term, meaning the worst loss likely to occur because of a single event.

5. A corner of the MICE Grand Ballroom, showing temporary partitions in open position.

6. Retail atrium.

7. Submerged egress tunnel at the South Crystal Pavilion.



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Technical challenges included providing sufficient exit points, so that the failure of a single exit would not impact significantly on the overall means of escape from the space. As part of this, non-lockable doors were provided for escape at temporary partition walls within the MICE meeting and ballrooms (Fig 5).

Grand Arcade and view corridors
These three zones comprise the Marina Bay Sands Shoppes. Uninterrupted by smoke curtains, each retail smoke zone is demarcated by the curves and bends of the impressive five-storey atrium design (Fig 6).

Technical challenges included determining the most advantageous location for the smoke vents (at the top curve of the roof), so as to limit visual impact for visitors to the fourth storey roof terraces and yet not compromise the efficiency of the vents during a fire. The smoke hazard management strategy used CFD smoke modelling of the building, with and without wind effects, for both small and larger fires so as to assess the buoyancy of smoke, as well as data obtained from wind tunnel testing of the façade.

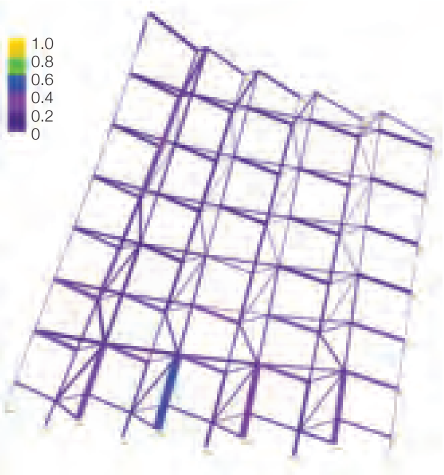
The Crystal Pavilions
For these two structures, located in the Marina Bay waters, among the fire design options considered at the concept stage were the use of rescue boats, floating decks, and submerged egress tunnels back into the podium (Fig 7). As built, these floating geometrical glass islands are accessible via both a deck at water level from the outdoor promenade and, deep within basement level 2 of the Marina Bay Shoppes, via a submerged tunnel (with an escape tunnel running parallel to the main entrance).

The Sands Hotel
Up to 23 storeys of glass and steel form the atrium that interconnects the three hotel towers at ground level. The elegant steel trusses are only partially protected with intumescent paint, as part of a performance-based fire safety approach which demonstrated that there is negligible impact of heat and smoke to the structure higher up (Figs 8, 9).

The Sands SkyPark
Where the SkyPark spans between each hotel tower and cantilevers off the end of tower 3, the huge structural steel members have no applied fire protection. Though this would have been a requirement under a

prescriptive design, with a performance-based approach it was determined that any structure outside the immediate zone around a possible worst-credible fire within the towers would be able to be unprotected and yet still maintain its stability.

A performance-based approach was also applied to the evacuation of the SkyPark (Fig 10). With possible populations of up to 3900 persons on the 56th and 57th storeys, the overall strategy is to evacuate people from the SkyPark deck to floors below and from the shadow of one tower to another.



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Award
In October 2011 Arup was recognised at the inaugural National Fire and Civil Emergency Preparedness Council (NFEC) Fire Safety Design Excellence Awards 2011, for its "outstanding work" on Marina Bay Sands.

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8. Fire loading analyses on hotel atrium structure, showing ratios of load to capacity.

9. Hotel atrium.

10. The public observation deck on the SkyPark.

Acoustics

Author
Larry Tedford

Success indicators
Successful acoustic outcomes for most projects are often difficult to define. If the design solution provides the intended experience for patrons, it is rarely noticed because it simply feels right. Further, there is nothing to see that proves that it works. It just does.

MBS has multiple points of success. Most are not obvious, but the challenges overcome manifest themselves as successful technical design, professional collaboration, and the gestation of a significant cultural shift. Awareness of the importance of acoustic comfort is a significant change in the quality-of-life improvements that support Singapore's burgeoning stature as an international destination for business and leisure pursuits.

The sheer size and scale of MBS has helped position Arup's acoustic practice as one of the premier design consultancies in Singapore. A fledgling group in the Singapore office in early 2006, the local acoustics team was initially formed to build upon two projects already in progress for the Australasian acoustics practice: Genexis Theatre and Singapore School of the Arts.

Responding to the demands of three large, sophisticated, and technically challenging projects was beyond the logistics of what was initially a four-person local team, so the support of acoustics colleagues in Australia, the UK, and the US became a distinct advantage. In addition to working with the local Singapore and Hong Kong multidisciplinary teams, the international acoustics team worked non-stop for the first six months – truly 24/7 – so that co-ordination and design guidance could happen simultaneously in the US with client Las Vegas Sands (LVS) and Safdie Architects, and in Singapore with Aedas and the local MBS client body.

Acoustic design embodied the importance of the project to Singapore, with acoustic quality taking a strategic "front-and-centre" position to help shape the design rather than merely react to it. Design progress also had to anticipate the potential impacts of procurement and construction practices unique to Singapore.

Project strategy
The primary goal was to ensure that patrons' experience was world-class. Standardised objective metrics of acoustic quality can demonstrate that design targets are achieved, but personal subjective response is the singular determinant. Simply put, acoustic quality manages noise disturbance and enhances desired sounds to create an effortless and natural sensory experience. While most other Arup teams had been full time on the project from July 2006, the acoustics team commenced work that December. To avoid an already advanced design strategy forcing any acoustic *fait accompli*, the following strategies became the cornerstones of project progress.

