Issue 1 2019

The Arup Journal

Contents

Seattle Space Needle, USA: *Nic Lehoux*

Strengthening connections

The Hong Kong-Zhuhai-Macao Bridge (HZMB) is the world's longest sea crossing. It promotes connectivity in a fast-growing region, significantly cutting journey times in the Greater Bay Area

Authors Naeem Hussain, Steve Kite, Samuel Kwan, David Pegg, James Sze, Peter Thompson, Fergal Whyte, Philip Wong, Ngai Yeung

On 23 October 2018, Chinese President Xi Jinping opened the world's longest sea crossing, the 55km Hong Kong-Zhuhai-Macao Bridge. Until then, travelling between Hong Kong and Macao/Zhuhai involved either a one-hour ferry ride (sometimes through bad weather conditions) or a four-hour detour over the Humen Bridge, a crossing to the north of the Pearl River Delta. With the opening of the HZMB, it is now possible to make the journey by car in a mere 40 minutes.

Arup performed a range of roles on the project, including creating and developing the concept and preliminary design for the main bridge and tunnel, and proposing environmentally friendly reclamation solutions for artificial island construction. Arup also worked on roads, tunnels, viaducts and other associated infrastructure.

Along the way, the firm had to be mindful of the scheme's impact on the surrounding environment and wildlife, the effect of extreme weather conditions on the programme and design, and the logistical challenges of coordinating and completing such a large and ambitious scheme – the HZMB took nine years to construct.

Developing a Greater Bay Area

The HZMB is part of a broader effort by the Chinese government to improve connections between 11 cities on the Pearl River Delta: Hong Kong, Macao, Guangzhou, Shenzhen, Zhuhai, Foshan,

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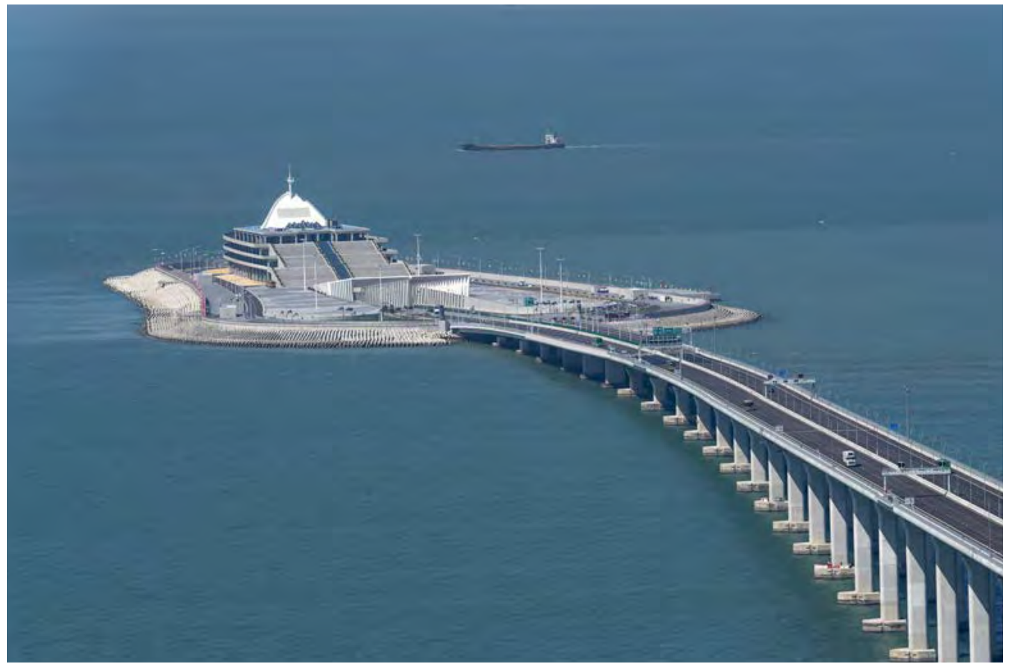
1: The 55km HZMB took nine years to construct



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2: It was necessary to construct a 6.7km tunnel to allow unobstructed navigation channels (Lingding and Tonggu channels)

3: An S-curved alignment was used adjacent to Hong Kong's Airport Island to avoid constraints relating to the airport runway and the Government Flying Service Headquarters

Zhongshan, Dongguan, Huizhou, Jiangmen and Zhaoqing. The intention is to create an economic and business hub, the 'Greater Bay Area', and to better connect Hong Kong and Macao to the Chinese mainland.

Three elements

The HZMB project comprised three key elements: the main bridge and tunnel; the boundary crossing facilities (BCFs); and the link roads connecting the three regions. Works spanned three geographical areas, Zhuhai, Macao and Hong Kong. In Zhuhai, which is part of China's Guangdong Province, Arup carried out the preliminary design for the main crossing, which consists of a bridge and a tunnel. In Macao, the firm was responsible for the overall planning and the preliminary and detailed design for the BCF infrastructure and the link road. In Hong Kong, Arup's role included planning, investigation and detailed design of the 130ha of land reclamation to create an artificial island for the BCF on the Hong Kong side of the crossing, and investigation and reference design for the 12km link road.

The section of the main bridge and tunnel in mainland Chinese territory was developed by the HZMB Authority, a body jointly organised by the three regional governments. The remaining sections of the link roads and BCFs were the respective responsibility of the three governments.

Main bridge and tunnel

Arup started working on the main bridge and tunnel in 2009 at the invitation of CCCC Highway Consultants, then known as the Highway Planning and Design Institute (HPDI). This process began with concept and preliminary design work. The overall route runs from the Hong Kong BCF, travels along the northern part of Lantau Island, enters Hong Kong waters and then crosses five water navigation channels – Tonggu, Lingding, Qingzhou, Jianghai and Jiuzhou Port. A tunnel of 6.7km runs between the first two, where the distance over the two channels was too wide for a long-span bridge. Three cable-stayed bridges cross over the last three channels. The total bridge length (including the three cable-stayed bridges and the shallow and deep water viaducts) is 22.9km. The crossing then reaches the artificial island where the Zhuhai and Macao BCFs are located.

In total, the crossing is 55km long – 29.6km for the main bridge and tunnel, a 13.4km link road in Zhuhai territory and a 12km link road in Hong Kong territory. Arup collaborated with the HPDI on the design of the elements on the Chinese mainland side and worked alone on the design for the elements on the Hong Kong side. The main bridge is a dual three-lane carriageway with hard shoulders (total width 33.1m), designed for a maximum speed of 100km/h. The tunnel under the Tonggu and Lingding navigation channels is made up of 33 tunnel elements, each measuring 180m x 38m x 11m.

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4: The HZMB project has significantly cut travel times in the Greater Bay Area

5: The Jiuzhou Bridge is a cable-stayed bridge with central sail-like towers and a central single cable plane

A project of such significance had to be aesthetically pleasing from all vantage points, as well as structurally sound in the face of frequent typhoons that occur in the region. The design and construction needed to take environmental considerations into account, in particular the impact on the Chinese white dolphins that inhabit the waters along this route.

The bridge's alignment was designed to ensure the least possible obstruction to the water flow, avoiding various site constraints, while also enhancing the views for bridge users. To achieve the latter, horizontal curves were added. To further improve the overall aesthetic of the HZMB, Arup proposed that all the bridges over the navigation channels be supported by cables, and that central towers of different shapes be placed between each span, each with a nautical theme. The main span of the 268m Jiuzhou Bridge has two symmetrical central towers shaped like sails; the Jianghai Bridge, comprising two 258m main spans, has three towers that resemble dolphins; and the 458m main span Qingzhou Bridge has towers shaped like the letter H, which feature cross-bracing like a Chinese knot. The first of these is the most visually exposed, as it can be seen from the restaurant-filled Zhuhai promenade. It therefore has the most striking design of all the bridges. The depth of the bridge deck was kept constant throughout, to offer visual harmony.

Arup designed a seismic protection system that satisfies the local codes of the three areas the bridge runs through. The frictional pendulum bearing absorbs the seismic energy in every bearing connection, thus isolating the seismic action from the foundation. The bridge decks are supported by single column piers with wide heads, and the bases are buried deep in the seabed. Single, rather than double, piers ensure that the dolphins' habitat and the flow of water under the bridge experience minimal disruption. In mainland China, spans between piers are typically 50m, but to help preserve water quality by minimising the number of piers that needed to be built, the spans were designed to be 85m for the composite deck in the shallow water to the west side of the crossing and 110m for the steel deck in deeper water in the middle and on the eastern sides. At the crossing between Hong Kong International Airport and Lantau Island, the span between piers is typically set at 75m, and up to 180m for crossing navigation channels and the headland between Sha Lo Wan and San Shek Wan. This meant fewer piers overall, and therefore less disruption during construction. Precast concrete shell construction was adopted for the pile caps to reduce the amount of temporary works construction required, and therefore lessen the impact on the environment.

The main logistical challenge of this part of the project was that all construction needed to take place in the sea. This meant that the construction materials had to be delivered to the site by marine vessels, and made working with in-situ concrete difficult. The solution was to precast as many of the

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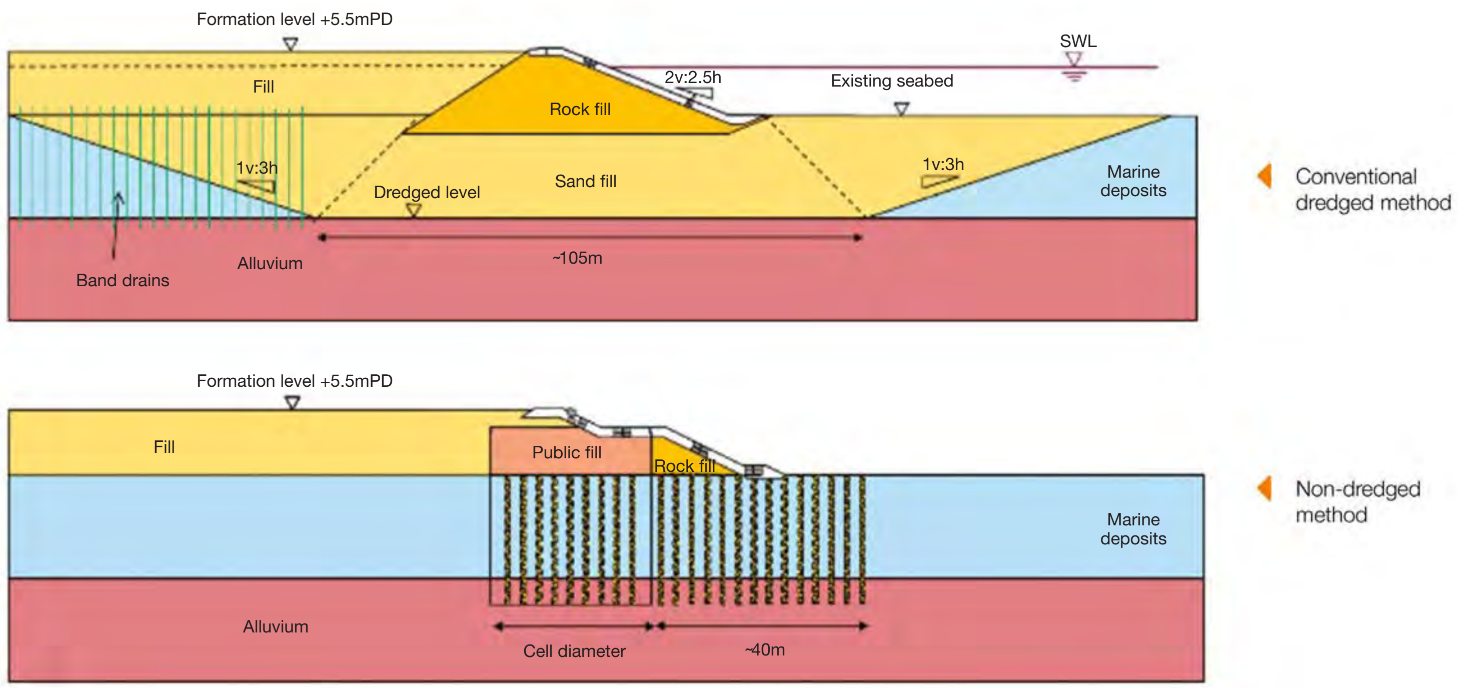

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6: Arup developed a non-dredged method of reclamation and seawall construction for the Hong Kong BCF artificial island

7: The Hong Kong BCF is located on an artificial island to the north-east of Airport Island

8: The composite section of seawall was constructed using a series of 32m diameter cofferdams without the need for dredging

7.

elements required as possible, including the pile cap shells, piers and deck segments. A floating concrete batching plant was used to supply the in-situ concrete needed to construct the foundation piles.

Hong Kong BCF

On the Hong Kong side, Arup's design included using a reclaimed area of 150ha to form an artificial island – 130ha to accommodate the Hong Kong BCF and 20ha for landfall of a connection road known as Tuen Mun-Chek Lap Kok Link (TMCLKL). Arup initially began working on this element of the project in 2006 by identifying the best possible site for the BCF. This area had to include clearance and transport facilities. Ultimately, it was decided that the BCF should be placed to the north-east of Hong Kong's Airport Island (an artificial island linked to Lantau), at a point convenient for travellers arriving into or departing from Hong Kong by air. This choice of location also avoided the need to reclaim land near the major sea channel to the north of the airport.

A particularly innovative element of the project was the development of an environmentally friendly non-dredged method of reclamation and seawall construction to create the artificial island for the Hong Kong BCF and the TMCLKL. This was the first time this method was used in Hong Kong. Typically, land reclamation projects such as this involve fully dredging the mud from the seabed and then laying down fill materials. Hong Kong's waters are full of sediment, which traps a lot of water, and so is not easy to squeeze dry for consolidation. This full dredging method is relatively quick, but it would have required a large amount of filler materials to replace the dredged mud. Moreover, when sediment is dredged, it then has to be disposed of in sea-based mud pits, a challenge complicated by the fact that much of this sediment can be contaminated. There was no space in Hong Kong for a new mud pit, so Arup developed a method for constructing the seawall for the land reclamation without dredging.

Building on the firm's experience in ground treatment methods and seawall building techniques, Arup developed two types of non-dredged seawall: a composite steel cell and rubble mound seawall, and a simple rubble mound seawall. For both types, the design solution required treatment using stone columns – 53,000 in total, each 1m in diameter – inserted into the soil to create a drainage path for water in the soft sediment to dissipate. These were compacted-gravel piles, installed using a vibratory method of construction.

On the composite section of the seawall, 85 circular cells, each 32m in diameter and formed by 200 straight steel sheets, were driven through the soft marine sediment layer down to the underlying alluvial layer to form cofferdams. These cofferdams were linked by two steel arcs made of similar steel sheet pile segments. These were backfilled to form a robust structure without the need for dredging. Although cellular structures on a similar scale have been used elsewhere, few have been used with the kind of deep, soft soils encountered on this project.

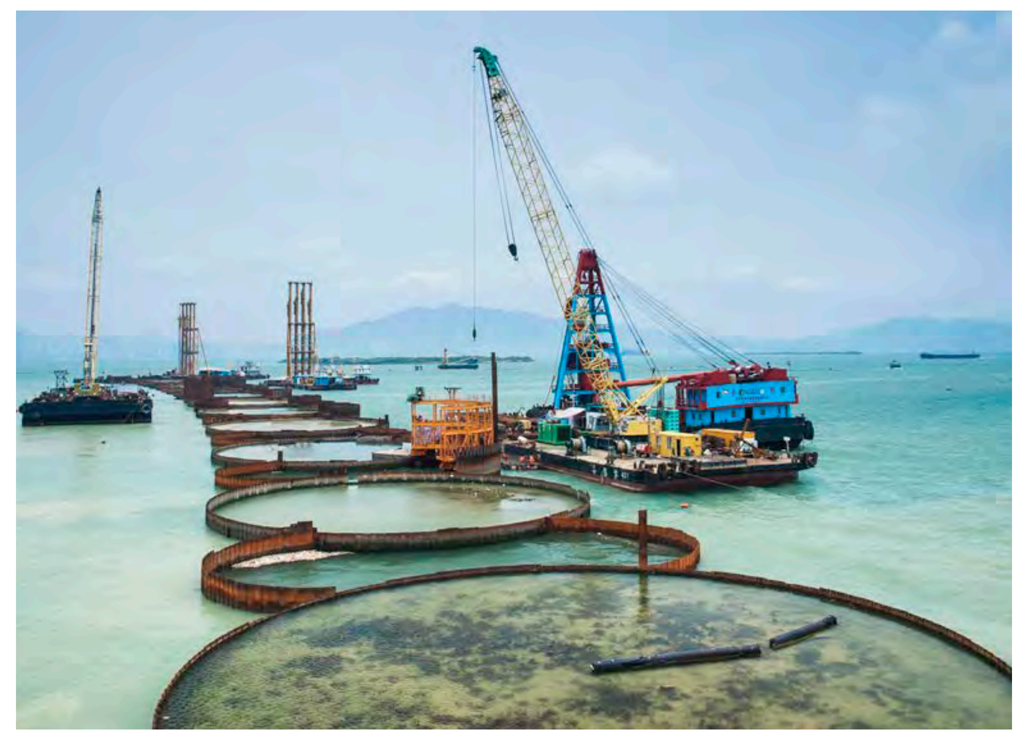
This innovative design meant that the soft marine sediment on the seabed could be left untouched. The reduction in construction work meant there was less impact on water quality and less disruption to the marine habitat, because of reduction of marine traffic volume during construction (which was cut by half) and the reduction in suspended particles in the sea by 70%. The non-dredged process significantly reduced adverse impacts on the environment.

The completed reclamation was tested by two severe typhoons that hit the area before the BCF became operational. Both the seawall and land reclamation remained intact under these conditions.

Hong Kong Link Road

Arup conducted the feasibility study, preliminary and reference design, contract procurement and construction supervision for the Hong Kong Link Road. This is a dual three-lane highway connecting the HZMB with the Hong Kong BCF. It comprises a 9.4km bridge section, a 1km tunnel section through Scenic Hill and a 1.6km at-grade section on reclaimed land at the east coast of Airport Island. The alignment is curved, as the bridge had to avoid various site constraints, in particular the airport facilities, operational requirements and developments. Moreover, the airport is developing a third runway to the northern side of the island, so infringing on this space was not an option. Placing the Hong Kong Link Road on Lantau Island was also out of the question, as this is an area of forests and natural beauty and is of great ecological value. Arup designed the road to run along the narrow marine channel south of Airport Island and north of Lantau Island before reaching the BCF, with construction beginning on this phase of the project in 2012.

The bridge section is made up of more than 5,700 precast bridge deck segments, arranged in 115 spans. The viaduct features long spans crossing two navigation channels and the headland between Sha Lo Wan and San Shek Wan. This area of headland is a designated site of archaeological interest, so to avoid negative environmental impacts on this zone, no bridge pier or additional construction works were proposed in this area. A special lifting frame was used for installation of the deck segments for this span.



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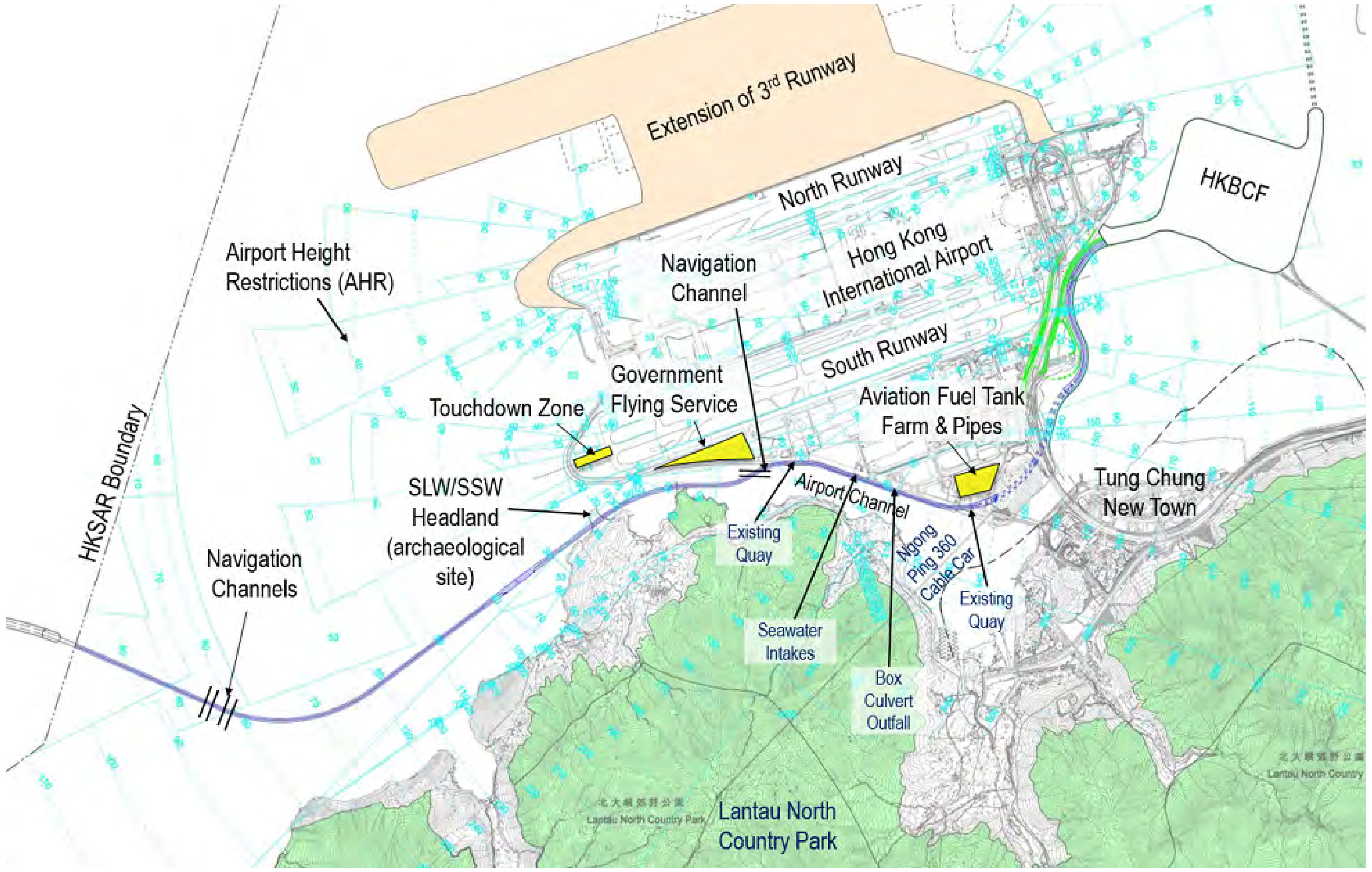
On the western side, where it faces open water, the viaduct spans are typically 75m. The western navigation channel has three 150m spans to allow two separate one-way navigation channels for shipping below the bridge deck. At the southern side, the viaducts run inside the channel between Airport Island and Lantau with spans in excess of 100m to minimise the number of piers and reduce hydrodynamic impact to the water channel. The span length is extended to 180m for crossing the navigation channel and the headland. These long spans were a particular challenge. The team considered various options for the design. A cable-stayed bridge was not viable because of the height restrictions imposed by the airport, and a composite steel and concrete deck was rejected for cost, maintenance and aesthetic reasons. Precast concrete segments were ultimately used – this was the longest span of this type of bridge in Hong Kong at completion.



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9: The Hong Kong Link Road was a complex part of the project, due to the geography of the area and various design constraints

10: To avoid any construction footprint in an area of archaeological interest at Sha Lo Wan Headland, a special segment lifting frame was used to install the bridge deck segments

Of the 725 piles used for this section of the project, 65 are on land (with a diameter of 2.8m) and the remaining 660 are at sea, and have diameters of 2.3m, 2.5m or 2.8m. The piles range from 7m to 107m in length.

Part of the link road is tunnelled, minimising the visual impact for local residents. It runs through Scenic Hill, under both the Airport Express railway and the Airport Road. Different construction methods were used for different sections of the tunnel. Drill and blast was utilised at Scenic Hill where the rock was particularly hard; mining techniques were used underneath Airport Road where the flow of traffic to the airport needed to be maintained during tunnelling; whole tunnel box jacking – a controlled shallow underground excavation process that causes minimal disruption – was used under the railway where there were railway tracks with stringent settlement requirements to be adhered to; and an open cut-and-cover method was used in the new reclamation area where there were fewer constraints.

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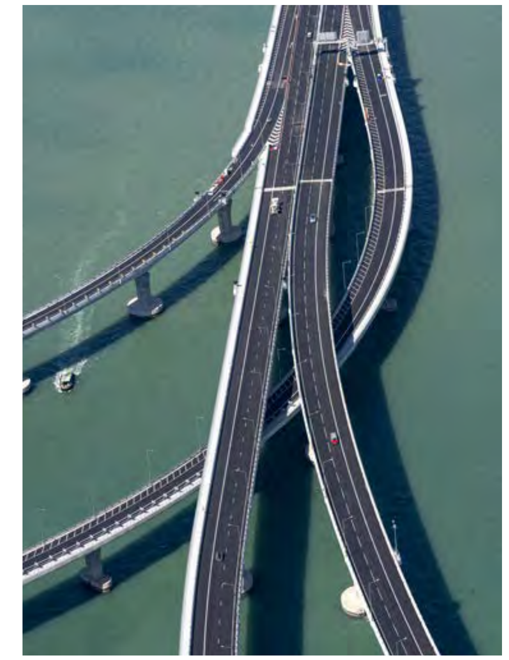

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11: At Scenic Hill, whole tunnel box jacking was used where the tunnel went under railway tracks, as there were stringent settlement requirements in this area

12: The southern section of the TMCLKL travels over 2km of water between Lantau Island and the Hong Kong BCF

When carrying out the box jacking, the team came up against extremely hard bedrock that had to be excavated manually, as blasting was not an option for the section underneath the railway. An additional smaller tunnel was excavated inside the main tunnel, using round-the-clock construction, to increase the rock excavation faces and accelerate the overall rock excavation. This was done at the same time as the box jacking on the other side, so the work could progress as efficiently as possible.

