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The Arup Journal

Contents

Front cover:
Elizabeth Quay Pedestrian and Cyclist Bridge, Perth, Australia.
Photo: *Arup Associates.*

Left:
Arnhem Station,
The Netherlands.
Photo: *Hufton+Crow.*

Lake Mead Intake No.3 USA

Location
Nevada, USA

Authors
Jon Hurt Luis Piek


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1. The ring of lighter rock around the water's edge in this aerial picture of Lake Mead shows how swiftly and extensively the water level has dropped.

Introduction
Orchestrating the design and construction of the world's highest pressure subaqueous tunnel, bored through the bed of Lake Mead reservoir, South Nevada, involved Arup's international tunnel engineering team designing one of the most difficult tunnelling projects ever attempted. It was an unprecedented challenge: the tunnel is big enough to accommodate a train, so it was similar to building a subway tunnel under extreme water pressure of up to 17 bar.

Construction was demanding and difficult, and the stakes were high. Lake Mead supplies water to 25 million people, including 90% of the drinking water consumed by the 600,000 residents of Las Vegas. The tunnel forms a new intake that is critical to maintaining supply.

Known as 'the third straw' because it supplements two existing intakes, the tunnel was unplugged in September 2015 when an 8.6 ton steel bulkhead was lifted from the top of the intake to let water flow to a pumping station. The project took eight years from inception to completion. Arup was lead designer, working with the Vegas Tunnel Constructors (VTC) design and build joint venture comprising Salini Impregilo and S.A. Healy.

Context

Lake Mead, the largest man-made reservoir in the United States, was created by construction of the Hoover Dam on the Colorado River in 1935. It has capacity for 34 billion cubic metres of water and is linked to the associated Colorado River system. Prolonged drought and a fast-growing population is straining the system, however, and the lake level has fallen drastically and dramatically. In 2007, Echo Bay Marina in Lake Mead National Recreation Area was full of sailing boats. Less than a decade later, the marina is dry and dusty. The water level fell by 30m in the eight years from 2007 to 2015.

With the reservoir down 38% from its peak in 1983, and the rate of attrition so swift, the Southern Nevada Water Authority (SNWA) feared that performance of the two existing intake tunnels from Lake Mead would deteriorate fast, drawing in water of poorer quality, then eventually running dry completely. To avert this potential crisis, SNWA launched a design-build competition, won by Vegas Tunnel Constructors and Arup, for the design and construction of a third intake through the bottom of the lake to safeguard supply and water quality.

The 'third straw' would draw water at lake elevations less than 300m above sea level, draining the snowmelt carried by the Colorado River from the Rocky Mountains further into the lake. It would substantially increase the reliability and flexibility of SNWA's water treatment and delivery system, providing water via a pumping station, even if lake elevations dropped too low for the Hoover Dam to release water to downstream users.


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Overview

The 6.1m diameter tunnel runs 5km under the lake from a 180m deep onshore access shaft. The tunnel boring machine used to excavate the tunnel encountered water pressures up to 17 bar as it ground through layers of rock beneath the 100m deep lake. To manage the risks, which included total inundation while connecting the tunnel to the intake, the Arup team developed an innovative and unique concept that involved prefabricating the intake structure in a hole at the bottom of the lake, surrounding it with concrete, then connecting the tunnel directly into this structure.

Rather than sinking a conventional drilled shaft in the lake and tunnelling into it, as the original brief suggested, Arup designed a precast 'elbow' that could be partially buried and capped on top. A tunnel boring machine (TBM) would fit precisely into the elbow, taking on water pressure while reducing risk for those working underground on the project. The TBM would bore 5km through complex and variable geologic features under the lake to connect the onshore access shaft with the intake riser structure on the bottom of the lake. Additional underground connections would link the new intake to the existing water intake system.

2. View of the Hoover Dam intake towers from the shoreline showing the original lake elevation and the drop in water levels.

3. Schematic of the first two shallower intakes, with Intake No.3 placed further offshore in one of the deepest areas of the reservoir.

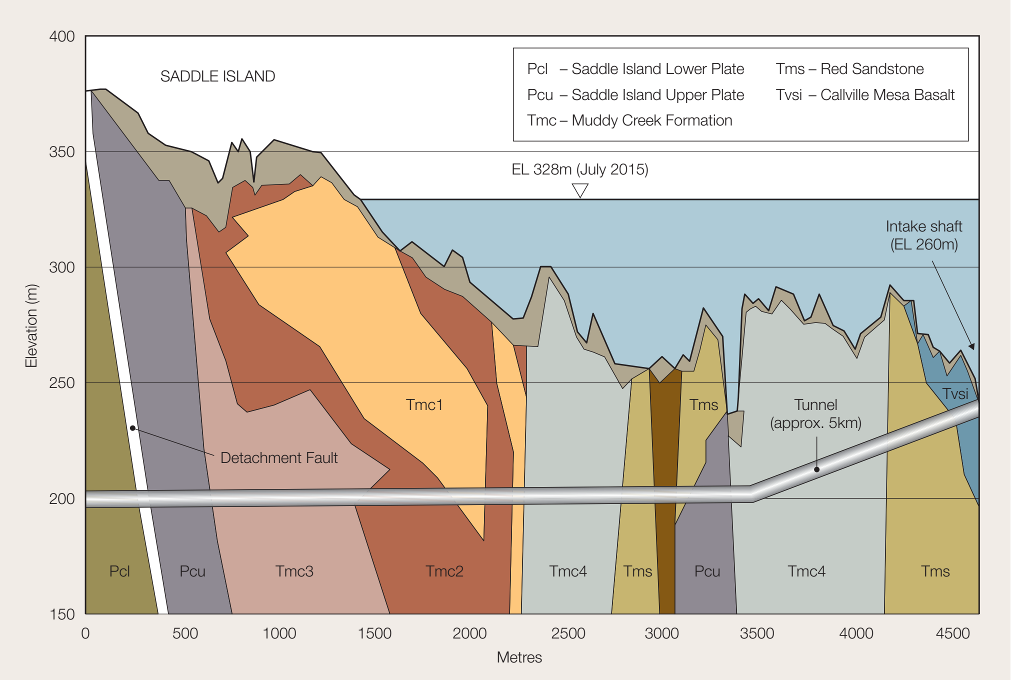
4. Geology encountered along the alignment.

5. Schematic of the access shaft showing the TBM assembly chamber, starter tunnel, and connection to Pump Station 3.

6. Photo showing the top-down construction methodology for the access shaft excavation.

7. Setting of the ring beam for the start of concrete works at the access shaft.

8. Face mapping the geology of the starter tunnel.



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Geotechnical challenges

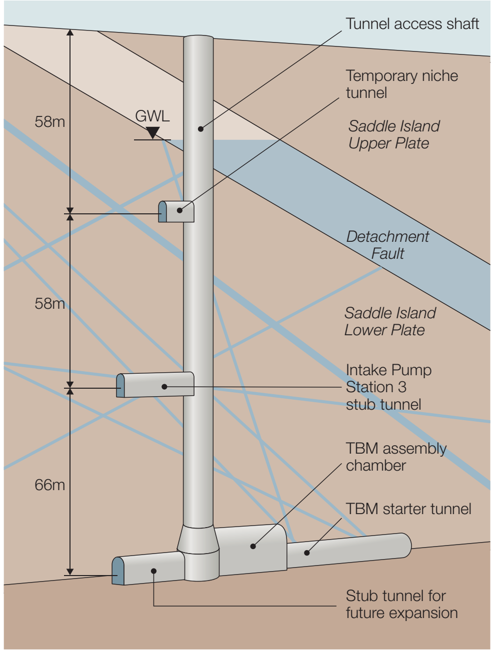
The tunnel access shaft, TBM assembly chamber, and starter tunnel are located within the Saddle Island Formation, which is a mass of Precambrian metamorphic rock approximately 3km long and 600m wide. The Detachment Fault is a major northeast-striking, northwest-dipping, low-angle fault that separates the island into two distinct geologic formations: an Upper Plate and a Lower Plate.

The Upper Plate is a heterogeneous assemblage of crystalline metamorphic rock, predominantly quartz-feldspar gneiss and mica schist, intruded by hypabyssal dacite and diorite of Tertiary age. The Lower Plate principally consists of variably mylonitised amphibolite and quartz-feldspar gneiss. Although the majority of the tunnel access shaft was constructed in the Lower Plate, the top of the shaft is in the Upper Plate and the Detachment Fault passes through the shaft between 15m and 45m below ground level. During construction, additional high-angle faulting was discovered in this area as well. The intake tunnel extends from the tunnel access shaft around the northwest tip of Saddle Island. On leaving the shaft, it passes from the Lower Plate through the Detachment Fault and into Upper Plate material and then into the Muddy Creek Formation.

The Upper Plate material was very challenging for tunnelling, as it was highly fractured and highly permeable, making maintenance of the TBM very challenging. The Muddy Creek Formation is a Tertiary sedimentary rock. Conglomerate, breccia, sandstone, siltstone and gypsiferous mudstone of the Muddy Creek Formation are encountered throughout much of the tunnel alignment corridor. The Muddy Creek Formation is divided into four sub-units primarily based on grain size and mineralogy. The sub-units are gypsiferous mudstone; interbedded siltstone, sandstone, and pebble conglomerate; tan conglomerate; and reddish brown conglomeratic breccia.

The Las Vegas Wash was the major drainage feature of the Las Vegas Valley before the area was submerged under Lake Mead. The submerged wash crosses the project area to the northeast of Saddle Island as a narrow and deeply entrenched channel extending to the pre-Lake Mead flood plain of the Colorado River. The wash is approximately 60m to 300m wide and is filled with alluvial sand, gravel, cobbles and boulders. The tunnel alignment crosses under the wash with approximately 12m of rock cover.

At the northeastern limit of the project area, an older Tertiary conglomerate of the Red Sandstone Unit is encountered adjacent to the younger Muddy Creek Formation, and this is overlain by basalt of the Callville Mesa Unit. The Callville Mesa Unit is comprised of several distinct flows of Tertiary basalt and, at the intake area, forms a cap rock that ranges in thickness from less than 7m to greater than 36m. The intake structure was located within the basalt cap.



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Access shaft
Work on the new intake began with the excavation of a vertical access shaft on a peninsula at the west side of the lake at Saddle Island. The 9m diameter shaft was designed for high compressive forces from the ground and groundwater. Recognising that the hoop stresses were generally uniform, the shaft was designed as a ring under compression, allowing a plain concrete lining to be designed.

A top-down construction method was adopted, with the permanent lining installed following initial excavation and installation of temporary support. This entailed evaluating the effects of blasting near freshly placed concrete relating to the peak particle velocity and peak particle acceleration. The process was essentially drill, blast, excavate, map the rock face, install initial support, lower form, cast concrete, repeat.

The 180m depth of the shaft resulted in high in-situ groundwater pressures. To reduce the effect of these pressures on the shaft lining, drainage holes were designed into the lining and the resulting influence of the groundwater was modelled. This careful approach resulted in a reduction of 50–75% in water pressure, depending on the elevation.

The load factors used for shaft linings were based on ASCE/SEI 7-05: Minimum Design Loads for Buildings and Other Structures. This specifies a load factor of 1.4 applied to fluid loads (based on filling fluid tanks), which would require significant capacity to be provided for the structure under 183m of water load. To enable an efficient, yet robust design, a reduced load factor of 1.2 was agreed. This was possible because the rate of fluid load change is slow, the maximum load cannot be exceeded by overfilling, the density of the lake water will not vary, and the number of load cycles is low when compared with a storage tank.

TBM assembly chamber
At the bottom of the shaft, a chamber was excavated to make space for the 7.1m diameter, 180m long Herrenknecht multi-mode tunnel boring machine to be assembled. The machine was lowered in pieces down the access shaft. The cavity was designed as a 'drained' structure for structural efficiency.

Excavation of the chamber was by drill and blast construction, with top heading and bench, and pre-excavation grouting where required. Insertion of temporary steel rock bolts was followed by permanent fibreglass rock bolts and finally a shotcrete liner was installed.

9. Completed TBM assembly chamber.

10. Photo showing the folds and weathering of the Saddle Island Lower Plate.

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Starter tunnel

By 2010, with the access shaft and TBM assembly chamber complete, work began on a starter tunnel – this was where the TBM would begin its three-year journey into the lake bed. Despite careful planning, the difficult nature of the ground conditions made this part of the project unpredictable and dangerous. In the early days, a 180m deep section of the tunnel collapsed, forcing the team to adjust the alignment of the starter tunnel.

The mining team worked at a rock face with the pressure of a deep lake immediately above and beyond it. The magnitude of the risk as they drilled into the rock was enormous and unprecedented – had the design team's careful calculations been wrong, immediate and catastrophic inundation could have resulted. As it was, the realigned starter tunnel was completed successfully to the stage at which the TBM could start work and take the majority of the risk.

Main tunnel

The 1,500 metric tonne TBM was designed and built specifically for this project. The VTC team worked with Herrenknecht AG, the machine's manufacturer and supplier, to ensure the specification exactly matched the job it needed to do. Designed to be driven in rock with water head up to 17 bar, it was also capable of grouting and ground improvement ahead of the face. The TBM was designed to excavate through the rock in both open mode – as a traditional hard rock style TBM, with pressures at atmosphere and screw extraction from the cutterhead – and closed mode, using pressurised slurry to extract materials from the cutterhead to prevent water ingress.

As the TBM advanced, approximately 2,400 precast concrete rings – each weighing more than 32 tons – were lowered underground to be used for lining and reinforcing the excavated tunnel. The rings were dispatched from the surface as six segments then reassembled behind the TBM as it went forward. Cast at a purpose-built facility 55km from the Lake Mead site, the traditional reinforced concrete segments had a minimum 40/50MPa concrete strength and 550MPa steel yield strength, and they required hot and cold weather curing due to the extreme temperatures encountered around Las Vegas.

The joint performance between the rings was critical because of the effect of bursting stresses due to high hydrostatic pressure. Localised ram forces resulted in contact stresses approaching 20MPa. These high concentrations of forces result in internal tensile bursting stresses at the extremities of the segmental lining, calculated using a well-known closed-form solution for pre-stressed concrete members (Leonhardt, 1964) and verified using a combination of 2D plane strain FE and 3D solid modelling. The final design solution combined an increase in the compressive strength of the concrete with high-strength welded wire mesh strategically located in the segmental linings.

Boring the tunnel was perilous and in 2012, tragedy struck when experienced miner, 44-year-old Thomas Turner, died in an accident during tunnel segment installation.

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This was hard for the team to bear, and these were dark days for the project as they came to terms with the loss of a respected colleague.

When the tunnel was completed, however, it was a tribute to Turner and all who worked on it. Bright, clean and big enough for a subway train, it sloped up slightly from the bottom of the access shaft on Saddle Island to a reinforced concrete chamber encased in tremie concrete on the lake bottom, capped by a hemispheric bulkhead – the intake structure that would draw water from the bottom of the lake.

11. Topside assembly of the main TBM components.

12. Ring stacks of the segmental tunnel lining.

13. Stainless steel top rack (inverted) of the intake structure.

14. Intake structure nearing completion from barges.

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Intake structure

The design of the intake, which involved assembling the structure on a floating deck and sinking it to the bed of the lake, was among Arup's key contributions to the project. There was a degree of flexibility in the contract requirements, which meant the design team could innovate to reduce both construction risk and schedule. By prefabricating the structure on the lakeside, then shipping it out and sinking it, the team was able to minimise underwater construction and avoid diving operations.

The intake is 30m tall, 5m to 8.5m internal diameter, 1,600 metric tonne dry weight, and 1,000 metric tonne buoyant weight. The lower section is concrete, designed to resist full lake pressure on the outside, while at atmospheric pressure on the inside. The base slab was cast on a floating platform, with the remainder of the structure cast in stages, the structure lowered into the water between each pour to maximise the benefit of the reduction in weight due to buoyancy.

The sequence saw the chamber structure cast, then the TBM soft eye (the point at which the TBM would break through), then the top of the chamber and the concrete collar. The upper steel section, comprising the riser section and the intake screen, was placed on top of the concrete base. Stainless steel was used to provide sufficient durability. The completed structure was then floated out into position.

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The design concept was developed at the bid stage. At this time, the whole intake structure was envisaged to be formed from steel. During detailed design, the use of concrete for the lower section of the intake was evaluated. Although the concrete solution was heavier, which added to the logistical challenges of construction on the floating barge, it allowed simpler construction overall and reduced material costs, and removed the need for extensive welding of steel sections up to 75mm thick.

Excavation on lake bed

Preparing the lake bed for the intake structure involved additional ground investigation, including a bathymetry survey of the lake floor (essentially, the underwater equivalent to topography). Excavation and blasting of the hole for the intake structure was done from a crane barge. The excavation was 17m wide, 28m long and 21m deep with approximately 20,000m^3 of material needing to be removed. Initially the overburden, which was between 2m and 5m thick, was removed with a clamshell and vacuum airlift.

The remainder of the excavation was in basalt rock. Underwater excavation of the rock comprised blasting to fragment the rock, removal of larger pieces with a clamshell, and final cleaning by vacuum airlift. The shaped charges used for blasting were lowered using a steel cruciform frame and located via GPS. The blast vicinity was cleared of boat traffic and charges were set off from the crane barge. An air bubble curtain was used to minimise the impact on fish.

Following each blast, underwater visual inspection was carried out via a camera mounted on a remotely operated vehicle (ROV), and a scan of the blasted surface was done. This process was repeated until the site was ready for the intake structure to be lowered. To minimise risk, there was no diving during this operation, with all observations made by ROV.

To make a base for the intake structure, underwater concrete was poured using the tremie concrete placement method: the lower end of the concrete delivery pipe is kept immersed in fresh concrete so that the concrete from the bottom displaces the water and avoids segregation of the mix. More than 1,000 concrete truck loads were transported to the site on 143 barge trips for this operation, which ran continuously for ten days.