Protect the architecture: The architectural themes embodied in Safdie Architects' design expressed a belief about what experiencing the resort should be like. As a significant environmental factor, acoustic design needed to respect that belief, and be integral to realising the functionality embedded in the form. In particular, the speed of project delivery meant a duality of acoustic design co-ordination between architectural developments with the Safdie team in Boston, and procurement, detailing, and implementation methods by the Aedas team in Singapore.

Think like Las Vegas: LVS's business model is extraordinarily successful because it combines understanding what appeals to the patrons with surgical efficiency in getting monumental venues built quickly. Aligning design delivery by understanding the client's drivers for success as the world's leading destination resort developer led to a constant focus on acoustic recommendations tested by first-cost practicality creating durable value.

Build like Singapore: Understanding how Singapore has transformed itself in 40 years leads to respect for its business environment and unique construction culture. Successful design should always anticipate the locale where it will be built. Providing acoustic design guidance required acceptance of the often counter-intuitive building process in Singapore – different from how a large-scale resort would be constructed elsewhere.

Right – right now: The density of patron activities for a full amenity resort juxtaposes competing requirements for acoustic experience. All design elements – be they architectural, structural, mechanical, transportation, or building operations – potentially conflict with acoustic comfort. Exponential design streams meant extracting the turbulent flow of information throughout, and this required forensic yet immediate design input that would streamline design co-ordination rather than complicate it.

Design process

Testing assumptions
Acoustic design is often more challenging for sophisticated architecture that embodies a highly visual aesthetic. Acoustic outcomes can't be seen – even poor acoustic quality photographs well. Singapore's increasing population, combined with accelerated economic growth, has led to greater tolerance of acoustic pollution, so there was little precedent locally to counter ingrained assumptions about acoustic quality and how it could be achieved. Fortunately, both LVS and Safdie Architects had a distinctly more contemporary perspective on acoustics and what it meant to this resort's successful realisation. To be world-class in every possible way, acoustic design had to support and even safeguard the greater aspirations of the architecture.

Arup's role was to embed acoustic design considerations as a highly visible and integral element in the process of design and co-ordination. Often, strategic planning is the most effective method of noise control for a multi-dimensional project.

1.

Change management

Change management is always difficult on large fast-track projects. Here, the bar was raised even higher because multiple buildings and associated design streams ran in parallel. The first issue was just to be aware of what was changing. The second was to be able to react and respond to what design changes meant to acoustic quality.

To allow all project design stream leaders to understand the acoustic impacts of rapid and evolving change, the acoustics team developed clear, objective, and high-level acoustic design quality criteria, often using language deliberately reflective of the client's project goals. In some cases, acoustic quality criteria were relaxed to respect the unique nature of the operations of some of the venues.

In MICE, for example, rapid room reconfiguration was fundamental to the business model and to accommodate this, slightly lower acoustic targets were agreed. But in some cases, acoustic targets were set higher. Hotel guestroom acoustic insulation, for example, aimed to be better than any existing Singapore hotels, and at parity with Sands properties elsewhere.

Technical solutions

Sands Hotel and Sands SkyPark

The three hotel towers would be the most visibly striking symbols of the resort's grandeur, so acoustic quality for guests needed to represent the luxury of – and sanctuary within – a memorable visit. The interstitial nature of the hotel's design, however, meant balancing structural complexity, mechanical services, sleek and slender façades, and an extremely active upper level – the SkyPark. Furthermore, the spa and luxury suites were placed directly below massive rooftop equipment plant.

As well as addressing acoustic control between guestrooms, a co-ordinated strategy of façade, structure, and cladding details was developed to minimise acoustic leakage at the slender architectural edges where guestrooms divide the span of the exterior envelope. Glazing configurations were selected to minimise traffic noise impacts on the south façade overlooking the East Coast Parkway, and details were co-developed with Arup's façades team to account for construction sequence, attachment to the structure, and to block acoustically weak pathways at mullion and floor slab interstices.

To maximise acoustic balance of transmitted sound between rooms and from corridors, the in-room ventilation units were reviewed and specified to provide neutral, but not silent, air-conditioning for sound masking.

Because air-conditioning is rarely turned off in Singapore, this reliable source of "covering" sound could account for separating wall constructions of an efficient overall thickness to maximise room size and meet targets for floor plan density.

In any tall building, the view from the top necessitates premium spaces being at the crown. However, supporting the SkyPark amenities led to conflicts in locating premium hotel guest suites and the luxury spa directly below major rooftop plantrooms.

This was another example of careful and co-ordinated planning: the use of offsets, intermediate zones for duct and sprinkler runouts, and advantageous use of structural elements as mass separations ensured that patrons could enjoy both panoramic views and solitude with no awareness of the major services directly above them.

Theatres

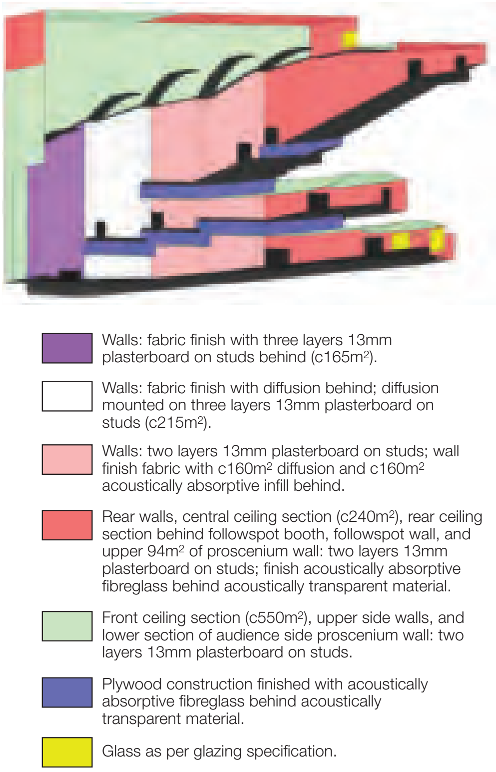
As already described on pp44-45, the theatres are embedded centrally in the north podium and retail concourse. Both are intended to be truly multi-purpose, and because of this need to credibly host almost any form of contemporary performance, the theatrical, technical, and logistical demands were challenging.

