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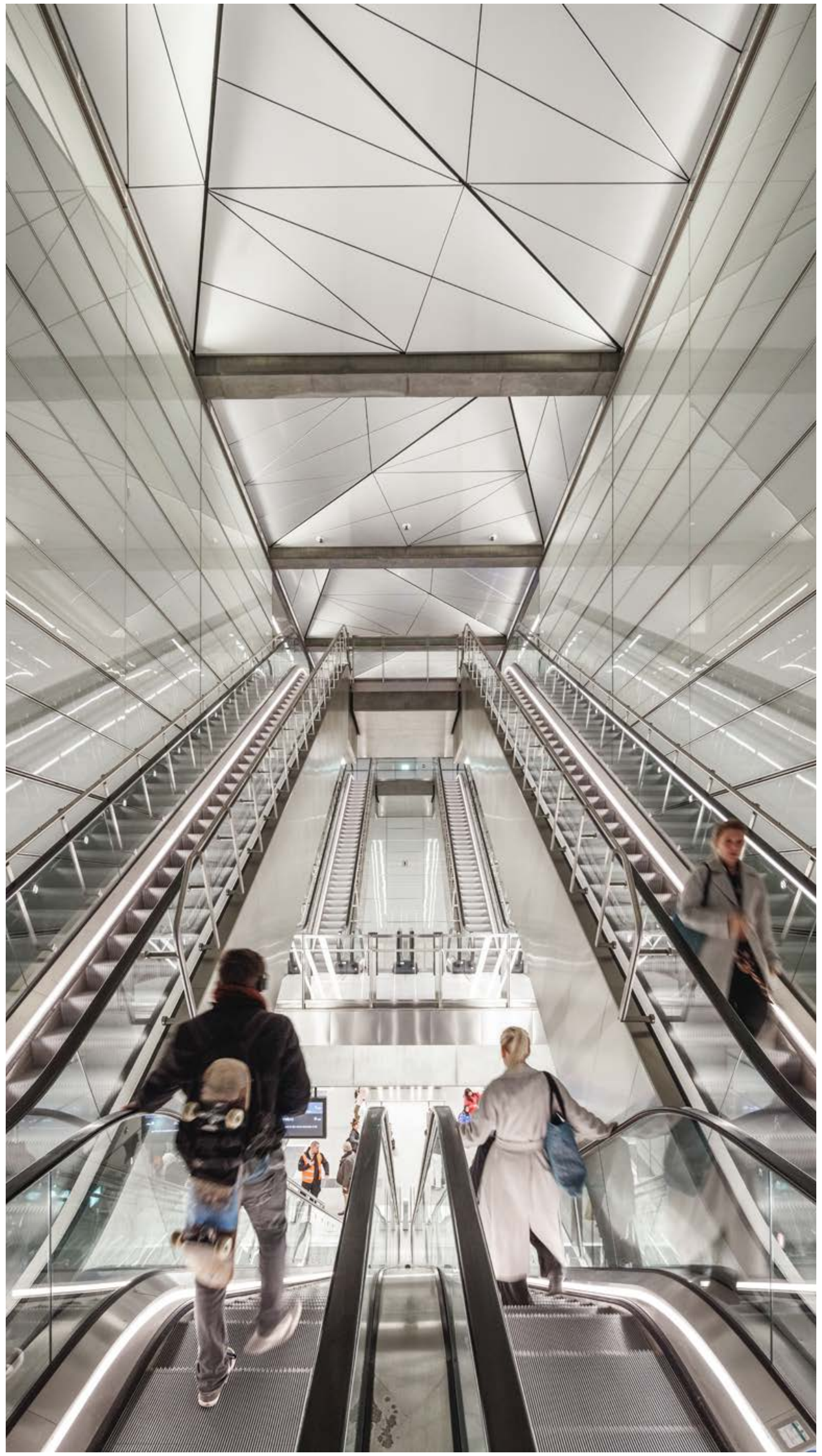
Enhancing the metro experience

Copenhagen's Cityringen metro line expands the city's existing award-winning underground system, making it even easier to travel around the capital

Authors Tony Evans, Katrine Falbe-Hansen, Neil Martini, Nille Juul-Sorensen, Mohammad Tabarra and Kristian Winther



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The Cityringen metro line, consisting of 16km of twin-bore tunnels and 17 new underground stations, provides a 24-minute loop around Copenhagen's city centre, interchanging with the existing metro, mainline services and buses. Cityringen runs 24/7 and seeks to encourage residents out of their cars and onto an environmentally friendly form of transit. It is a key part of the city's plan to become carbon neutral by 2025. Cityringen opened in September 2019; 85% of Copenhagen residents are now less than a 10-minute walk from a train station.

In 2007, Metroselskabet, Copenhagen's metro company, appointed Arup with joint venture (JV) partners COWI and SYSTRA to act as multidisciplinary technical adviser for this design and build contract. It was the city's largest construction project in more than 400 years. Working on the design and procurement strategy for the contract, the JV provided engineering, architectural and advisory services, including civil and structural design, risk assessment, cost estimates, and project and programme management. Arup was also responsible for the reference design safety case on the project.

For the concept and reference design, Arup (as part of the JV) provided a range of services, including geotechnics, structural engineering, tunnelling, tunnel ventilation, fire and life safety, lighting and construction planning. During the design and construction phase, the JV team acted as Metroselskabet's technical adviser, assisting the company with the tender evaluation, detailed design check, testing and commissioning, and construction management.

Arup led the architectural design for all stages of the project, taking a user-centric approach at every step. This has resulted in spacious, light-filled stations with distinctive internal façades that echo the locality above the stations.

Passenger-centred design

The original Copenhagen metro lines opened between 2002 and 2007 and were successful from the start. Building on this, the JV's design for Cityringen focused on enhancing the traveller experience by putting the emphasis on passenger comfort throughout the journey. The metro is a fully automated, high-frequency, driverless system. The stations do not have ticket barriers, and staff are available on concourses, platforms and trains to assist customers during their journey. Every station has two lifts that take passengers from the platform directly to street level, making the metro fully accessible for all.