TMCLKL

A new road was also required to accommodate the anticipated rise in traffic between Lantau Island and the North-West New Territories, a region of new towns and development in Hong Kong, which will also serve as an alternative route to the airport. The proposal was for this link road to start at the North Lantau Highway at Tai Ho, before running through the Hong Kong BCF. The road then travels northwards in tunnel form to connect to the existing Lung Mun Road in Tuen Mun and the future Tuen Mun Western Bypass.

Arup was one of the designers for the contractor of the southern section of the TMCLKL, which comprises about 9km of elevated viaducts. The southern section between Lantau Island and the BCF artificial island travels over 2km of water. The section that travels over land passes over existing railway lines at skewed angles, requiring spans of up to 100m. The viaduct structures were designed as prestressed concrete girders, which were constructed using the precast segmental method. The southern connection viaduct was designed with a seagull theme: the supporting piers over the water are shaped like the maritime birds, with the span lengths gradually increasing from the Lantau shore towards the Hong Kong BCF to imitate seagulls flying over the sea. The longest span is 200m where the viaduct spans the Tung Chung navigation channel.

The northern section is 5km in length and includes a sub-sea twin-bore tunnel between the BCF and landfall at Tuen Mun. Typically 14m in diameter and reaching depths of up to 60m below ground level, each tunnel accommodates two lanes of traffic. They were originally designed to connect with traditional cut-and-cover launch and reception shafts at either end within the newly formed reclamations. However, to speed up construction, the contractor's design team modified the tunnel design at the northern landfall by shifting the launch shaft 400m further north. This replaced the deepest section of cut-and-cover structure by extending the bored tunnel, significantly reducing the amount of excavation and lateral support works required at this location. The exit tunnel, which included an additional climbing lane, was formed using the world's largest tunnel boring machine (TBM), which is 17.6m in diameter. To create a large enough shaft to launch the TBM (which required clear headroom of 20m), Arup designed a bespoke caterpillar

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13: Arup developed the caterpillar diaphragm wall cofferdam, creating sufficient unobstructed space to launch the world's largest TBM

14: The 70ha Macao BCF is located on an artificial island

diaphragm wall cofferdam – the first of its kind used in Hong Kong. This cofferdam comprised a series of circular interconnected cells that formed an unobstructed strut-free excavation area by making use of hoop stresses within the diaphragm walls to maintain lateral stability.

The twin-bored tunnels are connected by cross-passages at 100m intervals that serve as a means of escape and allow access between the tunnels during an emergency. The original design had the mechanical and electrical (M&E) equipment required for tunnel operation located in every alternate cross-passage. This would have resulted in two different cross-passage sizes, one with a larger diameter to facilitate the equipment rooms and the escape passage. To simplify construction, Arup modified the design to relocate the M&E equipment. By making use of the void space created by the circular tunnel form, the equipment was placed within a service gallery in the carriageway inside the main tunnel with M&E islands every 200m. This allowed all the cross-passage sizes to be the same smaller size, facilitating easier operation and maintenance by providing a separate service corridor for maintenance purposes only.

A mini-TBM was used to construct the cross-passages, rather than mined construction with ground freezing (traditionally used for sub-sea tunnels). This method reduced construction risk, improved efficiency and significantly cut construction time. This was the first project in Hong Kong to use a mini-TBM for cross-passage construction.

Macao BCF and link road

In 2006, Arup was appointed by the Macao government to undertake a feasibility study for the Macao BCF and the associated link roads to the city. The original scheme had proposed two separate BCFs for Macao and Zhuhai, on two artificial islands. Arup rationalised this complex plan, following the decision by the Chinese government to combine these BCFs into a single artificial island of approximately 220ha. In 2009, Arup won the detailed design consultancy to design the BCF's infrastructure after developing the functional layout of the 70ha Macao BCF. Arup was responsible for designing the facility's viaducts, underpasses, roadworks, utility tunnel, drainage and sewerage, and functional buildings. Arup also undertook the detailed design for the link road connecting the BCF to the new artificial island, referred to as Reclamation A, which is located at the east of Macao Peninsula.

Management

A project of this scale presented major challenges when it came to management and logistics. Arup appointed a core management team to focus on issues such as risk management, design coordination, cost control, planning reviews, handling vast amounts of documents, interfaces and resources, and conducting quality assurance.

It was crucial to have a project and design review before every milestone, to make sure everything was on the right track. A review panel was set up and the budgets were assessed and refined to achieve the most cost-effective solutions. Arup's highly collaborative approach – bringing a broad range of disciplines and stakeholders on board – created a working environment that supported shared thinking, knowledge exchange and critical review, leading to a design that was best tailored to the client and the region's needs.

Increased connectivity

The HZMB provides the shortest link between Hong Kong, Macao and the western Pearl River Delta region. The connection between Hong Kong, Macao and Zhuhai has been greatly improved, significantly cutting the time it takes for people and cargo to travel across the bay.

With Hong Kong a well-known financial centre, Macao a major tourist destination, and abundant development opportunities in the Pearl River Delta and the Greater Bay Area, the whole area is experiencing considerable growth. The HZMB will encourage the connection of people and developments in this area. Being an impressive structure in its own right, the bridge is also a tourist attraction, providing magnificent views. It is hoped that this ambitious project will be the catalyst for further growth and integration in the area for years to come.

Arup technical services:

Hong Kong
Hong Kong BCF Reclamation: Feasibility Study, Overall Planning, Environmental Impact Assessment, Preliminary and Detailed Design, Construction Contract Procurement and Supervision
Hong Kong BCF: Feasibility Study, Overall Planning, Environmental Impact Assessment, Preliminary Design
Hong Kong Link Road: Feasibility Study, Overall Planning, Environmental Impact Assessment, Preliminary and Reference Design, Design & Build Contract Procurement and Supervision
TMCLKL: Feasibility Study, Detailed Design

Zhuhai
HZMB Main Bridge Preliminary Design

Macao
Macao BCF infrastructure: Overall Planning, Preliminary and Detailed Design
Macao Link Road: Detailed Design

Authors

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David Pegg was the Project Director for the TMCLKL southern viaduct section and is a Director in the Hong Kong office.

James Sze led the infrastructure team on the detailed design for the man-made island for the Hong Kong BCF. He is a Director in the Hong Kong office.

Peter Thompson was the Project Manager for the twin-bore tunnel section of the TMCLKL. He is a Director in the Hong Kong office.

Fergal Whyte was the Project Director for the HZMB main bridge and the Hong Kong BCF, and the Project Manager for the Hong Kong Link Road. He is a Director in the Hong Kong office and a member of the Arup Group Board.

Philip Wong was the Project Director for the Macao Link Road and the Project Manager for the Macao BCF. He is a Director in the Macao office.

Ngai Yeung worked on the HZMB main bridge and is an Associate Director in the Hong Kong office.

Project credits

Clients Highways Department, Hong Kong SAR Government; Gabinete para o Desenvolvimento de Infra-estruturas, Macao SAR Government; Hong Kong-Zhuhai-Macao Bridge Authority; Gammon Construction Limited; Dragages-Bouygues Joint Venture

Arup team

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Image credits

1-3, 5, 12: Marcel Lam Photography
4, 6-9, 11: Arup
10: Dragages-China Harbour-VSL JV
13: Dragages-Bouygues JV
14: CHEC

Building BLOX

BLOX has helped reconnect a section of Copenhagen's waterfront with the city by redeveloping a decades-old derelict site and turning it into a lively urban creative hub and public space

Authors Michael Bradbury and Chris Carroll

Located in a prime section of Copenhagen's harbour area, BLOX is a six-storey mixed-use building that is part of an exciting waterfront regeneration in the city. The 27,000m² venue is the new home for the Danish Architecture Center (DAC) and BLOXHUB, a new creative workspace initiative for companies, research institutions and organisations involved in sustainable urban development.

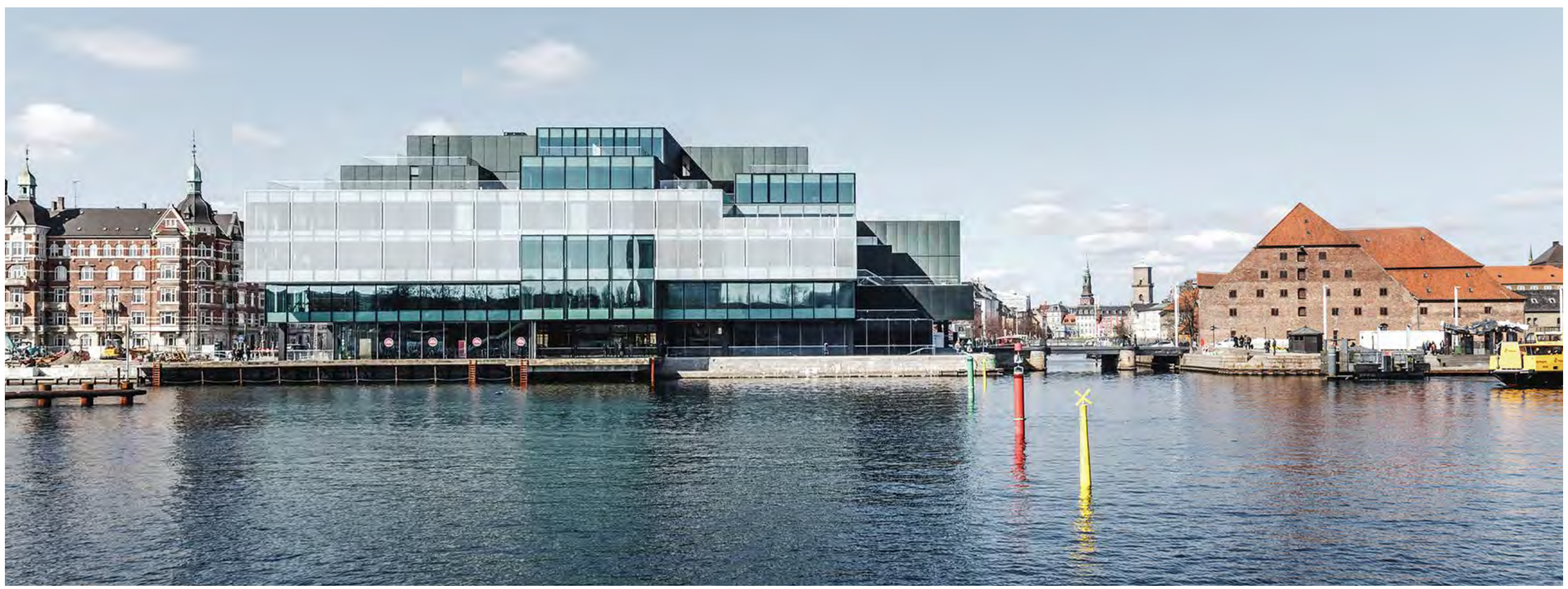
The building features an auditorium, exhibition spaces, cafés and offices, as well as 22 apartments across the top floors, and recreational indoor and outdoor areas. These differing spaces are arranged as a series of stacked cubes that form a terraced landscape, requiring a structural scheme with significant cantilevers, long spans, unaligned grids and double height volumes. The building was officially opened by the Queen of Denmark in May 2018.

Working in close collaboration with the Office for Metropolitan Architecture (OMA), Arup's engineering expertise helped shape a complex regeneration project that overcame the constraints that challenged the viability of the site for development. BLOX spans over and under the busy Christians Brygge ring road, with the site perimeter framed on two sides by the city's harbour wall and the Frederiksholms canal. Located close to a series of historic buildings, the ground works in particular had to be dealt with sensitively.

Arup provided structural, building services and façade engineering; sustainability consultancy services; ICT and AV; vertical transport; security; and daylighting, from inception to detailed design. The firm produced design solutions for and provided input on topics including energy efficiency, carbon neutrality, materials and embodied carbon. Arup also sought to address socioeconomic issues.

Site development

Philanthropic association Realdania invested in BLOX to help regenerate this section of the waterfront and strengthen the connection between the inner city and the harbour. Originally, the site was home to the royal brewery, Kongens Bryghus. The buildings were demolished after a fire in the 1960s.



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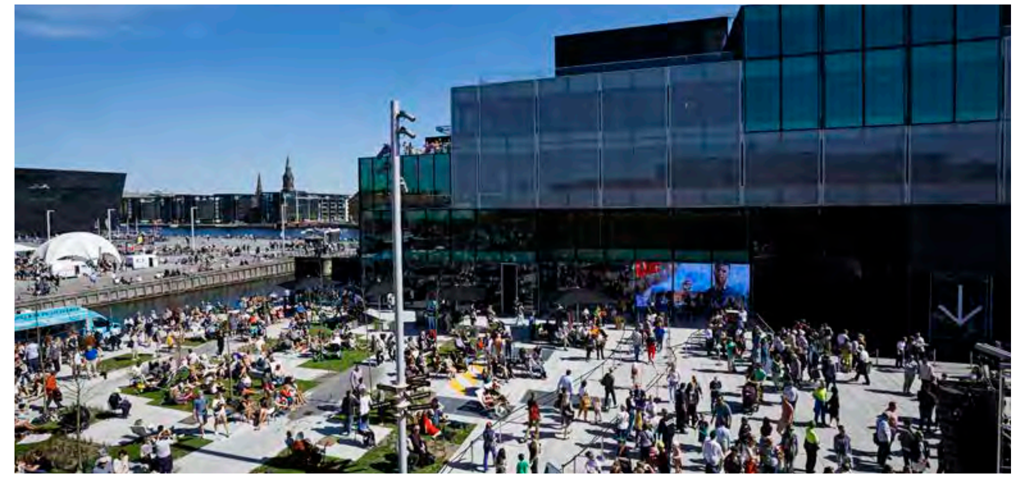

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1: BLOX is part of a new waterfront development in Copenhagen's harbour area

2: The development provides outdoor spaces for use by the public

3: The initial solution for the unconventional grid structure required 48 trusses

4: Arup rationalised the layout, developing a scheme that had an interconnecting framework of 18 trusses

Its location, locked in by the harbour and canal, with a busy arterial road bisecting the site, presented considerable challenges for development. Most recently, the site included a 350-space street-level car park and a small children's playground.

Structural frame

Arup worked closely with OMA to rationalise the structural layout so that it would support the series of stacked volumes within the building. The staggered pattern that forms the building's terraced landscape shape, the road through the building and the deep basement car park all put considerable constraints on where columns could be located and how loads could be transferred down to the foundations.

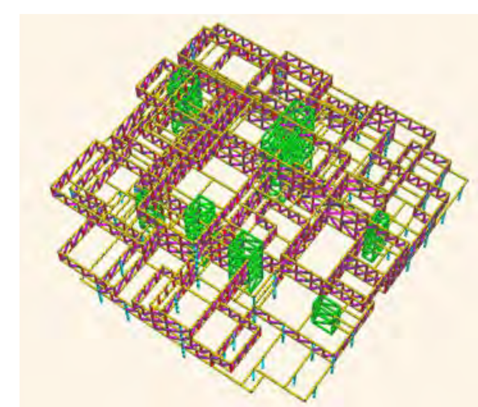
With a conventional grid structure not feasible because of the overlapping volumes and column-free spaces required, Arup developed a scheme comprising an interconnected system of transfer structures. By using a number of interventions such as downstand beams, trusses and hangers, an initial 48 truss solution was developed. With a working scheme in place, the challenge was to reduce the number of trusses to ensure construction viability and improve efficiency.

Through further detailed design and rationalisation, the grid was re-aligned and the trusses optimised, with Arup's final scheme an interconnecting framework of 18 steel trusses that typically span 30m. They include a number of one- and two-storey deep trusses with depths varying from 2.4m to 8.4m. These create large column-free spaces within the building and also bridge over the road.

The structural frame comprises steel beams and columns with precast concrete floor planks. The structural floor plate depth is typically 400mm, with the beams located within the depth of the planks to reduce the overall floor volume. The planks in the offices were grouted together without the need for a structural screed topping.

Due to the complex interface between the trusses, Arup's structural team devised a construction sequence in collaboration with the main contractor, Züblin. To determine the stresses that would build up in the steel frame during its assembly, Arup created a digital model of the construction sequence.

With the transfer structures and complicated load paths, it was crucial that deflections were controlled as stresses became locked in while



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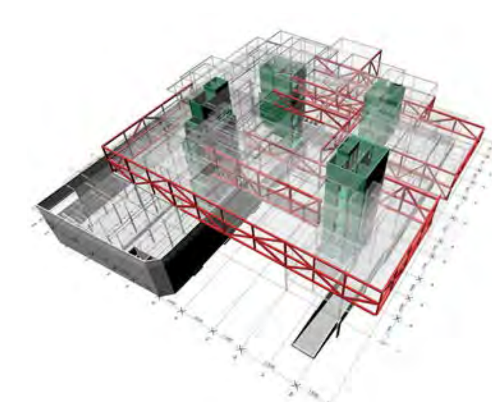

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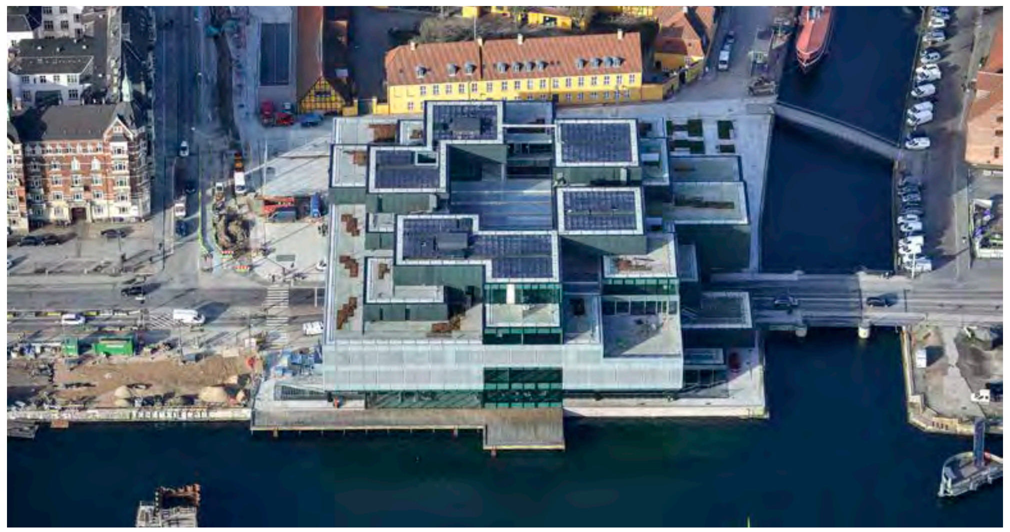
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5, 6 & 7: Aerial photos showing the construction of BLOX. The road crosses the site supported on a section of the building's ground floor slab

8: Careful construction sequencing was required, as only very limited closures of the Christians Brygge road were allowed

elements were constructed. These stresses and displacements were taken into account when developing the construction sequence and temporary propping arrangements, with a number of trusses fabricated with pre-cambers to take into account deflections.

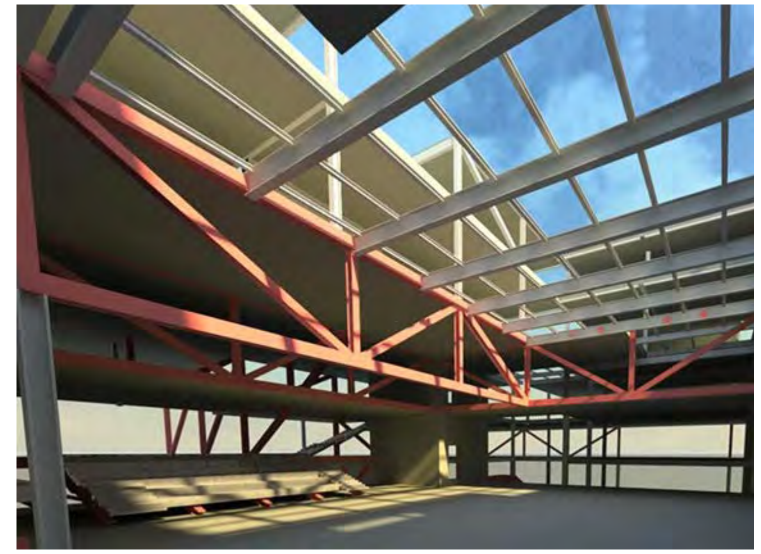
Arup adopted 3D design from the start. This was crucial in dealing with the complexity of the layout and building services. The design team was commissioned during construction to produce an integrated BIM model that was issued to the client and their facilities management team for use after handover.

Bridging over and under the road
One of the key elements to developing the site was to design a scheme that could span over and under the ring road, allowing pedestrians access to the harbour without having to cross a road that is used by more than 25,000 vehicles a day.

Traffic on Christians Brygge crosses the site supported on a section of the building's ground floor slab. To ensure this traffic does not cause noise or vibration issues within the building, 575mm deep precast pre-stressed concrete bridge beams with a 75mm concrete topping span onto isolating bearings on the supporting walls and a spine beam. Careful sequencing was required during construction, as only very limited road closures were allowed by the local authority. Prior to the trusses that span above the road being erected during overnight road closures, a crash deck was built over the road to protect vehicles.

The basement is 16m below ground at its deepest and required excavation adjacent to the harbour, canal walls and a number of historic buildings founded on timber piles. A detailed basement construction sequence and de-watering process were implemented to ensure construction did not adversely affect these buildings.

The eastern and southern site boundaries were originally retained by timber and stone block quay walls with ground anchors. As part of the construction sequence, a berm was placed in the water in front of the existing harbour wall to act as a temporary prop while the ground anchors were removed. A temporary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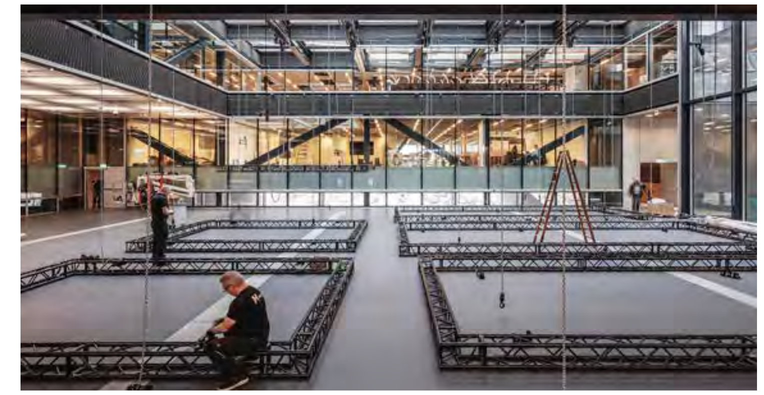
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11.

9: BIM model of the exhibition hall showing the layout of the trusses

10: The exhibition hall being set up for an event

11: The precast concrete floor in the hall has a reinforced concrete structural topping. This assists with acoustics as well as the floor's dynamic performance

sheet pile wall was installed to allow the basement excavation and construction of the permanent piled basement walls.

Using secant pile construction, the basement wall comprises interlocking bored concrete 880mm diameter piles at 1.1m centres, providing both the permanent and temporary support for the basement excavation. Following basement construction the berm was removed. Further out into the harbour a rubble reef was put in place to protect the harbour wall and building from collision with marine traffic.

Automated car parking
In the basement there is a fully automated 350-space public car park. It was a local authority requirement to retain parking on the site and minimise the number of vehicles entering the city centre just north of BLOX. The three-storey underground parking facility can handle up to 180 cars an hour.

Using an automated car stacker system has significantly lessened the space requirements within the basement compared with a more traditional car park. This reduced the volume of excavation required, simplified basement construction around the road and minimised the required air handling systems. Car engines are switched off as vehicles are delivered and returned to the stacked parking bays via the horizontal and vertical stacker system, keeping exhaust fumes to a minimum.

Exhibition floor
The main exhibition floor's structural depth is 2m, with the floor at this level spanning almost 24m over the road. This span is achieved with a 1.6m deep plate girder, supported on steel columns. A reinforced concrete structural topping to the precast concrete floor increases the structural mass for acoustic attenuation, although it is also beneficial for the floor's dynamic performance.