With the exception of the upper boundaries below the sculpted roofline, the bottom, lower sides, and outer perimeters of both theatres are close to various noise and vibration sources. Early in the design, the relationship of structure and geotechnics accommodation of site rail tunnels mere metres away from the theatre envelopes indicated that potential vibration transmission had to be fully understood.

Iterative review of structural interconnection and structure-borne vibration occurred regularly for six months, and analytical modelling of vibration transmission indicated that modified locations of lateral supports would reduce the need for a structurally floating outer theatre shell. Detailed study alongside structural design co-ordination led to confidence that the design for airborne noise control of the outer architectural theatre envelope would also control re-radiated noise from rail tunnel vibration. Another design strategy included detailing a special floating lower division below the theatres' structural floor to account for the car park and large exhaust fans directly under both theatres.

The interior acoustic quality was developed in tandem with the architectural concept for accommodating the vast range of artistic performances slated in both theatres. Elemental to the design, in addition to being quiet, was the need for the full theatrical and sound technical systems required. The room acoustic design strategy was to balance moderate reverberance with strong early reflection support. This environment also needed to be fully complementary to the full-range audio reinforcement system designed by SAVI Inc.

The primary room acoustic control strategy is invisible. Hidden behind an acoustically transparent architectural fabric facing are wall treatment zones that transition from sound reflective into sound scattering (acoustic diffusion) and then to sound absorbing at the rear of the audience seating.



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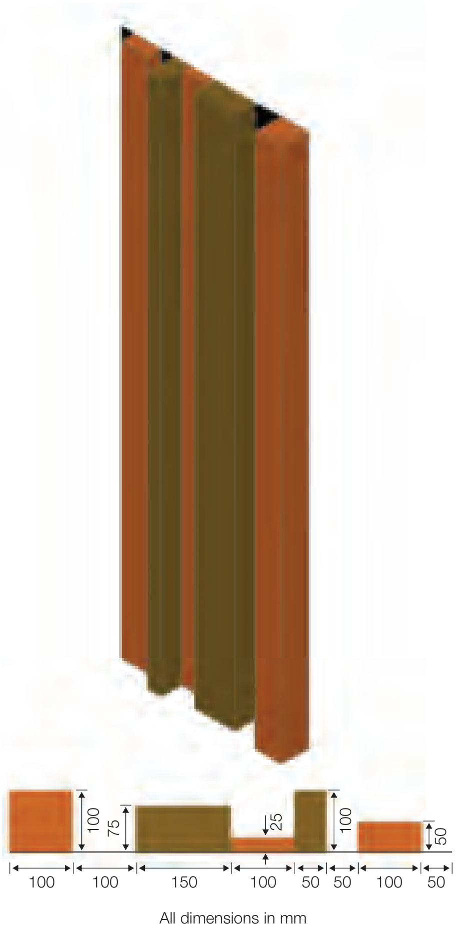

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A common issue with lyric theatres is that they tend to be too "dead" acoustically; while this aids speech intelligibility and doesn't compete with the audio systems, it can also lack a sense of spatiality and excitement. A collaborative process that optimised architecture, sound system design, and the right blend of acoustic energy redirection led to a sonic marriage for the MBS theatres that allows amplification to sound natural and transparent.

Hotel structural vibration

The same vibration analysis that informed the theatre structural design was also used to assess impacts on the hotel. Structure-borne vibration can transmit very efficiently over what may seem long and circuitous paths, and re-radiate as low-frequency noise.

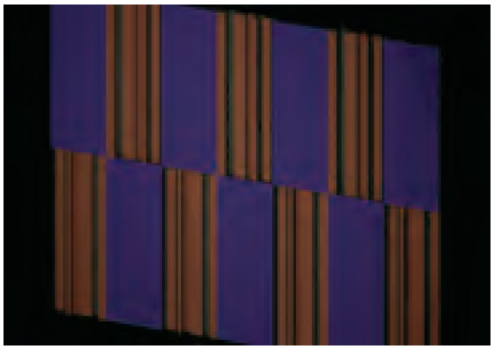
Full-scale guestroom mockups were built midway through the project design to assess fixtures, furnishings, façades, and constructability. Because these were spatially accurate representations of the eventual acoustic environment, the team recorded background noise in the mockup rooms with air-conditioning operating, and used an acoustic overlay of predicted low-frequency rumble to demonstrate the potential impacts of site rail transit on sleeping guests. This led to a recommendation to deal with rail vibration at source, rather than trying to design the hotel structure to minimise vibration transmission.

Sands Expo and Convention Center

From the outset, the operational importance of MICE to the resort was well understood. LVS was highly successful at hosting, reconfiguring, and seamlessly expanding or contracting the range of convention and exhibition gatherings at a mind-boggling turnover rate. To do all this necessitates the moving walls or operable partitions to be deployed quickly and flexibly, while enabling simultaneous adjacent use of potentially competing activities.

MICE has kilometres of operable partitions. As well as the cost of these systems, the design had to allow for various special configurations, minimising the storage footprint, speed of setup, long-term durability – all while meeting and maintaining an appropriate level of acoustic separation.

To activate a cost-effective design strategy, the Arup team worked with LVS to capture a knowledge base of operable partition use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1. (Previous page) The completed Grand Theater.