Tunnel depth has been minimised at station locations, thereby reducing passengers'

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1: The Cityringen line, which opened in September 2019, aims to encourage more citizens to use this environmentally friendly form of transport

2: Cityringen (represented on the map by a yellow line) adds a third line to Copenhagen's extremely popular existing metro system

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3: The stations have been designed to be relatively shallow in depth where possible, giving clear sight lines between street and platform level

4 & 5: Each station's surroundings have influenced their design. At Marmorkirken Station, the limestone cladding is a nod to the marble church above

travel time on escalators and lifts. As commuters enter the majority of the stations, the shallow depth helps them to see all the way down to platform level; and, conversely, at platform level they can see the exit above. These clear lines of sight help people to easily navigate through the metro. Based on extensive pedestrian modelling work, Arup developed the concept for station layouts, the new line's visual identity and signage for effective wayfinding. Static signs are combined with dynamic displays and interactive travel panels to generate a sense of security and physical comfort, while also optimising passenger flows.

Station identity

By incorporating ideas and motifs inspired by each station's surroundings, Arup's architectural design approach – using sculptural wall panels and cladding on the internal façades – draws each neighbourhood's identity into each station, making the metro a natural continuation of the surrounding area. It also helps with inferred wayfinding.

For example, in Marmorkirken Station the fossil-embedded, sand-coloured Swedish limestone cladding is a reference to the 19th-century marble church above. In Trianglen, mirrored glass panels have been used to reflect and multiply the colours worn by sports fans flocking to the adjacent national stadium, contributing to the lively pre-game atmosphere. Grey and yellow bricks are used in Nørrebros Runddel to complement the yellow brick wall around the churchyard located above the station.

Cityringen interchanges with the existing M1 and M2 metro lines at two locations (Kongens Nytorv Station and Frederiksberg Station) and the commuter/regional train at three locations (København H/Copenhagen Central Station, Østerport Station and Nørrebro Station). Grey natural stone was chosen for both Kongens Nytorv and Frederiksberg Stations, as grey cladding is used inside the existing metro stations, while red ceramic panels are used at the three rail transit stations, as the urban trains are red.

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Modular design

The architectural approach across all 17 stations was to use a 'kit-of-parts' design. This led to a cost-effective, rational design and modular construction system. Future-proofing the stations was an important design driver for Arup's materials and lighting specialists. They sought high-quality long-life fittings and durable self-finished surfaces, such as terracotta tiles and granite platforms, to provide high-impact solutions with low maintenance costs.

Where possible, fittings and finishes, such as the wall cladding, were specified in 5.5m modules. This matches the module of the passenger screen doors used on each platform to separate passengers from the tracks, with the repetition of this module at all stations reinforcing the identity of the new metro line.

Bringing light underground

Metro passengers can navigate from the street to the platform without feeling as though they are venturing underground. To achieve this, most of the 17 new stations feature skylights. These provide bright natural daylight at platform level, to help bring the outside in and improve energy efficiency within each station.

For the first phase of Copenhagen's metro, completed in 2002, Arup contributed to the design of the distinctive glass pyramids and skylights. For Cityringen, this was developed further, with the skylights also acting as emergency air vents, thereby reducing the reliance on mechanical smoke ventilation systems and the need for further in-station equipment rooms.

The lighting design is fully integrated with the architecture and uses the feature 'origami ceilings' as reflectors, complemented by bespoke LED lighting that helps avoid glare. The origami geometry was designed using 3D simulations and 1:1 mock-up testing of luminaires and

6: A 5.5m module is used for finishes to match the module of the passenger screen doors on each platform

7: Skylights provide natural light at platform level

8: The skylights' distinctive glass pyramids appear throughout Copenhagen

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9: The 'origami ceilings' act as reflectors for the daylight spilling in from the skylights

10: To minimise disruption, stations were built underneath pre-existing parks and squares where possible

11: Four TBMs had to tunnel through challenging ground when constructing Cityringen

12: Arup used advanced modelling techniques to analyse fire and smoke behaviour in the stations and tunnels

architectural finishes. A detailed 1:25 scale architectural station model was created in which the intensity of the daylight could be tested in relation to the station space.

Design integration

Each station has an approximate footprint of 64m x 20m and a 45m platform length. In order to minimise their impact on traffic, utilities and properties during construction, stations were placed under existing parks and squares wherever possible. This has allowed new landscaped plazas to be created above many stations, providing civic spaces for the surrounding community and simple, welcoming entrances and forecourts for passengers.

The compact, driverless metro trains allowed the JV team of engineers, designers and transport consultants to design smaller platforms, helping to shrink the overall footprint of the stations. This meant

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demolition was kept to a minimum, with just two buildings demolished for the new metro line. The life of the city was able to continue fairly undisrupted throughout construction.

Ventilation

Arup's work on the fire and life safety risk strategy and the tunnel ventilation during the concept design phase helped to reduce the number of intermediate escape shafts from 17 to three, significantly improving the visual and physical impact on the city, as well as reducing costs and disruption due to construction.

The ventilation design consisted of a single tunnel ventilation fan plant and single-pressure draft relief shafts at each station. The modular station design continued with the civil coordination of over-track ventilation ducts with the station structure. This was repeated along the metro line, where a single tunnel opening and multiple grille over-track openings were connected to the single ventilation plant via dampers.

Advanced modelling techniques were used to simulate all operating scenarios. A subway environment simulation software program was used for the 1D analysis of the tunnel network, with computational fluid dynamics used for the 3D analysis of fire and smoke behaviour in complex station geometries. A smaller, but statistically more likely, rubbish-bin fire scenario replaced the more traditional, and larger, baggage fire scenario in the design of station ventilation systems.