Breaking through

In December 2014, as the TBM finally approached the end of its three-year journey, Arup's Lead Tunnel Designer, Luis Piek, compared the moment of breakthrough to landing a 7m drill on a bullseye: "Mostly in tunnelling, when you break through, there is concrete coming down and there are people cheering but this breakthrough happened in complete darkness under 100m of water. Nobody witnessed it. When we thought we were through, we lowered an ROV into the intake, and it was only when we saw the cutterhead that we knew we'd done it."

Sustainability

A water sampling conduit and twin pipelines deliver ammonia and chlorine to the mouth of the intake, where they mix to create chloramine to eradicate quagga mussel larvae. Quagga mussels clog water pipes and cause maintenance problems.

The spoil from the tunnelling works has been reused by VTC for landscaping on site. Not only does this reduce the emissions and negative effects associated with transporting the spoil as offsite waste, but it also reduces the visual impact of the SNWA facilities within the Lake Mead Recreation Area.

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Conclusion

In the last decade, Arup has been involved in the design and construction of 200km of tunnels, including 60 transport tunnels and more than 30 for water and various other services. The team's learning from this highly demanding project undoubtedly augmented their expertise. Techniques developed are already being used to inform other projects such as Arup's design work on the Tuen Mun-Chek Lap Kok Link, an underwater tunnel for a highway in Hong Kong, currently under construction.

For SNWA, the Lake Mead tunnel represents an immediate solution to a pressing problem. SNWA General Manager John Entsminger said: "This is one of the most complex and challenging tunnelling operations ever attempted. Coupled with a future pumping station capable of withdrawing water even at extremely low lake levels, the new intake system will help assure a dependable supply of water for future generations of Southern Nevadans."

The pipeline won't draw more water from the lake than before, or make the surface level drop any faster, but it will keep the water flowing even if drought-stricken Lake Mead drops to its lowest-ever levels.

Authors

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Project credits

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Image credits

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4, 5 *Martin Hall*; 6–18 *Arup*.

15. Aerial view of the jobsite. The access shaft is at the top of the looped ramp. The tunnel extends to the left-hand side of the photo over 180m underground.

16. This picture shows face instability during excavation of the first TBM starter tunnel.

17. This picture shows the beginning of the realigned TBM starter tunnel on the right.

18. Finished tunnel prior to removal of utilities, heading towards the intake structure.

Arnhem Station, The Netherlands

Location
Arnhem, The Netherlands

Authors
Francis Archer Jeroen Coenders Sander Hofman
Pieter Moerland Joop Paul Siegrid Siderius Charles Walker

1. Exterior view of Arnhem Station, located near the city centre.

2. The form of the structure guides passengers, so there is minimal formal signposting: stairways, walkways and lighting are key to wayfinding.

3. This sectional view of the station shows the structural innovations, outlined in this article, that made such an unusual design possible.

Introduction

Curving elegantly into its city centre space, Arnhem Station is a distinctive new building that serves travellers and transport providers gracefully and efficiently. It's been said that it rewrites the rulebook on station design because whether travellers are homeward-bound, just setting out, or simply passing through, they are guided by the sinuous form of the structure along appropriate routes to their destinations. Minimal signposting is required: the intelligent design directs passenger flows with remarkable ease, and transport stops are perfectly juxtaposed.

Opened in November 2015, this busy transport interchange reflects the opportunities opened up to architects and engineers by the continuous refinement of digital techniques. Some of the design work that made this structure possible happened because the design team tailored software specifically to meet the unique challenges of this project.

Situated on a tightly confined site, where six modes of transport converge, it is the optimum solution to serve the passengers that currently use the station – almost 40,000

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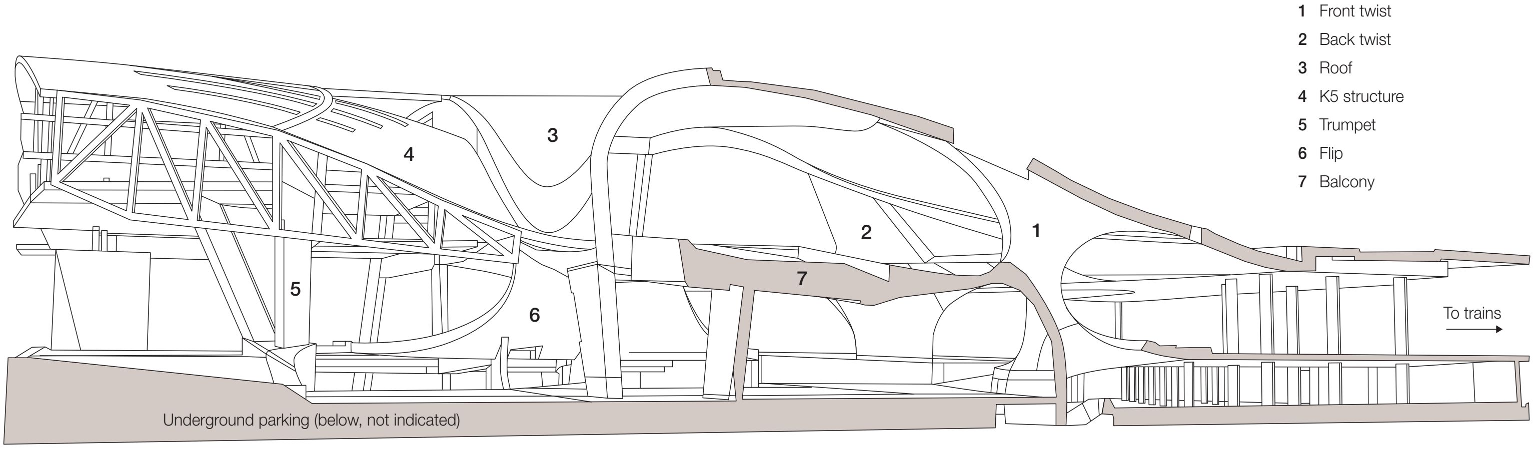
per day – and it will handle double that capacity as numbers increase in line with the Dutch Government's strategic rail plans. This article focuses on the collaborative work on the masterplan for the station area and, more specifically, on the structure of the station building carried out by architects at UNStudio and engineers at Arup.

Overview

Arnhem Station is designed almost entirely within the small footprint of the city's original station and bus square, which was built in the 1950s. Much of the design and engineering challenge in drawing up a masterplan for the redevelopment stemmed from the very small size of this footprint, necessitating real ingenuity to devise a passenger transfer hall and associated spaces and infrastructure that would work – both figuratively and literally – on many levels.

For the site as a whole, UNStudio and Arup demonstrated true architectural and engineering mastery in the way they created enough space for a new station hall, bus deck, bicycle storage, large parking garage, offices and shops. The transfer building was a particular challenge. To accommodate trains, electrical local buses (also known as trolleybuses), taxis, regional buses, cars, cycles and a continuous flow of people arriving and departing on foot, they had to develop a structure, above and below ground, that would be sufficiently easy to navigate, because it was essential for the transition from one mode of transport to another to be swift and efficient.

"We wanted to give a new and vital impetus to the design, so rather than designing the station around activities and people flows that already took place there, the expanded architecture of the new transfer terminal directs and determines how people use and move around the building," said Ben van Berkel, Founder and Principal Architect of UNStudio.



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Context

The redevelopment of Arnhem Station forms part of the Dutch Government's strategy for investment in national railway infrastructure. It is a key project – known as an 'NSP' – a status it shares with five other railway stations: Amsterdam, The Hague, Rotterdam, Utrecht and Breda. With work yet to start on the other stations, Arnhem Station has proved an important model for redevelopment. Its location makes it a vital transport node between Germany, The Netherlands and Belgium and its successful design means it functions well as an interchange for regional, national and international travel.

The Arnhem project was first mooted by the municipality of Arnhem, back in the 1990s, with UNStudio and Arup joining forces as long ago as 1996 on the first version of the masterplan for redeveloping the station and its surrounding area. Intensive research into passenger flows and transportation modes showed that a more radical solution than initially envisaged was required, however, and it was decided that the new terminal should expand to become what UNStudio dubbed a 'transfer machine' incorporating the whole spectrum of public transport. It was to be designed to meet the travel demands of the 21st century.

Design concept

Unlike most of The Netherlands' flat landscape, Arnhem has a relatively 'hilly' topography. This inspired architect Ben van Berkel to design an undulating roof for the station transfer hall that would give the city's landscape architectural expression. The landscape also inspired the interior of the building with its wave-like floors that connect the different levels of the building, from the trolleybus platform and underground parking in the basement, to the offices and balcony at the top.

The underground portion of the building is an integral part of what is above the ground, so although it was built separately for practical reasons, the substructure and superstructure were designed as one unified form.

The dramatic twisting structural roof geometry enables column-free spans of up to 35m in the main transfer hall and the design includes a series of curving forms, both inside and outside the building. The ground level curves up to negotiate the various level changes of the site, creating a complex network of split floors and ramps. The large areas of glazing that provide the building's façade extend up over the roof to form skylights. Other details include undulating timber ceilings.

Clearly, this project could only succeed if the team worked as an integrated unit and that was how the engineers of Arup and the designers of UNStudio approached the structural challenge before them.

Passenger flows

The intention of the building is to enable people to move around naturally and intuitively, to make them feel calm and comfortable. To create such a space, Arup and UNStudio had to understand how people moved around the station. To understand this dynamic, they had to find out what was going on outside the transfer hall.

Using data supplied by the municipality of Arnhem, the Arup team generated calculations clearly showing that while approximately 35% of passenger movements were related directly to the trains, the trolleybus station was also generating around 25% of all movements, while approximately 25% of footfall was just going through the building, in the direction of the city. For this reason, the station design would have to facilitate not only people boarding and alighting from trains, but also those using the city trolleybus and regional bus systems, bicycle and cars, or simply walking through. So crossing traffic and conflicting routes were minimised as much as possible.

When the initial design process took place (around the year 2000), Arup had not yet developed its now well-known MassMotion software for dynamically modelling pedestrian flows, so the team used models developed in the early 1970s by J.J. Fruin, which were generally regarded as the industry standard at that time. UNStudio then focused on the 'Klein bottle' analogy to design the passenger terminal around activities taking place in the transfer hall.

The 'Klein bottle' and lighting design

The 'Klein bottle' analogy, Felix Klein's mathematical visualisation of 1882, involves imagining a bottle without an inside or outside surface. It folds from inside to outside in a never-ending loop. Without thinking about an inside or outside of the transfer hall, it was possible to conceive a space in which people could move around without being hindered by structures such as walls and columns. This led to an architecture that 'dissolves' the transfer hall into its urban surroundings and resulted in the design of a large open space with unobstructed views from one side of the transfer hall to the other.

The same design philosophy was applied to the floors. When parking underground, for example, station users find their way upwards intuitively, ascending through V-shaped shafts that bring in daylight and accommodate the staircases. Likewise, the pedestrian route to the trolleybus station involves descending gradually sloping walkways, almost imperceptibly.

Lighting was integrated into the design to augment this intuitive approach to way-finding, most noticeably in the tunnel under the railway tracks that connects the platforms to the transfer hall. Lights inset into the tunnel ceiling are used to indicate the direction of the transfer hall. A similar solution was adopted in the bicycle parking area.

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4. The front twist opens up a large space to offer unobstructed views from one side of the passenger transfer hall to another.

5. Arnhem Station functions as an interchange for regional, national and international travel.

6. The glazing and lighting scheme ensures the station interior is brightly illuminated, day and night.

Developing the 'twist'

As the design did not aspire to the use of traditional columns to support the 46m roof span of the transfer hall, the structure of the building had to support the shell-shaped roof. This was achieved through adopting 'Klein bottle' and Seifert surfaces principles to continue the roof smoothly to the ground. Doing this with a 'twist' created a relatively compact support that would bend and curve to find stability. Such a design solution would also create holes in the ceiling through which daylight could flow into the hall below.

To study the concept, the Arup team examined how a soap bubble could be shaped by the bends and curves of a wire. Having found the approximate shape of the twist, they turned to computational form-finding using Oasys GSA software for further analysis and optimisation.

The calculations were based on Herbert Seifert's algorithm which enables mathematicians to define the process of generating an 'orientable' surface with one boundary. In this case, the boundary was a film of soap, though in Seifert's algorithm the boundary of the surface has a knot-like shape.

The result of the study was a curve diagram defining the single boundary of the building. The curve shaped the roof and the supporting twist, and gave form to other characteristic shapes of the building such as the 'back twist'. Moreover, the curve continues underground to integrate the box-shape of the underground parking with the less defined shape of the transfer hall above.

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Digital design and engineering

In 2000, the design of Arnhem Centraal, or 'definitief ontwerp', was approved. However, although definitive, the design wasn't finished. UNStudio and Arup proved that construction was technically possible, and a wax model of the twist was printed in 3D at the London office of Arup, then photographed to explain the imagined geometry. Nevertheless, the detailed design of complex parts of the building was still very much schematic, raising many questions about how to actually build it.

The uncertainty turned out to be an opportunity, with UNStudio and Arup together developing many ground-breaking digital techniques as they worked towards a more optimal solution. They used Rhino, which was new software at that time, to design the free-shaped superstructure. Although Rhino helped the architect give the building its shape, it wasn't suitable for structural engineering. To integrate design and structural engineering, this 'digital gap' had to be bridged.

Limited by time, computing power, and the design capacity of early versions of Rhino, the digital models only controlled the architectural form. In addition, the digital models of the roof-supporting twist could not be easily imported into the software that the structural engineers were using, making structural engineering on the geometry difficult and labour intensive. These two problems had to be solved before the project could move on.

To make the necessary calculations, therefore, Arup developed a plug-in for Rhino that mantled the geometry with a virtual mesh to represent the structure. By using the line pattern of this grid, the structural engineers were able to see the mid-point between two points on either side of the geometry and they could calculate and control the forces and form of the twist to support the then concrete roof of the hall. (It's important to remember that this was done in 2003–2006, before the advent of advanced Building Information Models.)

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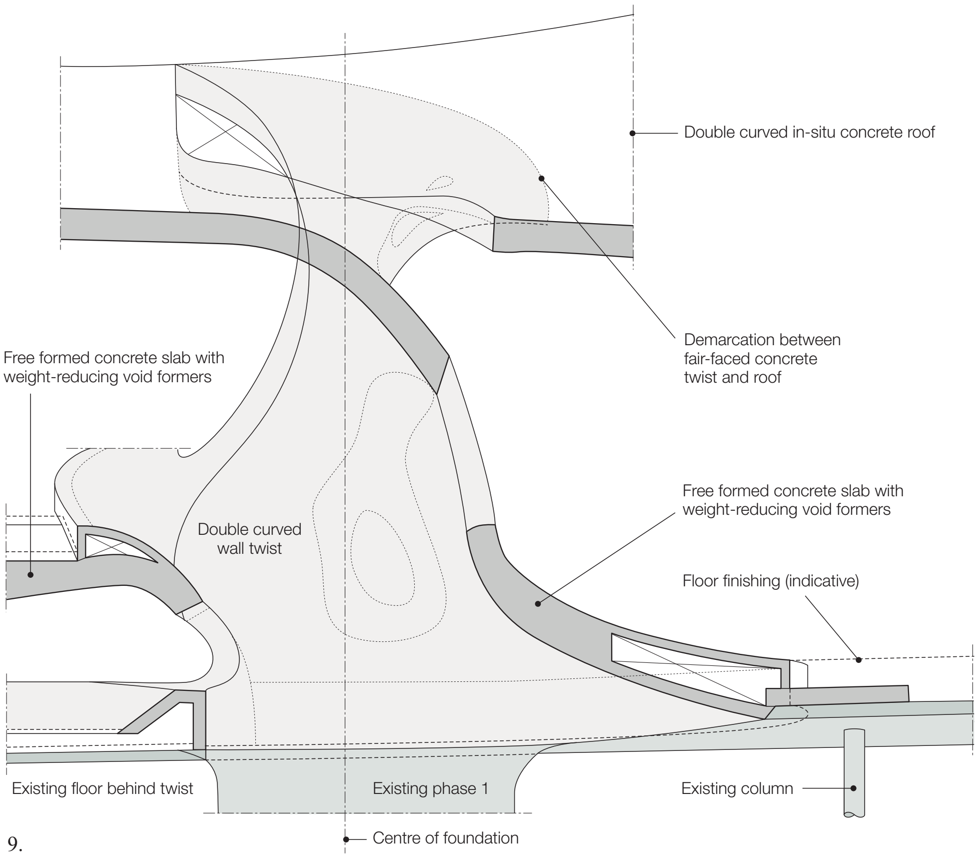

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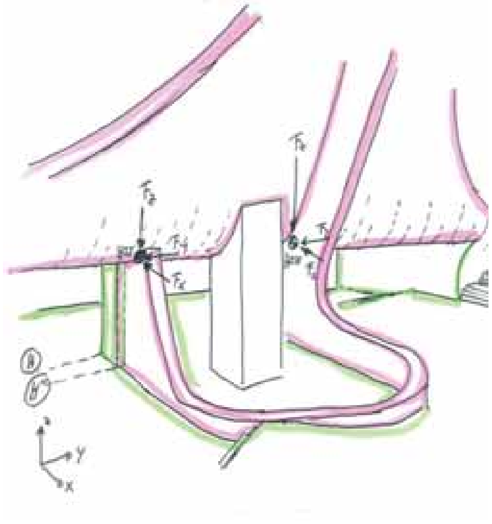

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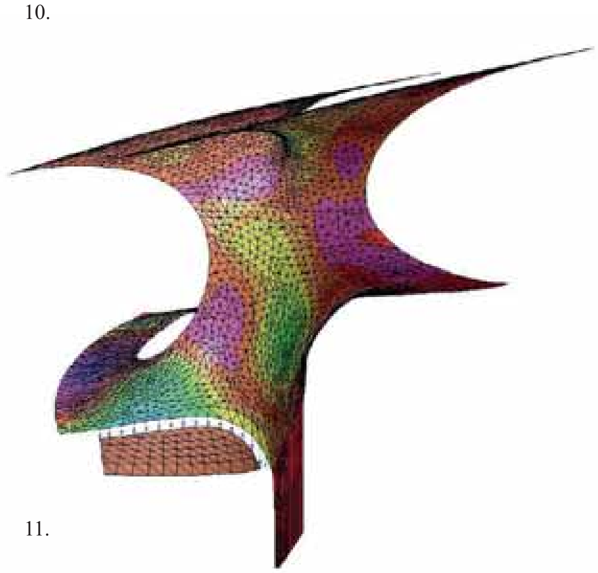

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7. The balcony, supported by the front twist, provides both interior and exterior views to assist in wayfinding.