2. Zones in the theatres for acoustic reflection/diffusion/absorption.

3. Custom acoustic diffusor.

4. Combination of acoustic diffusion + absorption into panels.

5. Acoustic diffusor + absorber panels being installed prior to covering with fabric-faced architectural finish.

6. Interior of Sands Theater showing all acoustic wall finish configurations in place prior to installation of final fabric facing.

from its existing properties. On-site acoustic tests, plus discussions and review from senior operations staff, allowed the team to accurately inform optimal design strategies. Design considerations included product performance, procurement, and most importantly, installation and operations impacts. This review enabled a less stringent specification standard for operable partition acoustic ratings, and yet maintain the usability and acoustic performance needed to suit the business and operations model.

ArtScience Museum: visualisation modelling

ASM is an architectural and structural marvel, even in the context of the resort's other aesthetic megaliths. There is nothing conventional about the building's expressive architectural form, and it would be difficult to predict sound propagation within the complex curvature of the interiors in a traditional way.

To understand the intricacies of how sound would reflect and move through the gallery "fingers", the team used 3-D sound ray propagation models to show the time and distribution sequence of acoustic energy. This provided a means to visualise the complexities of acoustic anomalies, and to explore architectural finish options.

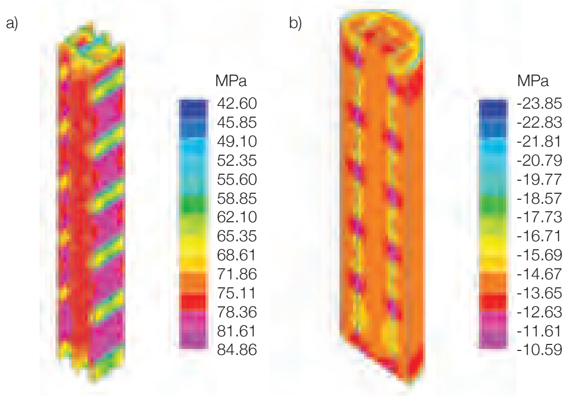
Implementation and constructability

To realise practical acoustic design outcomes, the devil is truly in the details. Much of what is needed for acoustic quality is embedded in seemingly benign details that can undermine acoustic performance. MBS, and the sheer size and speed of the design development to enable it, demonstrated that getting the right information at the right level of detail was a case of carefully "picking your battles". Knowing that thousands of details generated on the project would or could not be seen, the team's strategy was simply to focus on the key details that would be breakpoints for performance.

Fortunately, the way to attract attention to critical details was potential cost impact. Detailing for acoustic performance could either cost or save large sums since the typical multiplier – especially considering the number of hotel guestrooms and MICE operable partitions – would be in the thousands. This was an example of cost scrutiny giving acoustic design a position of significant leverage. And once the attention was given, it was a useful magnet for convincing the project team where detailing was critical.

Outcome

On any large project, quality outcomes for acoustics have a relatively low level of sheer luck as the determining factor. The MBS client and project team recognised early on that embedding acoustic design at every stage would favour a successful result. Singapore now has a signature destination resort that is a reference for quality, including sonic experience, while once again redefining its stature as a country small in geographical area, but with grand ambition.



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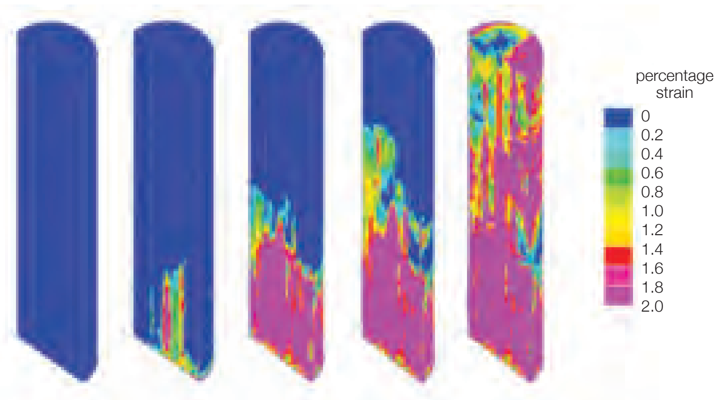

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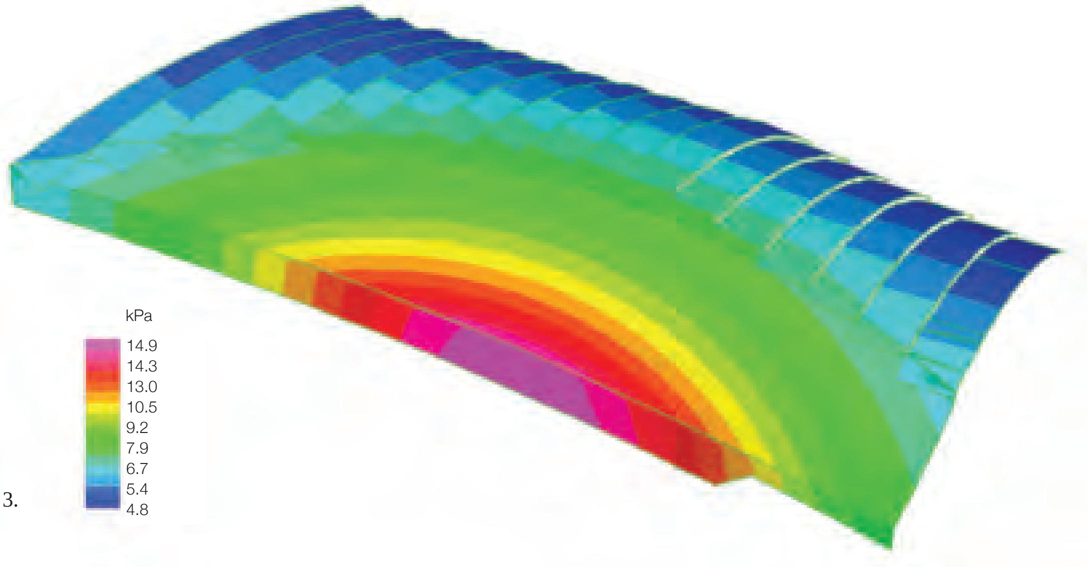

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1. Stresses calculated in fabricated steel (a) and steel-encased concrete columns (b) subjected to close proximity blast loading.