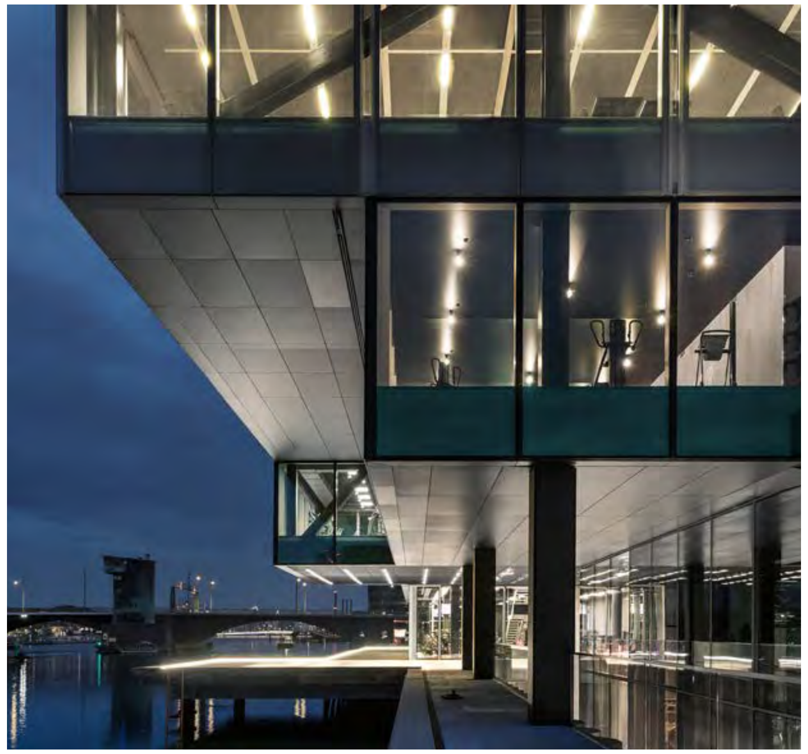
An assessment was made of footfall-induced vibrations that could occur from the exhibition floor to ensure vibration transfer did not adversely affect the other areas of the building. Arup's footfall analysis showed the typical accelerations were within acceptable limits.

Sustainability
Sustainability was a key driver for the project. Arup's Sustainable Project Appraisal Routine (SPeAR) was used to track the sustainability elements and help make important decisions during the design process.

Ambitious sustainability targets were set to address all aspects of the design, construction and operation of the building. This included reducing energy demand by 50% compared with local regulations. BLOX achieves the Low Energy Class rating, with primary energy usage of under 40 kWh/m²/year. This meets the LE2015 energy target under Danish regulations.

The desire to create an energy-efficient building significantly influenced Arup's building services design. The building is served by Copenhagen's district heating system, and the city's district cooling system was extended towards the site. The system is based on seawater cooling and the use of residual heat from electricity generation.

In addition to meeting the LE2015 energy target, other key sustainability strategies include:
- solar photovoltaic panels at roof level, which produce 145,000 kWh/year;
- use of lower emission heating, cooling and ventilation systems;
- a full materials assessment, screening all main materials for embodied carbon, life cycle and recyclability;



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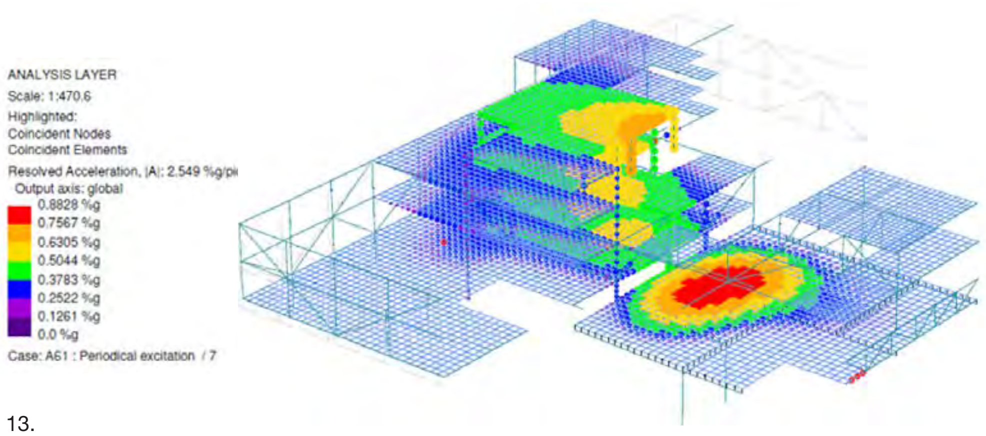

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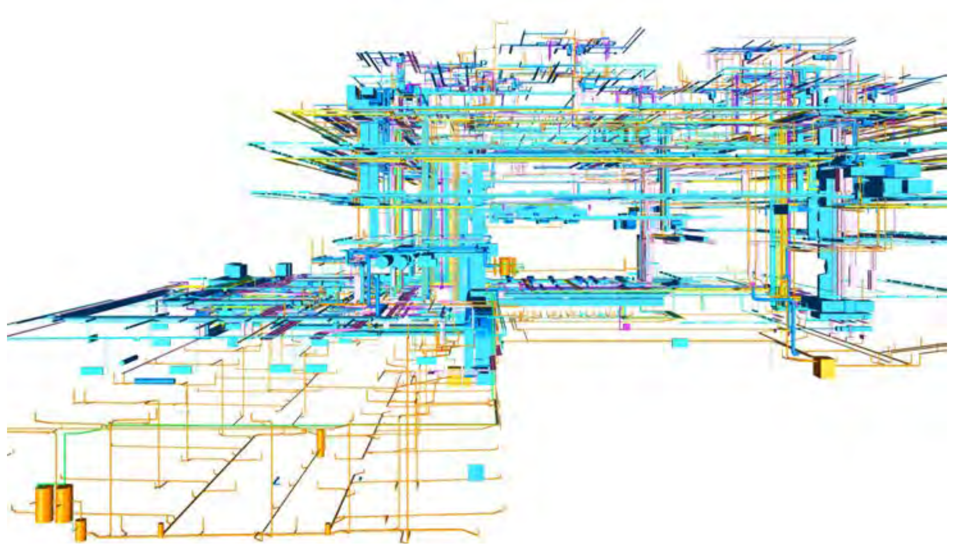

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12: BLOX is made up of a series of stacked volumes

13: 3D rendering of vibration analysis for events in the exhibition hall

14: BIM model of the building services

- appropriate intake and exhaust locations and separations to ensure effective ventilation (a particular challenge given the proximity to the road);
- a high performance building envelope;
- low water consumption; and
- improved local amenities and activation of public spaces.

BLOX is close to public transport, adding to its sustainability credentials. The mixed-use development promotes social integration, as the publicly accessible pedestrian route running through the building creates a new link between the city and the harbour.

The mechanical services required careful design to manage the variety of uses for the different spaces within the building. The layout is predominantly office space around the building's perimeter, with the large DAC exhibition space, auditorium and conference facilities located at the centre of the building. The ground floor includes a gym, restaurant and some retail spaces. Along with the basement car park, each of these areas have different drivers and requirements from a comfort and occupancy level.

Plant and building services

The mixed-use nature of the building, and the constraints of the road, meant that locating plant and developing the building services distribution strategies were critical to overall space planning and developing an efficient floor plate. Plant areas were located in various parts of the building. The basement has the main connections to the district heating and cooling, along with ventilation plant that serves the basement and the restaurant areas. Additional plant is located under the auditorium, with smaller plant areas serving the offices and apartments.

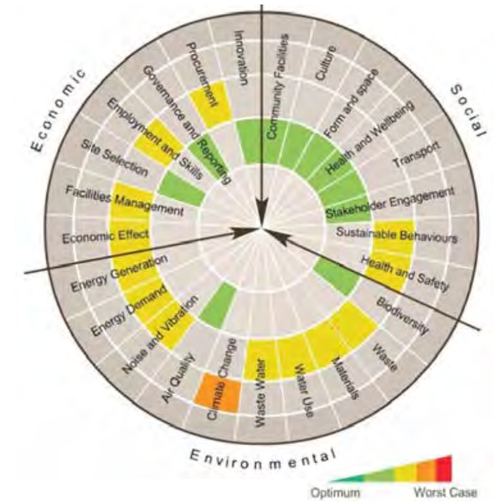
With quite a deep plan for the building, chilled ceilings were used in the majority of areas for cooling, with fresh air provided through the floor (along with distribution for power and data). Chilled beams were used around the perimeter to provide additional cooling at the façade.

The main exhibition space uses displacement vents to distribute air, with sidewall displacement vents used in the auditorium. The restaurant and apartments have their own dedicated systems.

Detailed thermal analysis was key to achieving a naturally ventilated and highly insulated façade. The performance of the façade required careful consideration in order to achieve the correct level of light transmission into the building to meet required lighting levels under Danish regulations, while also maintaining the appropriate U-value (thermal) and G-value (solar gain). Eight façade configurations were assessed across criteria including energy, daylight, cost, maintenance and aesthetics to determine the preferred option.

Transformation

BLOX has transformed this section of Copenhagen's waterfront into an inviting space for people to visit. In addition to providing the new pedestrian link between the city and the harbour, a new urban playground offers a safe space for play during the day, turning into a stage or amphitheatre seating in the evening. The building draws in visitors and is a landmark publicly orientated mixed-use building in the Danish capital.



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15: Arup used its Sustainable Project Appraisal Routine (SPeAR) to track sustainability throughout the project

16: BLOX has helped to transform a previously neglected section of Copenhagen's waterfront

17: 'Ove Arup and the Philosophy of Total Design' exhibition

Authors

Michael Bradbury was the Project Manager and lead building services engineer. He is an Associate Director in the London office.

Chris Carroll was the Project Director. He is a Director in the London office.

Project credits

Client Realdania
Architect OMA
Local architect CF Muller
Traffic, environmental issues, fire, risk analyses and local engineer of record COWI
Contractor Züblin
Structural, building services and façade engineering, and sustainability consultancy services, ICT and AV, vertical transport, security, daylighting Arup:
Yasmin Alam, Francis Archer, Marcus Arvidsson, Bibi Banjo, Jonathan Ben-Ami, Daniel Bergsagel, Michael Bingham, Kimberley Blackburn, Philip Bogan, Michael Bradbury, Alexis Brown, Emma Brunton-Reed, Giorgio Buffoni, Chris Burgess, Tony Campbell, Stuart Carey, Chris Carroll, Andrea Charlson, Mark Chen, Anna Coppel, Dominic Coyle, James Dare, Rica Dela Cruz, Andrew Duncan, Russell Fraser, Lesley Gale, Kieran Giblin, Andrew Grant, Duncan Gray, Ning He, John Heath, Stuart Hitchcock, Ed Hoare, Christina Hsieh, Dan Ingall, Craig Irvine, Ben Jones, Ben Kaggwa, Adri Kerciku, Vivien Kwan, Amy Leitch, Ben Lewis, Roland Li, Alexandra Lindesay-Bethune, Di Liu, Ian Lockwood, Georgina Lockwood, Paul Lynch, Mani Manivannan, Adam Martin, Nina McCallion, Ben Moss, Sheyda Okke, Julian Olley, Jean Parker, Dean Payne, David Penn, Stuart Pennington, Clare Perkins, Dan Pook, Tony Pullen, Rob Quail, Nihal Rajapakse, Vincenzo Reale, Tony Ricchetti, Amelia Rushford, Anokhee Shah, Amy Shen, Jamie Shewan, Tania Smith, Julian Sutherland, Mark Thomas, Mutlu Ucuncu, Nick Unsworth, Manja Van De Worp, John Verniers, James Whelan, Robin Wilkinson, Giovanni Zemella.

Image credits

1, 10, 16: Rasmus Hjortshøj
2: Søren Svendsen
3, 4, 8, 9, 13-15: Arup
5-7: BLOX/Dragør Luftfoto
11, 12: Delfino Sisto Legnani and Marco Cappelletti/OMA
17: Camilla Hylleberg

Ove Arup exhibition

From October 2018 to February 2019, the Danish Architecture Center hosted an exhibition on Ove Arup that celebrated the pioneering work and ongoing legacy of the Anglo-Danish engineer and designer.

The exhibition, 'Ove Arup and the Philosophy of Total Design', was first shown at the Victoria and Albert (V&A) Museum, London, in 2016 and provided an overview of Ove Arup's vision of 'Total Design'. The exhibition revealed Arup's collaborative approach to problem-solving in the built environment by harnessing the creativity and technical prowess of engineers, architects, urban planners, designers, consultants and technical specialists.

The exhibition featured archival materials from iconic projects such as the Sydney Opera House and the Centre Pompidou in Paris. Also displayed were digital exhibits featuring simulations and augmented reality that captured some of the most innovative infrastructure projects Arup has contributed to in recent times. They included a specially commissioned immersive installation about the Øresund Bridge and a recreated Arup SoundLab® presenting a range of acoustic studies, including of the BLOX building and Copenhagen city.

17.

Driving sustainability

Total design used to create a showcase for sustainability in a flexible highly automated manufacturing facility

Authors Mark Bartlett, James Finestone, Philip Hives, Sean Macintosh, Timothy Snelson, David Storer

1.

Drawing on decades of experience in the design of industrial buildings, Arup reinterpreted the traditional factory form to create a functional, flexible and sustainable facility for Jaguar Land Rover. Arup's architecture and engineering teams provided innovative low-energy design solutions for the engine manufacturing centre, a facility that has achieved a BREEAM 'Excellent' sustainability rating.

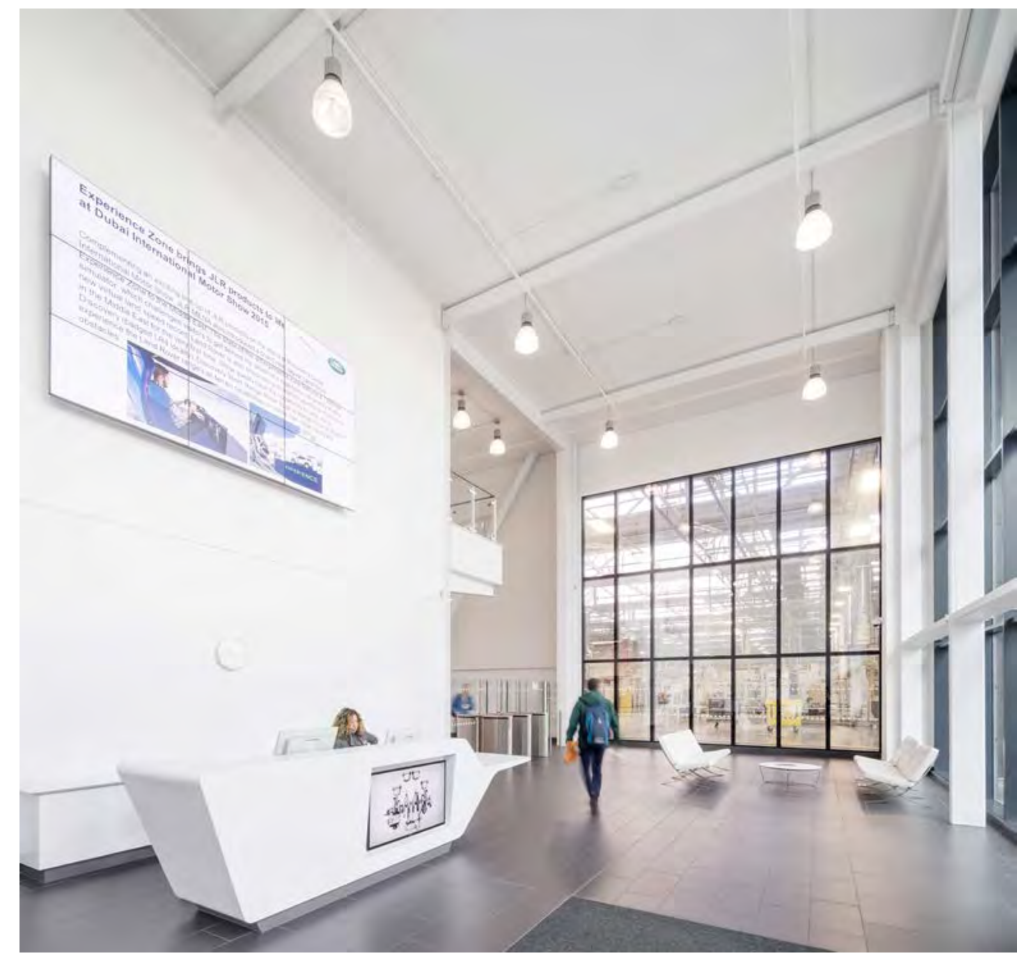
By providing an appealing, environmentally controlled working environment, Arup created a facility centred around worker wellbeing. Arup designed the building so there are visual connections between the different areas, breaking down the barriers between factory floor and administration areas and making as much use as possible of natural light. The traditional factory north-light windows at roof level are complemented by 2m high windows at ground level. These bring daylight deep into the production areas and provide views of the external landscaped areas.

The focus on a low-carbon strategy meant a wide range of sustainable features were incorporated within the facility. These include the largest roof-mounted photovoltaic (PV) array in the UK; transpired solar collector cladding; solar panels for heating domestic hot water; natural ventilation; displacement ventilation to provide cooling; lighting control with daylight dimming; variable speed drives to minimise pump and fan power consumption; heat recovery on air handling units (AHUs); grey water recycling; and storm water attenuation.

The first phase of the facility was handed over just 24 months after the design team appointment. The next two phases followed in a continuous sequence from 2013 to 2017. Arup provided architecture, transport planning, environmental engineering, landscaping and access advice for the first two phases, together with civil, structural, geotechnical, fire and building services engineering for all three phases.

1: The facility has a BREEAM 'Excellent' sustainability rating

2: The building is centred around worker wellbeing, with barriers between the factory floor and admin areas broken down as much as possible



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Layout

Arup developed the overall facility layout in conjunction with Jaguar Land Rover by mapping out the engine manufacturing process including equipment, people, materials, waste and transport movements. The first two phases of the project incorporated three linked, rectangular buildings. Efficiency in configuration coupled with future building flexibility underpinned the layout of the large factory halls (machine and assembly halls) and the connecting smaller two-storey staff support buildings.

The architectural form of the facility – with the saw-tooth roof profile commonly used on warehouses and factories around Wolverhampton – helped with the engineering solution. The north-lights allow diffused natural light into the building but limit heat gain. The south-facing elements of the roof, set at a 30° angle, are used to support the large PV array. The underside of the roof provides the primary route for distribution of services at high level, minimising the requirement for service runs in the floor slab and maximising production flexibility in the factory for future changes.

Site works and foundations

Following an enabling works package that included soil/cement ground stabilisation, Arup was able to design straightforward foundations with pad footings and ground-bearing concrete slabs. Steel-fibre-reinforced concrete slabs, ranging between 250mm and 350mm thick, are used in the factory halls and were designed to provide flexibility for equipment layout. In the staff support buildings, which have lower levels of loading, mesh-reinforced concrete slabs, ranging between 150mm and 175mm thick, are used. The site incorporates an extensive sustainable drainage system, featuring porous paving, swales and storm water attenuation ponds that control discharge to the surface water system.

Factory frame

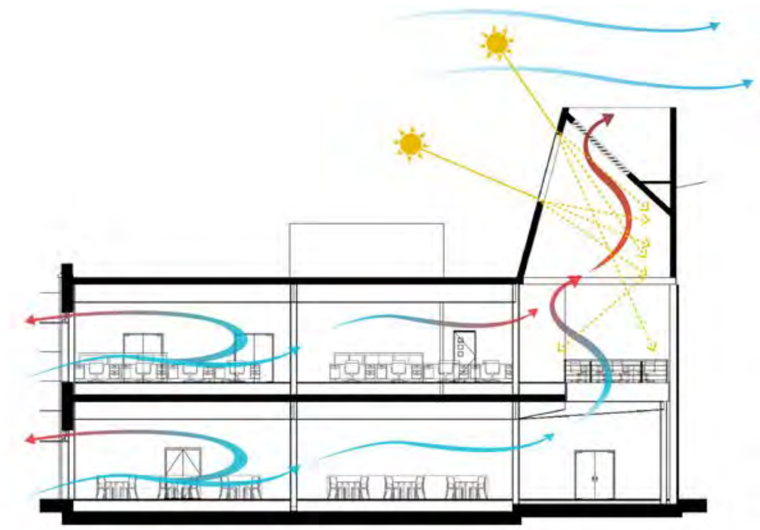
The factory halls are based on a single-storey braced frame, supporting multi-span mono-pitched roofs, with trusses designed for multi-bay continuity. The north-lights are formed using steelwork trusses that span 30m. In the machine hall, the grid is 30m by 15m, with a 30m by 30m grid in the assembly halls. This arrangement facilitates the production areas currently required by the client, giving clear spans without compromising the quantity of services the roof can support. The bracing is kept at the perimeter, which allows for the subdivision of bays and means the assembly lines can be reconfigured if required in future. Arup developed a loading manual for Jaguar Land Rover that sets out the design load locations and magnitudes.

In designing the roof trusses, Arup took the structural analysis output and, using automated member utilisation checks, optimised all the truss members. The wind analysis carried out on the roof took into account the roof's specific geometry and peak wind direction for the site, allowing uplift loads on the roof to be reduced by up to 70% for the majority of the surface area. These design processes resulted in significant savings, minimising the steelwork roof tonnage. At 28kg/m^2, the roof weight is light for a 30m-span roof that supports the quantity of services

3: The traditional factory north-lights work in conjunction with large ground-level windows to provide abundant natural light

4: The staff support buildings are bright, naturally ventilated two-storey buildings

5: The building grid layout is arranged to allow future changes in assembly line configuration



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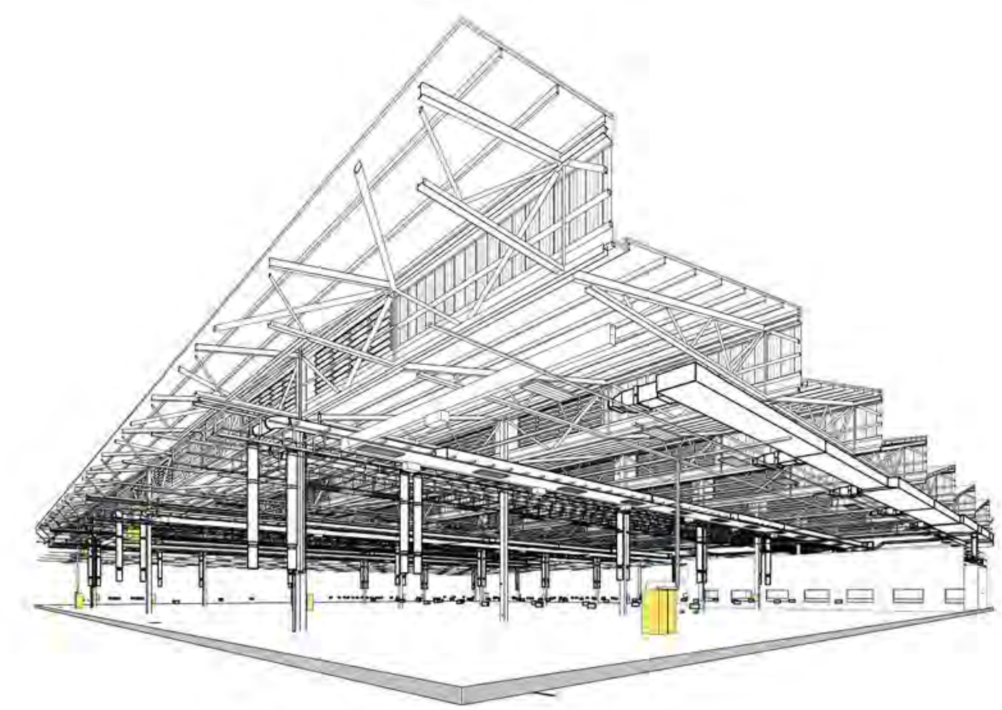

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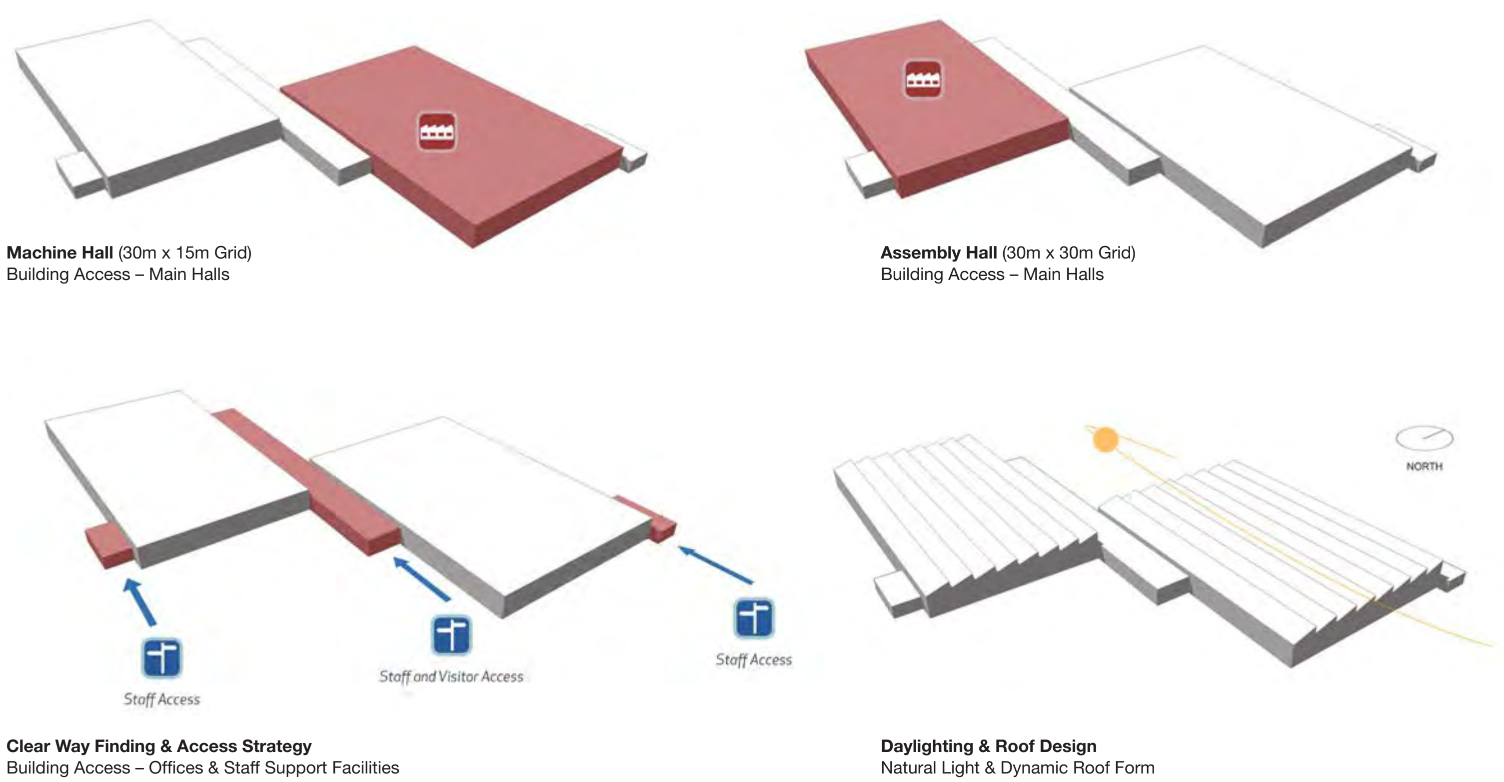

6.

required for this highly automated manufacturing facility.