8. The flowing smooth form of the twist is a result of the Seifert surface principle allowing daylight to enter through the roof.

9. Elevation of the twist showing the structural thickness of the concrete of the reference design at tender. This was changed after the awarded contractor proposed building it in steel.

10. Sketch of two of the supports of the superstructure depicting the locations of the reactions of the flip.

11. Structural model of the twist showing the changes in thickness, varying from 300mm to 700mm, in different colours.

12.

Materials

Armed with this new insight, Arup engineers could calculate the required exact position and thickness of the concrete. They worked out that the double curved design of the roof, and the irregular shapes of the twist and back twist, meant thicknesses would have to vary from 300mm to 700 mm. The thickness would influence how and where there should be reinforcement in the structure and predict the deformations and behaviour as creep and possible buckling of the concrete shell roof.

These considerations meant that designing and building the structure in clean concrete, as originally intended, would be challenging. The buildability and the risk of visible cracks in the concrete meant the construction companies that initially tendered for the project reflected this difficulty in the level of costs they proposed at a time when the building market was at its peak.

In fact, the first round of tendering failed in 2007 because the prices offered by contractors were simply too high. So after various changes, the work was reoffered for tender in 2013, with contractors invited to suggest their ideas for construction of this reference design. This was one of the main reasons the contractor that proposed to build the roof in steel, for the same budget but in order to minimise risk, was awarded the project.

Using steel, instead of concrete, made the structure more lightweight and techniques from the shipbuilding industry were employed to develop the necessary curvatures. The twist, in particular, is an engineering as well as an architectural feat. It comprises prefabricated coated steel panels made by shipbuilders in the northern Dutch city of Groningen, who also carved skylights out of the roof element.

Substructure

When the initial masterplan was approved in the 1990s, it was anticipated that the planned high-speed train from Amsterdam to Frankfurt would stop at Arnhem Station generating a large amount of 'park and ride' traffic. For this reason, Arnhem municipality decided to build underground parking at

13.

Arnhem Station for approximately 1,000 cars, together with extensive underground bicycle parking to meet demand from local commuters and students at the city's university and colleges.

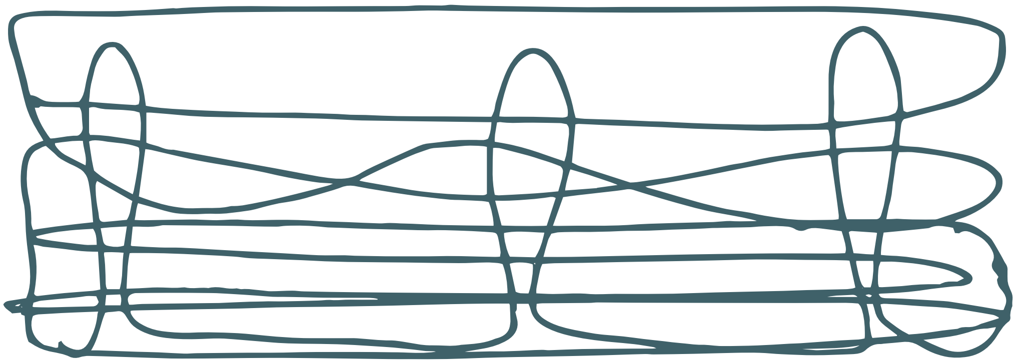
In addition to its relatively large size and underground entrance, the underground car park had to fulfil a structural and a conceptual role. Structurally, it must support the levels of the building on top of it. Conceptually, it needed to align with the 'Klein bottle' theme of openness.

The solution that UNStudio and Arup devised was based on V-shaped walls that were capable of supporting the floors, with different enlarging spans from bottom to top resting on the underground car park. This construction made it possible to use standard 16m long prefabricated floors for the underground parking facilities, creating the large open space needed for the desired intuitive environment. The V-shaped walls additionally form shafts through which daylight enters the underground public area. The V-shaped walls represent the structural and conceptual link between the substructure and the superstructure, and they are continued up into construction of the roof.

The car park was considered relatively easy to build, so these two phases were put out to tender first, then constructed between 2000 and 2003. This created a challenge for UNStudio which was still in the design process. In addition, it was discovered that the deep wall foundation of the underground car park couldn't bear as much weight as originally anticipated and that the underground bicycle parking facility, built in 2011 with a piled foundation, had quite different characteristics in stiffness. This meant controlling the design forces such that most of the weight of the building was transferred through the construction of the underground bicycle parking facility into the best suited foundation for a robust solution.

Superstructure
In addition to the twist, the roof of the transfer hall is supported by two other sculptural geometries known as the 'flip' and the 'back twist'. The flip, positioned under the city balcony at the apex of the building, comprises a wall 700mm thick. The wall supports both the balcony and a large portion of the roof and carries it to four supports. The back twist is situated opposite the twist, with the transfer hall in between. It consists of two distinguishable sections. The lower part, which is 700mm thick, was largely built in concrete during the first phase of construction in 2011. The sloped top-section, 600mm thick, is built mostly in steel.

The lower part of the back twist takes the vertical load from the roof and the road bridge on top of it. The top part of the back twist rotates above the road bridge into the shell roof, absorbing both vertical and horizontal downward forces. The kicking-out forces of the roof on the north side find their way through the back twist to balance with the opposite forces on the south side through the balcony and flip under it.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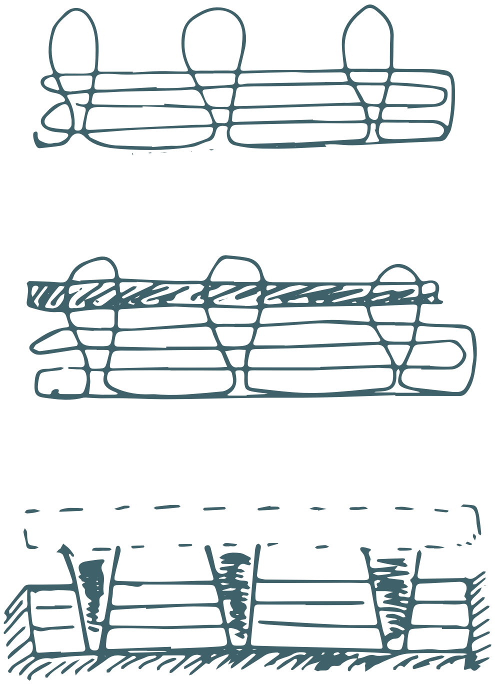
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In mathematical terms, the sculptural shapes of the design of the transfer hall, with the twist, back twist, flip and double curved roof being the most important, are referred to as NURBS or 'non-uniform rational basis spline'. In order to build a digital model of these NURBS, Arup's engineers divided the design into many triangles using the method developed in 1934 by the Russian mathematician Boris Delaunay.

With the design divided up into triangles, finite element (FE) analysis could be used to engineer the construction. The FE analysis allowed UNStudio and Arup to make non-linear calculations of the complex geometry. However, because design and construction were happening simultaneously, the design team had to continuously recalculate the thickness distributions of the double curved surface geometry and the effect it had on the construction.

To solve this issue, Arup developed a tailor-made parametric meshing toolbox which was used to make a detailed digital 3D model. When the construction started in 2013, the 3D model was used to explain to

12. Access to train platforms.

13. Construction of the trumpet.

14. Abstract scheme of the concept for the transfer hall.

15. Evolved abstract scheme showing light and platforms.

16.

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the client and hand over to the contractor how the reference concrete design of the transfer hall worked and could be built.

What made the geometry of the shell-shaped roof complex, and the tailor-made software necessary, was the extreme complexity. Where the design of concrete shell roofs are usually mirrored, or in some way standardised (for example the roof of the TWA Terminal in New York[1], or the roof of the Sydney Opera House[2]), the roof of the transfer hall of Arnhem Station isn't. Every single bend and curve in the geometry is unique and had to be calculated integrally.

Standard software lacked the computing capacity needed to do all the calculations as the geometry was very complex. Even with the parametric meshing toolbox, engineering the project was only possible after cutting up the total design into manageable parts: the freeform roof, the steel truss structure of K5 the office building, the balcony and bridge, and the bicycle parking facility. The detailed models were verified with a more coarse overall model.

Conclusion

The initial design of Arnhem Station, both the building and the associated masterplan, happened at a time when architects and engineers were in the process of adopting digital design. This meant that many digital design tools that are now familiar simply didn't exist. To make the integral design and construction of Arnhem Station possible, UNStudio and Arup developed tailored software.

The result is a building that is unique in many respects, its design and execution spanning a time when design and engineering has developed rapidly and in exciting new directions. Arnhem Station reflects the spirit of the times, providing the city with a landmark new building, and providing The Netherlands with a lynchpin for its 21st-century rail network.

References

[1] TWA Terminal, New York. Designed by Eero Saarinen, opened 1962.

[2] Sydney Opera House. Designed by Jørn Utzon, opened 1973.

Authors

Francis Archer, Structural Engineer and Associate Director, was involved in the project during the design phase.

Jeroen Coenders, Project Manager from the design phase, worked on geometry and computation.

Sander Hofman was Lead Structural Engineer from the design phase.

Pieter Moerland, Structural Engineer, worked on the project from the design phase, focusing on non-linear concrete behaviour.

Joop Paul, Structural Engineer, was Project Manager in the design phase, later becoming Project Director.

Siegrid Siderius worked on daylight and lighting design.

Charles Walker was Lead Structural Engineer during the design phase of the project.

Project credits

Client consortium: *ProRail, Ministry of Infrastructure & the Environment, the municipality of Arnhem* Delegated principal: *ProRail* Masterplan phase: Architect: *UNStudio* Structural/civil engineering, transport planning: *Arup* Design and specifications phase: Structural engineering: *Arup* (public transport terminal), *Van der Werf & Lankhorst* (bus station, car park, office square) MEP: *Arcadis* Fire safety: *DGMR Bouw BV* Public transport terminal lighting: *Arup* Public space lighting: *Atelier LEK* Wayfinding: *Bureau Mijksenaar* Building specifications: *ABT* Landscaping design: *Bureau B+B stedebouw en landschapsarchitectuur* Project management to definitive design: *Arcadis* Engineering and construction of pedestrian tunnel: Main contractor: *Besix-Welling* Tendering phase contractor:

18.

Arcadis Engineering and construction, phase 1 – Pedestrian tunnel and public transport terminal: Main contractor construction consortium: *BAM Ballast Arnhem Centrum VOF (BBB, BAM & Ballast Nedam)*; MEP: *BAM Techniek, Unica* Engineering and construction, phase 2 – Public transport terminal: Main contractor construction consortium: *OV-Terminal Arnhem (BCOVTA, BAM & Ballast Nedam)* Structural engineer: *BAM Advies & Engineering* ABT MEP: *BAM Techniek, Unica* Structural engineering, lighting, climate and sustainability, fire, wind, geotechnical: *Arup – Marcus Aberle, Sallam Abu Khalefa, Francis Archer, Cecil Balmond, Johan Beudeker, Bart Blans, Sander Boogers, Daniel Bosia, Jan Willem Breider, Jeroen Coenders, Simone Collon, Verner Cutter, Henning Czujack, Kayin Dawoodi, Marcel De Boer, Marco Del Fedele, Jorn De Jong, Marck de Leuw, Philip Dilley, Milu Evelina, Bert Fraza, Volker Hass, Sander Hofman, Mark Huibers, David Irvine, David Johnston, Ger Jonker, Philip Jordan, Karsten Jurkait, Gwenola Kergall, Bob Kleuters, Ben Kreukniet, Joost Lauppe, Rikje Maas, Rory McGowan, Kieran McKenna, Andrew McNeil, Narjas Mehdi, Masato Minami, Jules Misere, Pieter Moerland, Nadia Molenstra, Hamish Neville, Simon Newby, Joop Paul, Shibo Ren, Anke Rolvink, Chris Rooney, Nina Rutz, Iwona Semenowicz, Siegrid Siderius, Mark Siezen, Simon Smaczny, Peter Speleers, Sridevi Koonath Surendran, Patrick Teuffel, Deb Thomas, Roel Van De Straat, Rogier Van Der Heide, Lore van de Venne, Bastiaan van de Weerd, Wesley van der Bent, Petra van der Ven, Imke van Mil, Michael van Telgen, Bob Venning, Claire Verani, Rob Verhaegh, Peter Vermeij, Adam Vojtek, Charles Walker, Martin Walton, Ian Wilson, John Wooter.*

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Image credits
1, 2, 4, 6, 17, 18, 19 *Hufton+Crow*; 3 *Roel van de Straat/Martin Hall*; 5, 9 *Martin Hall*; 7, 8, 12, 16 *Ronald Tilleman Photography*; 10, 11, 13, 14, 15 *Arup*.

16. Geometric complex stairs leading to the underground bicycle parking.

17. An aerial view of the station shows its proximity to the city centre of Arnhem.

18. The trolleybus station adjacent to the transfer hall.

19. A see-through along the front twist to the roof.

Elizabeth Quay Pedestrian and Cyclist Bridge, Australia

Location
Perth, Australia

Authors
Alistair Avern-Taplin Nick Birmingham
Stewart Buxton Clayton Riddle

Introduction
In Perth, the new Elizabeth Quay development is graced by a distinctive, dual-arched bridge for pedestrians and cyclists. An artfully meandering structure, designed to delight those who use it, the bridge spans a newly-created inlet of the Swan River, its curvaceous form visually linking city and water.

Arup's design and engineering team delivered a bridge deck that was only 250mm deep at the edges. This elegance exceeded the client's aesthetic expectations and is a manifestation of the team's ingenious architectural and engineering approach to the project. The bridge is appealing and attractive from every angle.

Much more than simply symbolic, however, the bridge holds together a waterfront redevelopment that has transformed the previously underused river foreshore into a busy promenade, lined with bars and restaurants, and set to be surrounded by a vibrant mix of offices, apartments, hotels and shops. The bridge promotes continuous movement around the quay and links the island in the river to the popular 'bridges' recreational circuit. Visitors to the precinct can now walk, run and cycle across the bridge, enjoying spectacular views in all directions.

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Context

Perth's attractive Swan River waterfront developed into a promenade and leisure space during the 19th century. With public baths along the water's edge, it was a popular spot for picnics and paddling. As the city grew, however, land reclamation and new high-rise buildings started to separate the river from the city, and in the 1940s, when Riverside Drive was built, the connection was severed completely. The central business district (CBD) continued to develop thereafter on an east-west alignment parallel to the waterfront.

The Elizabeth Quay development takes the waterline back to its original position. Riverside Drive has been redirected and 150,000 cubic metres of soil have been removed to create a new inlet that allows the river to flow back towards the CBD. By reinserting the link between city and waterway, Elizabeth Quay creates for the first time a north-south axis for the CBD and adds a vibrant new destination for business, shopping and leisure.