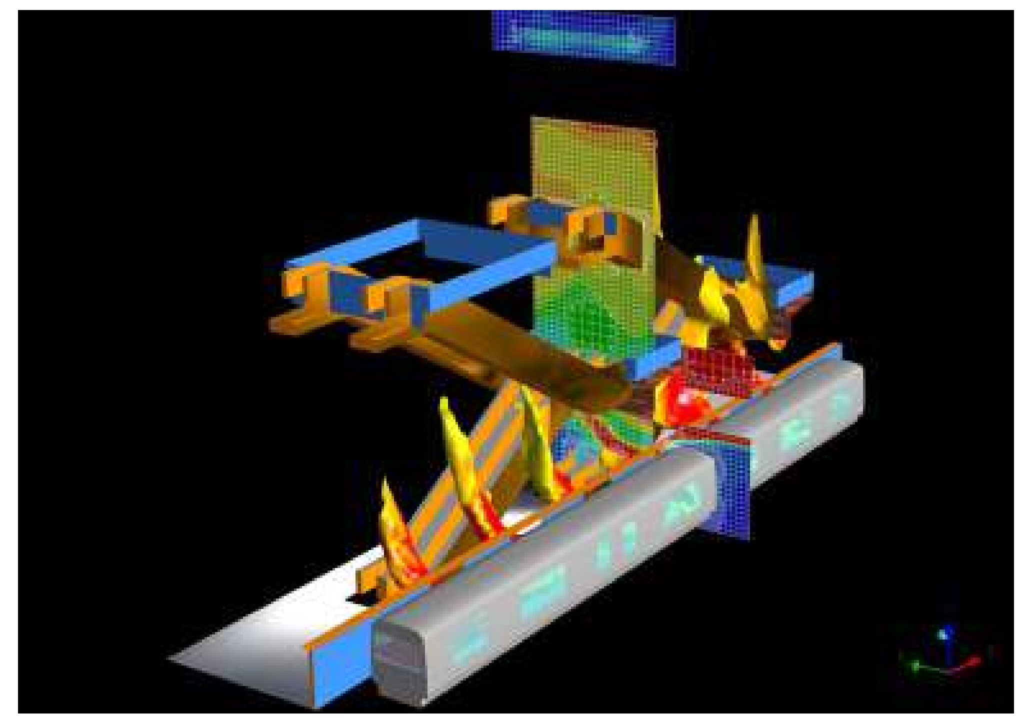
A simple emergency tunnel ventilation and evacuation strategy was adopted, where the default ventilation direction takes advantage of the residual train-induced piston airflow and is always in the direction of train travel. This was made possible by the short (39m) three-car trains used on the line – for short trains, the passenger risk exposure and therefore the emergency ventilation direction is far less dependent on the location of fire on a train. The fully automatic, driverless system allows fast reaction times, with minimum human interaction required during emergencies.

A mode table of all possible 'what if' scenarios, assisted by heat and smoke sensors in the tunnels and on board the trains, guides the control centre operator to arrive at the correct emergency response swiftly.

Construction

A major metro extension represents long-term disruption to any city, but Arup's careful programme management, together with Metroselskabet's intensive stakeholder management, ensured shopowners, residents and visitors could go about their daily lives with minimum disruption during the eight years of construction.

Embedding 17 new stations within a historical city was a delicate engineering design task. It was critical that the impact on heritage structures was minimised. At Marmorkirken, the station is 36m below ground and is carefully located in a narrow



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corridor adjacent to the 19th-century marble church's foundations.

At Gammel Strand, the station was partly built under the canal. The waterway was kept open for tourist boats during construction, with the worksite placed on a platform above the canal, allowing boats to pass beneath.

The stations were generally constructed at a depth of approximately 19m below ground using cut-and-cover box structures. All bar one of the stations used a semi-bottom-up method. In this method, the retaining walls and roof slab were constructed first, before excavating to the base level. Temporary props were placed between the station walls prior to the installation of the permanent floor slabs. Building the lid of the station first reduced the level of noise during the excavation and construction of the lower levels below the roof slabs. It also minimised settlement of the neighbouring buildings. In addition, the roof slabs offered further working space at ground level, helping to limit the extent of the worksites and thereby reducing disruption to the local community.

Four earth pressure balance type tunnel boring machines (TBMs) were used to construct the twin tunnels (of 4.9m internal diameter) to depths of between 20m and 35m. Two TBMs bored the first parallel drive, constructing the twin tunnels from the Nørrebroparken shaft to a shaft at Sønder Boulevard. This drive was predominantly through good quality hard ground beneath residential areas. These TBMs were then moved and relaunched for their second drive from Øster Søgade shaft to København H, passing through the heart of the city close beneath many sensitive heritage structures. At the same time, two other TBMs bored, in twin tunnel formation, from the Control and Maintenance Centre at Otto Buses Vej, underneath the main rail corridor into Copenhagen to the shaft at Sønder Boulevard. They were then relaunched to complete the drive from Nørrebroparken shaft to Øster Søgade shaft in challenging soft and mixed ground conditions.

Monitoring

Implementation of an exhaustive risk management programme to monitor and minimise damage to third-party assets and continuous monitoring of the ground, structures, groundwater, noise and vibration was critical to successful completion of the project.

The Cityringen station footprints have been inserted into the existing urban fabric, meaning that some station retaining walls are only 1.5m from existing buildings, including the foundations of the 260-year-old 'Marble Church'. The new line connects with three existing railway stations and two metro stations, so it was also critical that the existing transport network was not compromised during construction works.

13: At Gammel Strand, the adjacent waterway was kept open during construction by placing the worksite on a platform above the canal