Staff support areas
The connecting staff support buildings are bright, naturally ventilated two-storey spaces. Arup designed the bulk of the heavy plant – servicing the factory halls – to be located at the first floor and on the roof. This gives easy access to plant for maintenance and avoids the need to put heavy plant on the long-span roof trusses. The structure supporting the plant consists of precast hollowcore concrete slabs. The exposed thermal mass of the concrete slab soffit helps with moderating temperatures in the office areas, further reducing energy costs.

Arup's architectural design of the staff support areas provides a working environment that brings people together by providing visual transparency and social spaces. These areas have natural light and ventilation, with glazing providing transparency between the office areas and factory floors. Automated dimming controls for the lighting system reduce the need for artificial light, creating further energy savings, with LED lights specified in the most recent development phase.

Total design

Arup applied its total design philosophy to deliver technically creative and sustainable solutions at speed. Innovation, collaboration and worker wellbeing is at the heart of the success of this facility, which has won numerous awards.

2018
Structural Steel Design Awards: Winner, Project of The Year
World Architecture Awards: Shortlisted, Production Energy and Recycling Category

2017
CIBSE Building Performance Awards: Winner, Project of the Year
Royal Institute of British Architects Awards: Winner, West Midlands Sustainable Award and Regional Award

2014
Royal Institution of Chartered Surveyors National Awards: Regeneration Project of the Year

Renewable energy
As part of an initial energy study, Arup identified the potential for significant carbon savings by using a roof-mounted PV array and solar thermal installation on the façade.

More than 21,000 PV panels were installed on the south-facing areas of the roof. These provide over 5.3MW of power – equivalent to 30% of the facility's energy requirements – and reduce the factory's carbon footprint by at least 2,400 tonnes per year. Further power is supplied via a ground-mounted PV array, added as part of the most recent phase of works. Solar thermal panels also provide heating for domestic hot water.

Solar cladding
The factory features a transpired solar collector cladding system, which is used to preheat the supply air to the staff changing facility. Used on the south-facing façade of the staff support building, the outer steel layer of the system is a dark perforated profiled steel sheet. It is separated from the inner insulated layer by an air cavity. Solar energy warms the perforated steel skin and the air in the cavity, and a fan at high level draws the warm air out. This preheated air feeds the AHUs in these areas, reducing energy consumption and providing significant carbon savings.

This Colourcoat Renew SC cladding system, developed by Tata Steel and the University of Swansea's Innovation Centre, heats $5m^3/s$ of supply air, producing carbon savings of 1 tonne per 5m of solar collector. The system has also been used on the third phase of the project.

Dynamometers
As part of the engine testing regime, a sample of engines produced at the factory are tested using dynamometers. Arup worked with Jaguar Land Rover to design the system that takes the energy generated during testing and feeds it back into the building's energy distribution system.

Heating and cooling
The machine hall is heated from an all-air system with the heating diffusers located 3m above the factory floor. Six AHUs supply $85m^3/s$ of air to the space. This volume of air is required to maintain a 20°C temperature in the machine hall, and also to provide make-up air to supplement the extract system that removes the oil mist created during the engine manufacturing process. Fresh air, with 0.25 air changes per hour, is also fed into the machine hall for staff comfort levels. During the winter months, the manufacturing equipment in the machine hall provides heat to the space, with gas-fired AHUs providing top-up heat as required. In the summer, vents in the north-light windows can be opened to expel hot air, helping to reduce extract energy.

The assembly halls are heated and cooled using a displacement ventilation system, with five AHUs supplying $71m^3/s$ of air. To maximise the facility's future flexibility and adaptability in relocating process plant and layouts, the displacement terminals are located 3m above floor level. To reduce airborne contamination within the machine and assembly halls, the supply air is filtered through class F9 filters – the level below a cleanroom environment.

A gas-fired heating system, rather than a more traditional water-based system, was used to serve the production halls. A water-based system would have had the potential for significant heat and pumping losses due to the length of the pipe runs required for a facility of this size. The gas heating system overcame this issue, particularly as the gas distribution system was already required to serve process equipment.

Where possible, high-level services were supplied using modular technology. Arup's detailed design allowed for modules to be manufactured off-site to facilitate a quick and safe installation on-site. This method allowed for factory inspections prior to delivery on-site, and also reduced the amount of work required to be carried out at height.

Energy monitoring
Arup developed an energy management system in conjunction with Jaguar Land Rover to allow the client to monitor building energy consumption and energy used in each process of engine production. The system design included the communication infrastructure for the process equipment to support Industry 4.0 implementation, as well as the metering and monitoring mechanisms for all the building utilities. Arup's Building Performance and Systems team were commissioned after handover to carry out monitoring of the energy performance in the operational building and collate feedback from users. This work identified opportunities to reduce further electricity and gas consumption.

Digital design
The structural steel frame design was highly automated. Optimisation of design input to

7.

6: Arup, in conjunction with the client, developed an overall facility layout that focused on efficiency and future building flexibility

7: The assembly hall has a 30m x 30m structural grid

8.

8: Arup's design of the staff support areas provides a working environment that brings people together by providing visual transparency and social spaces

9: Drawing on decades of experience in the design of industrial buildings, Arup reinterpreted the traditional factory form to deliver a functional, flexible and sustainable facility

the analysis models was driven from spreadsheets, to minimise the risk of manual input errors. Subsequent results from the analysis were post-processed through spreadsheets for utilisation checks. Designing in this digital environment allowed changes to be incorporated into the design as the client updated their manufacturing requirements during the design process. The structural model was produced directly from the analysis model and exported to Tekla software for production of the fabrication drawings, thereby saving the steelwork fabricator significant modelling time.

The complete building was modelled in BIM. At construction stage, Arup carried out BIM management services on behalf of the main contractor, Interserve. The subcontractors' work was coordinated throughout the delivery of the project, and also with the fit-out requirements of the highly specialised robotics used for engine manufacturing (which were designed by PowerTrain for Jaguar Land Rover). The design model was integrated with the process and equipment model. This allowed coordination of process machinery and services, along with the building services and structural frame. The fully integrated model was issued as part of the completed project's operation and maintenance manual and included specification and data tagging of equipment and services for use post-occupancy. This ensured the client's facilities management team could utilise all the design information embedded within the model.

As the manufacturing process changed during the design phase, the digital design elements were used to take in those changes to minimise the potential of any delay. For example, when another 30m bay was added to the building, the automated work flow enabled the design checks to be carried out quickly. The models were updated to reuse already manufactured steel, and the new bay was inserted as the penultimate bay.

9.

Authors

Mark Bartlett was the lead electrical engineer and the Project Manager for the third phase of the development. He is an Associate Director in Arup's Midlands Campus in the UK.

James Finestone was the Project Director for the first phase of the development. He is Arup's Europe region leader for architecture and is based in the Milan office.

Philip Hives was the lead mechanical engineer and Project Manager for the second phase of the development. He is an Associate Director in Arup's Midlands Campus in the UK.

Sean Macintosh is a Senior Architect in the London office.

Timothy Snelson was the lead structural engineer and Project Manager for the first phase of the development. He is an Associate Director in the London office.

David Storer was the Project Director for the second and third phases of the development. He is a Director based in Arup's Midlands Campus in the UK.

Project credits

Client Jaguar Land Rover Ltd
Project manager Stace
Quantity surveyor (AECOM – formerly Davis Langdon)
Main contractor Interserve Construction Ltd (Phase 1 and 2); Vinci (Phase 3)

Architecture, transport planning, environmental, landscaping, and access advice (Phase 1 and 2); civil, structural, geotechnical, security, sustainability, fire and building services engineering (for all three phases) Arup: Muhammad Abdullah, Jorge Albert, Mehdi Alhaddad, Steve Allen, Simon Anson, Dimitri Argyros, Nohman Awan, Yiannis Baltagiannis, Andy Barnes, Daniel Barnes, Greg Barnes, Mark Bartlett, Gill Blackburn, Mark Bowen, Richard Boyd, Tom Brooks, Gemma Broughton, Alexis Brown, Alex Bunn, Kevin P Burke, Josh Chapman, Sean Chapman, Wayne Charles, Sam Collett, Carl Collins, Jose Pedro Conceicao Dos Santos, Tiago Contins Teixeira, John Corbett, Tian Coulsting, Arron Croft, Dominic Cropper, Sebastian Cumpatescu, Hal Currey, Hazel Dalton, James Davies, Sean Davies, Steven Davies, Matthew Davis, Jo Dicken, Natalia Duffy, John Edgar, Ed Elbourne, Karim Elgendy, Steve Fancourt, David Farmer, Ben Fenech, James Finestone, Kate Fletcher, Bob Flynn, Helen Foti, Sally Friswell, Carolyn Gallehawke, Amparo Galvan Nieto, Andrew Gardiner, Stephen George, Marten Gessen, Andrew Gibbon, Daniel Goodreid, Jack Goulding, Aidan Griffin, Paul Grosvenor, Craig Harkness, Mike Haydon, Christopher Hayward, Andy Heath, Cameron Heggie, George Hemsley, John Higginson, Philip Hives, Thomas Howes, Callum Hulme, Alan Jefcoat, Ian Jenkins, Joao Jesus, Ben Johnson, Matt Jones, Elida Karaivanova, Abdullah Khan, Michael Kinney, Maciej Krezolek-Shrewsbury, Martin Kuzmanov, Jason Kwong, Samantha L Godden, Oliver Lawrie, David Lee, Matt Lewis, Alvar Liebana, Mark Lusher, Sean Macintosh, Colin Magner, Alice Malaiperuman, Rajiv Malik, Natalia Mambrilla, Mei-Yee Man Oram, Ann Marie Aguilar, Barbara Marino, Tony Martin, Curtis Martyn, Paul Matthews, Alex May, Andrew McAleer, Rachael McAteer, Chris McCarthy, Gary McCarthy, Laura Mino, Jessica Monk, Philip Monypenny, Mostafa Moradalizadeh, Adina Nimas, Julia Novitchenko, Carlos Nunes Baptista, James O'Hanlon, Johnny Ojeil, Nick Olson, Petra O'Sullivan, Constance Pang, Yesol Park, Yona Park, Andy Payne, Tom Pearce, Anett Pengelly, Oliver Pengelly, Ryan Perry, Chris Powell, Jan Pratt, Sean Preece, Georgie Price, Danny Quartermaine, Mario Querol, Jon Rhodes James, Colin Roberts, Paul Robinson, Alberto Rossi, Luca Rossi, Dave Runaghan, Anand Sagoo, Tanvir Saini, Neil Scott, Andrew Sherratt, Michael Shuster, Lee Smith, Tim Snelson, Joaquin Soria Diaz, Chris Stanford, Michael Stevens, Calvin Stewart, Susanne Stolper, David Storer, Craig Stott, Eric Sturel, Mike Summers, Steven Swan, Martin Tarnowski, Thomas Taverner, Scott Thirtle, Xing Tong, Bernard Travers, Sara Turnbull, Ryan Turner, Tijl Uijtenhaak, Dora Vagiou, Michael Wadsworth, Julie-Anne Walker, Killian Walsh, John Walton, James Watts, Marcos Watts, Chris Webb, Luke Webster, Mel West, David Wheatley, Joe Wheelwright, Deborah White, Sam Williams, John Woodman, Darren Wright, Mat Wright, Evangelos Zacharis, Akhtar Zaman, Dima Zogheib.

Image credits

1, 7: Jaguar Land Rover
2, 3, 8, 9: Simon Kennedy
4, 5, 6: Arup

A dramatic refresh of Seattle's Space Needle

The use of cutting-edge techniques in the renovation of Seattle's most iconic structure has readied it for the next 50 years of its life, and means that the original concept for the Space Needle has finally been achieved

Authors Peter Alspach, Clayton Binkley, David Okada, Kristen Strobel, Cress Wakefield

A landmark on the Seattle skyline, the Space Needle was built for the 1962 World's Fair and stands 605ft (184m) above the city. It is the globally recognised symbol of Seattle and attracts more than 1.3 million visitors per year. The Space Needle Corporation engaged architectural firm Olson Kundig to help them create a new vision that would preserve the building's historic exterior while revolutionising the guest experience and clarifying the original conceptual design vision. Arup collaborated closely with the architects on the renovation, designing a seismic retrofit, accessibility upgrade and modernisation of building services. The firm provided structural, mechanical, electrical and plumbing engineering, as well as building physics and fire consulting.

The Space Needle structure consists of three main components – the Pavilion Level at its base, the Skyline Level at 100ft, and the iconic 'Atmos' 500ft above the Seattle streetscape. Within the Atmos, the guest experience is focused on two main areas: the 520ft level that includes the exterior observation deck and the 500ft level featuring 'The Loupe' – the world's first and only rotating glass floor. Connecting the two are the 'Oculus Stairs', two open half-moon shaped staircases made of wood, steel and glass that terminate in a glass-floored oculus.

From the tower's Atmos, visitors can now enjoy expansive and unobstructed 360° views of Seattle's skyline, as well as look straight down through the new rotating glass floor. To achieve these views, 176 US tons (160 tonnes) of structural glass was installed, increasing the glazed area by nearly 200%. The new design expands the publicly accessible area by 9%, all within the existing building space.

The general contractor, Hoffman Construction, worked around the clock on a tight schedule that avoided the peak tourist season. The Atmos stayed open to the public throughout. This 11-month period required constant communication and collaboration between the owner, contractor and design team. Arup provided on-call support to the contractor that at times included three-shift support for the 24-hour construction period.

Space Needle renovation facts

605 Height of the Space Needle, in feet

1,300,000 Visitors to the Space Needle each year

176 US tons of glass used in the renovation

196 Percent increase in the amount of glass installed at the Space Needle

360 Degrees of uninterrupted views of the Puget Sound region

50 Experts from around the world to advise on the renovation

500 Workers involved in the renovation

100,000,000 Dollars spent on the first phase of the renovation

520ft level

The work at the 520ft level included installing new stairs, an accessible lift and increased interior glazing, as well as the replacement of the exterior safety barriers at the external deck with glass vertical barriers featuring integrated glass 'Skyriser' benches. One of the primary goals of this work was to restore the transparency envisioned in the conceptual sketches for the original design, while making all public areas step-free and fully accessible for the first time.

The quest for transparency extended beyond the exterior skin – Olson Kundig wanted an open plan with as few obstructions as possible between guests' first steps from the elevator and the expansive skyline view. This inside-out transparency was a major driver for the building services modifications throughout the Atmos. One of the most impactful components was a tightly coordinated reroute of the kitchen exhaust ducts from their vertical path through the observation level space to a more hidden vertical course near the core.

At the exterior, the knee-high wall and wire caging at the edge of the observation deck were replaced with new glazed barriers and integrated bench seating. The modifications required retrofit work at each of the 48 existing radial trusses that support the observation deck. The top chord of 15 of the existing trusses was removed and lowered to allow for the new staircases and lift pit. Arup designed the retrofits to be installed without the need for shoring. This allowed the contractor to modify the trusses, while


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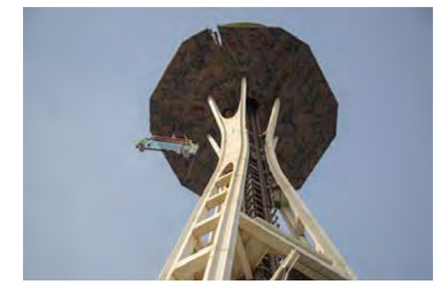
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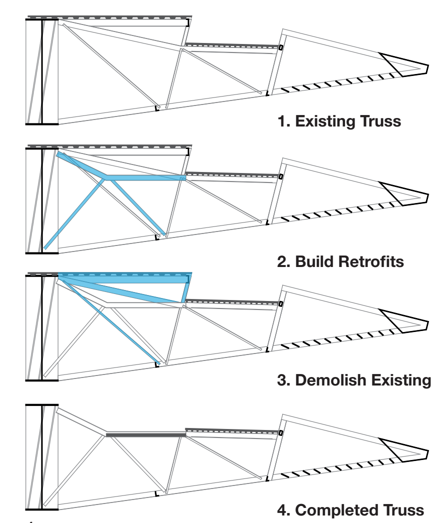

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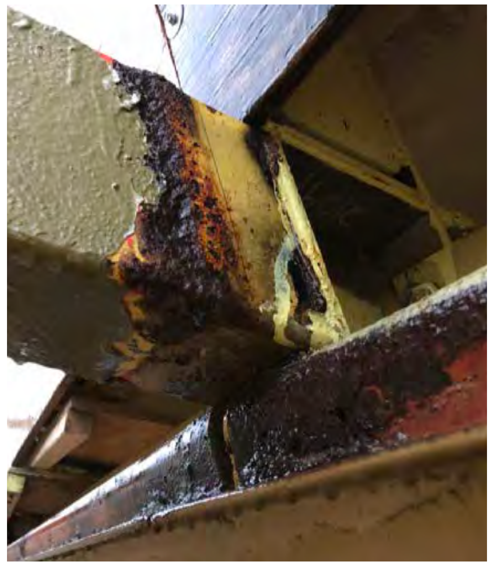
1: The iconic Space Needle was built for the 1962 World's Fair. At 605ft, it is a highlight of the Seattle skyline

2: 3D section of the 'Atmos', showing new Oculus Stairs and increased glazing

3: Some 176 US tons of glass was installed during the renovation

4: Sequence showing modifications made to 15 of the 48 radial trusses supporting the observation deck



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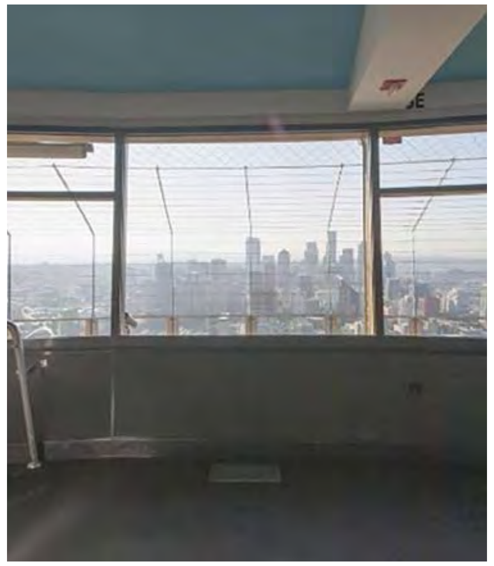

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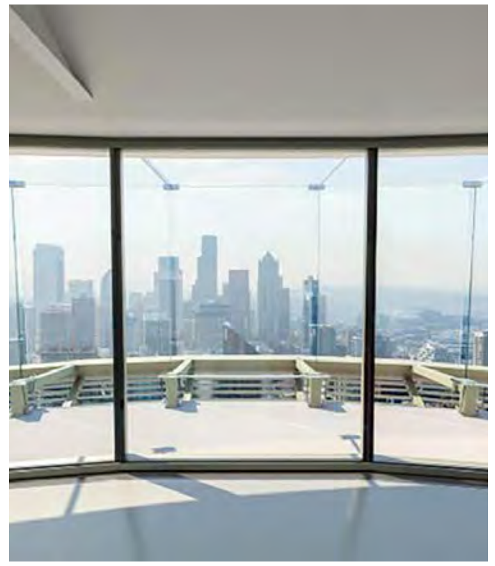

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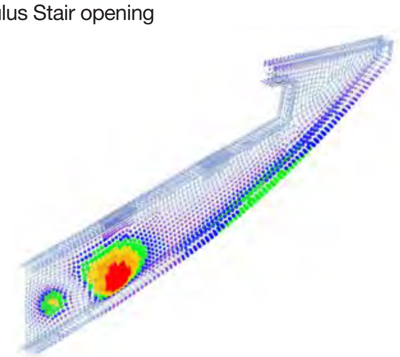
5: Repairs were made to parts of the existing structure that were found to have corrosion damage

6 & 7: The knee-high walls were replaced with glazing to optimise views

8: Arup carried out detailed flexural buckling analysis of the canoe beams

9: Construction sequence for installation of the Oculus Stair opening



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maintaining public access to the observation deck throughout construction.

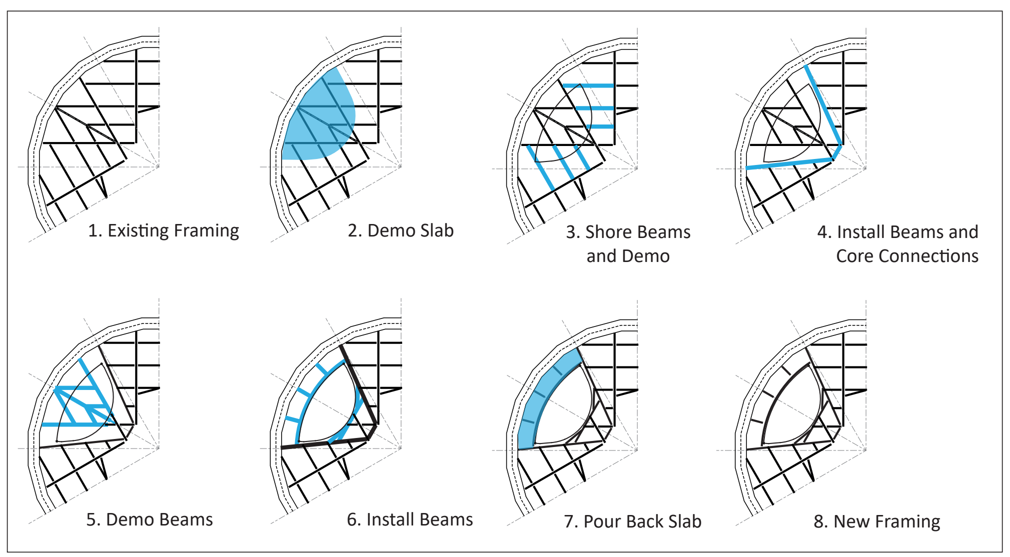
When standing on the observation deck, the guests' view to ground level is through the signature ring of louvers, also known as the halo, that gives the Atmos its distinctive flying saucer shape. During construction, significant corrosion, water infiltration and freeze/thaw damage was discovered in the rectangular tube sections of the halo structure that make up the last panel of the radial trusses supporting the observation level. With the building opened up and these zones accessible via scaffolding, Arup was able to conduct a full survey of all trusses. The team designed a retrofit scheme including a temporary support structure that relied on adjacent trusses and allowed the damaged tubes to be cut away and new sections welded in place without any additional shoring. The modification also included architectural detailing to improve drainage and prevent future water intrusion.

500ft level

The 500ft level was redeveloped into a flexible space that can serve as either an observation deck or dining area. The original (opaque) rotating floor at this level was replaced with The Loupe – a new glazed floor and soffit that allows views through the structure to the ground 500ft below. The new design also includes taller windows and updated architectural finishes. Steel plate shear walls have replaced the existing concrete wall to improve seismic performance and allow penetrations that increase circulation and improve access.

The structure of the building at this level consists of a 66ft diameter box-section ring beam that rests on top of the main tower legs. Inboard of the ring beam, six radial box beams connect the ring beam and legs to the central core of the tower. Outboard of the ring beam, 48 tapered radial built-up beams, dubbed 'canoe beams' for their shape, cantilever out to support the rotating floor.

The original building design used the area under the rotating floor to house building services and relied on a combination of flat-strap bracing and metal deck to brace the canoe beams against buckling. As the new rotating floor was to be completely transparent, all services needed to be moved out of this area and the existing structure renovated to accommodate the view.