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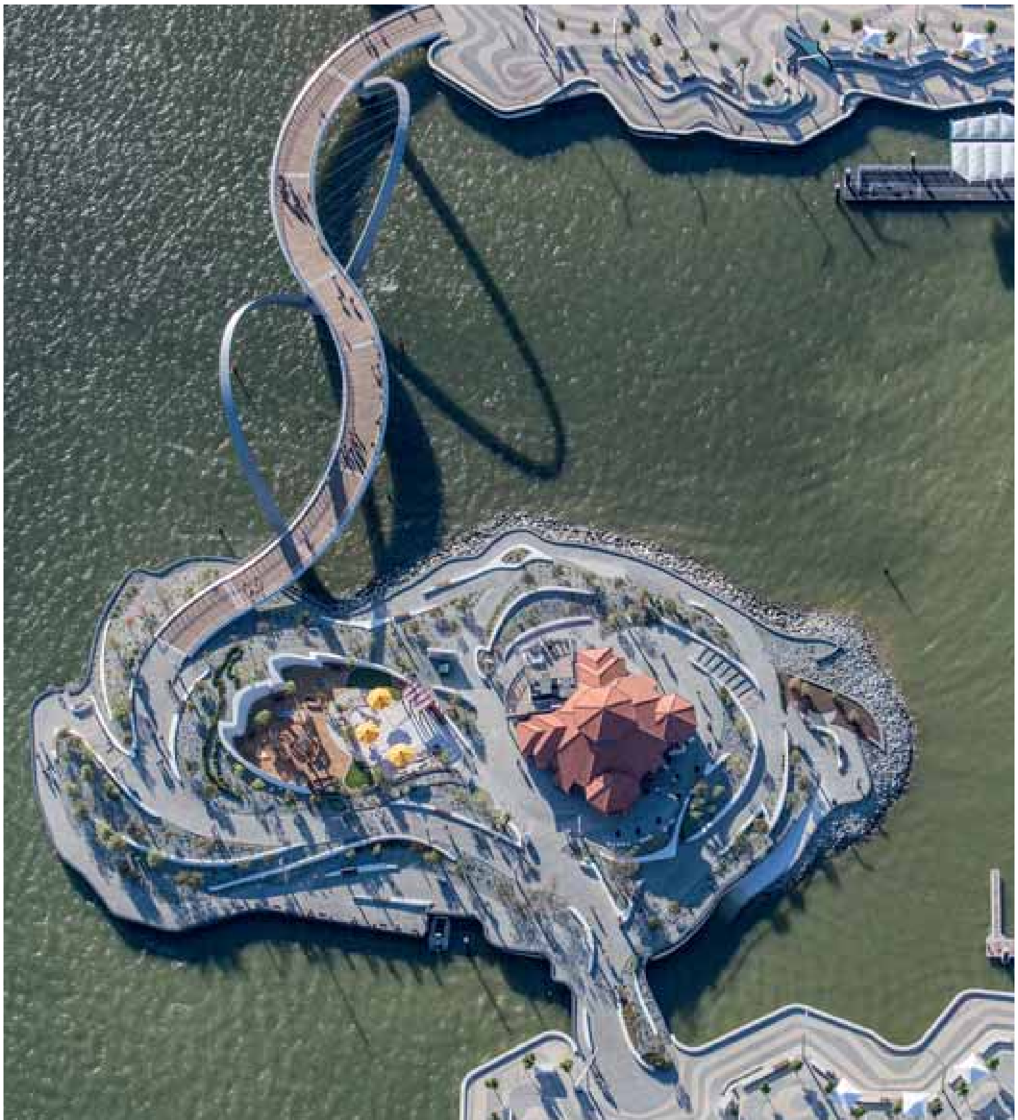

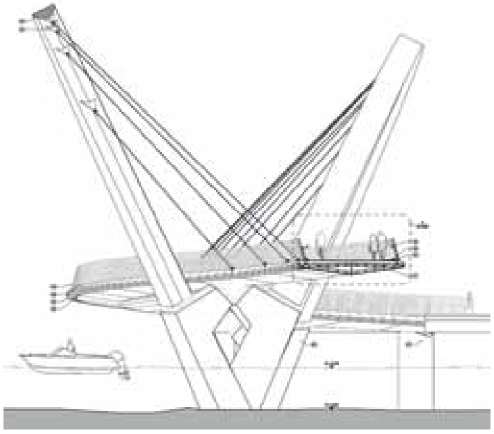

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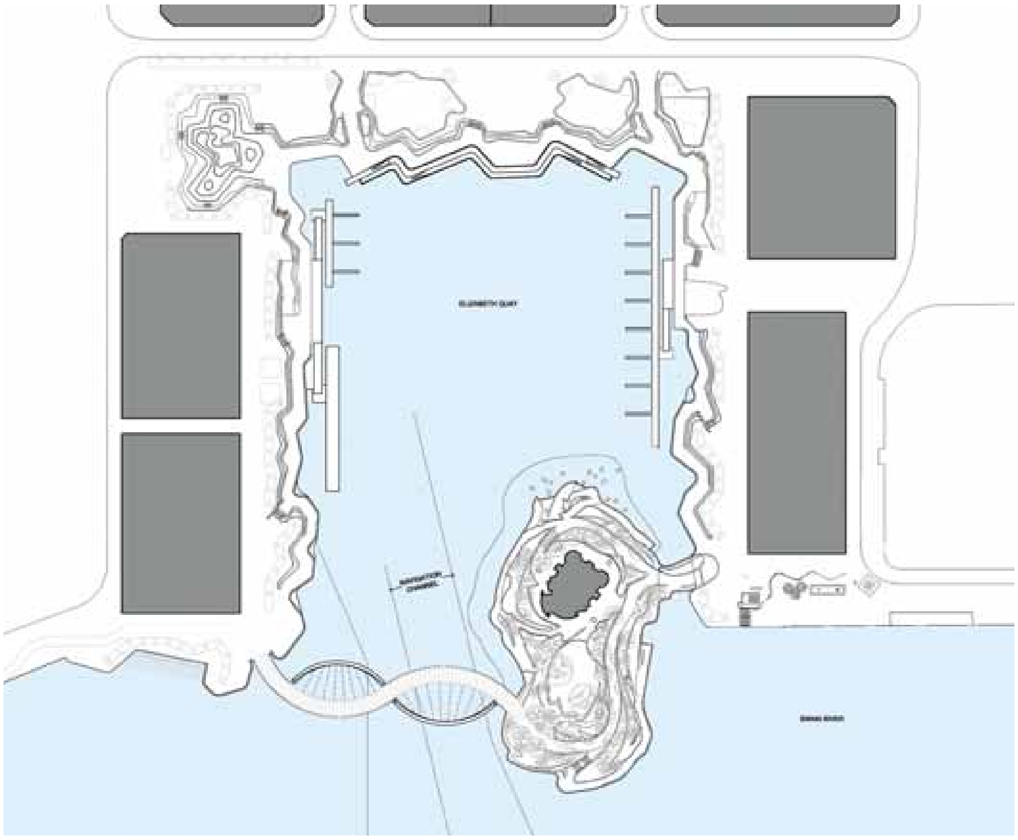
1. The fine curves of the bridge depend on detailed geometry. The bridge deck is just 250mm deep at the edges.

2. The 'S' form of the 110m long deck provides pedestrians and cyclists with dynamic and changing views of both river and city.

3. The new bridge at Elizabeth Quay viewed from above. The historic Florence Hummerston Kiosk (red roof), relocated from the Esplanade by Arup, will become a restaurant.

4. This drawing shows the exquisite balance integral to the design.



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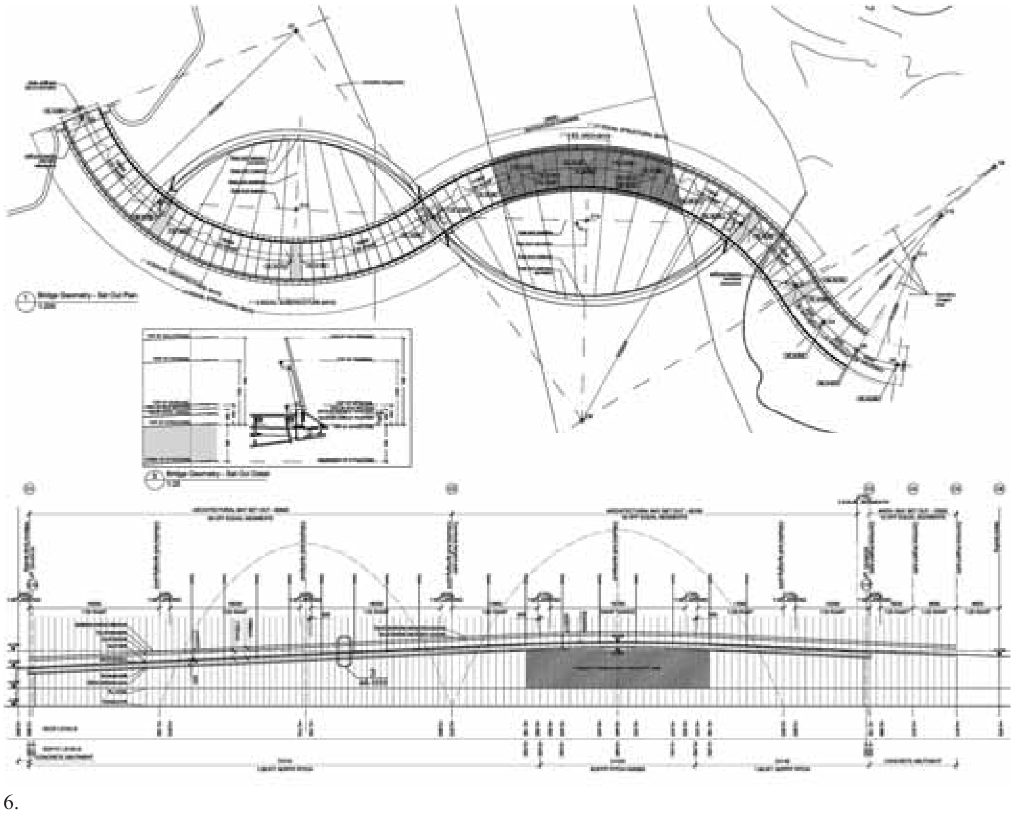

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The project

Elizabeth Quay is an essential element of the Western Australian Government's plans to revitalise central Perth by reconnecting the river to the city. Redirecting Riverside Drive signalled a move away from higher volume, higher speed roads in this part of the city to lower speed, shared-use roads, safer for cyclists and pedestrians and more amenable to city workers, residents and visitors. To create Elizabeth Quay, the managing contractor CPB (formerly Leighton) and Broad constructed a continuous bund out into the Swan River, behind which the bridge and new inlet could be constructed, the ground excavated to allow the water to flow in.

Arup was engaged by the Metropolitan Redevelopment Authority (MRA), and novated to the managing contractor, as lead consultant for the bridge to provide multi-disciplinary services from concept design through to construction completion. Services to be provided included civil engineering, geotechnical engineering, electrical engineering, materials specialist consultancy, advanced technology and research (AT&R), wind engineering, vibration engineering, and naval architecture.

In addition, Arup provided structural engineering and façade services for parts of the precinct, most notably the vehicle bridge, the inlet wall, and relocation of the Florence Hummerston Kiosk, a well-known local building, dating back to 1928, that was moved from the nearby Esplanade and will now become a restaurant.

Bridge brief

As a primary element, the bridge is a simple structure, yet its design presented three core challenges in response to the client's aesthetic and functional briefs.

First, though the bridge was in a constrained location, its design was to be simple, iconic and transparent; cognisant of the outstanding potential to frame exciting views of the city, the river and South Perth, it should also take into account views from the overlooking Kings Park.

Second, the bridge deck needed to be high enough for public ferries to pass safely beneath to access the new terminal within Elizabeth Quay, while satisfying requirements for universal accessibility.

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Third, from a functional point of view, the bridge must have a minimum clear width of 5m to enable pedestrians and cyclists to use it easily and pleasurably, and provide disabled access. This would encourage movement around the quay.

Arup Associates used parametric design tools to model a structure of complex curves that would respond to all three challenges, while Arup's engineers developed structural diagrams to complement the architectural investigations. The concept design was driven by the team's desire to achieve a form for the bridge that respected the masterplan, and used its location to advantage, while achieving the aesthetic and functional briefs.

The 'S' form of the 110m long bridge deck incorporates the necessary length required to clear the navigation channel while providing dynamic and changing viewpoints for pedestrians and cyclists using the bridge. This form creates natural vantage points out to the Swan River and back towards the heart of Elizabeth Quay with the Perth CBD as a backdrop. Day and night it acts as a focal point, with integral feature lighting creating a relaxing and sophisticated ambience on the quay when night falls.

The two 22m-high arches that support the deck lean away from each other acting as complementary foils to the bridge deck form. This simple arrangement of curved forms provides a series of different visual experiences, depending on whether the observer is using the bridge, visiting the precinct or looking at the bridge from the city.

Bridge geometry

Arup identified the critical dependence of the bridge design on the required clearance height over the navigational channel; for each 100mm increase in clearance, the bridge length would increase by at least 4.5m and up to 7m. The height of the public ferry was governed by a 1.5m high aerial fixed to the roof of the ferry.

To reduce the height of the ferries and the necessary clearance, Arup successfully negotiated with the governing and approving bodies for the relocation of this aerial on every ferry. This change not only achieved a significant cost saving for the project but also permitted a significantly shorter bridge length, fundamentally affecting the bridge's geometry. The curved design provided clear entry points to the bridge that were critical for integration with the overall aesthetic of the Elizabeth Quay masterplan.

Arup conducted an in-depth study of bridge widths within Perth, the state and nationally, to justify a reduction from an original 6m clear deck width to 5m in the client's functional brief. The benchmarking work presented by Arup was instrumental in this change, which allowed the counterbalanced arches to meet at water level, achieving the artistic and architectural aesthetic aspirations.

5. The bridge links the island to the quay. Its undulating form frames the entrance to the inlet.

6. The 'S' form of the deck provides the necessary length required to clear the navigation channel.

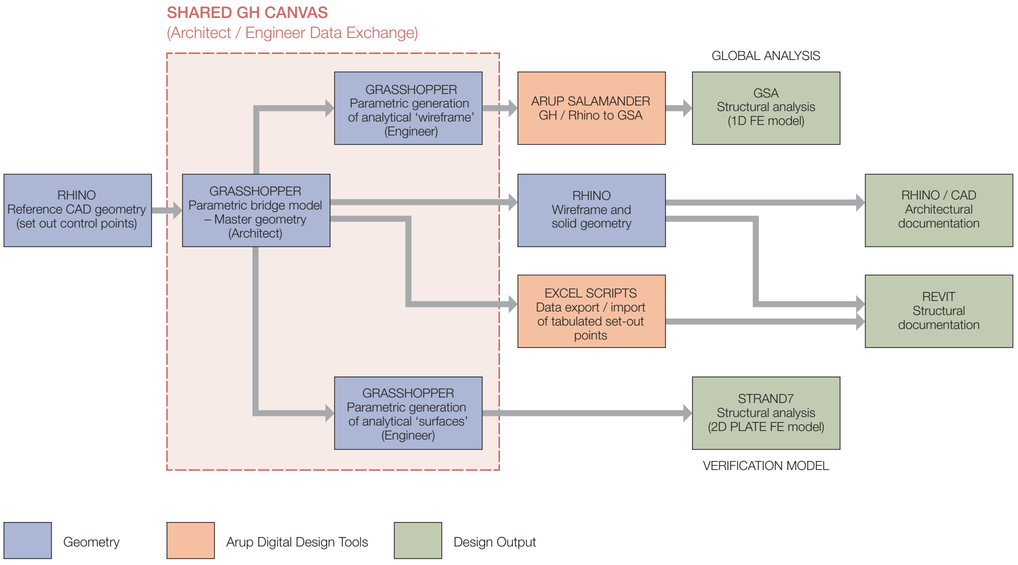
7. The bridge is proportioned for boats, including ferries, to pass beneath.

8. Digital workflow diagram.

9. Parametric modelling – shared Grasshopper canvas, architect and engineer.

10. Parametric modelling of internal steelwork.

11. Parametric modelling – architectural workflow.



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Structure

Having solved the initial geometric challenges presented by the concept design, Arup had to engineer a structural solution. The bridge's arches needed to echo the 'S' form of the deck with arch forms that enhanced the experience of movement through the structure and across the bridge. This would reinforce the sensations created by the curved deck constantly changing in height, and always curving in plan.

Parametric modelling software was used to optimise the geometry of the pedestrian pathway and overcome design constraints, including the range of different heights required at different sections of the bridge deck. The solution was two leaning arches with 45m spans, connecting in the middle, and sweeping down towards the water to rest on concrete piers supported on piles socketed into the rock bed.

The architects and engineers worked closely together using design analysis software to create efficiencies in the geometry of the arches relative to the bridge deck geometry. This ensured that the arches' dramatic leans were optimised in their cross-sectional form with the critical structural support they provide. Cables hung from the arches support the deck from outriggers only on the inner curve of the deck.

Despite the complexities within the design, the concept of maintaining visual simplicity is at the core of the bridge's design. There is clarity in both the architecture and structural engineering elements of the bridge, and where they have been pulled together, they have been kept as simple and as clean as possible. For example, where the lower edge of the bridge deck meets the fascia piece, the deck drainage channel is detailed to form a shadow line along the deck complementing the swept form.

To ensure that existing views across the river to South Perth were not obstructed by the bridge, elements of transparency were added to the bridge's balustrades. However, the bridge still needed some level of solidity in order to reduce wind-induced vibrations. Arup's wind engineers reviewed every surface in the bridge to mitigate vibration and overcome potential vortex-shedding issues.

Based on these analyses, and similar works in the other disciplines, Arup justified a bridge deck that was only 250mm deep at the edges. This elegant appearance exceeded the client's aesthetic expectations and is a reflection of the ingenuity of Arup's collective design team.

Digital workflow

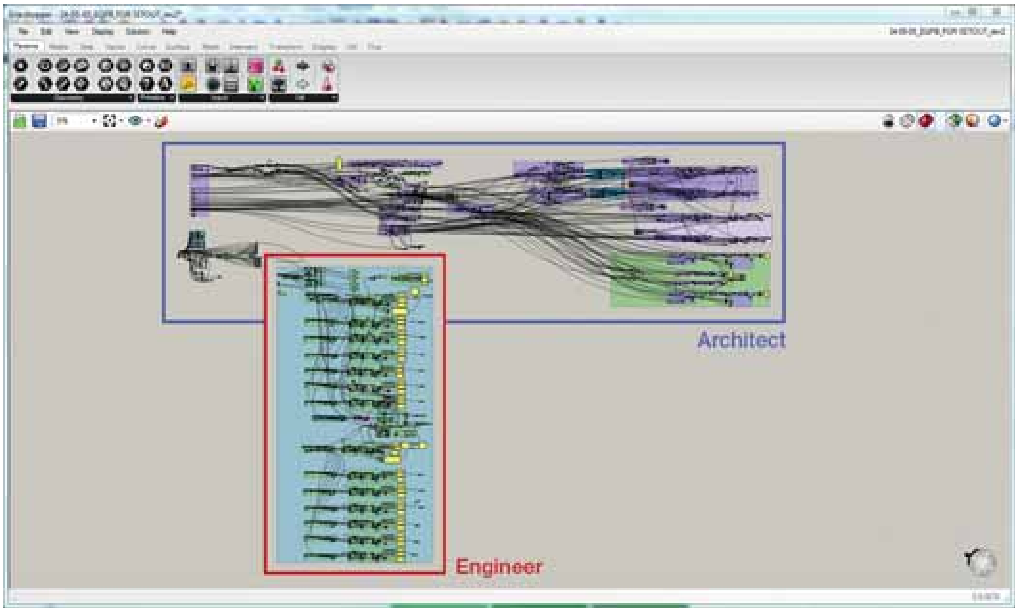
The digital design workflow was a highly collaborative process between Arup's architects and engineers and proved to be pivotal in the successful delivery of the project.