2. Time lapse strains experienced by concrete-encased steel columns, at intervals of 5 milliseconds, subjected to close proximity blast loading.

3. Blast pressure on the long-span roof generated from an externally detonated improvised explosive device.

Blast-resilient design

Author
Peter Hoad

Marina Bay Sands has effectively changed the shape of Singapore. Its iconic form and the amenities provided, adjacent to the central business district, are attracting a significant range of visitors, including many local residents, visitors, and dignitaries from within and outside the country. It is not just a casino, or hotel, or entertainment centre. It is all these and far more. With its diverse entertaining, learning and accommodation facilities in a very open and public site, the integrated resort is drawing people from all walks of life for a multitude of reasons.

Singapore's Ministry of Home Affairs (MHA) takes an active interest in the safety and security of the country's people, and of particular interest are facilities that are likely to attract mass gatherings, as these could be considered a target to some terrorist groups. So when the MBS integrated resort project was first mooted, MHA advised of its requirement that the facility be designed with special consideration for the protection of its inhabitants in the case of a terrorist event in or nearby.

Arup was engaged by the Marina Bay Sands owning/operating company, through the local project architect, Aedas, to provide a threat and vulnerability risk assessment. This considered several terrorist threats that had been defined by the MHA. On completion of the assessment, Arup undertook a detailed study of the designed form of the resort to ascertain its resilience blast loading, based on potential scenarios included in its threat and vulnerability risk assessment and agreed with the MHA.

As a result of this study, particular vulnerabilities were identified in the proposed building structure and façade, and Arup recommended measures which were then introduced into the base design to "harden" the structure and façade to overcome the vulnerabilities identified and thus afford better protection to the occupants of the building.

Blast analysis to assess (and upgrade) blast resilience of the façade and structure included use of:

- limited issue military-derived software
- Arup-developed single degree of freedom analysis software
- sophisticated 3-D, non-linear analysis software.

Output from the Arup resilience, security and risk team was combined with input from the numerous other Arup designers from the structural engineering and façade engineering teams to deliver a fully integrated blast-resilient design facility, in accordance with the requirements of the MHA.

Delivering success

Site phase supervision

Author
Wah-Kam Chia

Introduction
In the decades before Singapore gained full independence in 1965, the Marina Bay Sands site was a landing area for shipping, both large and small. It was subsequently reclaimed using sand fill, and the soil investigation report showed this to lie above a very thick layer of soft peaty clay.

The close surroundings offered other challenges – to the east across Marina Channel was the busy East Coast Park, immediately adjacent to the site's northern extremity was Benjamin Sheares Bridge, and to the west lay the waters of Marina Bay – and in addition the project had to be completed within 3.5 years from the date the site was awarded to the client.

Monitoring excavations and substructure
Arup's innovative use of circular and peanut-shaped diaphragm walls both to minimise lateral movement during excavation and provide obstruction-free excavation spaces has already been described (pp12-15).

Constant monitoring of all the wall deflections was a statutory requirement; if they were not within agreed limits, the site supervision team had to order the work within that area to be stopped.

In practice, the monitoring confirmed that the system was working well within the predicted values generally approved by the local authorities. Throughout the deep excavation, Arup's proposed construction method proved to be successful.

Project and construction management and supervision
This was an exceptionally large project, even for Singapore. The client, Marina Bay Sands Pte Ltd, itself took the role both of project management and construction management (PMCM), engaging about 400 multinational full-time site project management and construction engineering staff to manage the numerous contractors.

The presence of so many project and construction managers, as well as the contractors' own staff, gave the Arup team a challenging re-alignment of the role of its resident site staff – Arup's Singapore practice had been used to the "normal" way of managing projects. The fact that the client had appointed its own managers meant that Arup site staff had to deal with them rather than liaise directly with the contractors, and it therefore took a while before the Arup team became accustomed to the system.

The scale of the integrated resort meant that, at the peak of construction site activities, Arup had more than 80 full-time resident site staff. These had to be split into three eight-hour daily shifts as the construction work was based on a 24/7 schedule. As the "Qualified Professionals" who were responsible for the design and construction supervision to Singapore's Building and Construction Authority (BCA), Arup therefore had to deploy not one QP for the supervision in accordance with the BCA's minimum requirement, but three.

Risk and safety
Inevitably such an enormous project was not completed entirely without site accidents. Though regrettably there were two fatalities and some serious injuries, these were mainly due to individual negligence and not to any design inadequacies. Arup was fortunate in that none of the firm's staff was involved in any mishaps, and greatly appreciated the involvement of a senior safety specialist from the Melbourne office, who monitored throughout construction with constant reminders that safety in every aspect was of the utmost importance.

The local team was also guided by the risk and security leader of the Australasian practice through the process of risk analysis during construction, covering every aspect of risk. This helped the team to keep abreast of any potential risks as well as reminding each member during day-to-day supervision.

Leveraging global skills

Author
Peter Bowtell

Rarely does a project need the global reach of an organisation to be fully engaged. However, delivering Marina Bay Sands required Arup to draw deeply upon its global skills and bring expertise to bear from all over the globe. In terms of sheer scale the conceptual undertaking was enormous, with billions of dollars of construction to be delivered in less than two years. Manpower was a key strategic resource and each region did its part in shouldering the load.

While Arup's Singapore practice had delivered significant infrastructure projects, Singapore as a country to work in was new to nearly all the Arup staff involved from other regions, and the design conceived by Safdie Architects was complex. However, pre-existing knowledge of the client Las Vegas Sands' requirements from the East Asia region's experience on the Macau casinos on the Cotai strip provided an invaluable jump start.