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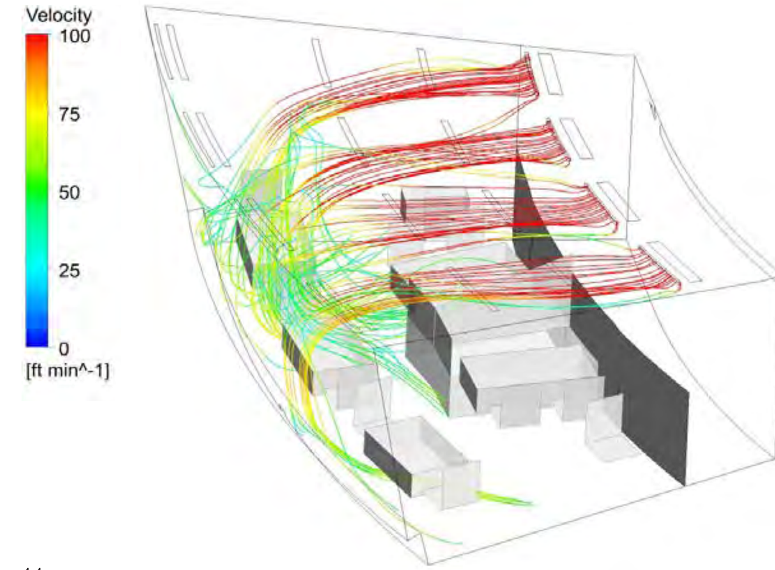

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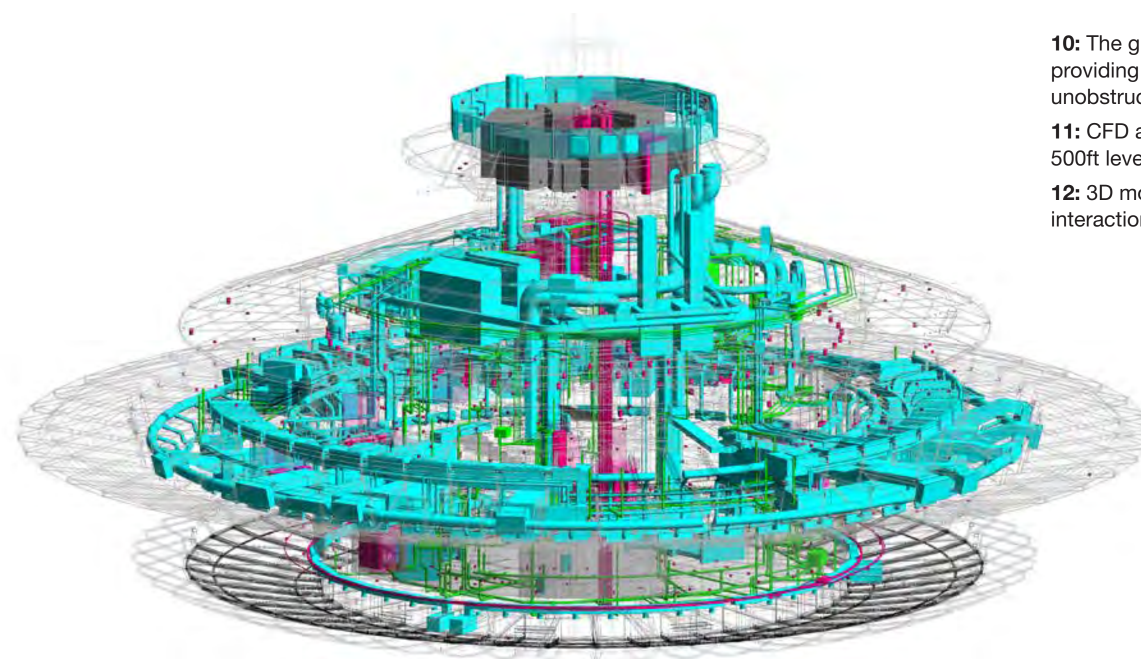
Arup created a detailed finite element model of the canoe beams to determine their lateral torsional buckling capacity and ability to resist the increased weight of the rotating floor with reduced out-of-plane bracing. Several retrofits were installed to strengthen the existing canoe beams, with welds added to the bottom flange to allow the structure to support clamps for rope-access maintenance loading.

The existing strap bracing diaphragm below the rotating floor was replaced with stainless steel tension rods. As these rods are visible below the glass floor, it was architecturally important that they be cleanly detailed and as small as possible, to minimise any visual obstruction.

Providing thermal comfort across the range of possible operating conditions was the focus of Arup's mechanical design in this space and required careful consideration due to the increase in the glazed surface area at this level. The original heating, ventilation and air conditioning system provided heating at window sills from fan coil units located in the cavity below the rotating floor and cooling via large round ceiling diffusers. Underfloor services were no longer an option, as the cavity below the rotating floor was now visible.

The air distribution approach was refined to incorporate separate linear supply diffusers for heating at the perimeter windows, cooling supply diffusers toward the interior and a return airflow path at the centre of the structure. All air distribution elements are coordinated with the sculpted ceiling contour. Arup's building physics team used computational fluid dynamic (CFD) analysis to optimise the design and ensure a comfortable guest experience.



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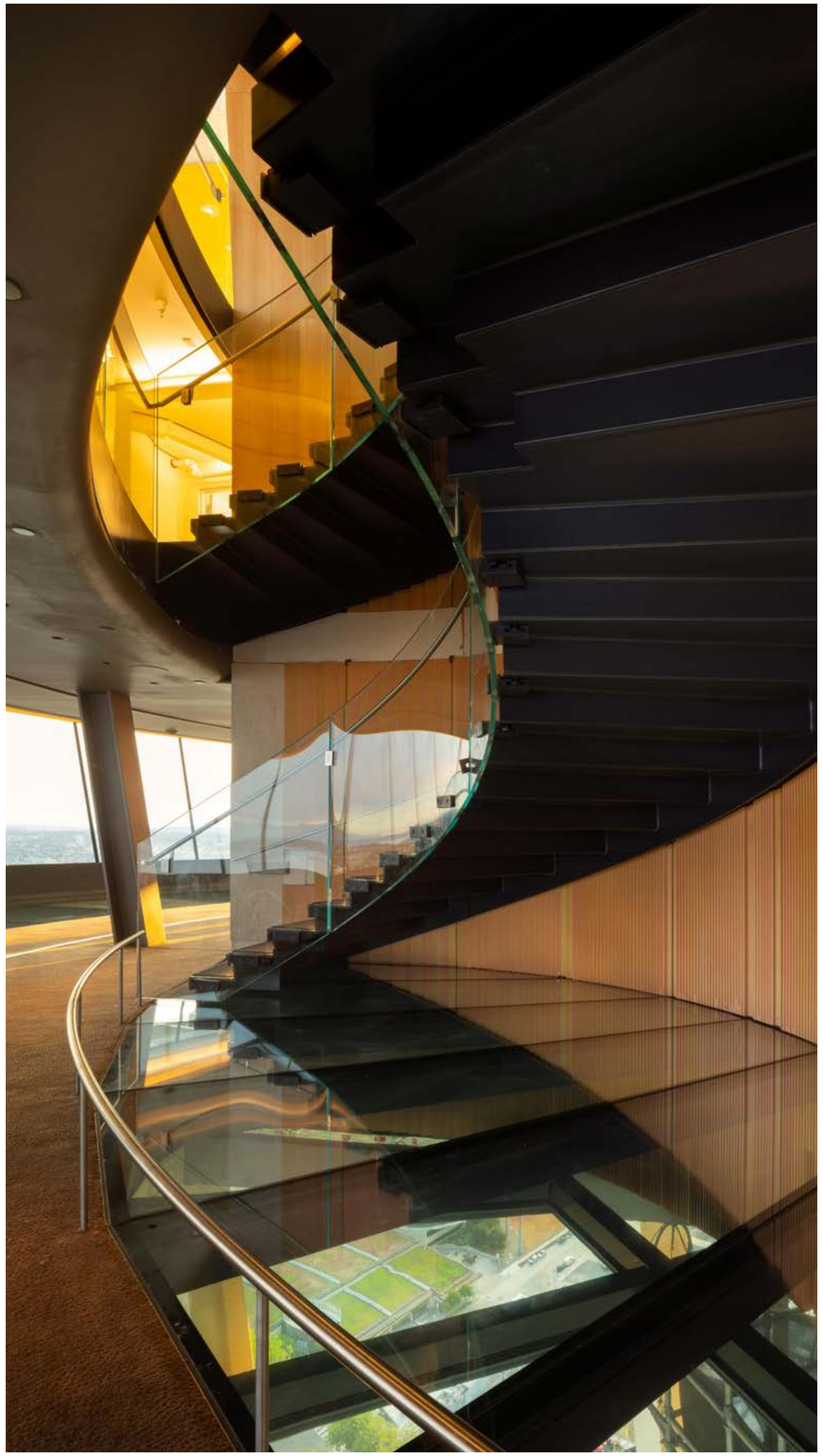
10: The glazed area was increased by 200%, providing visitors with magnificent unobstructed views

11: CFD analysis of air distribution at the 500ft level

12: 3D model showing the complex interaction of building services in the Atmos



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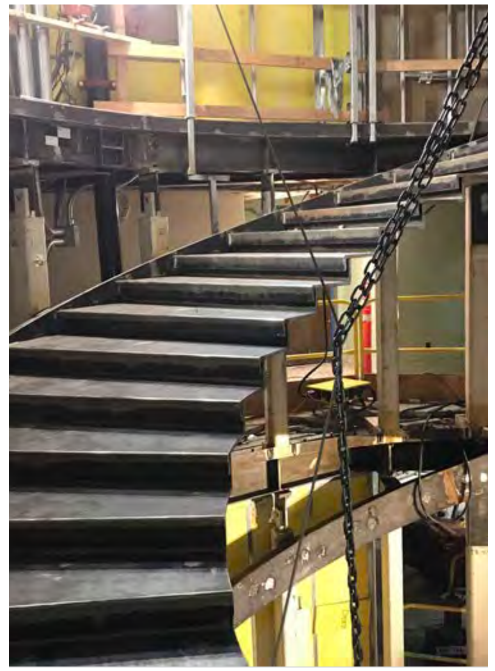

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13, 14 & 15: The Oculus Stairs connect the 520ft and 500ft levels. They encircle a central opening that culminates in the glass floor oculus

The creation of the rotating glass floor means there is a fully glazed cavity between this floor and the lower glazing that wraps under the building structure. Dust build-up and cleanliness of this cavity was a major concern and led Arup to incorporate a dust control fan system that circulates and cleans the cavity air. The design of the system used CFD to determine the airflow rates and design of the nozzle providing dust control, as well as to help understand thermal comfort due to the glass floor.

Oculus Stairs

The Oculus Stairs are a set of two new curved feature staircases that connect the main public 520ft and 500ft levels, along with the intermediate service level. The stair encircles a central opening of 6ft x 12ft (1.8m x 3.6m) through each floor that culminates in the glass floor oculus that allows visitors a view to ground level 500ft below. The Oculus also gives visitors views of the structure, and the elevator and counterweight operations.

These stairs are highly trafficked, as most visitors arrive on the 520ft level and walk down the staircase to exit via the elevator lobby on the 500ft level. With the staircase such an important circulation path, Arup paid particular attention to its dynamic response across a range of loading conditions. The finished stair looks light but feels solid underfoot.

The structural frame of the stair is made up of steel tube columns with a plated, curved rectangular tube stringer beam, all of which is hidden behind an architectural wood slat wall. Each stair tread is fabricated out of folded 0.75in (20mm) thick plate that cantilevers out from the stringer beam, creating the appearance that the stair floats within the oculus opening.

The opening itself was created by cutting out one-sixth of the existing floor framing at each level. Because this framing stabilised a storey-deep ring girder between the service and observation levels, the sequencing of this work was important in order to maintain stability throughout. The framing for the opening was designed such that new primary edge beams could be installed adjacent to the existing girders prior to the existing members being cut away. The new beam connections to the central core rely on the remaining portion of the existing girders in order that all the work points remain unchanged.

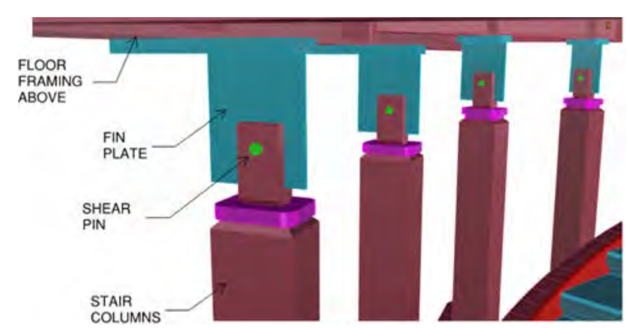
The connection of the stair to the surrounding primary structure was carefully considered under both normal and seismic loads. Under normal conditions, the stair columns are connected to the floors above and below, providing the necessary stiffness to control vibration and deflection of the treads. Under seismic loading, the stair itself can resist the applied loads; however, the floor framing that it connects to cannot resist the resulting forces from the stair frame while the two floors are linked together but trying to move separately. The challenge was to make a structure that was stiff during normal conditions to control the footfall response, but flexible under a seismic load. To achieve this, Arup designed the top connection of the stair column to incorporate a shear pin that is calibrated to break away during a large seismic event. The stair remains stable, albeit more flexible, without this top connection intact, and is free to move without significantly damaging the floor framing above and below.

Services upgrade

A comprehensive building services upgrade was required due to the age of the building as well as the extent of interventions across all the levels in the Atmos. The main service level is between the 520ft and 500ft levels, with plant located between the radial trusses supported off the storey-deep ring girder.

In a more conventional building of this size, a single air handling unit (AHU) would serve the floors above and below. Due to space constraints, eight smaller AHUs are located between the radial trusses to serve this function. This space outboard of the ring girder also accommodates ducts, variable-air-volume boxes, piping, electrical distribution equipment and lighting power supplies.

Arup carried out detailed coordination to incorporate all this equipment in the truss space while improving maintenance access. New access doors at the service level upgrade the previous floor hatches (which had meant that access was previously only available from the level above). With the redesign, a clear walking path was established, eliminating the need to step over truss chords at each bay; AHU access doors were located between truss chords, greatly improving accessibility.



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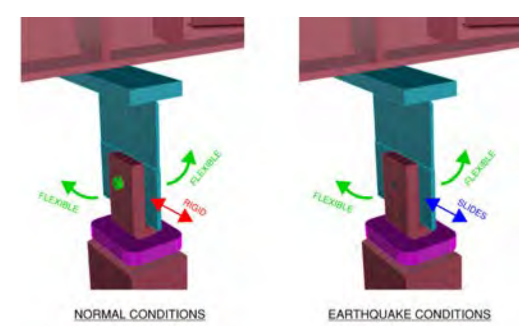

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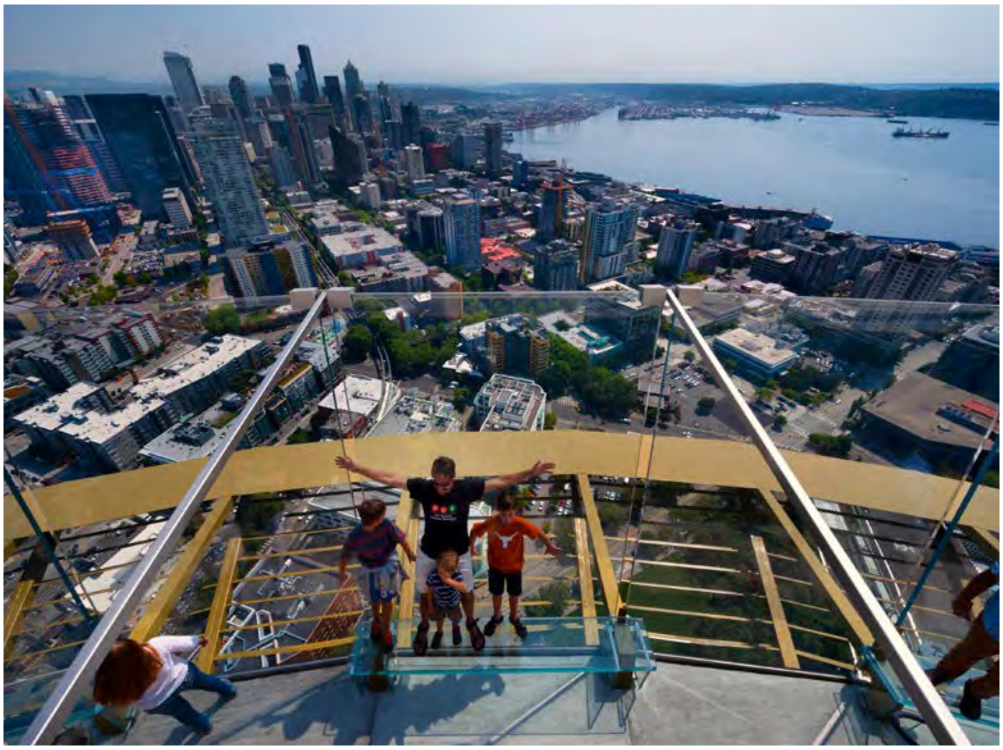
16 & 17: Stair top connection detail – shown under normal and seismic loading



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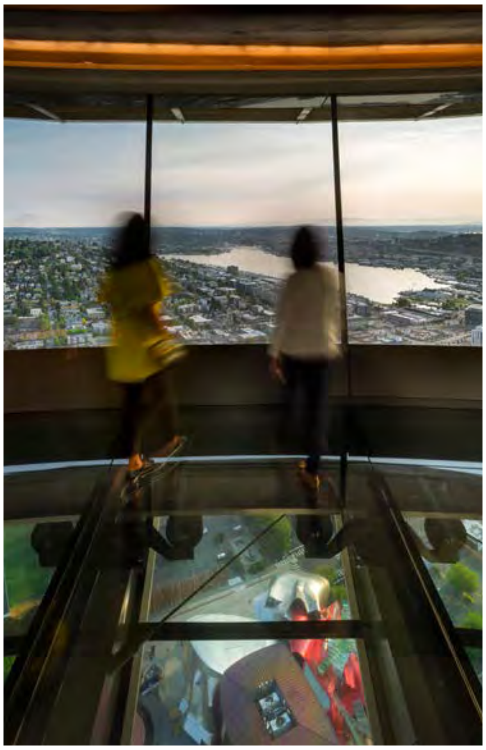
18: One of the aims of the increased glazing at the observation level was to achieve the transparency envisioned in the original design

19: The glazed floor in The Loupe



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In addition to increased maintainability, the services upgrades brought the Atmos up to current code requirements across all disciplines. This was no small feat from an energy perspective, with the redevelopment having a glazing increase of almost 200%. There was no special energy code concession for the iconic status or unusual nature of the building. To show compliance, the renovation was compared not just to the existing condition but requirements for new construction, including the prescriptive 30% window-wall ratio and fully insulated floors.

A performance-based compliance path was selected, trading off energy-efficiency measures for the shortcomings of the historical envelope and expanded glazing. Arup performed detailed analysis of thermal bridging in the building structure, de-rating the building envelope for all the locations where steel elements penetrated the building insulation, including the service level trusses, girders and beams below the 500ft level, and within the roof. Generally, as much insulation as possible was added to the opaque areas of the building, and points of thermal bridging were addressed where possible to improve the envelope performance despite the increase in glazing.

Energy-efficiency measures included installing efficient domestic hot water and space heating plant, varying kitchen exhaust volumes based on real-time cooking needs and implementing 100% free cooling with outside air at all levels.

Century Project

The redevelopment was dubbed the 'Century Project' and was just that – a comprehensive renovation that looks back to the structure's historic vision and first half century of operations to set the stage for the next 50 years and beyond. Final phases of the project will include updating the elevators, repainting and a roll out of a new dining experience at the 500ft level on The Loupe.

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David Okada is a mechanical engineer in the Seattle office.

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Project credits

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General contractor Hoffman Construction
Development manager Seneca Group
Glazing consultant Front
Structural, mechanical, electrical and plumbing engineer Arup:
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Image credits

1, 13, 18, 19: Nic Lehoux
2: Olson Kundig
3: Space Needle LLC
4, 5, 8-12, 14, 16, 17: Arup
6, 7: Space Needle LLC and Olson Kundig
15: Space Needle LLC and Rod Mar

1.

A heavyweight lift

It took just ten seconds to lift the topside of Shell's Brent Delta oil and gas platform clear from its concrete base, yet this was the culmination of years of planning, design and structural works to the platform, and a record-breaking event

Author David Gration

1: Allseas' *Pioneering Spirit* carried out the world's heaviest offshore lift when it removed the Brent Delta platform topside

This was the first major decommissioning project in the North Sea using Allseas' single lift technology to remove the entire topside of a large offshore platform in one piece. The topside housed the accommodation block for staff, a helipad, processing facilities, power generation, compression, flare and the drilling and operational areas, along with associated equipment. Its safe removal enabled dismantling onshore, significantly reducing offshore risk exposures.

The size of the task was reflected in the use of the world's largest construction vessel, Allseas' *Pioneering Spirit*, undertaking what was at the time the world's heaviest offshore lift.

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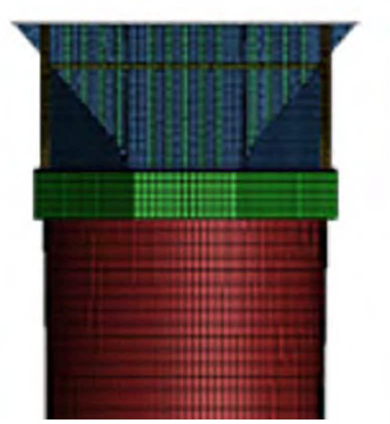

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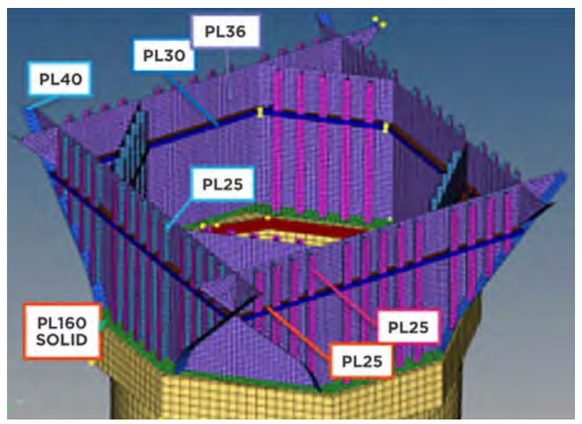

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2: Underdeck and GBS legs of Brent Delta

3 & 4: 3D non-linear finite element model of transition piece, strengthening and concrete shaft

5: Shear restraint inspection at the manufacturer

Arup supported the decommissioning of the platform by designing the strengthening required to enable cutting the three supporting concrete legs to allow the separation of the topside from its supporting base. Arup determined that strengthening works were required at the cut locations and designed the shear restraint system that provided this necessary strengthening.

This design made it possible for the platform to be de-manned several months before the topside removal. Arup also designed the concrete caps for the legs – which were put in place after the topside was removed – and worked on the strengthening of the infrastructure in the receiving harbour to ensure it could accommodate the massive topside structure for dismantling.

Brent oil and gas field platforms

The Brent oil and gas field,186km north-east of the Shetland Islands, is one of the largest fields in the North Sea. The field has four platforms – Alpha, Bravo, Charlie and Delta – situated in 140m deep water. The topside of the Delta platform was made up of a plate girder deck structure connected via 5.5m deep steel transition sections to a concrete ring beam at the top of each of the three concrete legs. These legs were in turn connected to a concrete gravity base structure (GBS) on the seabed. The Brent Delta topside had a footprint of 72m by 47m, with a 44m height to the helipad and an overall weight of approximately 24,200 tonnes.

Decommissioning

Traditionally, platforms have been dismantled offshore on a module by module basis, but with Brent Delta, Shell took the decision to remove the topside in one single operation. This allowed the de-construction work to take place onshore in a more controlled environment, where detailed inspection and dismantling could be undertaken efficiently, and reduced personnel exposure due to the significantly smaller workforce required.

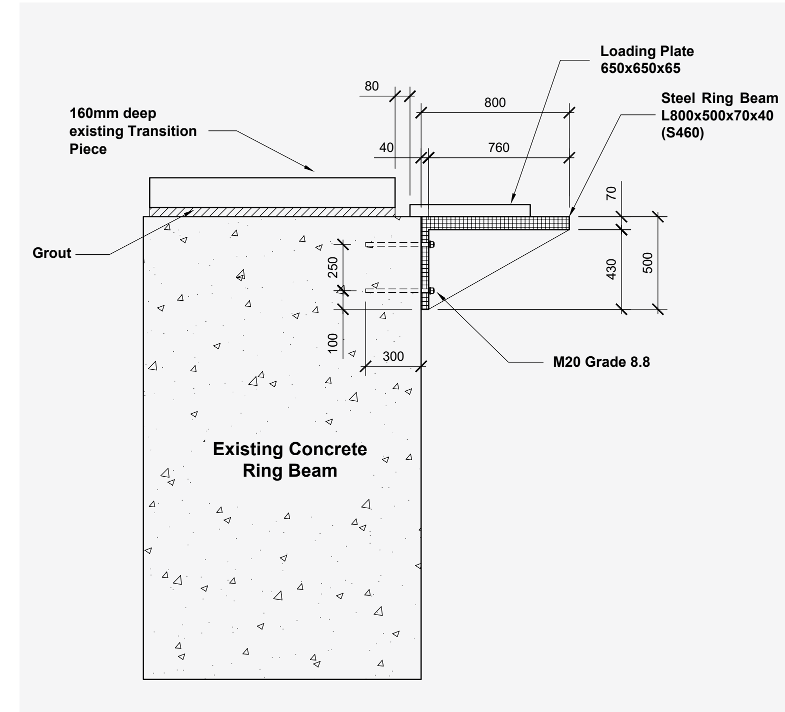
Arup was commissioned by the offshore contractor Allseas to develop, from concept through to detailed stage, the design for the strengthening works required post-cut, prior to the removal of the topside of the platform from its supporting structure.