The architects initially used Rhino + Grasshopper as a parametric tool to solve the geometrical constraints set by the client, allowing them to quickly converge on the architecturally desired and conforming S-shaped bridge concept. Preferred sculptural forms of the bridge were further developed parametrically by the architect using Grasshopper in the subsequent design phases, opening up the opportunity for the engineers to link into the architects' parametric scripts to integrate the design workflow.

Working from the same shared Grasshopper canvas, the engineering team was able to generate analysis models to assess the structural performance of the bridge form as it developed in concept. 1D finite element models were parametrically generated directly from Grasshopper to GSA using Arup's Salamander plug-in. These direct digital links provided the design team with the ability to optimise and rationalise the profiles of the complex bridge form in a very short time-frame.

Engineers also extended the architects' initial Grasshopper scripts to generate all the internal steelwork necessary to describe the structure. This geometry was then referenced into Revit to populate the BIM model and produce structural documentation. A fully detailed Strand7 analysis model consisting of 2D shell elements was also translated from the Grasshopper surface geometry and used for final structural verification.

The holistic workflow approach meant that direct relationships were made to the shared geometry between architects and engineers via their linked scripts. This association meant that architectural and structural refinements could occur in parallel without



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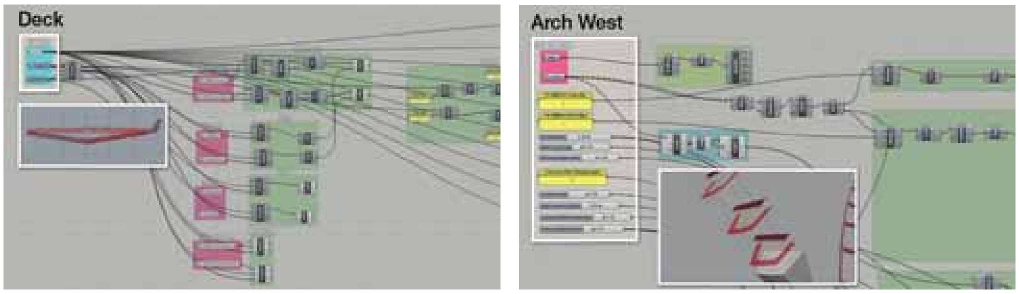

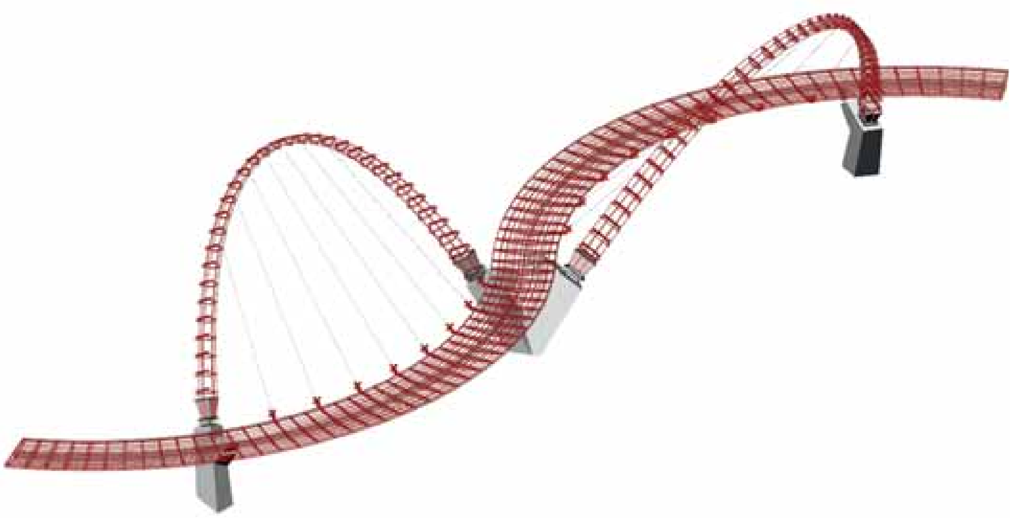

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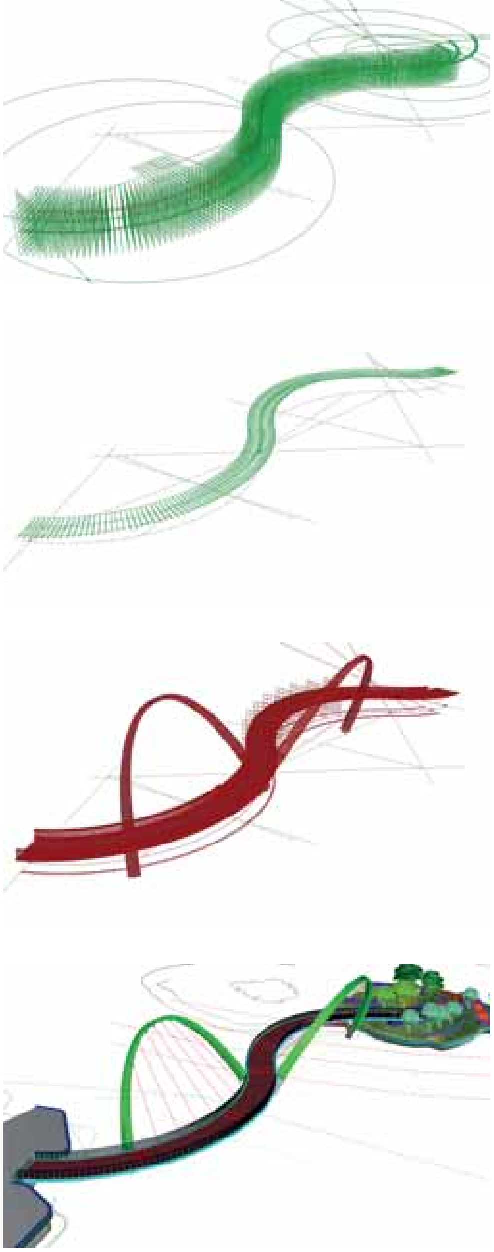

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losing element-to-element connectivity or resulting in the separation of modelling parts which avoided rework at each design update. As an outcome of the digital workflow, complete coordination and alignment of design between architects and engineers was maintained throughout.

Parametric modelling

The plan geometry of the bridge was set out parametrically from a series of arcs, subdivided by equally spaced planes, perpendicularly aligned to their varying radii. Each of these planes was then set out vertically via an unrolled section, taken through the bridge centreline. Onto each plane, a detail of the bridge cross section was projected, and then lofted together from plane to plane. This in turn set out all the various 3D elements of the bridge: the structural section, fascia panels, timber decking, handrails and balustrade.

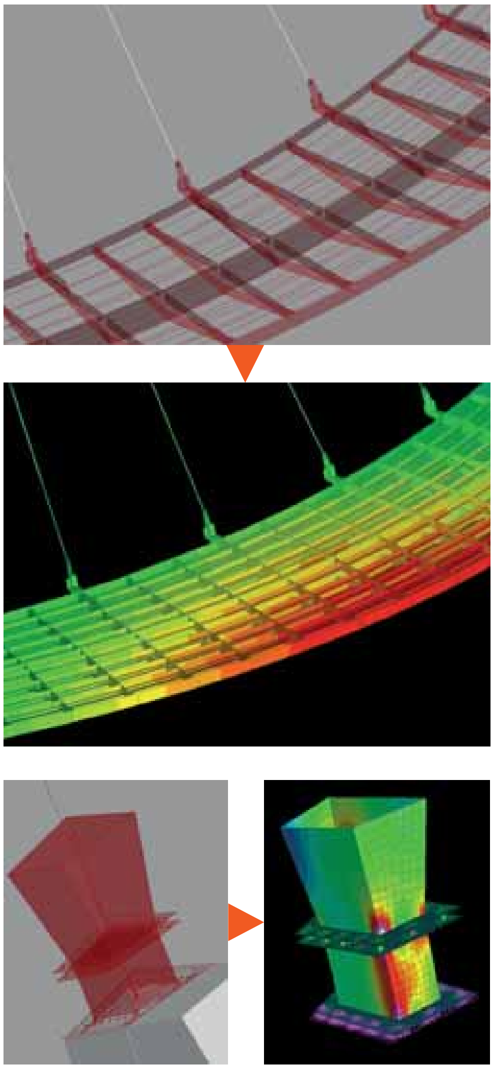
A typical Grasshopper workflow would be defined by numerical inputs; sliders, formulas and graphs, linked by often restrictive and complex relationships, to drive the 3D geometry design. In turn, sections could be retrospectively cut from the baked geometry and transformed into drawings. However, for the set-out modelling of the Elizabeth Quay Pedestrian and Cyclist Bridge, physically drawn inputs were used to drive the centreline and cross-section model. This short-cut the parametric process, where many rules can often be forced upon the designer by a strict definition. Instead the definition provided the conduit, using directly drawn 2D information, to create the 3D geometry. The 3D geometry could then be immediately updated, interrogated and assessed. Changes could be fed back rapidly by updating simple sections and detail drawings.

Analytical modelling

The use of Arup's Salamander plug-in for Rhino + Grasshopper permitted instant generation of the structural analysis model. Analytical centreline geometry was directly obtained from the architects' Grasshopper scripts with the varying section profiles of the deck, piers and arches generated from parametric planes made at finite cuts appropriate to the level of analysis. Salamander components in Grasshopper were used to translate this information into 1D finite element model using Oasys GSA.

The parametrically-linked analysis model meant that changes to the bridge architecture could be implemented into the analytical model in real time. This workflow led to direct saving for the client, through reduced steel tonnage, and, indirectly, through avoiding additional items, such as tuned mass dampers. Aesthetically, the depth of the bridge deck was reduced significantly through analysis modelling to the extent that it exceeded the expectations of the client, the artist and the architects who all wanted to achieve the thinnest possible deck profile.

For final structural verification, a 2D plate finite element model was produced using Strand7. This model was also generated from the parametrically defined surface geometry in Grasshopper and read directly into Strand7 for auto-meshing. All plated steelwork, including the deck and arch profiles, the internal network of stiffener plates, and connection at interfaces, were meshed into the Strand7 model. The detailed model verified final design: confirming overall bridge performance, dynamic behaviour, section and stiffener buckling capacity, and ensuring that stress concentrations at critical connections were within acceptable limits.



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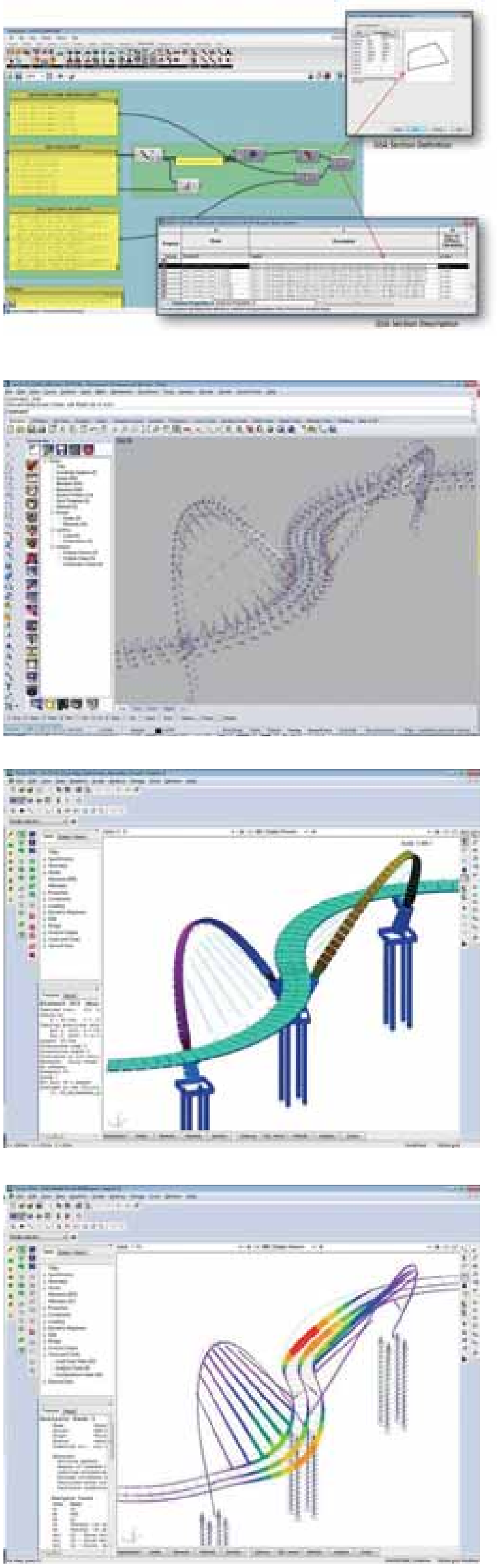

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12. Grasshopper to Strand7 finite element analysis.

13. Grasshopper to Oasys GSA using Salamander plug-in.

14. Uplighters line the inner edges of the bridge deck, part of a lighting concept designed by Arup to accentuate the form of the structure.

15. Production of Revit structural documentation.

16. Clash detection modelling of the densely reinforced concrete bridge piers.

Documentation and BIM

Given the seemingly complex form of the bridge, the Rhino + Grasshopper workflow adopted on the project provided meticulous control of the bridge's geometry. This enabled both the BIM model and drawing documentation to be produced rapidly as a direct by-product.

Revit was essentially chosen as the platform to host the model, and although 3D modelling of the bridge was generated outside this environment, the workflow was very effective in managing the production of structural documentation. 3D geometry was referenced directly into Revit from Rhino exports along with automatically generated coordinate data – streamed live from Grasshopper and linked to Revit drawing sheets via Excel. This workflow helped to ensure accuracy, flexibility and speed of documentation.

Architectural documentation was also produced in CAD from the Grasshopper output and was essential in communicating the site-wide setting-out principles of the bridge and detailing visually important elements such as the profiled fascia, balustrades and timber decking.

The application of BIM on the project enabled Arup to resolve many geometric issues prior to construction. Virtual design reviews were held with the fabricator to ensure design conformance relating to assembly of parts, weld sequencing, and steelwork tolerances. In some instances, geometry was fine-tuned to meet fabrication needs by altering parameters in the legacy Grasshopper script – such as the rationalisation of plate curvatures to remove warping deficiencies outside the limits of the fabricator's machinery.

The BIM model also enabled the ability to carry out clash detection of critical model parts. Extensive rebar modelling of the heavily reinforced concrete pier blocks was undertaken to resolve and ensure proof-of-design. This process ensured full conformance of design and eliminated the consequence of costly site-phase remediation.

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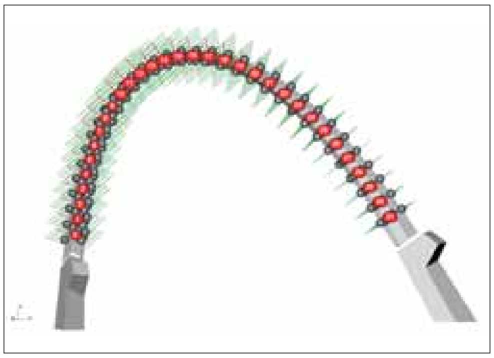

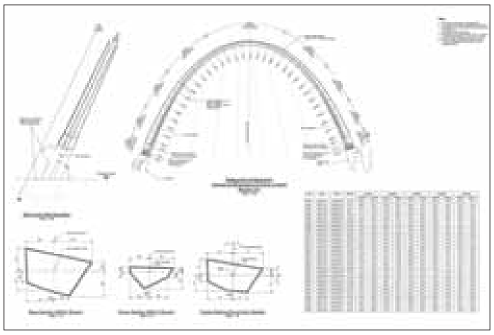

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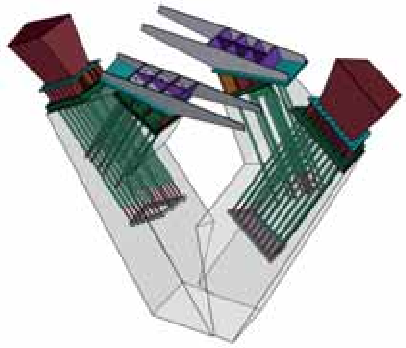

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Lighting

The illuminated arches needed to be clearly visible from both sides of the Swan River, from the city, and from South Perth. To achieve this, the inner face of each arch top was split to create a five-sided cross section at the apex: this optimised illumination provided by the deck uplighters to maximise the visibility of the arches in all directions. The 16 uplighters lining the inner edges of the bridge deck, and complementing the lights at the bridge piers, were designed by lighting specialists ElectroLight. The lighting arrangement makes the entire bridge visible from every angle. Many different design inputs came together to create the final lighting solution and it was only

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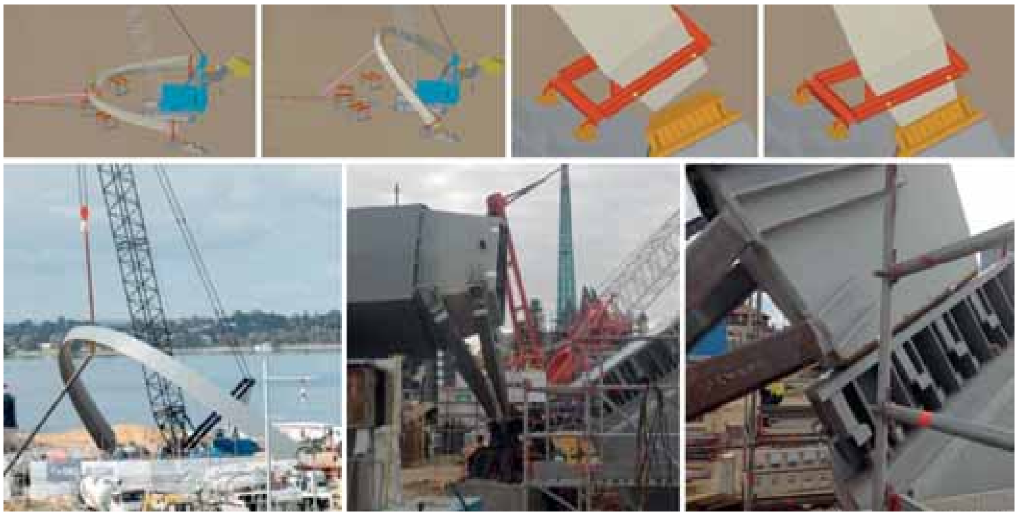

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17. Jarrah wood, native to Western Australia, is the hard-wearing material selected for the bridge decking.