Knowledge of client preference for structural systems enabled scheming to commence from day one, even before the architectural concepts were laid out on butter papers. Arup's Hong Kong team mobilised with lighting speed, marshalling resources, reinforcing the local Singapore practice, and co-ordinating with the concept team in Boston. Senior leaders relocated at a moment's notice and in just a few weeks a fully capable design team was operating with the best resources from Singapore, East Asia, Australia, and the USA.

Design activities split across the globe. In Boston, the local office combined with the New York team to scheme the above-ground elements, working side-by-side with the Safdie office. In Singapore, conceptualisation of the in-ground works moved ahead with breakneck speed, to enable early commencement of the excavations. Technology enabled rapid communication between global sites, with *See and Share* virtual collaboration meetings happening frequently throughout the days and weeks. Client briefings led by Safdie Architects were held monthly, with key team members meeting in Boston to present to the client team. Decision-making was rapid and concepts were finalised using virtual prototypes and physical models. Key to the process was concurrency and the ability to feed back development between teams on a daily basis. Globally-connected file servers meant that real-time information was available to all as and when required.

Six months saw the conclusion of all schematic design and the team relocated to Singapore where the site clearing had already commenced. Advanced BIM modelling was leveraged for the design, with massive models defining the built works in an ever-changing environment. In Singapore the team swelled to over 80 design professionals, supported by about the same number of on-site inspection staff.

As designs approached completion, specialist expertise was mobilised from London, Sydney, Melbourne, Brisbane, Shenzhen, Manila, South Africa, the USA and beyond. Advanced dynamics, façade, acoustics, fire engineering, traffic, structural, civil, geotechnics, security risk and resilience advice – all were much in demand across the project.

Arup had been involved in major Singapore projects for 40 years, but Marina Bay Sands was unprecedented, testing and challenging the firm's ability to deliver world-class engineering on a massive scale. To judge from the success so far of the end-product, it proved equal to the challenge.

Bring on the next one.

Marina Bay Sands Integrated Resort is already an icon for Singapore – an industry-revolutionising project that will change the face of construction for the next decade.

Completing the programme

Authors
Va-Chan Cheong Joe Lam

"Impossible is nothing"
To complete a project with total ground floor area of 540 000m² – equivalent to seven of London's 46-storey Heron Tower, or three of Hong Kong's 88-storey International Finance Centre (2IFC) – in 48 months seemed unachievable to everyone in Singapore. This is understandable given that in the history of Singapore no project on this scale had ever been built, not to mention the very tight programme.

Arup has often taken on major engineering and design challenges but, combining the difficulties of a five-level deep basement next to seawater; three long-span steel roofs over the casino, theatres, and Sands Expo and Convention Center; the longest building cantilever in the world supporting the northern end of the Sands SkyPark; and the geometrically challenging lotus-like ArtScience Museum, "unachievable" seemed not to be an overstatement and "impossible" maybe a more appropriate word.

Instead, the whole Arup project team seemed to take the *Adidas* slogan on board from day one: "Impossible is nothing".

But from behind the scenes one could see what others could not. This was why Arup pursued this challenge. Combining the good relationship that the US offices had with Moshe Safdie himself, the expertise of the Advanced Technology Group and its global project track record, the firm's BIM capabilities, the list of projects with deep basement and geotechnical challenges, the fast-track, large-scale project experience for several Venetian developments in Macau, and the client's previous trust in Arup, and you start to omit the "im" in "impossible".

Expediting construction
To meet the tight programme, the team had to consider how to accelerate construction during the schematic and design stages. Precast concrete construction and prefabricated steelwork were used wherever appropriate to increase off-site and minimise on-site construction work. For the geotechnical design, the innovative introduction of circular cofferdams allowed no use of shoring while excavation advanced. For the ArtScience Museum, the perfectionist Moshe Safdie required much tweaking of the geometry before the design met his standards.

This would have been excessively time-consuming with 2-D drawings co-ordination, but Arup's strong BIM capabilities enabled the architect's *Rhino* model to link with the team's own 3-D structural model, thus automating the process. This allowed many options to be studied quickly and at least three times the effort saved during detail design compared with transferring the architect's geometry in 2-D only to the structural model or drawings. In addition, the use of BIM helped speed the steelwork shop drawings review and cut down requests for information by over 80%.

Maximizing the battlefield
On site, the project was divided into 140+ packages, excluding fit-out works. Interface co-ordination between packages was very important to allow smooth transition from one contractor to another, and Arup worked closely with the client's project management team to execute this package arrangement effectively. Although there were more issues to be handled, they were not on the critical path and the result was completion of the programme in an amazing 48 months.

Credit for completing the programme so quickly initially seems due to the Arup office running the project, but it would have been impossible without matching enthusiasm and expertise from colleagues elsewhere.

The success of this project lay not only in Arup's technical capabilities *per se*, but in how its offices could work together as a team to deliver the project to the highest quality possible. Marina Bay Sands, together with other high-profile projects in Singapore, has set new standards for the building industry in East Asia.

Conclusion

Authors
Va-Chan Cheong Otto Lai

Challenges
Using its knowledge and determination to strive for excellence, Arup strove to provide the best solutions for the client's requirements. This *Arup Journal* describes how the firm drew on its global expertise for the many aims and aspects of the project, in particular the difficult tasks such as the 120m diameter cofferdams for substructure works, the 66.5m long cantilever steel structure, the unique geometry of the ArtScience Museum, the glazing for the Crystal Pavilions, and the long-span roof trusses for the podium structures.

Almost every aspect of MBS was technically challenging, and stretched the limits of engineering. In responding, the team adopted new and innovative technologies that pushed the boundaries of current software and systems, pulling together as a design team of global skills from four continents to communicate effectively and deliver outcomes to meet the client's needs and turn the design concept into reality.