Topside removal design development

Arup began the project with a workshop, which resulted in over 30 design proposals. Using a qualitative assessment, these were then rationalised down to the five most viable solutions. Following scoping calculations and after agreeing relevant selection criteria with the client, Arup used a trade-off matrix to select the preferred option for detailed design.

Using a variety of skills, including first principles structural design, non-linear analysis, laser scanning and wave simulation, Arup designed a system that was both structurally effective and reduced installation complexity. The scheme involved cutting the legs just below the topside to facilitate its removal. Non-linear analysis was used to simulate the post-cut situation, with a 3D non-linear finite element model developed for the concrete legs, associated steel transitions sections and proposed remedial works to facilitate the lift.

This cutting work had to take place ahead of the removal of the topside due to the limited weather window available for the topside lift and the availability of the *Pioneering Spirit*, the only lifting vessel that could accommodate such a significant load. Arup's analysis found that the shear forces that needed to be transferred across the cutline between the legs and the topside exceeded the justifiable frictional capacity of the cutline. To resolve this issue, Arup designed a shear restraint system that allowed the topside to safely remain in place after the cut.



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6: Section through the concrete ring beam showing the connection details of the steel ring beam

7: Shell's Brent Delta platform in the Brent field prior to topside removal

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Shear restraint system

There were several complex design requirements for the shear restraints. The system had to be installed in a simple manner offshore, the topside needed to be kept in place after cutting, and it had to disengage during the lifting process without manual intervention.

Arup designed the restraint to carry the circa 20MN shear force per leg across the cutline from the topside transition piece into the concrete leg and down into the GBS. A steel ring beam (circa 40 tonnes of steel per leg) was connected to the concrete ring beam at the top of the leg just below the 160mm-deep flange of the 5.5m tall steel transition piece (TP). Made up of eight steel fabricated angle sections that follow the internal shape of the concrete ring, the steel beams formed a continuous compression ring. Twin loading plates were shop welded to the ring beam in each of the eight corners.

To create the required load bearing connection between the TP and the compression ring, a corner plate was positioned between the loading plates. These elements were machined in the shop but put in position offshore. A trial assembly was built in the shop to check the accuracy of the manufactured elements.

In the installed condition under shear load, the TP flange contacted the corner plates, which in turn contacted the loading plates. In this way the load was transferred from the TP flange into the steel ring beam. This load was transferred around the steel ring beam in compression and then

8.

8: Topside being lifted clear of the concrete legs

9 & 10: Plan showing the shear restraint system

11: Concrete legs following topside removal but prior to cap installation

12: Concrete leg caps being lowered into place on top of the legs

13: The *Pioneering Spirit* moves clear of the concrete legs following its successful lift of the platform topside

into the concrete ring beam and the legs below. The shear restraint provided no vertical fixity between the TP and the concrete ring beam, so no disengagement of the shear restraint was required before the topside was lifted. This minimised health and safety risks by avoiding the need for any manual intervention during the lifting process, a critical part of the brief. This design solution allowed the topside to be lifted with no personnel on the platform – and some months after the platform had been de-manned.

Rather than tailoring the components to the individual internal leg dimensions for each leg, the dimensions were laser scanned internally, with the steel ring beam fabricated slightly smaller than the internal diameter. This simplified installation works offshore by allowing common components to be used and enabled them to be assembled to tighter tolerances. Once installed, the gap between the ring beam and the concrete leg was filled with cementitious grout, which accommodated any surface irregularities. During the fabrication and installation of the shear restraints, Arup provided technical support to both Allseas and Shell.

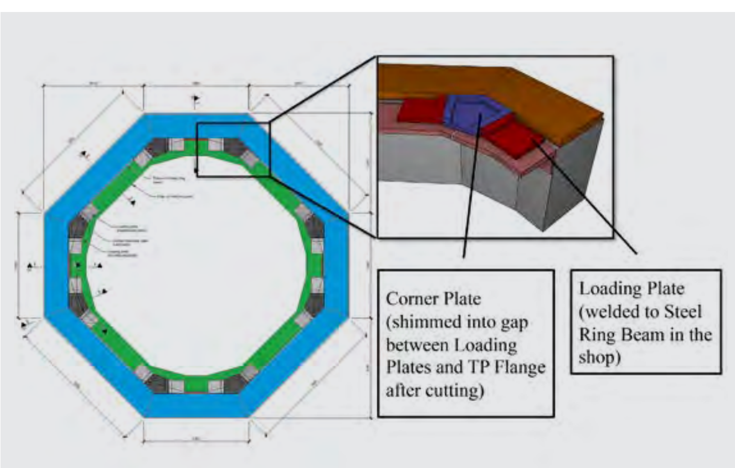
The shear restraints were designed to withstand all-season waves. This allowed the legs to be cut and the platform de-manned well in advance of the topside lift, which reduced the offshore risk exposure for the workforce.

Cutting the legs

After Shell decommissioned the pipework and equipment within the legs and installed the steel shear restraint system, the shaft cutting could proceed well in advance of the topside lift. Cut UK had conducted all the onshore cutting trials in preparation for executing the diamond wire cutting offshore on the Delta platform.

The cut was made just below the TP flange plate, cutting through the grout and the post-tensioned bolts that connected the plate to the concrete ring beam, but above the post-tensioned tendons anchored within the concrete ring beam at the top of the legs.

Diamond wire cutting was deployed inside the 14m wide legs, which are approximately 1m thick. The cutting sequence was determined based on a review of the expected weather window during the cutting operation. Holes were drilled at specified centres through the concrete ring beam. A diamond wire was then threaded through two adjacent holes before the cutting process began.



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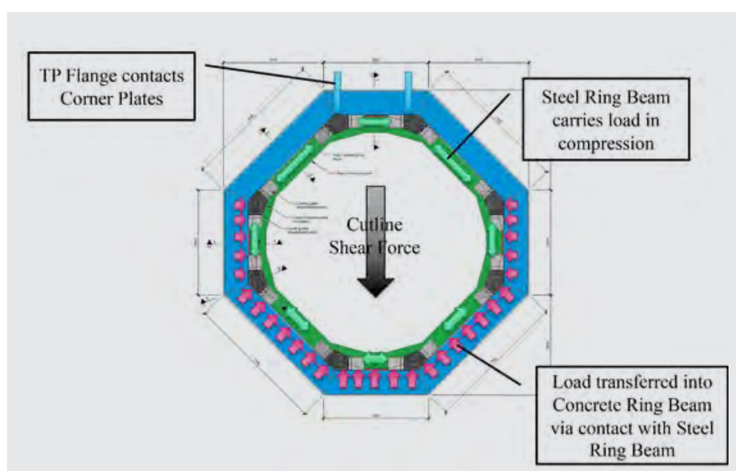

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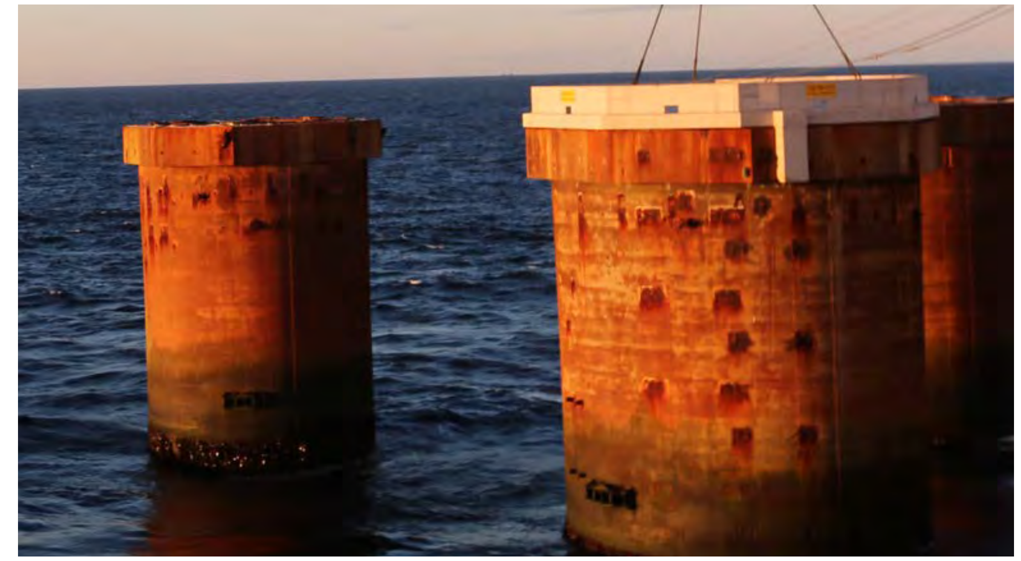

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Lift

The lift was carried out by Allseas' *Pioneering Spirit* in April 2017. Specifically designed for the single lift installation and removal of oil and gas platforms, the twin-hulled vessel is 382m long by 124m wide and can accommodate lifts of up to 48,000 tonnes. A 122m long and 59m wide slot in the bow of the vessel was used to position around the platform, with the lift using eight sets of horizontal lifting beams.

Over a 12-hour period the vessel was positioned under the topside, with each lifting beam aligned to touch the designated lifting points. Hydraulics enabled positive contact to be kept with the topside, all the while taking into account the movement of the vessel. The ballast was removed from the vessel before the operation, which meant that virtually all of the topside weight could be taken before the short lift – which lasted just ten seconds – took the topside clear of the legs.

The topside platform was transported 388 nautical miles to within five miles of the shore and the decommissioning yard. As the water depth at the Able UK Seaton Port in Teesside was insufficient to accommodate the *Pioneering Spirit*, the topside was transferred via the 200m by 57m wide cargo barge *Iron Lady*. The platform is currently being dismantled and recycled with the aim of re-using over 97% of the material in the platform.

Concrete leg caps

Following the topside lift, with the legs sitting close to 20m above the sea, concrete leg caps designed by Arup, each weighing approximately 300 tonnes, were placed on top of the legs.

Each cap has three installation guides. These helped to position the caps when lowered from a crane on a moving vessel. As well as closing off the top of the leg, one of the covers provides a foundation for the navigation aid used to alert passing ships of the presence of the concrete legs and GBS below.

13.

Onshore harbour works

Arup was involved in supporting Shell to ensure the harbour infrastructure was capable of receiving the topside, performing an independent technical review of the detailed design of the receiving quay and the critical structural interfaces with the *Iron Lady* barge. Arup reviewed site investigations around the quayside, attended the quay upgrade works and witnessed piling.

Next steps

The design developed by Arup reduced work offshore, minimised cost and health and safety exposure, and facilitated the heaviest offshore lift to date. The Brent Delta platform is one of an estimated 600 installations to be decommissioned in the North Sea over the next 30 to 40 years. The lessons learned from Brent Delta will be invaluable for future projects that involve concrete GBSs.

Author

David Gration was the Project Director. He is a Director in Arup's Advanced Digital Engineering team based in the London office.

Project credits

Owner Shell UK

Main contractor Allseas

Arup: Ian Ashcroft, Giacomo Caleffi, Jac Cross, Andy Gardner, Kazuma Goto, David Gration.

Image credits

1, 8, 11-13: Allseas

2, 5, 7: Shell UK Ltd

3, 4, 6, 9, 10: Arup

Preserving Malaysia's natural heritage

An elegant solution to traffic congestion ensured minimal environmental impact on a world-renowned heritage site

Author Wan Anuar bin Wan Endut

1.

Malaysia has undergone rapid economic growth in recent decades, with a rising population and increased vehicle ownership placing escalating pressure on its road infrastructure.

Rawang, a former mining town founded in the 19th century that has become a base for commuters to Kuala Lumpur, was particularly affected by road congestion. Located 23km north of the capital on Federal Route 1 – the oldest national highway in Malaysia – its position on this major thoroughfare made it a traffic bottleneck. The journey to Kuala Lumpur could take over two hours at rush hour. Vehicles using the road travelled through the centre of Rawang, a route lined with shops, roadside parking and eight traffic signal junctions.

Alleviating this problem was identified as a priority as far back as 1997 by the government's highways planning division. The Asian financial crisis around this time meant the project was put on hold, before the plan to construct the 19km Rawang Bypass was revived in the early 2000s.

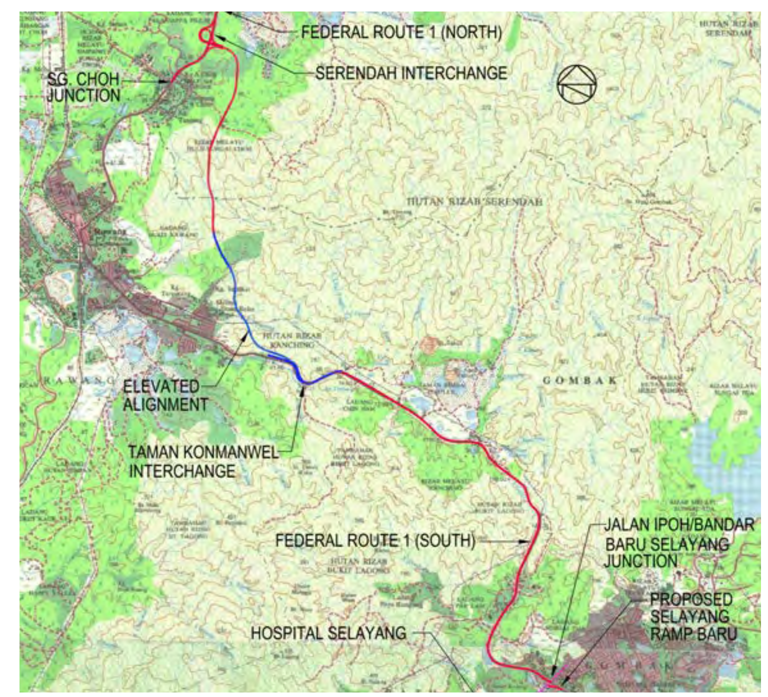
Bypass route

The project was divided into three sections. The first comprised upgrading the existing federal road, transforming the single lane carriageway (starting at Selayang Interchange just outside Kuala Lumpur and ending at the Templer Park area just outside Rawang) into a new dual carriageway with 2m-wide paved shoulders. The second element was the construction of a completely new section of road – a bypass to divert the traffic north around Rawang town centre. The final section of the project was building a trumpet interchange and upgrading the 2km federal road on the north side of Rawang leading to Serendah, a popular tourist spot.

The project was tendered as a design and build contract and was awarded in 2003 to a partnership between Arup and local company Panzana Enterprise Sdn Bhd. Arup provided full engineering services, and was the full-time site supervision consultant for the project.

Kanching Forest Reserve

The team started on the detailed design in 2004. Sections 1 and 3 were relatively straightforward and progressed smoothly, but Section 2 was far more challenging. This part of the project entailed building a bypass around Rawang that, under the government's original plan, cut through Kanching Forest Reserve. This hilly forest is an area of outstanding natural beauty and ecological value. Referred to locally as Taman Warisan ('heritage forest'), it is a rich reserve of waterfalls, flora and fauna, and attracts eco-tourists from around the globe. It teems with wildlife, including rare and protected plant species such as the Giam Kanching tree, of which only 400 are left in the world.



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1: The Rawang Bypass travels through the Kanching Forest Reserve, with the road almost at treetop level for sections of the route

2: Map showing Federal Route 1, an important north-south thoroughfare in Malaysia

3.

3: Part of the bridge travels over the existing federal trunk road. In order not to disrupt traffic, a cantilever method of construction was used at this point

4: Box girder construction was used for the bridge section above the federal trunk road

5: Typical bridge deck cross-section at pier location

6: To avoid extensive earthworks and minimise deforestation, the high-level bridge deck was constructed using a movable scaffolding system

In 2005, the state government designated the forest as an official heritage site, meaning no major development that could affect the reserve's ecology was allowed.

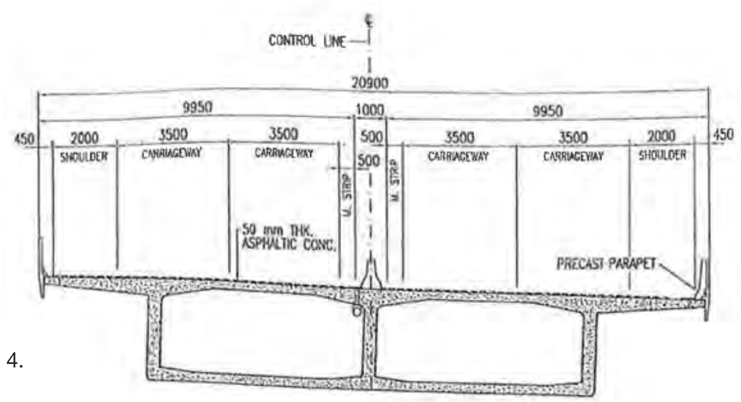
Finding a solution

Although the road was an essential part of improving Malaysia's transport infrastructure, the risk was that any construction work would require extensive deforestation, resulting in an unacceptable impact on the natural environment. The Malaysian Public Works Department, which commissioned the project, requested Arup revisit the concept design and review the road alignment. For Arup, the challenge was to redesign this vital bypass to minimise deforestation, ensuring little impact on the environment during the construction phase and after handover.

Finalising the design took almost a year and involved an intense process of engaging with the Malaysian central government and other interested parties. Through meetings, presentations and public hearings, Arup gathered input from public representatives, local authorities, the country's Forestry Department and NGOs such as the World Wildlife Fund (WWF).

Arup devised an elegant solution to the problem: an elevated bridge structure over the outer fringes of the forest, moving the route initially suggested by the Public Works Department down to the foothills of the forest. This ensured that the bypass would be located at the edge of the heritage area, reducing the need for forest clearance.

This amended route required the road structure to be raised significantly above the ground to match the vertical alignment of the other sections of the road. The final design included a 2.7km elevated structure supported by piers that are up to 58m tall. This makes it the longest and highest bridge in Malaysia, with vehicles on this section of the road almost level with the treetops of the surrounding forest.



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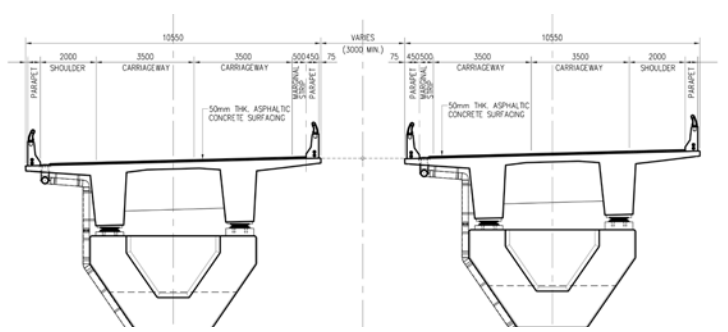

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7: The Rawang Bypass reduces peak time journeys to Kuala Lumpur by 90 minutes

Foundation and pier construction

Having determined a more sustainable route for the bridge, it was important that the construction process also had a minimal impact on the area by avoiding extensive earthworks and deforestation. For the construction of the pier foundations, Arup devised a method that avoided using heavy machinery on site, reducing disturbance to the forest's ecosystem. With the mountainous terrain, it would have been difficult to manoeuvre large machinery on site. This would have required removing trees and levelling the ground, with this latter activity having the potential to cause soil erosion.

Rather than using piled foundations, which require large drilling equipment, light machinery was used to dig caisson foundations. The construction works could therefore be spread over a smaller area than would otherwise be necessary. This method required only a narrow 50m corridor for the construction of the foundations and bridge piers. The foundations range between 1.7m and 6m in diameter, and were dug using jack hammers and hydraulic rock breakers. The piers were built using slipform construction, allowing each pier to be constructed quickly, safely and accurately.

Movable scaffolding system

With the need to avoid extensive earthworks and deforestation fundamental to the choice of construction method, a movable scaffolding system (MSS) was adopted to construct the high-level bridge deck. The MSS provided a quick, reliable and economical solution for construction of the elevated bridge. This was the first time this method was used in Malaysia.

With an MMS, a hydraulically operated giant steel gantry, formwork and platform slides from pier to pier, enabling the beams and concrete slabs to be constructed from the top of the piers. Once each section is completed, the formwork is released and pushed to the next pier, meaning that workers, equipment and materials have minimal impact at ground level. In total, 50 sections of 40m span were constructed using this method. Two 600-tonne gantries were used for the installation.

7.

However, the 51st to the 53rd spans required a different construction method. With the bridge at this point travelling over the existing federal trunk road near Templer Park at a skewed angle, an MSS could not be used due to the large 114m span between piers. In addition, as an MSS is an underslung system, steel frames hung below the bridge had the potential to interfere with the headroom of vehicles travelling on the road below. A more conventional balance cantilever method of construction was used at this location, with the remainder of the spans built using traditional inverted-T post-tensioned beams.

Arup's design allowed the project to progress as quickly and efficiently as possible, ensured minimal disturbance to the forest's ecological system and permitted access for animals to travel below the bridge during construction and following completion of the works.

Collaboration

Teamwork was key to the project's successful completion. A project office was set up near the site, allowing Arup to work under the same roof with the client, the contractor and other team members.

Monthly meetings took place on site, where external stakeholders were also invited, including utilities companies, representatives of the local council, Forestry Department officials and, when there were particular issues to address, NGOs. This meant that all concerned parties were kept abreast of the project's progress.

Safeguarding Malaysia's natural heritage

The Rawang Bypass opened to great acclaim in November 2017. For its breathtaking views over the forest, the bridge has received resounding public approbation and the approval of organisations concerned with protecting wildlife and preserving the environment. Arup's strategy for the construction meant that deforestation and earthworks were minimised. Passing high amid the treetops, the elevated bridge respects the ecosystem below, as well as easing congestion in the adjacent town, cutting peak journey time through this area by 90 minutes. In completing the project, Arup has designed a piece of infrastructure suitable for the needs of Malaysia's ambitious, fast-growing economy, without causing damage to the country's ancient natural heritage.

Author

Wan Anuar bin Wan Endut was the Project Director and is the Managing Director for Arup in Malaysia.

Project credits

Client Malaysian Public Works Department (Jabatan Kerja Raya). Thanks to Haji Abd. Rahman bin A. Aziz as Superintending Officer's Representative

Bridge engineering, infrastructure and geotechnical design, electrical engineering and construction supervision
Arup: Wan Anuar bin Wan Endut, Wong Chee Thong, Ng Say Gim, Muhd Khairul Asyraf bin Abd Rani, Mohd Nazri bin Mat Daud, Adlie bin Mohd Ali, Muhd Bazli bin Omar, Azeri bin Ahmad.

Image credits

All images: Arup

Lowering Leeds city centre flood risk

The Leeds Flood Alleviation Scheme is one of the largest flood defence projects in the UK and the first in the country to use movable weirs

Authors Michael Nichols and David Wilkes

1.

1: Completed Crown Point replacement weir – part of the Leeds Flood Alleviation Scheme, which provides 100-year storm flood protection

2: Arup developed a web-accessible BIM model for the scheme

The first phase of the Leeds Flood Alleviation Scheme was completed at the end of 2017. The works have significantly reduced the risk of floods that have the potential to cause devastating physical and economic damage to the heart of the city.

Previously, 3,500 residences and 500 commercial city centre properties were at high risk, as were key access routes to the train station area, data and telecommunications infrastructure, electricity sub-stations and more than 300 acres of developable land.

In 2015, Storm Eva hit the city, with the resulting flooding causing an estimated £37 million worth of damage. This highlighted the importance of completing the flood alleviation measures as quickly as possible. The first phase of the scheme provides protection to the city without compromising the character of the waterfront, with careful interventions maintaining the important connection between the city and the River Aire.

Scheme development

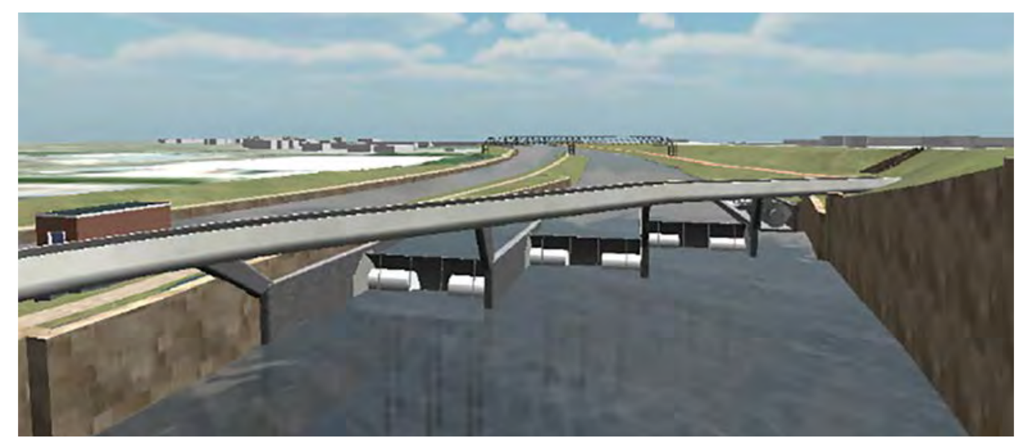
In 2011, the UK government's Department for the Environment, Food and Rural Affairs, and the Treasury, rejected a proposal from a different firm for a £190 million flood scheme due to the excessive cost. That scheme advocated the construction of 3m high walls and embankments. While these would have provided flood protection, they would have also severed the physical connection between the city and the waterfront. Such high walls would have had a negative effect on the café and bar culture along the river, and a pleasant waterfront walking and cycling route would have been lost.