18. 4D construction staging was carried out to verify the proposed erection methodology of the steelwork arches.

19. Opening of the bridge in January 2015 was celebrated with a light and water display that illuminated the arches against the night sky.

possible through the use of shared modelling, with both the architect and engineers using Rhino + Grasshopper scripts to control the geometry definition. The scripts were shared on a daily basis to maintain coordination between the structural analysis and the architectural geometry.

Materials

Presented with a windy riverside location and the sometimes harsh Western Australian climate, the architect carefully selected materials for the bridge that were relevant, locally sourced, and of the highest quality. Materials were chosen for aesthetic appeal, ability to reduce wind impacts and vibrations, and ease of ongoing maintenance. The Jarrah wood that forms the bridge decking, for example, is hard-wearing and a Western Australian native, familiar to many people using the bridge.

Stainless steel was selected for the balustrading and other architectural elements because of its durability and, in particular, its resistance to salt and wind corrosion. The stainless steel mesh balustrading will stand the test of time and provides the desired level of transparency to permit unrestricted views across the river.

In-depth consideration was given to internationally sourced structural steel. The design team sought advice from Arup material experts to inform the client and stakeholders regarding the risks and opportunities, such as cost, time, compliance with Australian standards, and consistency of chemical composition. These investigations concluded that the local Australian steel market offered both the best quality and best value product for the bridge.

Fabrication

Perth-based steel fabricators were selected to manufacture the structural steelwork for the bridge's arches and deck. This permitted close collaboration between the design team, contractor and fabricators. The required construction tolerances were necessarily onerous to achieve the structural adequacy and aesthetic aspirations; compounded construction tolerances were considered unacceptable.

Collaboration with the fabricators commenced with a briefing during which Arup shared the parametric scripts used to create the bridge geometry. This allowed architectural, structural and fabrication 3D models to be created from the same base parameters, to optimise the coordination.

The arches were fabricated offsite in three lengths, and the deck in twelve lengths. The modules were fabricated adjacent to each other and match-fit in the fabricator's yard to ensure construction tolerances were achievable. The high level of attention given to coordination and tolerances throughout fabrication directly improved the constructability of the bridge, and contributed to the success of its delivery.

19.

Constructability

Interfacing with the urban design of the adjacent promenades and the island was a very important consideration in design. The constructability and safety of the bridge construction was significantly improved by the decision to create a temporary bund around the bridge site to permit working from dry ground. This was demonstrated most clearly by the arch construction.

The prefabricated arches were delivered to site in three parts which were then aligned and welded together. Standing each of the two arches was done in a single operation lasting about two hours, during which time the arch that was being lifted was always fixed to the ground by hinges at the base connections and a central crane. Neither arch was ever lifted free of the ground.

The crane lift trailed a central strut along a temporary track. This configuration provided full support for the arch being lifted at all times and this planning allowed for the arch to be securely locked into place and the site evacuated quickly and safely at any time if needed. The planning and constructability assessments also enabled the arches to be constructed within 2mm of the documented position.

Conclusion

A striking architectural feature, the bridge gives substance to the MRA's slogan: 'The River. The City. Together Again'. The design of the Elizabeth Quay Pedestrian and Cyclist Bridge is everything the MRA sought to achieve in terms of simple and pure structural forms, complemented by a rationalised modular architecture to the fascia finishes, balustrading and timber decking. The design solution overcame every technical and construction challenge while ensuring the bridge's visual appeal was at the forefront of the design.

The use of shared modelling was pivotal to successful delivery of the project, with both architect and engineers using Rhino + Grasshopper scripts to control the geometry definition – scripts that were shared on a daily basis to ensure that structural analysis kept pace with architectural geometry.

Alistair Avern-Taplin, Arup's Perth office Leader, said: "It's very rewarding to see our design come to life. We are incredibly proud to have been involved in delivering the bridge and being a part of the transformation of Perth's Swan River waterfront. It is an iconic project that will forever change the way people enjoy one of the country's most vibrant and diverse cities."

Authors

Alistair Avern-Taplin is Arup's Perth office Leader.

Nick Birmingham worked with the architectural team based in London, where he was involved in the design process from conception to construction. He is an Associate at Arup Associates, based in the London Office.

Stewart Buxton was the Lead Structural Engineer and Project Manager for the bridge and also worked on numerous other small projects within Elizabeth Quay. He is an Associate in Arup's Perth office.

Clayton Riddle was responsible for implementation of digital workflows and steelwork design. He is currently a Senior Engineer in Arup's London office.

Project credits

Client: *Perth Metropolitan Redevelopment Authority (MRA)* Architect: *Arup Associates* Managing contractor: *CPB (formerly Leighton) and Broad* Structural engineering and façade services, civil engineering, geotechnical engineering, electrical engineering, materials specialists, advanced technology and research (AT&R), wind engineering, vibration engineering, and naval architecture: *Arup – Andrew Allsop, Alistair Avern-Taplin, Nick Birmingham, Peter Burnton, Stewart Buxton, Efren Cerrero, Anthony Ferrau, Anastasia Fragoulis, Kathy Franklin, Ruby Heard, Milena Kovac, Mira Lee, Michael Lin, Angus Low, Lewis MacDonald, Georgie Prie, Anu Ramachandran, Clayton Riddle, Nic Scanlan, Ed Spraggon, Julia Summers, Kai Tan, Jess Watts.*

Image credits

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The Ribbon Chapel, Japan

Location
Hiroshima, Japan

Author
Ikuhide Shibata

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1. The Ribbon Chapel, its design inspired by a spiralling ribbon, overlooks the Inland Sea of Japan.

2–4. The bride and groom climb separate stairways for a blessing from heaven, then descend as a couple to the chapel below. The chapel occupies the space at the core of the spiral's orbit and the chapel aisle faces towards a long-established tree, an enduring part of the landscape.

Introduction

It must rank as one of the most romantic places to get married in the world – and from an engineering viewpoint, one of the most intriguing.

The ingenious Ribbon Chapel, perched on a cliff-top overlooking the Inland Sea of Japan, comprises interlinked spirals of steel supporting two staircases that are essentially the floors, walls and ceilings of the building. The directionally opposed staircases meet at the top, symbolising two paths ending in marriage.

This delicate structural design was developed by Ikuhide Shibata of Arup working in collaboration with architect Hiroshi Nakamura, and his firm Hiroshi Nakamura & NAP. It is a triumph of symbolism and practicality, with the building becoming part of the marriage ceremony as the bride and groom climb separate stairways for a blessing from heaven, then descend as a couple. The chapel's structural system of hoops and 3D bracing is believed to be unique.

Arup's brief

The chapel is situated at one of Japan's leading resort hotels: Bella Vista Spa and Marina, Onomichi. Nakamura's concept, based on a spiralling ribbon, takes full advantage of the spectacular sea-views afforded by the chapel's position high above the calm waters of the Seto Inland Sea.

Arup worked with Nakamura to refine and deliver the concept, providing multidisciplinary services including structural engineering, geometric engineering, mechanical, electrical and plumbing services (MEP), lighting design, acoustic and façade consultation.

Chapel structure

As a single spiral would sway from side to side and vibrate vertically, making it very unstable, a self-standing structure was created by linking the two spirals to support each other. The spirals join smoothly at the 15.3m summit to form a single ribbon. Occupying the space at the core of the spiral's orbits is the chapel where wedding guests wait for bride and groom to descend the staircase.

The chapel aisle faces towards a well-established tree, which has been growing on the hillside for many years, again a choice of deliberate symbolism. The altar stands before the tree, and 80 seats are positioned for views of the sea through the trees.

The structure can be regarded as a coiled spring that twists and expands outwards, while moving up and down with pressure from above. Arup's solution for stabilising the movement was to have four connections where the inner and outer spirals meet. This creates a basic structural concept of hoops and a 3D bracing system that allows an overhang of the spiral. It is believed to be the only structural system of its kind in the world.

The spiral stairway comprises two steel tubes (318.5mm in diameter, 7.9mm and 16mm thick) and tie members (16mm and 25mm thick flat bars) bridging the steel tubes, with steel floor plates (9mm and 12mm thick) mounted on them. The tie members enhance the torsional stiffness of the stairway and suppress buckling of the steel tubes, while the steel floor plates play a role in smoothing transmission of the horizontal force by ensuring in-plane stiffness.

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5, 6. The structure is stabilised by four connections, situated where the inner and outer spirals meet, and the basic structural concept of hoops and a 3D bracing system allows an overhang of the spirals. It is believed to be the only structural system of its kind in the world.

7. The spiral stairway comprises two steel tubes constructed from 88 joined sections of different two-dimensional arcs.

8. The inner stairway is supported by vertical prop supports.

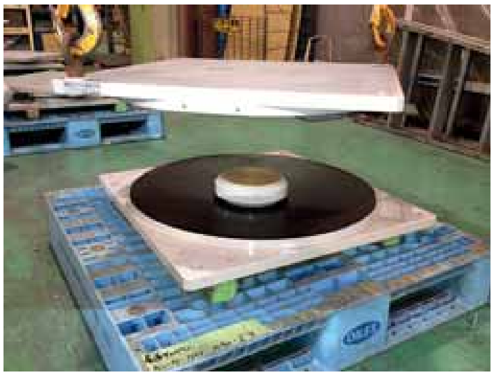
The inner stairway is supported by vertical prop supports (100mm diameter solid steel rods), while the outer stairway overhangs, supported both vertically and horizontally by four coupling beams (318.5mm diameter steel tubes). The fact that they are so coupled that they suppress each other's deformation improves the vertical and horizontal stiffness dramatically. This creates an overall tube-like structure that resists external force. Indeed the four coupling beams play a pivotal role for the structure.

There were three points of concern, where the floor's natural vibration frequency was under 8Hz, so three cantilever-type tuned mass dampers were installed to reduce floor vibration for visitors' comfort.

Base isolation system

A friction pendulum system (FPS) base isolation system was installed to reduce seismic force and increase durability, making it unnecessary to modify the form, system, regulations or specification of materials. The resulting structure is a seemingly totally independent floating spiral staircase, with unobtrusive vertical support posts.

The FPS is a seismic isolation device that consists of an upper/lower spherical plate, its



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sliding surface applied with a special non-oily coating, and its moving disc made of sliding material. In accordance with the principle that the period of a pendulum is determined by the length of the string, regardless of the mass of the weight, the FPS sets the period with the radius of the spherical sliding surface and has the function to restore.

Structural model with 3D torque

It was foreseen that when shoring was removed, the building would undergo rotational sagging of up to 30mm under its own weight. So a structural model was made applying the same amount of reverse torque as the predetermined natural rotational force, the amount of possible deformation calculated through computer simulation. As a result, the studs, which were deliberately angled for construction, became perpendicular at the time of completion, and stayed within a 2/1,000 margin of error between floors.

Geometric engineering

In order to reduce cost and construction time, a spiral steel tube approximately 280m long and 318.5mm in diameter, that had been designed to form a single uninterrupted free curve, which was replaced with 88 joined sections of different two-dimensional arcs, with radii ranging from 1.5m to 9m. The difference (10mm maximum) from the actual free curve was compensated for by the base material of the finish, resulting in the seamless flow of a helical curve.

Normally, a building consists of the separate elements of roof, walls and floors, but in the Ribbon Chapel the intertwining ribbon creates the space, forming the roof, eaves, walls and floor. The width of the spiral stairway varies according to location and function. It is wide enough at the top for the couple to stand and face each other, where the eaves are lowered to provide shelter from the sun, and it narrows in places to focus on the emergence of an attractive view.

Surfaces

The building's exterior is clad in vertical wooden slats, painted white to acquire a patina over time. The narrow width of the slats, just 80mm, allows them to fit to the curved surface. The other surfaces adopt titanium-zinc alloy, resistant to salt air and sufficiently pliable to hug the three-dimensional contours of the surface. Using zinc alloy on the coping, walls, ceiling and window sashes unified the design by means of a single material.

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9. The base isolation system is based on a moving disc.

10. Sections of two-dimensional arcs are lifted into place to form the staircase.

11. The staircase narrows in places, as an attractive vista comes into view.

12. Cladding unifies the structure: white wood slats and titanium-zinc alloy to resist the salty sea air.

Air-conditioning, lighting and acoustics

As the interior space has a maximum ceiling height of 14.2m, there were concerns that if the air-conditioning vents were positioned in the ceiling, the air would not circulate evenly and cold air would blow directly onto guests. To resolve this problem, ingenious use was made of an underground pit that was dug in order to install a seismic isolation system. An underfloor air distribution system was adopted around the perimeter zone to enable efficient temperature control focused on the area occupied by everyone involved in the ceremony. This means the spiral reveals its pure expression on the interior, interrupted only by lighting and speakers.

The lighting fixtures are fitted below the spiral and to create a romantic ambience, detailed simulations were carried out before the selection of lighting was made and positioning was decided, taking the effect of the curves into consideration.

Acoustics were also a challenge, given the curved and circular shapes and limited surface available for sound absorption materials. Acoustic simulations were used to confirm acceptable levels of sound reverberation that were satisfactory to the client.

Façade engineering

The windows vary in height, shape and thickness, and each joint of their glass panes varies in angle. In anticipation of a certain displacement due to the self-weight load, the glass panes were produced by measuring the actual size of all openings, following erection of the steel frames and placement of concrete which account for 80% of the cause of such displacement. To protect the glass panes from the three-dimensional torque of the structure during earthquakes and strong wind, they are secured with dot-point-glazing (DPG) fixtures, and suspended in front of the rise of the waterproof titanium-zinc alloy coping, making them lower sash-free.

Although there are only two bearing points, at the top and bottom of each pane, in consideration of the vista from inside, thicker glass had to be used, thus resulting in a higher load. This meant that the treatment of the lower sash, if adopted, would be extremely complex, as it would have to both

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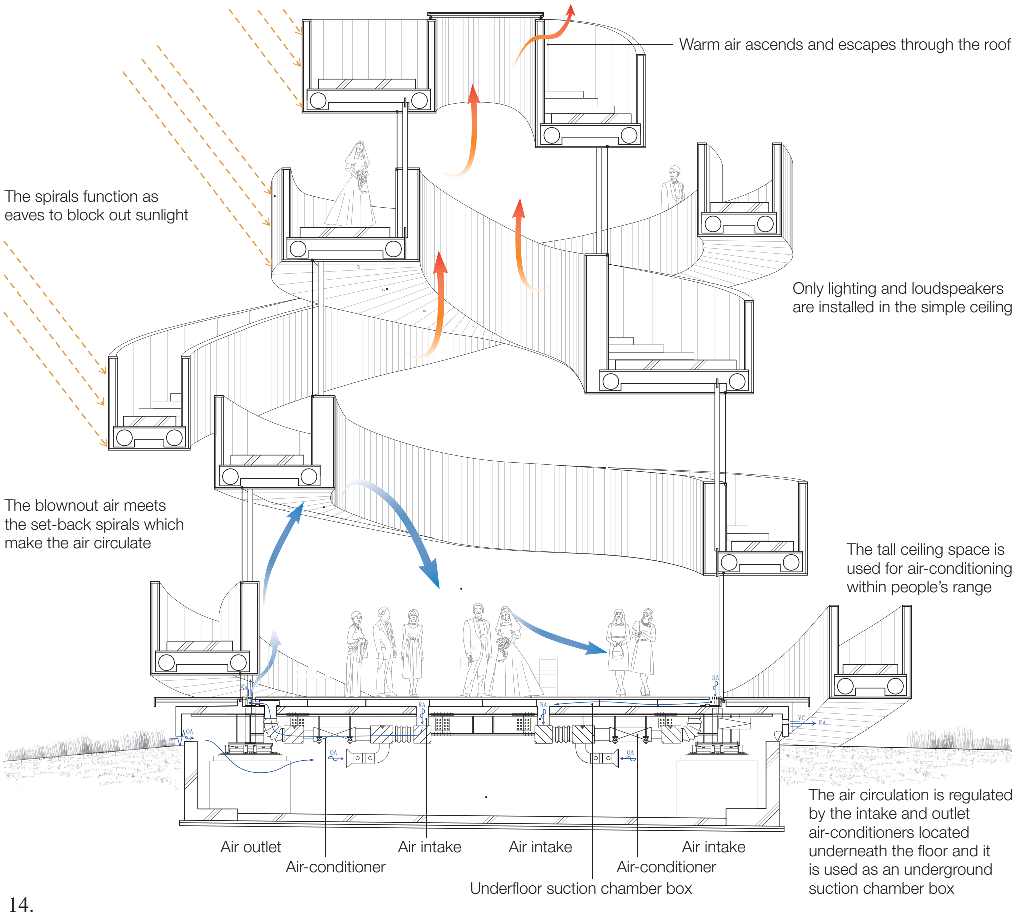

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withstand such load and accommodate the waterproofing of curved openings. The solution was to fit the top of the pane in a sash inset into the ceiling and to make the lower end a seamless finish along the waterproofing rise of the titanium-zinc alloy, with the use of DPG fixtures, thereby concealing such fixtures as well as achieving complete water-sealing of the curved openings.

At the very top of the building is a skylight where the ribbons converge, that lets light into the chapel below.