Benefits
The integrated resort elevates Singapore's tourism and business opportunities, its facilities enabling it to be a leading Asian MICE hub. In addition MBS provides employment opportunities for many.
The local community benefits from the district cooling plant by avoiding the need for chiller plants and cooling towers on buildings. This in turn optimises the use of water and other natural resources for generating energy.

There were doubts that this project could be completed, due to site constraints and technical and economic difficulties. However, the design team approached all this in ways that opened up new resources and enhanced experience and knowledge across Singapore's building industries.

It exemplified what can be achieved in situations that need engineering judgement beyond what is distinctly covered by code. The MBS project also benefited the Singapore BCA (Building and Construction Authority) engineer and accredited checker of the project, broadening the mindset on how to overcome such challenges, and raising the bar of what can be accomplished with international resources.

Authors

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Franky Lo is a senior engineer in the Hong Kong office. He was a leader of the design team for the ArtScience Museum, Crystal Pavilions and theatres.

Rudi Lioe is a senior engineer in the Singapore office. He was a member of the design team for the hotel towers.

André Lovatt is a Principal and leads the Singapore office. He jointly led the fire safety design team for Marina Bay Sands.

Juan Maier is an Associate in the Singapore office. He led the design team for the structural steel roof of MICE, the casino and the theatres.

Brian Mak is an assistant engineer in the Hong Kong office. He was a member of the design team for the SkyPark, ArtScience Museum and Crystal Pavilions.

Patrick McCafferty is an Associate in the Boston office. He was the Americas Region Project Manager for Marina Bay Sands and helped lead the structural design team.

Brendon McNiven is a Principal in the Melbourne office. He was the Professional Engineer responsible for statutory design submission for the MICE/casino/theatre roof steel structures, hotel atrium steel structures and SkyPark structures.

Jack Pappin is an Arup Fellow in the Hong Kong office. He oversaw and led most of the geotechnical design for Marina Bay Sands.

Moshe Safdie is an architect, urban designer, educator, theorist, author, and founder of Safdie Architects, designer of the Marina Bay Sands integrated resort.

Mac Tan is a senior façade consultant in the Singapore office. He was the façade package leader in charge of all façade systems covering the hotel towers and atrium, SkyPark, ArtScience Museum, and Crystal Pavilions.

Larry Tedford is an Associate Principal in the San Francisco office. He led the acoustics design team for Marina Bay Sands.

Alex Wong is a façade designer in the Singapore office. He was the façade package leader in charge of all façade systems covering the MICE, casino, and theatres.

Ruth Wong is an Associate in the Singapore office. She jointly led the fire safety design team for Marina Bay Sands.

Wijaya Wong is a Senior Associate in the Singapore office. He led the design team for the hotel and SkyPark. He was the Professional Engineer responsible for statutory design submission for the hotel.

Xiaofeng Wu is an engineer in the Singapore office. He was a member of the design team for the hotel atrium, MICE, events plaza, promenade, ArtScience Museum and Crystal Pavilions.

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Project credits

Clients: *Las Vegas Sands Inc/Marina Bay Sands Pte Ltd* Architect: *Safdie Architects* Singapore architect: *Aedas Pte Ltd* Geotechnical, civil, structural, façade, fire, BIM, acoustics, audiovisual, blast and security consultant: *Arup* Building services engineers: *Parsons Brinckerhoff Pte Ltd/Vanderweil Engineers* Quantity surveyor: *EC Harris/Rider Levett Bucknall* Landscape architect: *Peter Walker & Partners/Peridian Asia Pte Ltd* Hotel contractor: *Lian Beng Construction Pte Ltd/SsangYong Engineering & Construction Ltd* SkyPark contractor: *Yongnam & JFE Engineering Corporation JV* ArtScience Museum contractor: *Penta Ocean* MICE/retail steelwork contractor: *Alfasi Constructions Singapore Pte Ltd* Casino and theatre steelworks contractor: *Singapore Jinggong Steel Structures Pte Ltd* Foundations contractors: *Soletanche Bachy Singapore Pte Ltd/Sambo Geo-Tosfoc Co Ltd/L&M Foundation Pte Ltd* South/North Podium excavation and reinforced concrete contractors: *KTC Civil Engineering & Construction Pte Ltd/Yau Lee Construction Pte Ltd/Sembawang Engineers and Constructors Pte Ltd* ArtScience Museum cladding contractor: *DK Composites Sdn Bhd* Retail canopies contractor: *YKK Architectural Products Inc*
Tenant fitout in South Crystal Pavilion: *Pure Projects Singapore Pte Ltd* Theatre planning and engineering design consultant (for both theatres): *Robert Campbell, Associate Principal, Fisher Dachs Associates*
Performance sound, video, and production communications design consultant (for both theatres): *Michael Cusick, President, Specialized Audio-Visual Inc*
Signage subcontractor: *Crimsign Graphics Pte Ltd.*

Project awards

Association of Consulting Engineers Singapore
ACES Engineering Excellence Award 2011:
Civil & Structural Engineering Consultant
Hotel and SkyPark

Bentley 2010 Be Inspired Award Winner

Institution of Structural Engineers
Singapore Structural Awards 2010 Award for Structures
Hotel and SkyPark

Singapore Structural Steel Society
Structural Steel Design Award 2010 Award for Commercial Structures
Podium roof and canopy structures

National Fire and Civil Emergency Preparedness Council Fire Safety Design Excellence Awards 2011
Hotel and SkyPark

The following past and present staff members from Arup offices worldwide are among those who made significant contributions to the design of Marina Bay Sands.