With the rejection of this original scheme, there was a risk that the flood alleviation initiative would be removed completely from the list of national infrastructure spending priorities. For Arup, whose Leeds office is located on the River Aire, getting involved in developing a new scheme was an opportunity to propose a more sustainable solution. The firm, working together with Leeds City Council, developed an alternative proposal more in keeping with the city's character and landscape. Arup focused on reducing obstructions that were causing water levels to rise, meaning the length, visual impact and cost of the riverside defences could be significantly reduced.

By identifying which flood defence measures would provide the most immediate benefits and developing the project in stages, Arup believed it could make substantial improvements on a smaller budget, adding more sophisticated measures when further funding was secured – an attractive proposal during a time of economic recession.

The design comprised three main elements: the removal of the river's two main navigation weirs, replacing them with moving mechanical weirs that allow the water level to be better controlled; installing 10km of linear defences in the form of walls along 5km of the city centre waterfront, embankments and landscape improvements; and the removal of a 600m-long man-made island that separated the river and canal, thus eliminating a bottleneck for water flow.

In November 2011, the Environment Agency commissioned Arup to develop the scheme further and the project subsequently secured funding. With Leeds due to connect



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with the High Speed 2 (HS2) rail link, and with the city's South Bank being one of Europe's largest city centre regeneration initiatives, the flood alleviation scheme was identified by the UK government as an important strategic project.

Digital construction and collaboration

Arup developed a web-accessible interactive Building Information Modelling (BIM) model for the scheme. Through this virtual environment, the project team could digitally navigate the complete scheme, including the flood defence walls, proposed weirs, and new and existing bridges. They could call up project data that was linked to the model, such as drawings and photographs.

The aim was to ensure that everyone involved in the project had a sound understanding of the scheme's fundamentals and access to all the technical information whenever needed.

Working from this common data environment ensured that the project team, including the client, the design and build contractor and other stakeholders, had access at all times to the most up to date project information. This helped to manage workflows and speed up the approval process. It enabled better coordination and collaboration, allowed the early mitigation of any critical issues before site works commenced and reduced risk overall. The model also helped provide greater certainty regarding the construction costs. Following completion of the works, all this information was made available to the client and their team who were responsible for maintaining the flood alleviation infrastructure after completion.

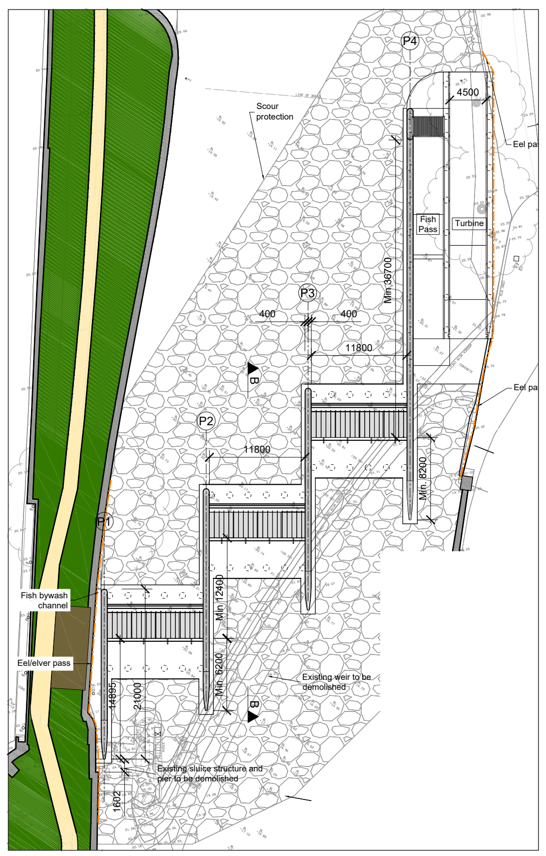
The design team of Arup, Leeds City Council and the Environment Agency was based in the same building. Following the contract appointment, the contractor and their designer joined the project team on site. This structure ensured there was good collaboration across the complete project team.

Replacing the weirs

The existing masonry weirs on the river dated from the Victorian era, when the River Aire valley was home to industries such as carpet and cloth making, and coal mining.

These fixed weirs made the river navigable through the city centre, forming an important trade and passenger route linking Hull, the Humber ports and Liverpool with several cities and market towns. The weirs kept the river level high enough to allow large barges carrying industrial cargo to navigate the waterway. However, when the water level increased during flood conditions, the weirs hindered the flow, significantly increasing flood risk.

The previous scheme did not seek to change these weirs; however, Arup saw them as a crucial element of the flood management strategy. The firm proposed replacing the existing weirs at Knostrop and Crown Point with movable mechanical weirs. These would maintain the river at a navigable level in normal conditions, but could be lowered in advance of extreme weather conditions, thereby reducing the flood risk. The mechanical gates control the water level using bottom-hinged steel plates supported on bladders, which can be inflated or deflated with air to lift the gates up or down as required.



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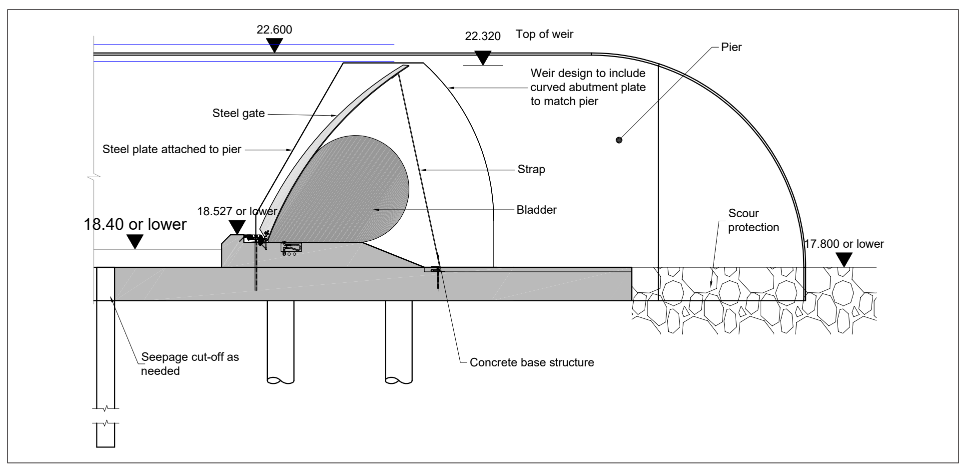

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3: Storm Eva caused an estimated £37 million of flood damage in Leeds when it hit in 2015

4: The detailed plan for the new weir at Knostrop shows the elements aimed at encouraging local wildlife, such as eel and fish passes

5: The water level is controlled using bottom-hinged steel plates supported on inflatable bladders. These movable weirs can be lowered in advance of extreme weather, thereby reducing flood risk

6: Arup used physical models of the weirs to test flow patterns

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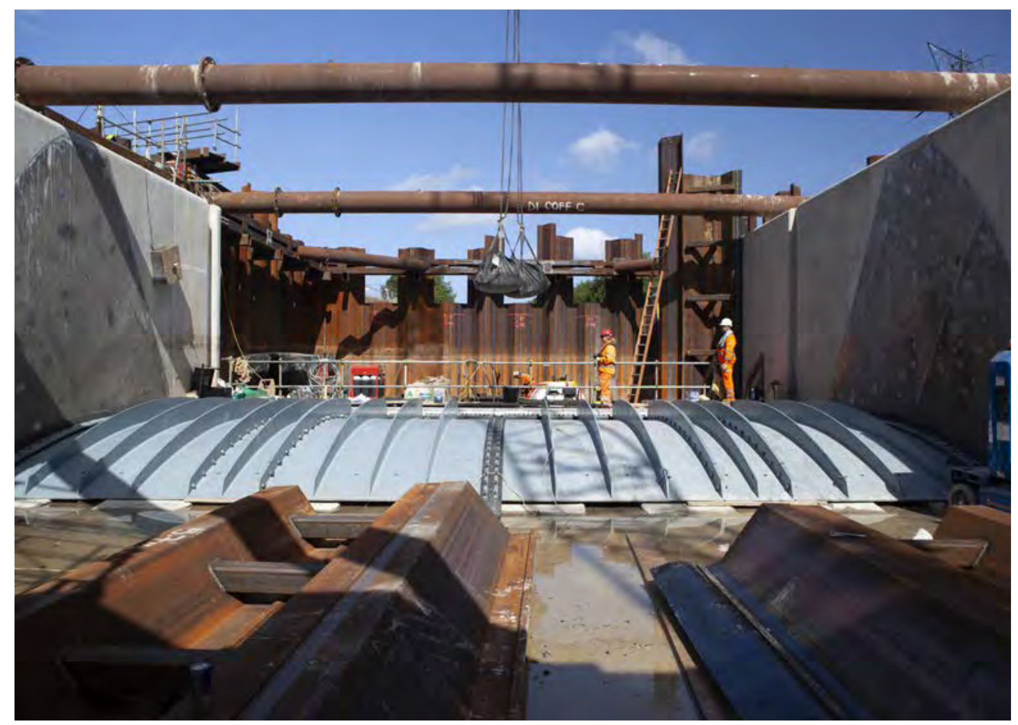

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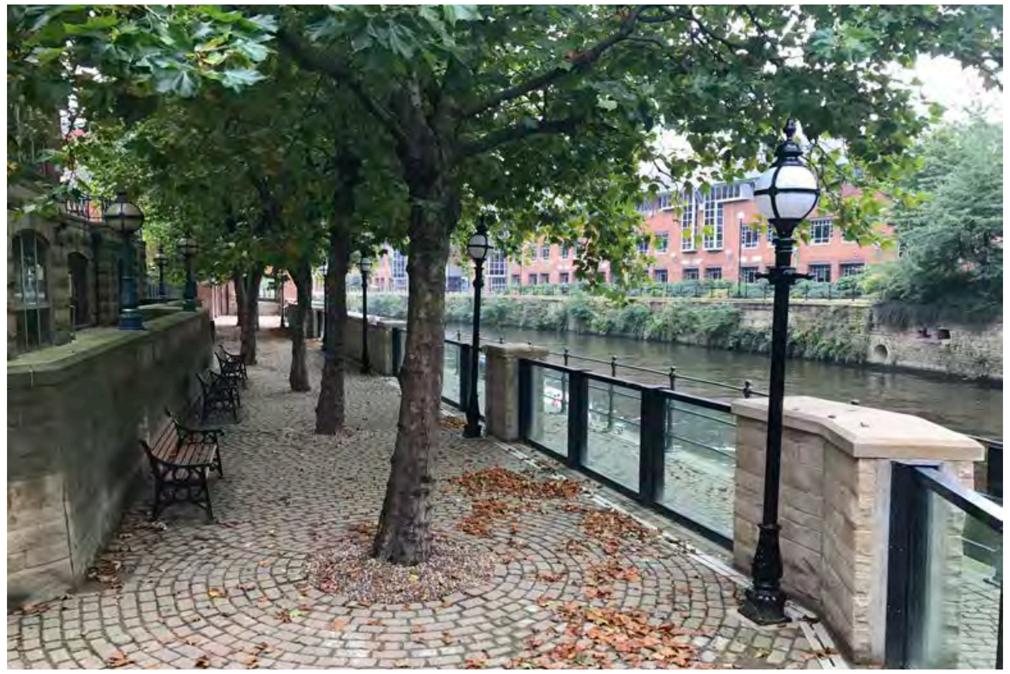
7 & 8: The mechanical weir at Knostrop, shown raised and lowered during construction

9: Crown Point replacement weir under construction



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In normal conditions, the gates are at a 45° angle, which maintains the high river level and allows for navigation. However, as the waters rise, the gates can be progressively lowered towards the riverbed over a two-hour period, removing the barrier to flows and greatly improving water conveyance. This reduces high-flow water levels by 2m at the weir locations and by approximately 1m in the city centre.

Mechanical weirs are used in other countries – in the US and Canada, for example – but typically to control the flow of water into hydroelectric plants. Arup's scheme in Leeds, using weirs developed by Dryhoff, is the first time movable weirs have been used as part of a flood alleviation scheme in the UK.

Configuring the system's layout and installation correctly was crucial. As part of the design process, Arup used both digital and physical models of the weirs to test the various flow patterns ahead of construction.

In addition, the 3D digital model helped plan the weir construction sequence. The model was also used to create a video that showed how the weirs worked, illustrating the process to the wider public.

Arup worked with the design and build contractor to design the system, which had to meet strict requirements for control of flood risk and needed to maintain navigation during construction. For example, a temporary weir was installed upstream at Knostrop, which allowed construction work to be undertaken in a safer manner in shallower water, and ensured the flood risk to surrounding properties was not increased during construction.

Linear defences in the city centre
The second element of the scheme was to build flood defences on each river bank to protect a 5km section of the city centre, as the water level could still rise above the original riverbank during a flood event.

10: In order to ensure the connection between the city and the River Aire was maintained, flood-proof glazed units were installed along a stretch of the riverbank most used by the public

11: Natural flood alleviation methods were also used, such as planting trees

12: The Trans Pennine Trail was relocated so that it now crosses the river on a 70m span bridge installed to connect the trail and the north bank of the Aire

There are many high-quality public areas along the River Aire, so a priority was to preserve these and the relationship between people and the water. As the movable weirs reduce the flood water level in the city centre, this means that the walls could be much lower than the previously proposed 3m height. Arup's design ensured the majority of the walls were less than 1.2m high and were clad in stone and brickwork to match their surroundings. In the areas most used by the public and near residential areas, flood-proof glazed units were installed to make sure that views of the river could be maintained. A testament to the project's success was that a very active residents' committee with properties along the river was satisfied by the result.

Eliminating another barrier
The final element of this phase of the flood alleviation scheme was the removal and relocation of a man-made island at Knostrop, which separated the river and the Calder and Hebble canal along a 600m stretch. This eliminated a water flow bottleneck. Its removal was another element in Arup's strategy to prevent flooding by eliminating blockages rather than relying on excessively high flood protection walls. To facilitate the removal of the island, Arup designed the diversion of the Trans Pennine Trail (used by walkers, cyclists and horse riders across the Pennines). The trail was relocated by creating a new 1km walkway on the left bank of the river that included measures to encourage wildlife and plantlife and improved public wayfinding and interpretation of the environment.

11.

12.

The trail needed to cross the Aire, so a locally manufactured bridge was installed at the weir location connecting the diverted trail with the north bank of the river. Weighing approximately 150 tonnes and spanning approximately 70m, the bridge was designed by Arup, Knight Architects and the BAM Nuttall/Mott MacDonald joint venture.

Some 180,000 tonnes of material was excavated during the re-shaping and re-grading of the river. This was reused on a local development site and also for the diversion of the Trans Pennine Trail, resulting in a saving of £6 million.

Integrated urban drainage model
In addition to minimising flood risk from the river, Arup created a digital model to identify the risk of residual surface water flooding issues, looking at the combination of heavy rainfall and high river levels. The $275km^2$ model – one of the biggest of its kind in Europe – brought together all the elements of local and highway drainage and both the current and historical water company records. It created a detailed picture of Leeds and its flooding hotspots. This means that measures can be designed in the future to tackle spot surface water flooding in Leeds, which has a high river flow and intense local rainfall (1,025mm per year over 152 days).

The cutting edge
The implementation of this £50 million scheme puts Leeds at the cutting edge of national flood defence schemes. The movable weirs allow a significant reduction in the height of the walls and embankments within the city compared with the previously proposed scheme. Together with terracing and landscaping, this maintains physical and visual connectivity with the waterfront.

The scheme's success has protected the city centre from flooding – providing a 100-year storm standard of protection up to 2069, taking into account climate change – and ensured that the development of Leeds South Bank can progress with confidence. This project has the potential to create 35,000 jobs and 4,000 homes, and will house the terminus of HS2.

Arup's scheme has enhanced the area's natural habitat, encouraging local wildlife to flourish. The new weirs include fish and eel passes that allow baby salmon to come down the river and for mature adult fish to swim back up. It also provides a habitat for mammals such as otters and beavers. For the first time in about 200 years, there is now a small otter population living in Leeds city centre. In addition, as part of the natural flood management techniques used by Arup, over 700 trees have been planted.

By improving river accessibility and securing the future of local leisure and business establishments, Arup's flood alleviation scheme has also added to local employment in the city. It has created 150 direct jobs and will safeguard 22,000 more over the next ten years, supporting further growth and regeneration of the Leeds regional economy.

Authors
Michael Nichols was the Project Manager and is an Associate Director in the Leeds office.

David Wilkes was the Project Director. He is an Associate Director in the Leeds office and is Arup's Global Flood Resilience Leader.

Project credits
Client Leeds City Council
Contractor BAM Nuttall
Civil, water, geotechnical, mechanical, electrical, structural engineering services in addition to hydraulic design, commercial management, environmental impact assessment Arup: Daniel Aspden, Chris Baker, Luke Ballantyne, Niall Bourke, Adam Broadhead, Eric Buffin, Olly Carlton, Oliver Clarke, Paul Davies, Richard Deakin, Alan Dean, Paul Dickens, Mike Dobson, Stephanie Dye, Mike Farrer, Nick Ferro, Paige Garside, Libby Gibson, Arlene Goode, Llew Hancock, David Hardy, Milly Hennayake, Dean Hogg, James Holloway, Sophie Hornsby, Jon Horrocks, Lan Huang, Andera John, Michael Jones, Christian Junge-Filipek, Jenny Lightfoot, Jou Lin Ng, Amy Martin, Mark Matthews, Will McBain, Michael Nichols, Alex Nicholson, Daniel Patten, Matthew Peacock, Miguel Piedra Lara, Novlet Pitter, Ruairi Revell, Felicia Rhodes, Victoria Robinson, Marcus Shepherd, Paul Simkins, Paul Smith, Hannah Smith, Alex Smith, Veronika Stoyanova, Martyn Tattersall, Trevor Taylor, Lee Wallace, Jen Whelan, David Wilkes, Sam Wright.

Image credits
All images: Arup

1.

Beauty and innovation

A sustainable modern building that draws on traditional Korean design to provide a headquarters for one of Asia's largest cosmetics companies

Authors Francesca Coppa, Eva Hinkers, Julian Olley, Alexander Rotsch, Nigel Tonks, Frank Walter

Founded in 1945, Amorepacific is the largest beauty and cosmetics company in South Korea and one of the biggest in Asia. Towards the end of 2017, the company moved into its new headquarters in the centre of Seoul, on a site that has been occupied by the cosmetics giant for over 60 years. The new building is an elegant 110m tall cube centred around a courtyard, part of which is glazed to provide natural light into the atrium below. With its striking outer façade of vertical fins, the building is a distinctive and innovative take on office accommodation.

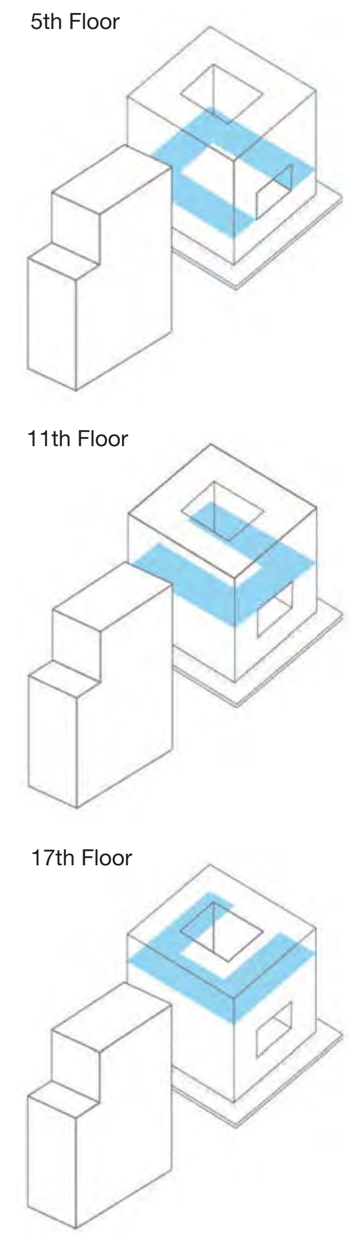
Inspired by references to traditional Korean courtyard architecture and with energy efficiency and wellbeing at the centre of its design, the building is punctuated by three large openings on the 5th, 11th and 17th floors. These are landscaped with gardens and terraces, and open onto an inner central courtyard that features a reflecting pool. The openings allow natural light and ventilation to enter the heart of the building, and frame dramatic views across Seoul.

The architectural design was led by David Chipperfield Architects (DCA), with Arup collaborating with DCA on the design of the building, supported by a team of Korean consultants on the project delivery. Arup's London and Berlin offices provided all technical engineering services, including structural engineering, building services, geotechnical,

1: The Amorepacific headquarters, which combine traditional Korean architecture and technological innovation, are based in the centre of Seoul

2 & 3: There are three openings at different levels of the structure

4: Daylight analysis of the 17th floor



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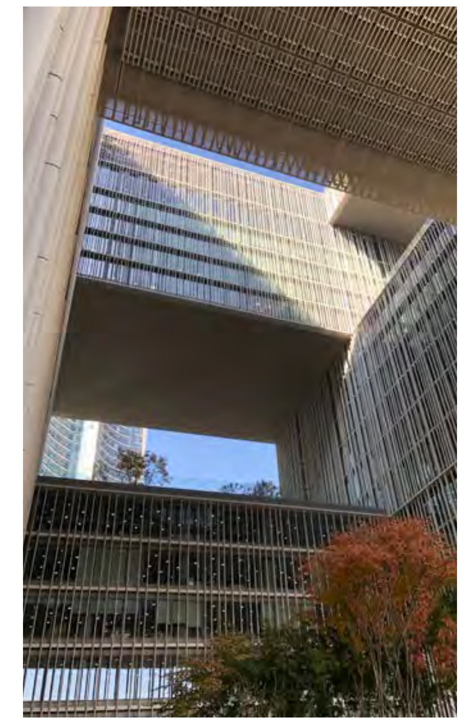

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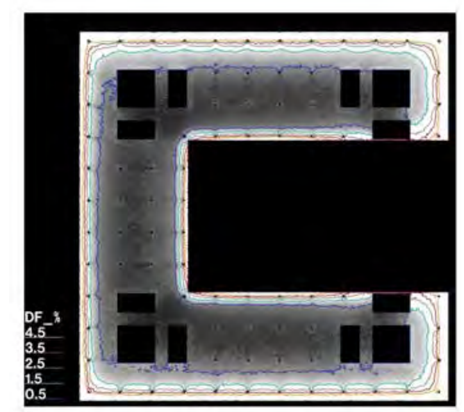

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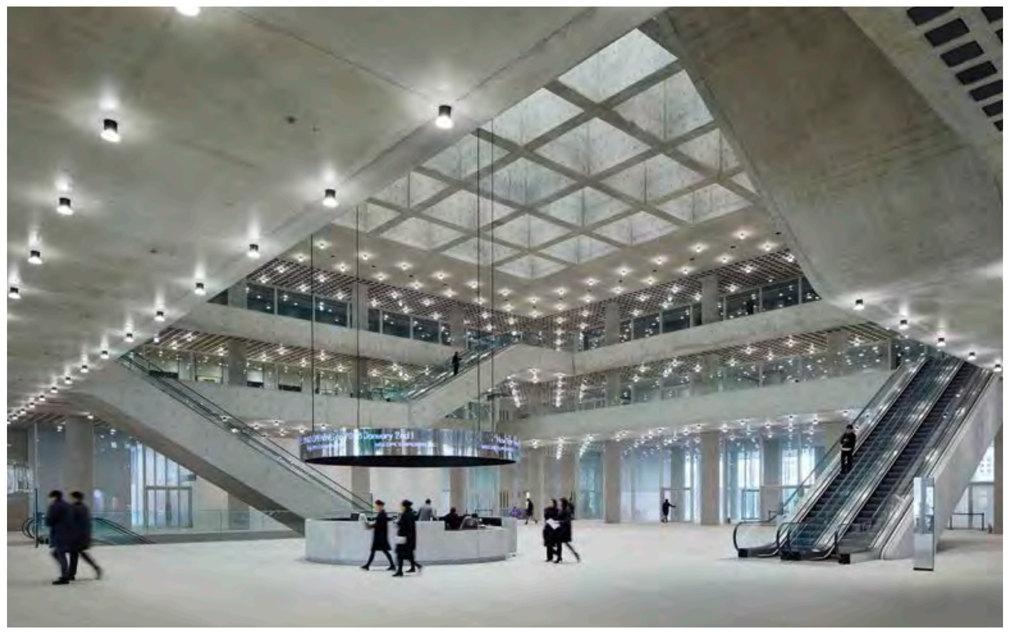

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5: The three openings in the building's façade contain landscaped elements, providing natural spaces for staff high above the city

6: The atrium's glazed ceiling ensures the space receives natural daylight

building physics, acoustics, vertical transport, fire, wind, lighting and façade design.

Arup focused on incorporating passive environmental design solutions such as daylighting, shading, building massing, orientation and natural ventilation into the early concepts. These design solutions significantly reduced energy demand within the building, and improved occupant comfort and wellbeing.

DCA and Arup developed a fully integrated façade and environmental moderating system, combining shading and ventilation with permanent access for cleaning and maintenance. This is a bespoke composite system in which every component has been designed from first principles. The system contributes to the look, feel and operation of the headquarters. Within the building, Arup and DCA designed many systems that were specifically developed for the project, and even patented the modular LED luminaire system used throughout the building.