Conclusion

Arup developed innovative solutions to deliver architect Hiroshi Nakamura's vision, in particular an unusual structural system that is believed to be the only one of its kind in the world. The Ribbon Chapel exemplifies the Arup concept of total design, combining a durable structural system with simplified fabrication methods for cost and time efficiency.

In recognition of this achievement, the project has already received the Grand Award from the Japan Commercial Environment Design Association (2014), the Outstanding Achievement Award from the Japanese Society of Steel Construction (2015), and the Japan Society of Seismic Isolation Award (2015). It was Overall Winner of the LEAF Awards 2015, which celebrate excellence in building design on an international basis, and Ikuhide Shibata, who designed the solution for Arup, won the Japan Structural Design Award 2015.

Author
Ikuhide Shibata is a Senior Associate, Project Director and Leader of the building engineering team in the Tokyo office.

Project credits
Client: *Tsuneishi Holdings Corporation* Architect: *Hiroshi Nakamura & NAP Co Ltd* Structural engineering, MEP, lighting design, acoustic consulting: *Arup – Ikuhide Shibata, Junichiro Ito, Kentaro Suga, Celso Soriano Junior, Chieri Iizuka, Michael Whiteman.*

Image credits
Koji Fujii / Nacasa & Partners Inc.

13. Lights are strategically placed within the curve to create the perfect ambience, day or night, while a skylight where the ribbons converge funnels daylight into the chapel below.

14. Using an underfloor pit as part of the air-conditioning strategy ventilates the unusual space within the chapel unobtrusively and effectively.

15. Subtle interior lighting creates appropriate ambience at all times of the day and night.

16. The glass window panels are secured using fixtures to defend them against the three-dimensional torque of the structure during earthquakes and strong wind.

Curtis Island LNG Jetties, Australia

Location
Queensland, Australia

Authors
Matt Hodder Jesper Jensen Peter Kastrup

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1. Overview of the Curtis Island LNG plants.

2. Santos GLNG.

3. Queensland Curtis LNG.

4. Australia Pacific LNG.

Introduction

Growing demand for energy in South East Asia and the Pacific region has resulted in a vast increase in gas exploration across the continent of Australia. With liquefied natural gas (LNG) widely recognised as a more sustainable source of power generation than coal or fuel oil, it is a popular component of the energy supply strategy of many nations in the region.

Arup Australasia and John Holland Group (JHG) entered into a Memorandum of Understanding (MOU) in 2009 to collaboratively tender for and deliver LNG export facilities across the Australian seaboard. The intention was to provide all parties with valuable design and construction experience in this developing sector.

The strategy that underpinned the MOU led to the award of the Curtis Island LNG Jetties projects. Throughout the five-year collaboration that followed, the design and construct (D&C) relationship between Arup and JHG demonstrated the benefits of incorporating multidisciplinary capabilities into a ‘one team’ approach. The first gas was shipped from the Queensland Curtis LNG Jetty on 5 January 2015.

The project

On the southwestern shoreline of Curtis Island, there are three LNG plants: Queensland Curtis LNG (QCLNG), Santos GLNG (GLNG) and Australia Pacific LNG (APLNG), all of which are accessible only by water. In 2010, the Queensland Government approved these, with the project partners across the three projects being: QCLNG – QGC(BG), China National Offshore Oil Corporation; GLNG – Santos, PETRONAS, Total, KOGAS; APLNG – Origin, ConocoPhillips, Sinopec.

Bechtel was awarded the engineering, procurement and construction contracts for all three projects and JHG was awarded the marine jetty subcontracts, including the procurement, fabrication, construction and commissioning of the structural, mechanical and electrical components of the product loading facility. JHG appointed Arup in a D&C collaboration for the permanent works design. Arup also provided engineering expertise and design support during construction, certifying that the works met the design intent.

Context

With multiple project governance levels, establishing a clearly defined relationship within the D&C team was critical from the outset. Underpinned by the MOU, the project delivery structure was developed as a Collaborative Consultancy Agreement (CCA).

The pre-existing MOU relationship between Arup and JHG enabled the team to identify the requirements for successful collaborative and cohesive working early in the project. The design complexity, logistical challenges, and the need for design to be driven by constructability requirements, made this approach essential. Early constructability considerations played a vital role in the success of the projects because marine construction methods often influence the permanent works design.

Careful coordination between Arup's design team and JHG was essential in reaching a solution that achieved the design intent and could also be constructed safely and efficiently. The CCA established clear lines of communication to facilitate engagement and transparent reporting throughout the project.

Arup's role

As design partner, the scope of Arup's involvement spanned the design for the roadway trestle, pipe rack modules (QCLNG only), loading platform, mooring dolphins, berthing dolphins and interconnecting walkways, as well as site-phase services and construction certification. (A dolphin is a man-made marine structure that extends above the water level and is not connected to shore.)


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5. Dolphin temporary support lifting.
6. Inside a pile plug reinforcement cage.
7. Piling using floating barge.
8. Plug cage.
9. Superstructure selection comparison.

The team managed design work both from Arup's Brisbane head office and remotely from the Gladstone site. The full time site presence and continuity of staff throughout design and construction meant the projects had access to engineering staff who were able to facilitate timely RPEQ (Registered Professional Engineer of Queensland) construction certification and make on-the-ground design changes, as and when required.

Other aspects of Arup's role that were key to the successful development of the scheme included early collaboration with the client to understand the ancillary functional requirements of the dolphins, early input during tender selection, and involvement with the contractor to understand the constructability needs.

Concept considerations

Constraints associated with constructing over water were one of the defining considerations in the structural form selection. Early understanding of the contractor methodologies, plant preference and availability, and the programme needs were imperative to developing the optimum solution.

Assessing the relative merits of vertical piles versus raked piles, and reinforced concrete (RC) superstructure versus steel frame, were major considerations.

Piling

Vertical piles are simpler to install than raked piles and they offer the flexibility to adjust rock sockets to manage geotechnical uncertainty. The main disadvantage of vertical piles is the complex 'pile to superstructure' connection to accommodate lateral loads.

Raking piles have better structural efficiency. They can resist lateral forces, partially as an axial load, but they are more difficult to install. They rely on increased certainty of ground conditions due to the difficulties in extending raked socket. Floating plant may not be practical for installation, however, and pitch can be difficult to control when driven to seams of hard or firm material.

The high variability of the ground conditions in Gladstone Harbour at Curtis Island, together with concerns over geotechnical risk, governed the decision to adopt a vertical pile solution. This was chosen over raking piles for the ease of installation and

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Item	Advantages	Disadvantages
RC superstructure	Can be constructed in stages to satisfy the maximum crane lift capacity.	Availability of quality concrete and restrictions on concrete delivery to offshore location.
	Ability to accommodate pile installation out of tolerances.	Heat of hydration concerns with large concrete pours.
	Standard formwork allows quick installation of form base and reinforcement fixing.	Labour intensive. Practical issues when form is within tidal zone. Setting out cast-in items is a challenge.
	Permanent precast formwork saves on temporary works, onsite steel fixing, and removal of formwork.	Staged pours may be required. Preparing the horizontal construction joint can be challenging.
	Precast fabricated in a controlled environment, which gives opportunity for improved appearance. Where marine grade precast concrete is used for the critical exposed sides and soffit, it may be possible to use in-situ concrete with lower durability and strength.	Consideration should be given to tidal variations in relation to the temporary support scheme.
	Increased control of material quality with steel truss typically fabricated offsite in a controlled environment.	In-situ welding is likely to be required for connection to piles – or a sleeved option may be preferred. Difficult to install with raked piles incl. sleeved option.
Steel superstructure	Prefabrication can reduce in-situ labour and construction time significantly.	Reduced ability to accommodate piles installed out of tolerances.
	If no design corrosion allowance, full steel section can be utilised for structural capacity.	Potential vortex-induced vibrations during transportation may be governing.

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flexibility. Vertical piling also meant that more costly jack-up barge mobilisation would not necessarily be required.

A traveller was used to install the trestle piles (and headstocks, pipe rack modules and deck units). The use of a traveller allowed for the piling to be done independently from the water and intertidal area, which reduced risk of downtime due to wind, waves, tides and currents.

The vertical piling decision had a major influence on the structural jetty design, which is discussed in the following sections.

Superstructure selection comparison

Assessing the advantages and disadvantages of RC superstructure versus steel frame involved weighing up a whole host of options, which are summarised in the table above.

For constructability purposes, an RC superstructure was selected. The reasons are detailed in the sections below.

Rock socket/anchor

Due to the design criteria, loading and structural layout, some of the dolphin piles were subject to tension forces, which required rock sockets/anchors to fully transfer the design forces to the ground. Arup and JHG assessed options such as RC rock sockets and post-tensioned grouted rock anchors. The geotechnical conditions meant that the RC rock socket was deemed the most effective and flexible option. The bored in-situ concrete rock sockets could be extended where required to counteract the ground condition variability and manage geotechnical uncertainty.

This constructability decision impacted on incorporating this element into the pile design. When included in the dolphin pile analysis, the RC rock socket attracted not only axial force, but also shear and bending moment, and the connection detail to the steel liner had to be developed. To transfer the forces from rock socket to liner, Arup and JHG developed a solution using internal shear beads, which were designed to a size not protruding past the pile shoe to mitigate risk of damage during pile driving. In turn, this detail led to requirements for cleaning of the rock socket and bottom part of the liner to ensure adequate concrete placement and bond.

Trestle

A traveller was used on all three projects to install the trestle piles, headstocks and deck units. This constructability decision impacted the pile and headstock permanent works design.

The crane on the traveller was used to lift piles, headstocks and deck units; hence the reaction forces from these load cases were incorporated into the design of piles and headstocks. In addition, the deck units were transported from land to the traveller using a self-propelled modular transporter (SPMT), so the deck units were also designed for this purpose.

Arup and JHG assessed headstock options, including a box section slotted into the pile and a box section placed directly on top of the pile. Due to the preference for not cutting the slot in the pile, design loadings, and criteria including a significant corrosion allowance, it was decided to adopt the steel box section welded to the top of the pile.

Although adopted for the abutment headstock, a typical concrete headstock was not preferred due to constructability considerations such as maximising headstock installation time, traveller speed and practical design aspects requiring a steel section for load capacity at the critical locations.

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Concrete deck units were designed for the temporary works load cases (in addition to permanent load cases), including the lifting case, and to provide compression throughout the cross section. Arup and JHG developed the design of the deck units to fit within the lifting capacity of the crane proposed for the traveller.

Loading platforms

The loading platform size and deck level varied between all three projects, though JHG preferred a universal pile size to facilitate use of the same piling equipment across all of them.

A concrete superstructure was adopted, and the designs were in all cases heavily governed by the constructability requirements. Wind forces on loading arms were also governing factors. The vertical pile arrangement meant that a relatively large quantity of reinforcement was required for the pile cap or headstock. Detailed space proofing was prepared considering piling and precast tolerances and cast-in temporary works members.

QCLNG loading platform

Precast pile caps were used on QCLNG. Primary precast deck planks were then placed on top of the pile caps followed by secondary precast deck planks, which were placed to create the full soffit of the platform.

One area of the deck had to be completed first, so that JHG could install a crane here to facilitate the rest of the loading platform construction.

A detailed staged analysis was performed to overcome the challenge of designing the precast, including pile caps, and in turn, assess and advise of allowable crane pad locations for an incomplete platform.

GLNG loading platform

The GLNG loading platform was designed and built with precast headstocks spanning in the direction of the quay line. Precast deck planks span the headstocks to complete the concrete soffit. This design avoided the need for pile caps, however, requiring larger lifts than QCLNG.

The platform was built partly using a crane on a floating barge and partly using the traveller crane once it had reached the platform location.

APLNG loading platform

The APLNG loading platform was designed and constructed in a similar way to GLNG. Precast headstocks were placed directly on top of the piles without the use of concrete pile caps. Secondary precast planks span the headstocks to create the permanent soffit of the structure.

Dolphins

The dolphin design was also heavily influenced by the construction method decisions. A main factor was whether or not to adopt a precast shell or use a conventional temporary formwork strategy for the reinforced pile cap. Another key component was the pile plug, which is a reinforced concrete plug within the top of the piles.

The construction of these structures was done in different ways on the three projects. Due to the vertical pile arrangement, a large

10. Overview of dolphin and loading platform.

11. Curing.

12. Span 14 walkway with bearings.

13. Northern dolphin overview.

14. Berthing dolphin on GLNG jetty.

15. Socket cage.

16. Precast berthing dolphin shell after reinforcement installation.

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quantity of reinforcement was required within the pile cap, which proved challenging when also having to account for piling tolerances and cast-in items such as fenders, mooring hooks and internal temporary works members.

QCLNG dolphins

For the berthing dolphins, the pile extends into the cap. On QCLNG it was decided to prefabricate the pile plug reinforcement cage and attach this to the top part of the pile, which also had externally welded shear keys. This assembly was then welded with full penetration butt welds onto the pile at the surveyed level.

Temporary works members were also incorporated into this assembly, facilitating less work over water when subsequently installing the temporary formwork. For QCLNG, Arup and JHG further developed a modular concept for the pile cap reinforcement, which was another measure adopted to reduce work done over water.

GLNG dolphins

The construction methodology that Arup and JHG developed for GLNG was different to the other projects in a number of ways.

A precast shell (soffit and sides) was used to avoid the need for temporary formwork over the water (temporary supports to the piles in the tidal zone were required to land the shell).

Also, instead of traditional round reinforcement bars, a predominantly steel plate-based reinforcement concept was adopted to provide less congestion within the cap. This steel plate arrangement was fully prefabricated offsite and lifted into the cap in two pieces.

The precast shell facilitated the early installation of walkways to provide access for staff and enable concrete pumping from trucks on the loading platform rather than delivery by barge.

APLNG dolphins

The APLNG dolphins were designed and built using standard formwork. For the mooring dolphins, the pile plug reinforcement cage extended fully into the pile cap and had to be designed to allow for the temporary works supports.

JHG also used early installation of walkways on the APLNG dolphins to improve access for staff and concrete pumping practicalities. This was also a critical factor in being able to reduce the time from concrete batching to the point of discharge. This was important to control the placement temperature during the summer months.

Innovation

Much new learning was gained from the success of the Gladstone Jetties projects. Experience was shared across the three projects, in design and construction, and the open communication pathways made it easy for learnings from one project to be applied to the other jetties.

17.

18.

During design phase, modular construction methods applied to guardrails, dolphins and trestle deck units saved time and money when used for subsequently constructed marine facilities. During construction, lessons learned relating to heat of hydration were implemented in pedestal reinforcement to resist cast-in stainless steel plate welding temperatures. The introduction of modular construction methods saved time and increased safety while working above water.

Arup's design, in collaboration with JHG, featured many innovative improvements from the reference design to achieve less onerous impacts on the marine construction plant, while detailed planning of the temporary works design reduced construction costs. For example, Arup carried out very detailed mooring, geotechnical and structural analysis to justify saving two rock sockets per dolphin. This resulted in a 20% cost saving for the dolphins without compromising the required design criteria.

Reduction in steel reinforcement, congestion and clashes was achieved. Supported by both JHG and Arup, a dolphin BIM model was developed to optimise the design and ultimately develop a cost-saving modular reinforcement concept. With Arup completing the detailed design, the benefits of the BIM modelling were transferred back to JHG to enable reinforcement fabrication. This successful BIM process reduced time and cost onsite.

19.

Similar dolphin designs were developed. The reuse of dolphin temporary works structures enabled the dolphin construction crew to complete the QCLNG jetty and immediately move on to the other two jetties. The projects benefited from construction efficiencies, improved safety and reduced costs because the crew was already experienced at dolphin construction and able to utilise structural components with which they were familiar.

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Conclusion

Due to the structure of the CCA, the programme of work allowed for implementation of lessons learned as the projects progressed. This resulted in incremental improvement in the delivery of the projects and a reduction in the necessity for JHG design management.

Through staff continuity and clear communication protocols, the team was able to navigate design challenges with a complete understanding of JHG requirements and expectations.

The benefits of a one-team approach were evident throughout the projects and all three LNG jetties are now completed and fully operational.

Authors

Matt Hodder, Senior Engineer, Dolphins and Walkways Design; *Jesper Jensen*, Senior Engineer, Dolphins and Walkways Design; *Peter Kastrup*, Senior Engineer, Dolphins and Walkways Design.