Joy Aclao, Nur Liyana Ahmad, Ian Ainsworth, Graham Aldwinckle, Jarrod Alston, Evan Amatya, Joseph Amores, Richard Andrews, Christine Ang, Ling Ling Ang, Siow Ting Ang, Christopher Anoso, Easy Arisarwindha, Mark Arkinstall, Feng Bai, Jaydy Baldovino, Warren Balitcha, Venugopal Barkur, Rachel Baylson, Dan Birch, Hay Sun Blunt, Greg Borkowski, Sarah Boulkroune, Nick Boulter, Peter Bowtell, Ashley Bracken, Claire Bristow, Daniel Brodkin, Jessica Cao, Neil Carstairs, Matt Carter, Kartigayen Poutelaye Cavound, Chee Wah Chan, Chris Chan, George Chan, Kam-Lam Chan, Ken Chan, Marco Chan, Michael Chan, Tat-Ngong Chan, Wayne Chan, Yun-Ngok Chan, Renuga Chandra, Angela Chen, Carrie Chen, Chi-Lik Chen, Melissa Chen, Harold Cheng, Cecilia Cheong, Joy Cheong, Patrick Cheong, Va-Chan Cheong, Kenny Cheung, Henry Chia, Wah-Kam Chia, Reve Chin, Clyfford Ching, Park Chiu, Derek Chong, Sok Poi Chong, TS Choong, Henry Chow, Hee Kung Chua, Wee Koon Chua, Rene Ciolo, Richard Clement, Ranelle Cliff, Lyonel Cochon, Russell Cole, Yimin Cong, George Corpuz, Joseph Correnza, Anne Coutts, Robert Coutu, Raymond Crane, Josh Cushner, Richard Custer, Yang Dang, Bruce Danziger, John Davies, Lauren Davis, Ethelbert Derige, Antonio Diaz, Mike DiMascio, Ran Ding, Nick Docherty, Graham Dodd, Matt Dodge, Andrew Douglas, Pierre Dubois, Andy Ellett, David Farnsworth, Garth Ferrier, Kai Fisher, Raymond Fok, Clarice Fong, Raymond Fong, Vivien Foo, Kathy Franklin, Feng Gao, Chris Gildersleeve, Gina Goh, Gladys Goh, Ian Grierson, Ken Guertin, Liana Hamzah, James Hargreaves, Rotana Hay, Donal Hayward, Eric He, Zheng-Yu He, Grace Hendro, Kok Hui Heng, Argi Hipolito, Andy Ho, Chong Leong Ho, Don Ho, Kent Ho, Stanley Ho, Wee Keong Ho, Peter Hoad, Dennis Hoi, Martin Holt, Anna Hon, Andrew Hulse, Sarah Huskie, Philip Iskandar, Mellissa Ismail, Sha Mohamed Ismail, Anthony Ivey, Frank Jeczmionka, Steven Jenkins, William Jimenez, Hong Geng Jin, Matt Johann, Carl Jones, Steven Jones, Edmond San Jose, Chak-Sang Kan, 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Lin, Jonathan Lindsay, Brett Linnane, Rudi Lioe, Amy Liu, Charlie Liu, Chris Liu, Xi Liu, Franky Lo, André Lovatt, Sin Ching Low, Danny Lui, Jack Lui, Kwok-Man Lui, Marcellus Lui, Kok Mun Lum, Malcolm Lyon, Michael Macaraeg, Juan Maier, Alex Mak, Brian Mak, Dylan Mak, Louis Mak, Louise Mak, Martino Mak, Dexter Manalo, Mukunthan Manickavasakar, Anand Mariyappan, Patrick McCafferty, Sean McGinn, Brendon McNiven, Maciej Mikulewicz, Wing Sze Mo, Junaidah Mohd, Martin Mok, Polly Mok, Lydia Mokhtar, Andrew Mole, Rodel Moran, Jon Morgan, Dean Morris, Samir Mustapha, Vaikun Nadarajah, Bob Nelson, Andrew Neviackas, Derek Ng, James Ng, Jason Ng, Ka-Yuen Ng, Peck Nah Ng, Andrew Nicol, Phamornsak Noochit, Alison Norrish, Ada Oh, Edwin Ong, Janice Ong, Natalie Ong, Khine Khine Oo, Kamsinah Osman, Ayca Ozcanlar, Jin Pae, Priya Palpanathan, Jack Pan, Kathy Pang, Jack Pappin, Stuart Pearce, Alan Philp, Maggie Puvannan, Chris Pynn, Jie Qian, Virgilio Quinones, Jim Quiter, Nizar Abdul Rahim, Mohan 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About Arup

Arup is a global organisation of designers, engineers, planners, and business consultants, founded in 1946 by Sir Ove Arup (1895-1988). It has a constantly evolving skills base, and works with local and international clients around the world.

Arup is owned by Trusts established for the benefit of its staff and for charitable purposes, with no external shareholders. This ownership structure, together with the core values set down by Sir Ove Arup, are fundamental to the way the firm is organised and operates.

Independence enables Arup to:

- shape its own direction and take a long-term view, unhampered by short-term pressures from external shareholders
- distribute its profits through reinvestment in learning, research and development, to staff through a global profit-sharing scheme, and by donation to charitable organisations.

Arup's core values drive a strong culture of sharing and collaboration.

All this results in:

- a dynamic working environment that inspires creativity and innovation
- a commitment to the environment and the communities where we work that defines our approach to work, to clients and collaborators, and to our own members
- robust professional and personal networks that are reinforced by positive policies on equality, fairness, staff mobility, and knowledge sharing
- the ability to grow organically by attracting and retaining the best and brightest individuals from around the world – and from a broad range of cultures – who share those core values and beliefs in social usefulness, sustainable development, and excellence in the quality of our work.

With this combination of global reach and a collaborative approach that is values-driven, Arup is uniquely positioned to fulfil its aim to shape a better world.

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