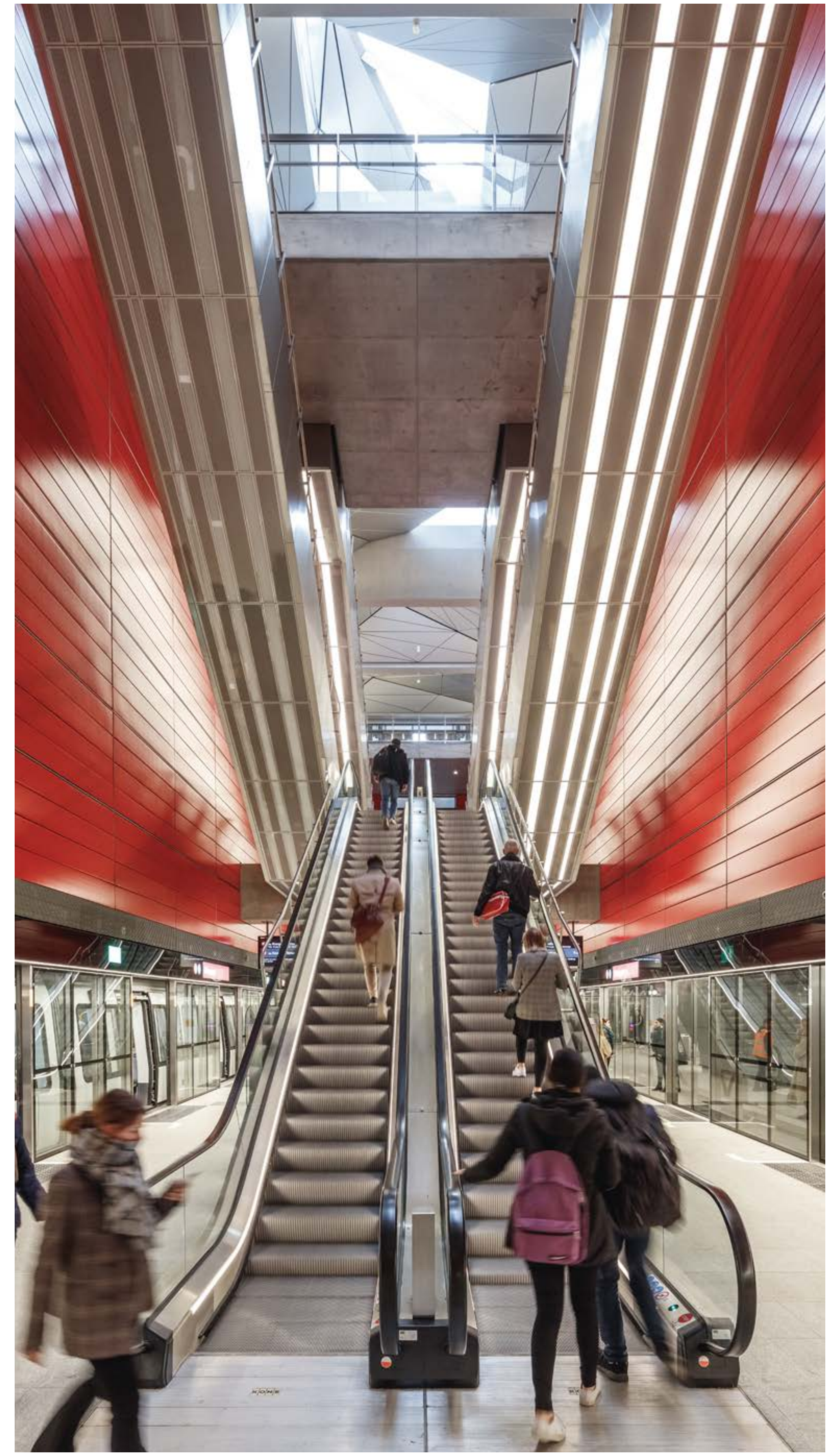
14: The abundance of natural light means using Cityringen does not feel like being underground

During construction, groundwater was managed by a comprehensive re-infiltration system implemented and monitored closely, as groundwater is extracted for drinking in Copenhagen. Re-infiltration also ensured that the large number of historical buildings that are founded on wooden piles were not adversely affected by dewatering.

In order to track building settlements unrelated to Cityringen, and for the seasonal fluctuations of heave and settlement in the ground to be recorded, initial baseline monitoring was carried out by Metroselskabet from 2009 onwards (three years before the contract was signed with the contractor) on a number of buildings along the Cityringen alignment. Furthermore, building condition surveys of hundreds of buildings along the metro route were carried out both before and after construction.

Arup's reference design for the new metro took into account the sensitivity of existing buildings and set out the framework for the design and build contractor to carry out the works. During the design and construction phases, Arup was responsible for reviewing and following up on the contractor's building damage assessments, including at Marmorkirken Station, the Magasin du Nord department store building, and tunnel crossings under and above surface railways and existing underground metro tunnels. Alert and alarm values from the damage assessments informed the monitoring plans and the emergency plans.

Detailed monitoring by both the contractor and Metroselskabet took place during the works to confirm the assumptions for the design models, and to record the impact of the construction works on existing



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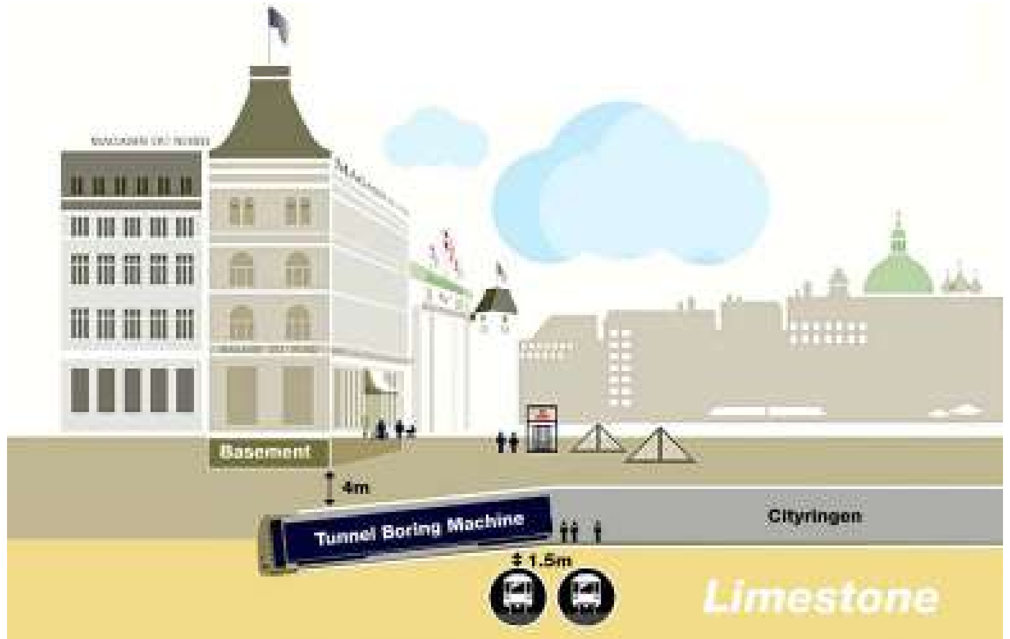

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15: The TBM passed very close to the shallow foundations of the Magasin du Nord department store

16: Kongens Nytorv Station was one of the most challenging locations, with mixed ground conditions, and nearby metro lines and shallow building foundations

structures and infrastructure. More than 22,000 monitoring stations provided 200,000 readings every day. Automated monitoring occurred at variable frequency but often took place every 30 seconds when tunnelling was close to the monitoring points. Monitoring data fed into an extensive, real-time database.