Project credits

John Holland Group, Bechtel, QCLNG, GLNG, and Australia Pacific LNG. Arup – Zulfiqar Ahmed, Marilou Alzate, Ravi Anegondy, Davar Abi-Zadeh, Manoj Aravind, Craig Baas, Andrew Batts, Michael Bieganski, Roger Blackwell, Kelvin Bong, Paul Brady, Peter Burnton, Stewart Buxton, Christophe Bragard, Mark Brand, Ger Breen, John Cain, Cossel Chang, June Chen, Jason Chin, Katie Cook, Steven Cook, Shane Collins, Tom Crocker, Wilma Cruz, David Dack, Ian Darlington, Joseph Donohue, Jochem Dorst, Peter Duggan, Peter Dunn, Roy Everett, Jared Fetherston, Silvia Ferrero, Anthony Folan, Owen Francis, Stephen Fraser, Jon Gerig, Chris Gildersleeve, Marcin Glowacz, Matthew Gordon, Adrian Goh, Steve Grigg, Andrew Grime, Catriona Gurney, Andrew Herriman, Claire Heumann, Glyn Hickling, Patrick Hinde, Matt Hodder, Andy Horton, Min Huang, Wendy Humboldt, Austin Inglis, Peter Ingvorsen, Emilia Ismail, Greg James, Piers James, Jesper Jensen, Robert Jones, Peter Kastrup, Michael Kelleher, Micheal Killeen, Ben Kirkwood, Nick Knook, Mathias Kuhn, Wilson Lam, Kaitlin Langdon, Simon Larsen, Bob Lea, Peter Lees, David Lewin, Bogumil Lipiecki, Brian Lord, Leon Lorenti, Josephine Luarez, Gary Lucas, Jing Lucena, Chris Lyons, Lewis Macdonald, Sarah Madrigal, Rowena Mangilit, Dorothy Mao, David Marshall, Olan Masula, George McCarthy, Colm Mckenna, Ian Mcrobbie, Dara McDonnell, Keith McSweeney, Robert Meyer, Russell Millard, Lloyd Millenstead, James Mortensen, Tobias Motz, Lisa Naylor, Jay Noonan, Joanna O'Brien, Liam O'Donohue, Eoin O'Donovan, James O'Dwyer, Claire O'Hara, Karen Oj, Eoin O'Malley, Jasvinder Opkar, Bernard O'Shea, Robert Ou, Carla Poulson, Nadine Radburnd, Hamed Rahimi, Hasnat Rahman, Andrew Richardson, Antony Schofield, Rohitesh Reddy, Sangeri Retnam, Nathan Roberts, Sarah Robinson, Peter Rooks, Iemke Roos, Rob Ryan, Horacio Salerno, Joel Savage, Joao Sela, Robyn Shaw, David Skinner, Mark Skinner, Emma Steer, Massimo Silvestri, Mike Straughton, Astrid Stuer, Jeremy Sue, Julia Summers, Amir Tabei, Kai Tan, Edmond Tang, Tom Tang, Yan Tsang, Luke Tarasuik, Adeline Teo, Jakki Thompson, Tim Thompson, Ally Thomson, Kieran Toon, Lloyd Twomey, Andrew Turnbull, Nathan Walding, Jordan Wan, Michael Ward, Chris Webb, David Whitaker, Emily Whitehill, Craig Wiggins, Lukasz Wojnarski, Michael Wong, Alastair Woodland, Eddie Woods, Lawrence Wu, Pete Zbrojkiewicz.

Image credits

Arup.

22.

17. Walkways.

18. South-side overview.

19. North-side overview.

20. Berthing dolphin on APLNG jetty.

21, 22. Methane Rita Andrea LNG vessel at the QCLNG berth (first vessel to ship gas from Curtis Island).

CapitaGreen, Singapore

Location
Singapore

Authors
Michael Chin Scott Munro Xu Jingfeng Peter Tomlinson

1.

1. CapitaGreen is distinctive in appearance, yet evidently a commercial building, standing tall within the CBD.

2. The greenery that is visible across the façade (below the rooftop sky forest) is planted between an exterior layer of frameless glass and an interior layer of high-performance, double-glazed, unitised curtain wall system.

3. Cool void ventilation system draws air from the sky and delivers it to each floor.

Introduction

CapitaGreen in Singapore's central business district (CBD) is a premium commercial development, remarkable for the lush greenery growing inside its ingenious double-skinned façade and ventilation modelled on the respiratory system of a plant.

Arup worked with internationally acclaimed designer Toyo Ito on the environmental and façade strategy for this innovative 40-storey building, which combines the best of modern office technology with a level of sustainability that led to a GreenMark Platinum Award from the Building and Construction Authority (BCA) of Singapore.

CapitaGreen was named 'Best Tall Building in Asia and Australasia' by the global Council on Tall Buildings and Urban Habitat (CTBUH) in 2015.

Project overview

Singapore-based developer CapitaLand wanted the design and engineering of CapitaGreen to incorporate exemplary sustainability features that functioned well in an urban setting. From the initial design vision of a tower breaking away from the earth's surface, Toyo Ito and Arup developed the concept of the building as a living, breathing plant growing towards the sky.

As a result of this collaboration, CapitaGreen looks distinctly different from the surrounding built environment. The tower is topped by a petal-like structure that serves as a wind scoop, while the innovative 'green'

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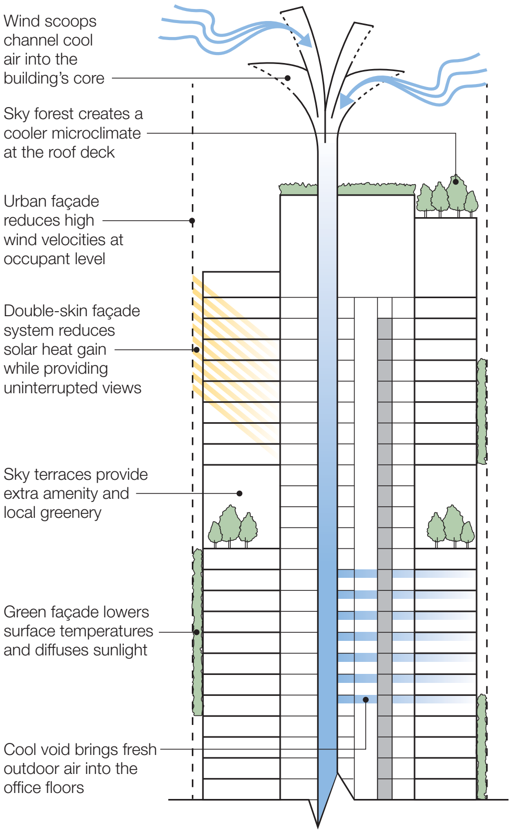

3.

façade represents a genuine breakthrough in how the performance of a double-skin façade can be enhanced to deliver increased sustainability benefits.

Commenting on the project's success in the CTBUH awards, Antony Wood, Executive Director of CTBUH, Chicago, said: "CapitaGreen indicates a new way forward for high-rise vegetated façades by placing them within the double skin. This offers the potential for solar shade and even agricultural output, as well as environmental and psychological benefits. The way CapitaGreen's 'living wall' connects a series of indoor and outdoor communal gardens, culminating in the grand roof terrace, is also commendable."

Arup's role

Arup's team, led by Project Director Michael Chin, provided environmental and façade consultancy and engineering, acoustic consultancy, and vertical transport engineering. Across all disciplines, the shared focus was sustainability, while the shared context was that the building should exude style and quality to attract the highest-calibre commercial tenants. The cool void ventilation system, innovative façade and energy-efficient lift service therefore sit unobtrusively into a building that is clearly designed for business.

The generous 3.2m floor-to-ceiling height windows, for example, provide uninterrupted views of Marina Bay and the rest of the CBD while flooding the building with maximum natural light and reducing traffic noise from the street outside. What is less obvious is the ingenious integration of the windows into a double-skin façade that reduces solar heat gain by up to 26%. The planting within some sections of the double skin lowers surface temperature, diffuses sunlight, and in many parts of the building creates an attractive dappled lighting effect.

This article examines the various interlinked features Arup worked on designing for this unusual building.

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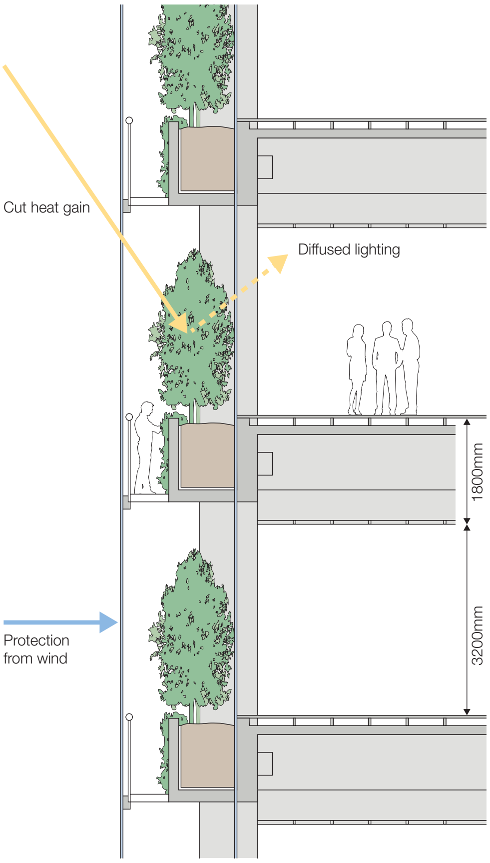

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Cool void ventilation

CapitaGreen has a 'sky forest' on the roof, lavishly planted with tropical trees. The forest is supplemented by lush planting on every floor and extensive sky gardens on three levels. For those who use the building, these gardens are an attractive amenity, yet they are also inextricably linked to the functioning of the building because the ventilation system developed for CapitaGreen draws cool air from the sky forest and delivers it through an empty central core to each floor.

The apex of the system design is appropriately at the building's crown, within the sky forest, where cool air is efficiently scooped into a distinctive wind funnel designed to look like a flower petal. The system works using the induction ratio principle, whereby the cool air drawn at the top of the funnel translates the dynamic pressure of wind, and converts it into positive static pressure to reduce the AHU (air handling unit) fan energy. Cooler air is supplied to the AHU fan at every level and the overall energy consumption is significantly lowered as a result.

The central core, called the inner tube, functions as a 'tree trunk' or 'plant stem' taking the flow of people up and down the building in elevators and, at the same time, carrying a continuous supply of cool fresh air, so that the whole building operates a circulatory system much like a living plant. The efficient airflow allows carbon dioxide to be absorbed more efficiently by the plants, thereby further mitigating the building's carbon footprint.

The building also features adaptive controls that adjust indoor temperatures to suit the diurnal fluctuations in external temperatures.

Façade

As part of the environmentally responsive design, Arup conceived the double-skin façade, consisting of an exterior layer of frameless glass and an interior layer of high-performance, double-glazed, unitised curtain wall system, with greenery between the skins in selected sections. Although the exterior of the building looks like glass, the perimeter of the façade is 55% planted with vegetation. This enhances the quality of daylight entering the interior spaces by diffusing the sunlight and reducing direct glare.

The façade delivers on value, performance and architectural expression by reducing wind velocities at occupant level, letting in diffused natural light and reducing solar heat gain.

Acoustic design

Another function of the façade system is to control the noise intrusion from the busy CBD traffic. As part of Arup's integrated design, Arup acoustic and façade engineers worked together to design a double-glazing system that effectively minimises the traffic noise intrusion to the interior spaces.

Building services equipment such as pumps, AHUs and chillers are major noise and vibration sources in a commercial building. Arup worked together with the contractor on every detail – from selection to installation and commissioning to ensure the designed noise and vibration control systems are implemented at the highest quality.

As a premium commercial building, CapitaGreen provides a high level of privacy for tenants. Arup's acoustic design paid meticulous attention to inter-tenancy walls to ensure seamless integration between the

6.

7.

4. The petal-like wind funnel in the sky forest on top of the building is also part of the cool void system.

5. The double-skin façade system, with planting between the interior and exterior skins, creates comfortable conditions for the building's occupants, as well as being environmentally responsive and energy efficient.

6. Sky gardens terraced into levels 5, 14 and 26 form part of CapitaGreen's cool void ventilation system.

7. The elevator system, based in a stylish lobby with bespoke 'earth plaster' walls, groups passengers with similar destinations to reduce journey times and increase energy efficiency.

8. Planting at ground level, as well as within the façade, instantly distinguishes this building from those around it.

9. At night, the rooftop wind funnel is decorative, as well as functional.

10. Level 38 features a swimming pool and gym facilities.

8.

9.

ceiling void, partitions, mullions and building services. The precision with which they join produces a successful acoustic design that enhances occupant comfort and productivity.

Materials and vertical transportation

An expansive lobby, with a triple-height ceiling and bespoke Kakiotoshi walls, receives visitors as they enter the building. The Kakiotoshi technique is essentially a scratched finish to soften the effect of a lime, sand and cement mix known as earth plaster. Popular in Japan, from where the name comes, it is durable, economic – and, in the case of CapitaGreen, where the finish is design-led, very stylish.

It was CapitaLand's desire that the vertical transportation system achieved an internationally comparable Premium Grade level of service, while at the same time supporting the project's sustainability initiatives.

Destination Control Services was selected to increase the elevator system's performance. By grouping passengers with similar destinations into common elevator cars, Destination Control Services reduces the elevators' round trip time, increasing the system's handling capacity and reducing waiting times.

Supporting the project's sustainability initiatives, the elevator system incorporated regenerative drive technology, which allows the elevators to generate power back into the building's internal electrical system when the out of balance load is assisting the direction of travel.

Use of materials such as timber and low-VOC (volatile organic compound) throughout the building further reduces the building's environmental footprint. CapitaGreen was also the first building in Singapore to use 'Supercrete', a special grade 100 ultra-high-strength concrete that significantly reduced the amount of concrete needed, saving energy and manpower as a result.

Conclusion

CapitaGreen provides approximately 700,000 square feet of premium office space, with exceptional facilities, inside a building that is far less conventional than it appears initially. The sustainability strategy is delivering environmental and health and wellbeing benefits on a daily basis.

Michael Chin, Arup's Project Director, said: "CapitaGreen showcases the collaboration among our multidisciplinary teams and how the integration of adaptive strategies into our engineering design has resulted in an environment that optimises aesthetics and thermal performance while raising occupants' health and comfort levels."

Authors

Michael Chin, an Associate Principal in the Singapore office, was Project Director and led the façade engineering design team.

Scott Munro is an Associate Principal in the Singapore office and led the environmental design team.

Xu Jingfeng is an Associate Principal in the Singapore office and led the acoustic consulting team.

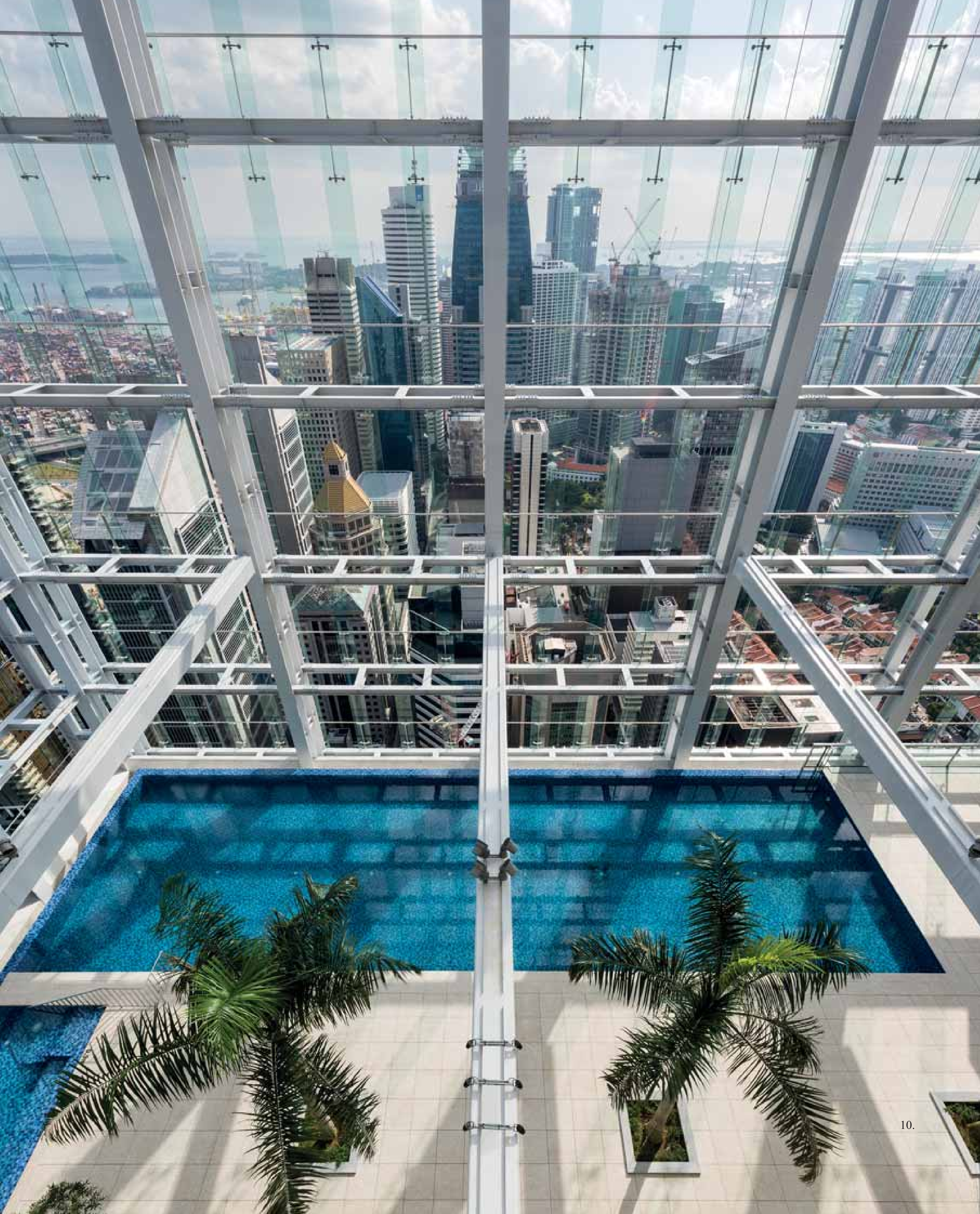
Peter Tomlinson, an Associate Principal in the Sydney office, led the vertical transportation design team.

Project credits

Owner: *Joint venture of CapitaLand, CapitaLand Commercial Trust and Mitsubishi Estate Asia* Architect: *Toyo Ito & Associates* Main contractor: *Takenaka Corporation* Acoustic and environmentally sustainable design, façade engineering, and vertical transport design: *Arup – Wei Cheng, Michael Chin, Majal Dag, Lauren Davis, Gino De Castro, Steve Drane, Xu Jingfeng, Kate Meyer, Chiam Ming Lee, Scott Munro, Jason Nutter, Samantha Peart, Teri Tan, Jocelyn Tay, Kai Ling Tho, Peter Tomlinson, Paul Sloman, Dino Van Deijzen, Alex Wong, Wu Xuchao, Derrick Yap.*

Image credits

CapitaLand, Arup.



10.

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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