The building incorporates renewable energy technologies, including solar panels and geothermal heat pumps that work together with energy recovery devices to minimise energy consumption. Rainwater harvesting, wastewater treatment, low-flow water fittings, and extensive public amenity and landscaped terraced gardens further support the sustainable building concept. This commitment to sustainability secured LEED Gold certification for the headquarters in May 2018.

Inception

Amorepacific's brief was clear in its aspiration to create a headquarters with presence and character that evoked the brand values of the company, which seek to celebrate Asian beauty by blending traditional wisdom, fine ingredients and technological innovation. The headquarters were to comprise 80,000m² of office space, with numerous amenities for staff and the public, including a museum (located in the basement), an archive, tea room, restaurants, retail spaces, product testing spaces and a 450-seat auditorium.

DCA invited Arup to team up for the design competition in 2010, during which many of the key massing, shape and design principles were established. Collaboration was so close during this phase that the completed project bears a significant resemblance to the competition entry, despite a further three years of continuous design refinement and value engineering leading up to the start of construction in 2014.

The winning submission proposed a sustainable and technologically advanced building influenced by tradition. The design allowed for abundant natural daylight and natural ventilation – something not common in Seoul high-rise office buildings, which tend to rely on artificial lighting and air conditioning.

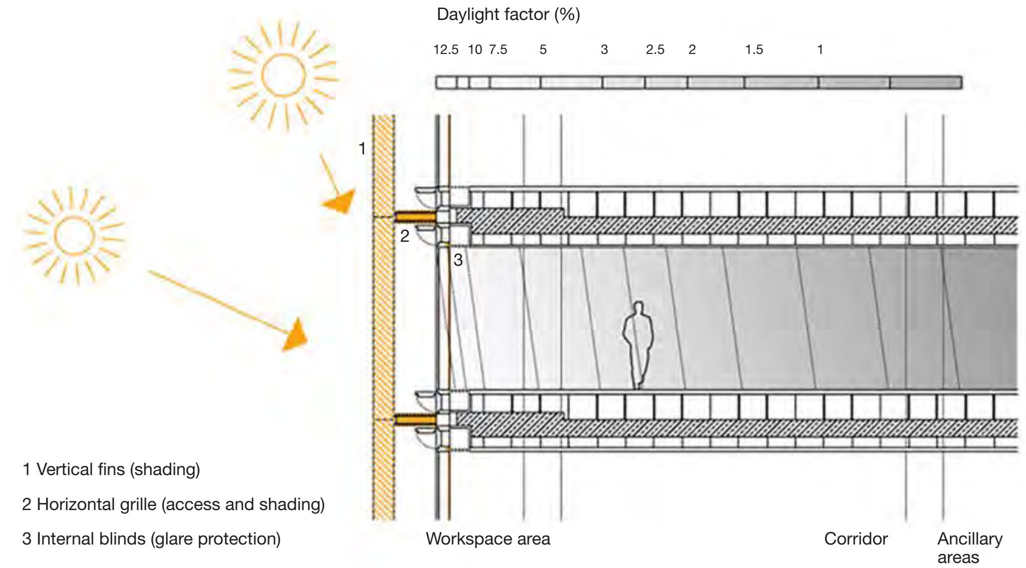
Layout

To mediate between the adjacent Yongsan Park and surrounding high-rise developments, the team developed a 22-storey (above ground), medium-rise building. While the site was generous enough to accommodate large floor-plates, a novel design was required to avoid deep plan spaces that place occupants unacceptably far from windows, natural light and ventilation.

7: A 70mm deep reflecting pool covers the atrium glazing in the courtyard

8: Solar gain is controlled primarily by vertical fins that form a brise-soleil. The access walkways also provide additional solar shading

7.



8.

The key to unlocking this solution lay in traditional Korean architecture, where living spaces were arranged around a courtyard. Placing a central courtyard within the building created a quadrangular floor-plate, drawing daylight into an open, well-lit and naturally ventilated dual aspect working environment.

In a significant adaptation of the traditional form, large horizontal openings were inserted into three façades. This was necessary to provide a greater connection between the inner courtyard and the outside of the building. These openings bring light, ventilation, exterior views and an enhanced sense of openness to the inner courtyard. They also create space for landscaped elements in the upper reaches of the building. The introduction of nature at an elevation high above the Seoul streetscape provides pleasant recreational spaces for staff and visitors. Voted by staff as their favourite areas of the building, they contribute to a greater sense of wellbeing, as well as enhancing the biodiversity of the development.

As sunlight strikes the courtyard floor in all seasons, during design development a glazed floor was introduced to admit daylight into the spacious atrium below. A 70mm deep reflecting pool in the courtyard covers the atrium glazing, adding to the calming atmosphere and enhancing the aesthetics of the space.

Motorised ventilation louvers at high and low level ventilate the perimeter spaces in spring and autumn. Underfloor mechanical ventilation serves the central floor zone and provides mixed mode ventilation.

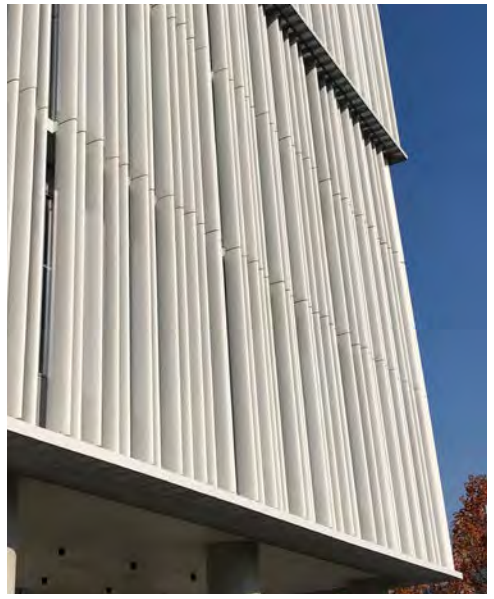
Wind

Arup optimised the locations of the large horizontal façade openings, modelling for the impact of the prevailing wind direction, wind movements down the façade onto the entrances and traffic noise. For example, the largest horizontal opening, which faces south-east towards Yongsan Park, was strategically placed in relation to the prevailing wind direction to reduce the effect of downdrafts above the main entrance. The mid-level opening is located on the Hangang-daero highway. The opening's elevation shields the courtyard from traffic noise. The uppermost opening is placed on the north-east façade, where prevailing wind and down-wash effects are less critical. In this orientation, the elevated opening also overlooks the city, giving views towards Namsan Mountain.

Façade

The orientation of the building is such that elevations stand at an angle towards the cardinal points. The 52° north-south orientation results in all sides of the building being exposed to direct solar gains, with the south-east and south-west façades receiving more solar exposure than the north-east and north-west façades.

Responding to this challenge led the design team to customise an engineered response to reduce energy consumption that also became a signature feature of the building: vertical fins that form a brise-soleil, which is connected to the building by accessible walkways, wrapping all elevations. As well as adding to the building's



9.

distinctive appearance both during the day and at night, this system maximises transparency, controls daylight and provides views out across Seoul. It also assists with managing the solar heat gain within the building.

Arup performed daylighting and structural testing to optimise the geometry and pattern of the fins. The system comprises approximately 1,150 aluminium fins in four sizes – 450mm, 350mm, 250mm and 200mm deep. Although these have a uniform appearance, the fins are grouped in patterns that vary around the building, tuned for orientation, based on sun-path solar exposure. For example, on the north-east and north-west façades, direct solar exposure is minimal during summer months and during normal working hours. The fin pattern on these façades comprises mainly shallow fins to maximise natural lighting and views. On the south-east and south-west façades controlling solar gain and glare is more critical. Here, deeper fins provide a higher degree of solar shading to significantly reduce solar gains and, consequently, reduce the energy consumed by the building's cooling systems.

There was little codified guidance for designing such large elements. Typically, wind loads are anticipated to be greatest at the corners and edges of a building, where wind speed accelerates. However, the configuration of the brise-soleil affects these predictions: the presence of the fins provides resistance to the wind and the repeating pattern of fins could provide sheltering effects near the corners. Surrounding buildings create additional turbulence, which can result in significantly increased wind loads at the building's corners.

In order to optimise the fins' design, Arup conducted a series of wind tunnel tests of the brise-soleil at different scales to determine the response to wind effects.

The fins' size meant they could not be modelled at normal wind tunnel testing scales of 1:400–1:300. Arup's wind specialists developed a customised approach to testing. Preliminary small-scale, whole-building testing in South Korea was followed up by 1:70 scale fin tests in Europe's largest atmospheric boundary layer wind tunnel in Milan, Italy. The design of the fin section was further refined to an aerofoil shape with tapering edges, with additional testing carried out at this stage of the design.

This combination of tests enabled Arup to predict the behaviour of wind at the edges of the large façade openings, the down-wash impact at entrances and, crucially, to be able to refine the structural robustness of the exposed parts of the fins. The fins have pinstripe surface protrusions along their vertical axis that become visible only when near the building. While these make a strong visual contribution – purely rounded shapes can be difficult to process visually – Arup introduced the 3mm linear protrusions to encourage vortex shedding. Micro turbulence created by wind passing over the stripes reduces deflection and vibration effects as well as improving robustness.

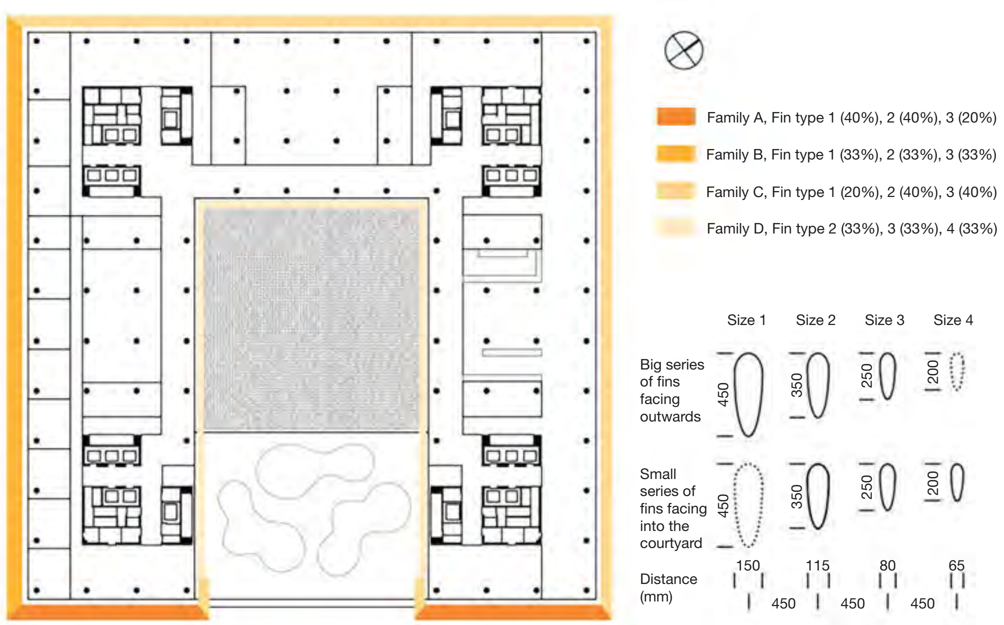
Arup integrated the structural and the shading performance needs in determining the fin patterns, recommending appropriate sizes and weights of fins for different locations around the building. For example, shallow fins were dominant in locations with lower wind pressure and deeper fins were prioritised at the corners of the building.

Walkways

A typical challenge for external shading, which is exposed to the elements, can be the difficulty of maintenance and cleaning. For Amorepacific's headquarters, the layer of vertical fins is separated from the building's glazing by a series of grillages at each floor level that serve the triple function of horizontal shading, fin support and access walkways. These allow the outside of the windows to be cleaned easily and give access to the fins and motorised ventilation louvers for inspection and maintenance. The external shading has no external moving parts, greatly simplifying its maintenance requirements.

9: The fin pattern, with various fin sizes used, gives the building its unique look, while also managing daylighting requirements and solar heat gain

10: The fins around the façade are of various sizes in order to manage solar gain and glare depending on the façade orientation



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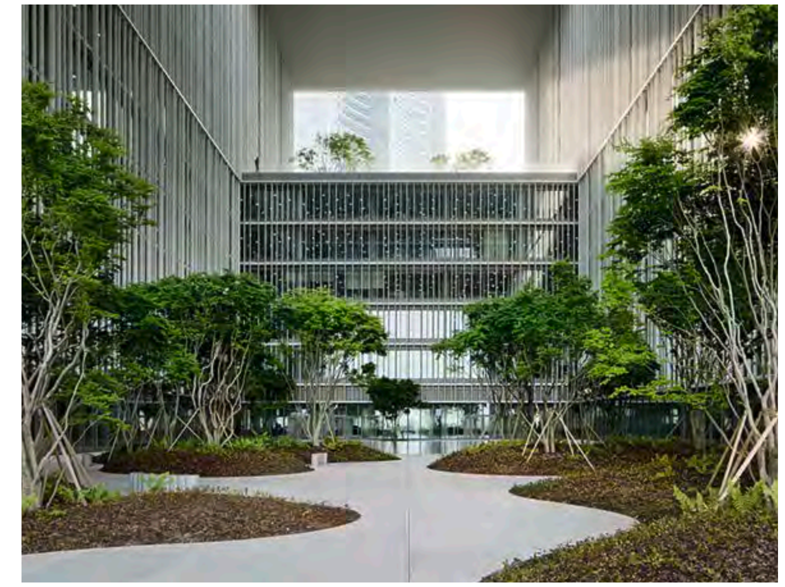

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11: BIM model of the building services showing the cores positioned at the four corners of the building

12: The building's arrangement around a central space allows natural daylight to flood into the courtyard, which is landscaped with various natural elements

Vertical transport

The latest advances in lift technology have been used in order to provide a high level of service and reduce waiting times, thereby facilitating rapid mobility around the building while minimising the lift core sizes. Waiting times are nine seconds in normal service and 15 seconds at peak times. This is highly advantageous in a culture where work arrival and departure times and lunch times are commonly punctual, often leading to lengthy waiting times.

The central courtyard arrangement precludes the use of a central lift and staircore. Instead, cores are positioned at the four corners of the floor plates and comprise five passenger lift shafts, and one service and one firefighting lift. Each passenger lift shaft contains two lift cars operating independently. The advantage of this 'twin lift' system, with hall-call control, over a conventional 'double deck' system is an increase in capacity and reduction in waiting time, as well as a reduction in energy consumption. This application is the largest of its kind in the region.

Courtyard, atrium and glazed floor

By locating the stair and lift cores in the corners of the building, it became possible to create a large ground floor atrium below the courtyard. The importance of this space for Amorepacific goes beyond the functional brief, which was to provide secure access for staff and visitors. It is also the setting for the public entrance hall used by people visiting the building's amenity spaces. These include the art museum, tea room, auditorium, childcare centre, product testing areas, retail spaces, restaurants and cafés. The atrium also creates a pedestrian link to the adjacent Yongsan Park.

The early design envisaged an artificially lit space. Arup worked with the architect to bring natural light into the expansive space. This

13.

13: The award-winning headquarters provides views over Seoul and links with the nearby park

14.

14: Arup and DCA created a luminaire system that uses a single luminaire body shape that can be adapted for various applications

15: The courtyard provides a natural link between the inner building and the outer environment

was achieved by creating a glazed ceiling for the atrium, with a deep clear-span structure supporting the courtyard floor and the reflecting pool. The solution provides daylight to the ground floor and, looking up from below, provides a view of the sky, giving a connection with the outside.

A precise integration of structure and services defines the character of the atrium. Lighting, diffusers and sound absorption are integrated with the structure so that the exposed concrete soffit requires no additional ceiling treatment. Despite its busy public nature and hard surfaces – with natural stone floors and concrete columns, walls and ceilings – Arup's acoustic designers created a controlled environment while maintaining its live nature.

Acoustic panels are discretely integrated with the raw finish of the space to create an effective system that is also aesthetically pleasing. The panels are located in areas where people congregate and have conversations. Corridor ceilings are treated with sound-absorbing panels comprising a 50mm mineral wool core covered with a 70% perforated metal sheet, recessed within the concrete coffers of the exposed structural soffit. The outcome minimises high noise levels and disturbance, and so facilitates comfortable conversation among small groups.

In the auditorium adjacent to the atrium, Arup designed a variable acoustic system to allow the venue to be used for amplified and unamplified scenarios (i.e. music and speech) by deploying two layers of acoustic curtains and diffusers on the auditorium side walls.

Lighting
Amorepacific currently operates 28 brands under one roof, creating the need for various light atmospheres and a high level of future adaptability.

15.

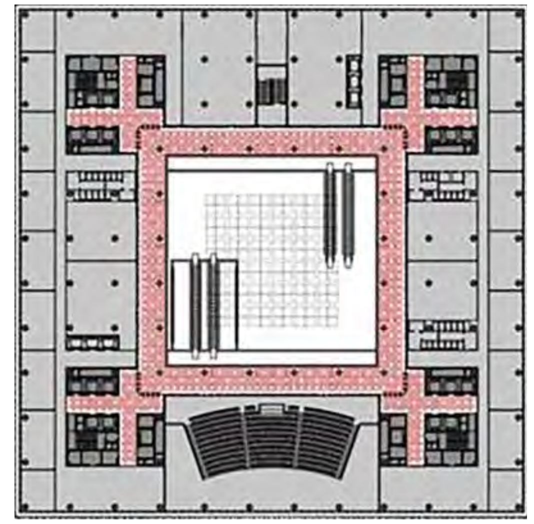
Taking a conscious low material wastage, high recyclability approach, DCA and Arup created a modular, re-usable and adaptable luminaire system that provides a huge variety of lighting performances. The system uses a single luminaire body shape with interchangeable optical lenses for different applications throughout the building. This is an innovative and sustainable departure from the conventional approach to lighting flexibility, which relies on different luminaire products and manufacturers for different settings. The emitting surface of the optical lenses is covered with microlenses of different shape, producing wide, medium, oval or narrow light distributions. The unique optical system combines reflection inside the lens with refraction at the underside of the lens, and offers 12 different light distribution performances in up to 30 possible combinations. Available as recessed, surface-mounted, adjustable and pendant versions, the system provides the optimal light for any desired lighting atmosphere and room use, and forms a decorative element that compliments the architecture.

Every component is replaceable and the lights can be modified for any changes in the building's use without compromising the appearance of the ceiling. Patented by the design team, the lighting system, manufactured by Italian company Viabizzuno, is commercially available.

Museum
Designed to international museum standards, the Amorepacific Museum of Art focuses on traditional and contemporary Korean art and crafts. Careful integration of structure and services has created a gallery space that is re-configurable to allow one main exhibition or a combination of smaller exhibitions.

Arup advised on providing a dedicated art handling truck-lift at street level to transport vehicles to the basement level secure art handling area for the museum. This greatly simplified vehicle movements near the building and freed up a greater site area for landscaping and planting.

Award-winning
Amorepacific's headquarters are innovative, highly sustainable and distinctive. The building has been awarded the KIRA Korean Architecture premier prize and won the 2019 Council on Tall Buildings and Urban Habitat Award of Excellence for the Best Tall Building (100-199m), as well as the MEP Engineering Award for the building services systems. It won the 2018 Tall Building of the Year at the Dezeen Awards.



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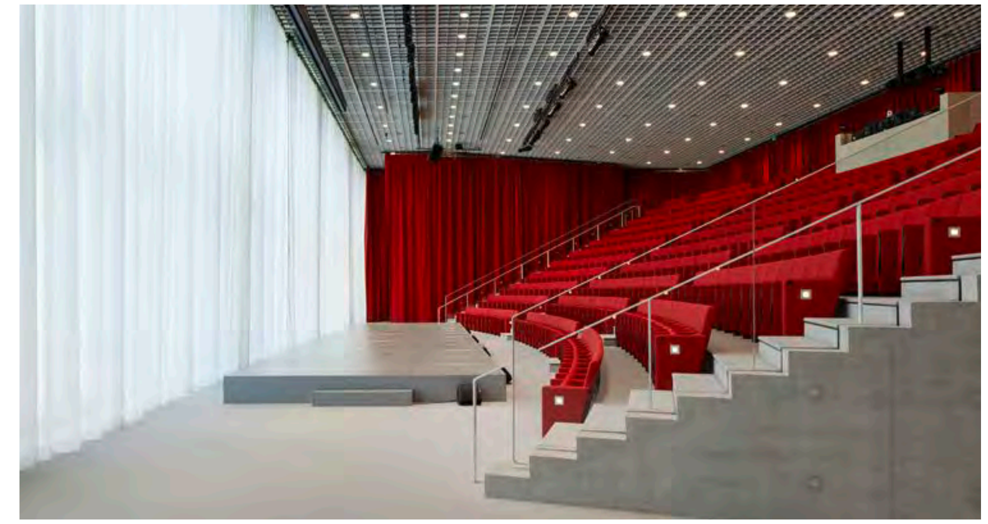

17.

The design team has created a building that embraces the climatic and cultural characteristics of Seoul. The work spaces are naturally ventilated and provide extensive levels of daylight and good views across the city.

Arup's total design approach, working in close collaboration with DCA, local consultants and the client, has resulted in an innovative building incorporating inventive façade, lighting, ventilation and lift systems. The result is a flexible and healthy working environment for staff and visitors.

16: Reflected ceiling plan showing sound-absorbing panel distribution in the atrium

17: DCA, with Arup, designed a variable acoustic system for the auditorium

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General contractor Hyundai Engineering & Construction
Structural, building services, geotechnical, façade, wind, fire engineering services, lighting, sustainability, LEED, vertical transport, acoustics, building physics, security Arup

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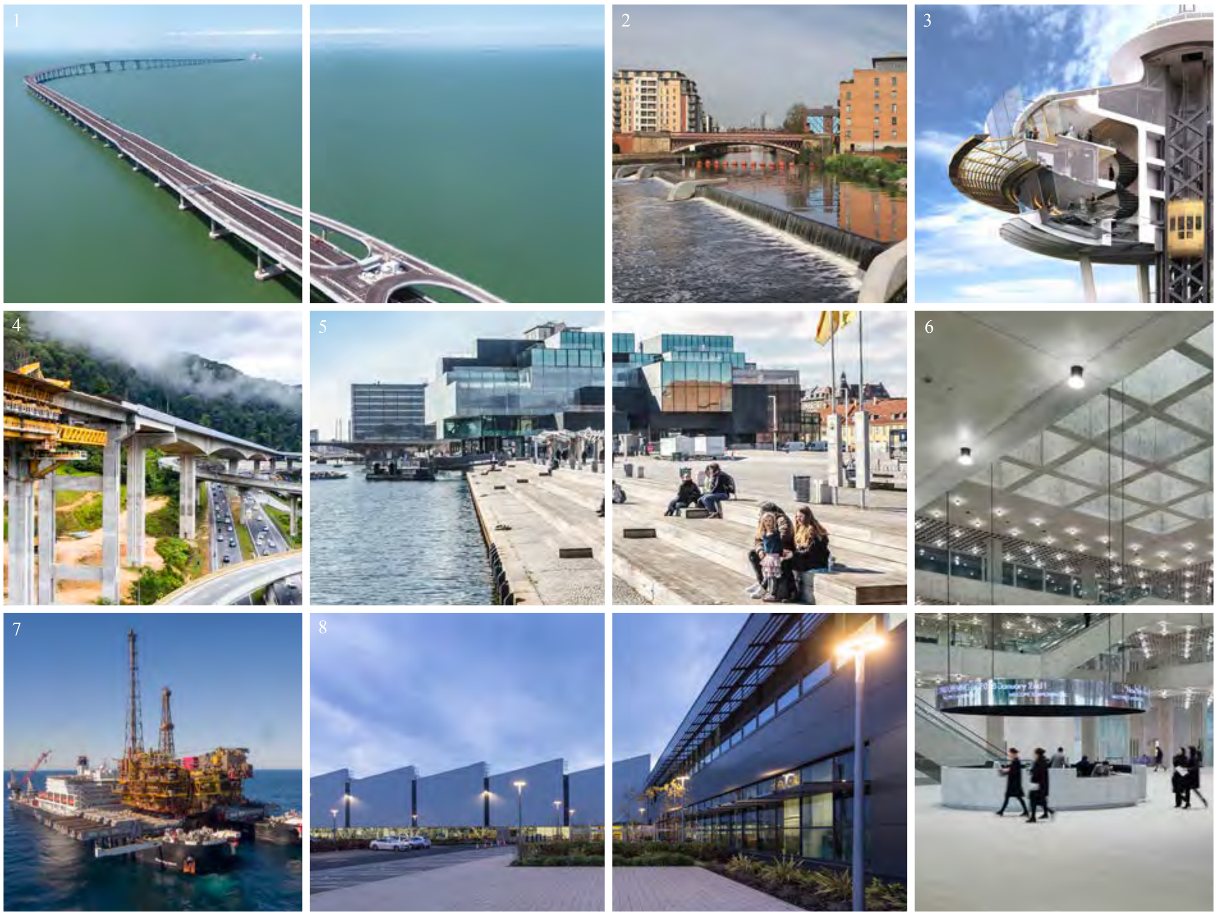

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Front cover image: Hong Kong-Zhuhai-Macao Bridge, Greater China: *Marcel Lam Photography*.

The Arup Journal
Vol.54 No.1 (1/2019)
Editor: Macdara Ferris
Designer: Wardour
Email: arup.journal@arup.com

Published by Arup
13 Fitzroy Street
London W1T 4BQ, UK.
Tel: +44 (0)20 7636 1531

Printed by Geoff Neal Group
Produced on FSC paper
and printed with vegetable-
based inks.

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