Both the contractor and client had dedicated teams to manage the extensive quantity of data acquired. All site managers and relevant members of the contractor's technical department, including TBM technical staff, had full access to the monitoring database and had specific duties and roles regarding monitoring. A dedicated emergency action plan was continuously updated and in use during construction, with precise procedures detailed in case any threshold values were exceeded.

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The settlement data and TBM parameters on the database helped the contractor to tunnel in difficult soil conditions. Monitoring data acquired during the project allowed for design optimisation and helped to avoid unnecessarily costly and disruptive mitigation measures in the centre of Copenhagen by allowing the contractor to precisely predict the volume loss from TBM boring.

Protecting heritage buildings
The contractor was required to carry out the works on the project without causing significant damage to third-party assets. Acceptable limits for typical building damage were outlined within the contract – damage should be limited to category 1 according to the classification in BRE Digest 251, which defines damage as "fine cracks which can be treated easily using normal decoration. Damage generally restricted to internal wall finishes; cracks rarely visible in external brickwork. Typical crack widths up to 1mm". Category 2 damage, where serviceability would be affected – requiring external repointing of brickwork and doors/windows needing repair – with crack widths up to 5mm, was not acceptable. Historical building archives were used to provide information for the assessment of building damage.

Kongens Nytorv was one of the project's most challenging locations. In this area, the TBMs had to break out of the new station at Kongens Nytorv, tunnel through shallow, soft ground in mixed-face conditions, pass above the existing metro tunnels with a clearance of only 1.5m, before diving, with very limited clearance, beneath the shallow foundations of several heritage buildings, including the flagship Magasin du Nord department store.

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The risk of settlement and associated damage to buildings and utilities in this area would have been lessened if a deeper Cityringen station was constructed, with the TBMs passing beneath the existing metro and through good soil conditions. However, this option would have significantly increased passenger time on escalators and lifts, increased the excavation required and would have led to higher costs.

The contractor performed a detailed assessment at Kongens Nytorv, involving the analysis of a fully coupled 3D geotechnical and structural model, with the advancement of the two TBMs modelled ring by ring in order to identify all possible settlement scenarios. The initial analysis predicted that damage to the buildings would be at unacceptable levels, so additional mitigation measures needed to be put in place.

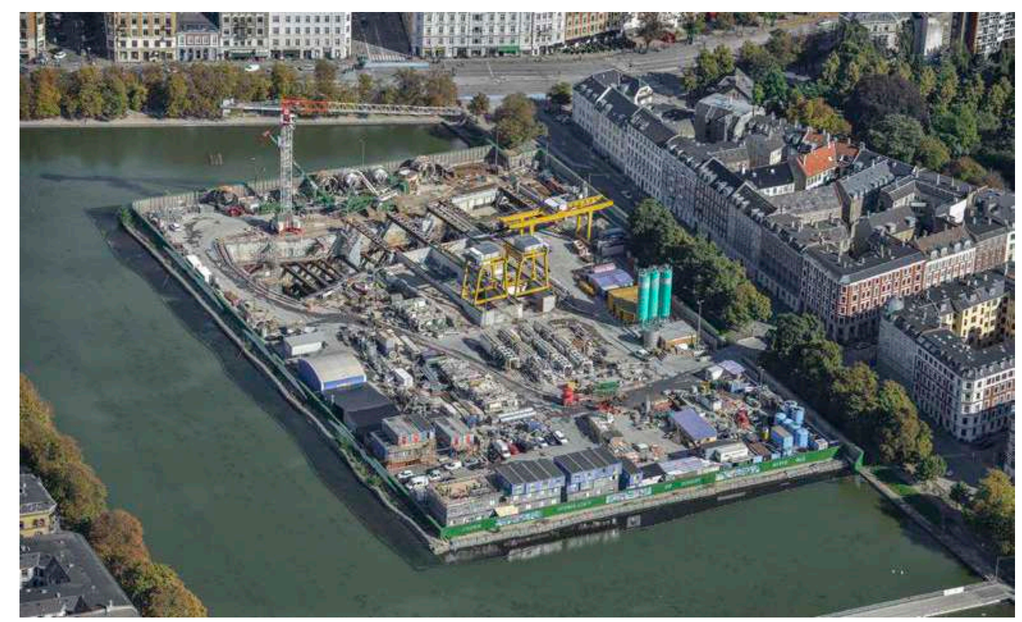
A further design challenge to tunnelling below Magasin du Nord was the complexity of the department store's structural system. It consists of multiple interconnected buildings constructed at different times, with different materials, on a range of foundation types. In addition, in 2000, the building's basement was lowered by approximately 1m to accommodate an additional shop floor and provide access from the original Kongens Nytorv metro station. There was a possibility that micro-piles used in that construction were still in place, with a risk that the TBM could hit these as it passed below the building.

To reduce the building's predicted settlement, and the risk of encountering the micro-piles, the contractor proposed lowering the new Kongens Nytorv Station and the Cityringen tunnel alignment to within 1.5m of the existing metro tunnels. A detailed analysis of the effect of the TBM passage on the existing metro tunnels was conducted to determine the potential implications. The results showed that the deflections and stress levels in the existing metro tunnels were negligible and could be accommodated by the tunnel structure. After crossing the tunnels, the TBMs dived down at the maximum allowable gradient (6%) to clear the underside of the Magasin du Nord foundations and any micro-piles that may still have been in place.

The contractor used both preventative and corrective measures to mitigate the

17: The driverless metro trains run every three minutes at peak times, and every five minutes during the rest of the day

18: The Øster Søgade shaft was used to launch the TBMs and to incorporate bifurcation structures for the metro extension to Nordhavn



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risk of damage to the buildings at Kongens Nytorv. The preventative measures included lowering the tunnel alignment as described above, filling disused underfloor heating conduits with lean concrete and using localised jet grouting to underpin sensitive foundations. Corrective measures included an extensive compensation grouting array and the preparation for emergency dewatering if required in order to allow access to the TBM face. A comprehensive liquid levelling monitoring system was installed in the basements and ground floors of the buildings most at risk of settlement, 3D prisms and levelling bolts were installed on building façades and an automatic 3D monitoring system was installed inside the existing metro tunnels to detect tunnel convergence.

The compensation grouting array consisted of 45 horizontal tube-a-manchettes ranging from 15m to more than 40m in length, with grout valves every 0.5m. Where the liquid levelling systems indicated a localised foundation movement, the array enabled a direct and immediate response with grout, quickly re-establishing the foundation stability. A maximum settlement of just 1.2mm was measured during the passage of the first TBM, and a maximum value of 0.8mm for the second, proving that the hard work by Metroselskabet, the designers and the contractor had paid off. The best solution possible had been achieved for the station at this location.

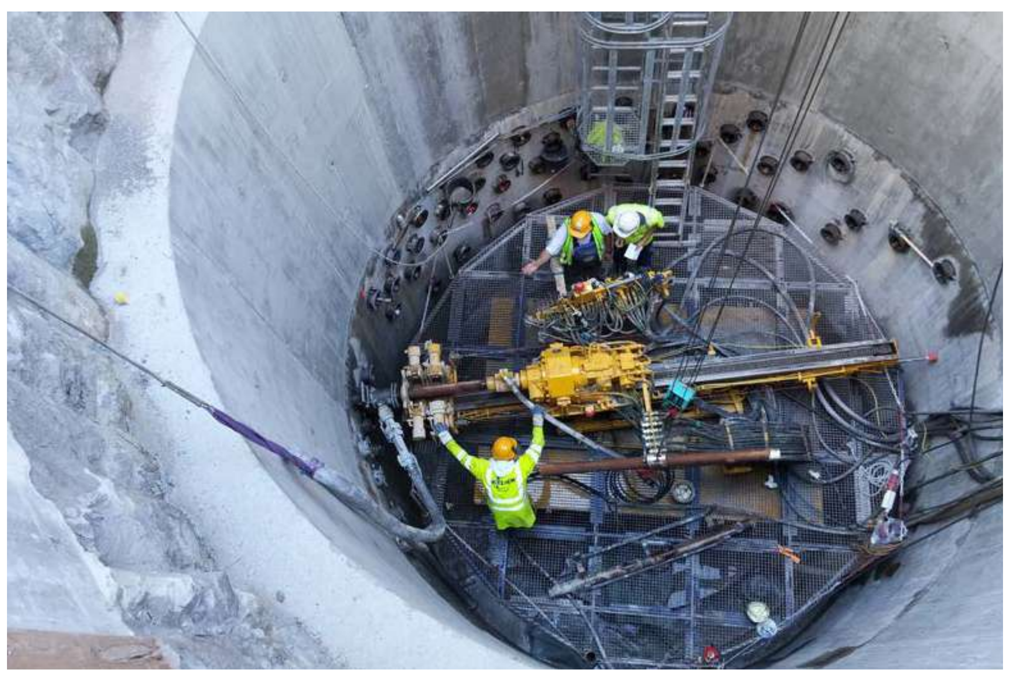
Transport network expansion

Arup is continuing to work on expanding Copenhagen's transport network to the north and south of the city. The Nordhavn branch of Cityringen, with two new stations, will create a transport hub for the docklands redevelopment north of the city centre and opened in March 2020. To the south-west, Arup is working on the detailed design of the five-station underground extension to the Sydhavn district. This is set for completion in 2024, as part of the regeneration of the city's south harbour area. To ready the transport network for these new elements, two bifurcation structures were incorporated during Cityringen's construction. This required modification to the already planned Øster Søgade shaft and the introduction of a new shaft at Havneholmen.

The changes to the Øster Søgade shaft saw the introduction of two additional tunnel interfaces to the western edge of the shaft. This was a complex project, as the worksite was also a tunnel construction service site for the TBMs creating the eastern part of Cityringen between Øster Søgade and København H. The design for the modification to the shaft minimised the disruption to the Cityringen works and maximised future flexibility for the addition of the Nordhavn branch to the metro network. Crucially, the design also minimised any unnecessary change that might impose additional cost or disruption on the surrounding area. The Havneholmen bifurcation chamber was a tapered (in plan) reinforced concrete shaft with stacked track bifurcation on the two lower structural levels, 15m and 26m below ground level, and with a technical level housing equipment and plant rooms approximately 7m below ground level.

For the larger crossover caverns where tunnels branch off towards Nordhavn and Sydhavn, Arup designed a novel, lightweight fire board panel system, supported by a steel frame for the over-track exhaust duct in the ceiling. This replaced the heavy and cumbersome fire-rated metal sheet work, traditionally used in other metros, saving time and cost on the construction programme.

Cityringen opened in September 2019. Trains run every three minutes in the peak morning and evening commutes, and wait times are less than five minutes during the rest of the day. The line is forecast to transport up to 120 million passengers a year, with 85% of all Copenhagen residents now within 600m of a metro or train station. The new line is a fantastic example of elegant, efficient and intuitive rail design, centred on delivering an effortless and enjoyable travel experience for Copenhagen's citizens and visitors, and building on the strengths of the city's existing system. It proves that the architecture of rail systems can contribute greatly to a city's identity, with a sustainable design that can be maintained cost-effectively, long into the future.



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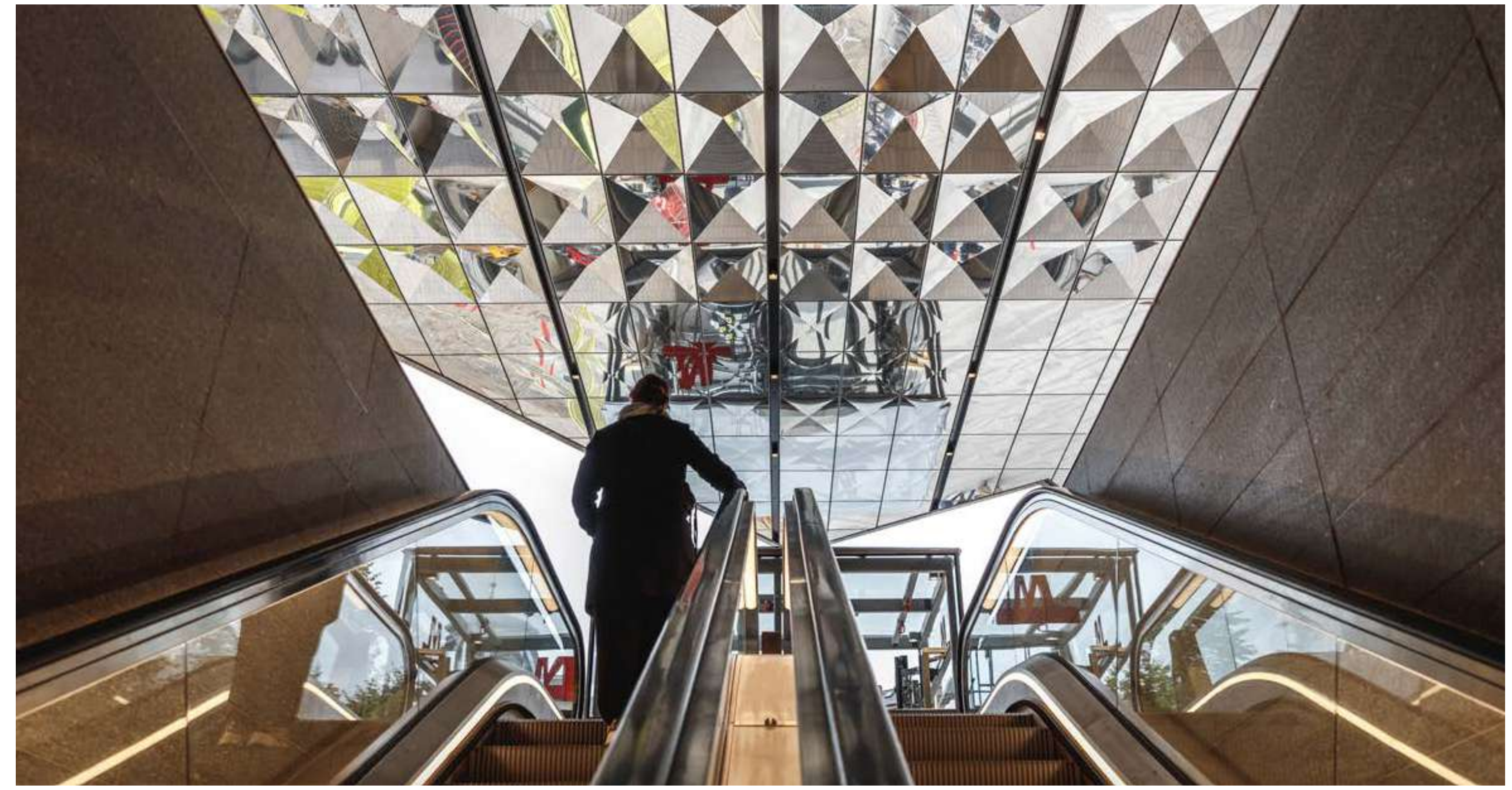
19: Compensation grouting was used to prevent the risk of excessive building movement

20: Cityringen opened in September 2019; some 85% of Copenhagen residents are now within 600m of a metro or train station



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Authors

Tony Evans was seconded into Metroselskabet's construction management team as Technical Manager during the project. He is an Associate Director in Arup's Midlands Campus in the UK.

Katrine Falbe-Hansen was seconded into Metroselskabet and was responsible for building assessment coordination and third-party issues for Cityringen. She is a senior civil and structural engineer and is based in the Copenhagen office.

Neil Martini was the Project Manager. He was seconded into Metroselskabet as the tunnel design manager during the project. He is an Associate in the Copenhagen office.

Nille Juul-Sorensen was the lead architect on the project. He was also previously responsible for the design of Copenhagen's M1 and M2 metro lines. He is Arup's global leader for architecture and a Principal in the Toronto office (he was formerly based in Copenhagen).

Mohammad Tabarra was responsible for the tunnel and station ventilation design on the project. He is Arup's global tunnel ventilation lead and an Associate Director in the London office.

Kristian Winther was responsible for design and coordination of the main concept for the station architecture. He is an Associate in the Copenhagen office.

Project credits

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Design and build contractor Copenhagen Metro Team (Salini-Impregilo, Tecnimont and Seli)
Joint venture partners COWI, SYSTRA
Acoustics, architecture, civil engineering, construction management, electrical engineering, façade engineering, fire engineering, geotechnics, lighting design, materials science, mechanical engineering, pedestrian modelling, programme and project management, structural engineering and tunnel design Arup: Yakup Akkas, Jarrod Alston, Ambrogio Angotzi, Giulio Antonutto-Foi, Eva Arquero, Mo Attia, Enrica Barzaghi, Andrés Bascones, John Batchelor, Charles Betts, Johan Beudeker, Joanna Bielecka, Paola Blasi, Andre Blokker, Tamas Bodri, Lucio Boscolo Mezzopan, Brendan Bradley, Nicholas Bruce, Edel Casserly, Tim Chan, Man-Yiu Cheuk, Francisco Cortes-Franco, Piotr Czapko, Andy Davidson, Fred Deacon, Tim Dixon, Jim Dunne, David Eborall, Anna-Maria Ejrup, Matthew Evans, Tony Evans, Katrine Falbe-Hansen, Andrej Fojkar, Pernille Fournais, Jens Frederiksen, Jens Fugl, Salome Galjaard, Mads Gandil, Valentina Gastaldi, Tim Goeckel, Rene Guenther, Na'amah Hagiladi, Stuart Hall, Diana Hare, Ali Hariri, Alexis Harrison, Chris Harvey, Des Hendrick, Michael Hess, Daniel Hof, Tom Honnywill, Andrew Jenkins, Aslak Jensen, Inge Jensen, Nille Juul-Sorensen, Tomasz Kasprus, Areti Kavoura, Kasper Kramer, Ben Kreukniet, Sachin Kumar, Maciej Kupczyk, Tatjana Lampe, Eduardo Landete Mata, Jens Larsen, David Leal, Yu-Chen Lee, Chris Lees, David Loosemore, Helle Lyng Svensson, Steve Macklin, Guy Macleod, Enrico Manganelli, Neil Martini, Stuart McClymont, Jonathan McKiernan, Charles Milloy, Phil Morley, Sabine Moser, Trent Murrihy, Omid Nakhaei, Paul Newton, Anders Nohr, Alberto Palma, Dinesh Patel, Aitana Paya Perez, Giuseppe Pelagalli, Francesco Petrella, Saskia Polster, Gregory Quinn, Dirk Regenspurger, Mhairi Riddet, Derek Roberts, Nina Rutz, Prakash Sabapathy, Russell Saltmarsh, Sheela Sankaram, Cornelius Schneider, Nazaneen Shafaie, Ruth Shilston, Siegrid Siderius, Derek Smyth, Jamie Stern-Gottfried, Colin Stewart, Igor Stipac, Louise Stroud, Julia Summers, Matt Sykes, Sebastian Szafarczyk, Mohammad Tabarra, Rachel Taylor, Nick Troth, Rogier van der Heide, Alexandra van Tintelen, Jeroen Verwer, Ida Villumsen, Marie West Henriksen, David Whittles, Heather Wilson, Kristian Winther, Kevin Womack, Anna Wudzka, Jan Wurm, Clara Yeung, Pietro Zanetti, Gertraud Zwiens.

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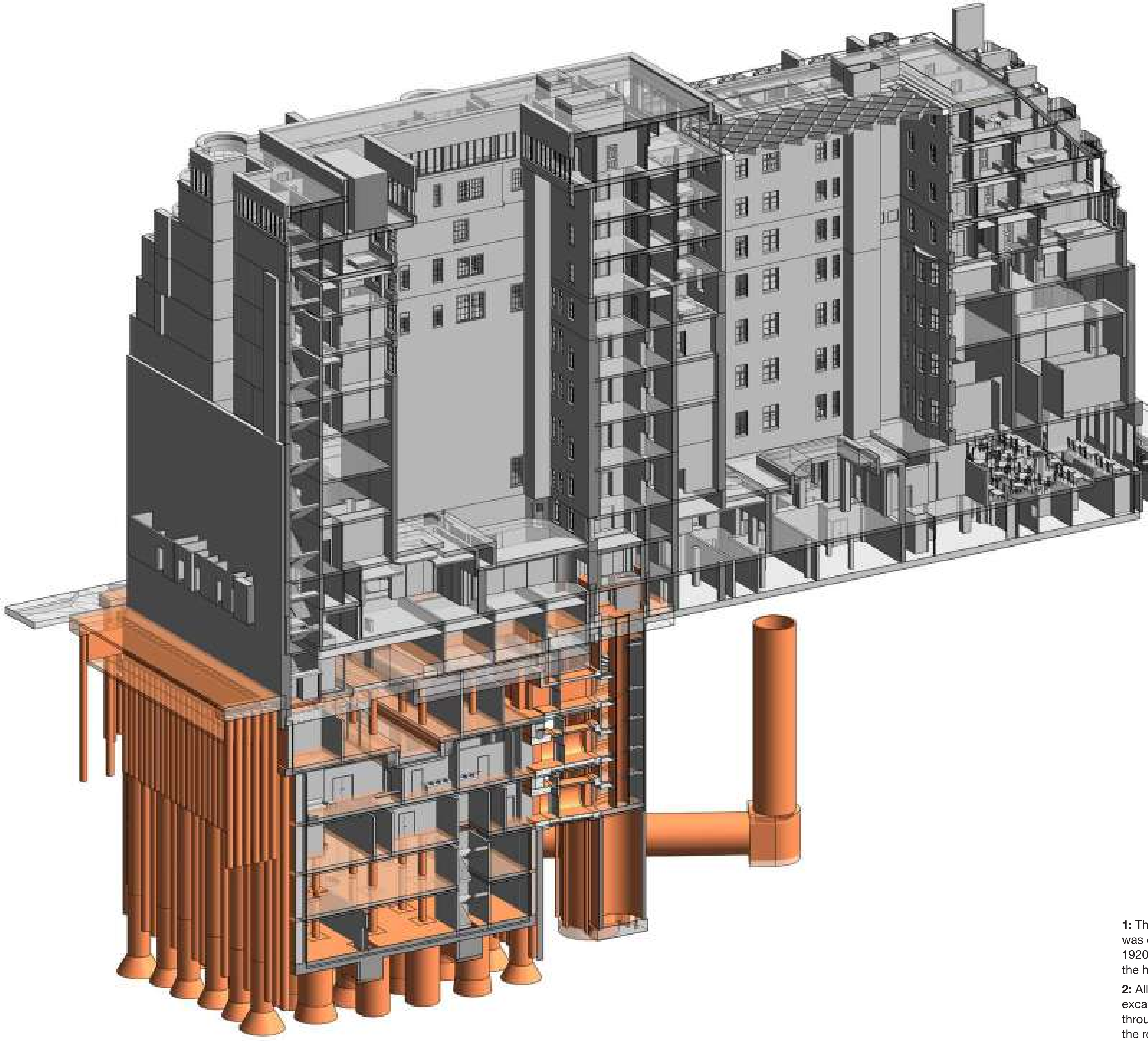

1.

Digging deep

Creating a five-level basement below a fully operational five-star hotel in London's Mayfair

Authors Alice Blair, Sarah Glover, Dinesh Patel and Andy Pye

The owners of Claridge's, a five-star hotel in the heart of London's exclusive Mayfair district, wanted to enhance the services offered to their guests and increase capacity. To do so, they needed to expand the hotel. Planning reasons meant they could not increase the height of the building, so an alternative solution was needed. Could a modern extension be created by excavating below the building – without disrupting the hotel services or disturbing the guests?

In 2007, when the Maybourne Hotel Group initially proposed extending Claridge's by constructing two basement levels below the Grade II-listed building, they were advised that the hotel could not remain open during the works. But closing Claridge's temporarily was not acceptable to the owners. A closure of any kind would jeopardise client loyalty – the hotel has long boasted an impressive guestlist that includes Hollywood celebrities, rock stars and royalty. The owners required a solution in which facilities could be upgraded while the hotel remained fully operational.

The project was put on hold following the 2008 global financial crisis. When the client revisited the idea in late 2015, they had even more ambitious plans – they now wanted to develop a five-level basement. Having successfully collaborated on projects previously, Arup and the design and build contractor, McGee, worked together on a methodology to excavate and construct the basement using mining techniques.

This was a uniquely challenging project, as it required the design and construction of a 22m-deep basement and 30m-deep foundations beneath a 90-year-old concrete raft slab founded on material that was difficult to safely excavate. Adding to the complexity, in order to avoid disruption to hotel guests, all construction materials, machinery and excavated spoil needed to pass through a single 2m x 2m window to the rear of the hotel. The construction operation was performed from a single 7m^2 room, which was the only available space that the client could afford to give to the construction team; later, a second room was provided at the front of the building.

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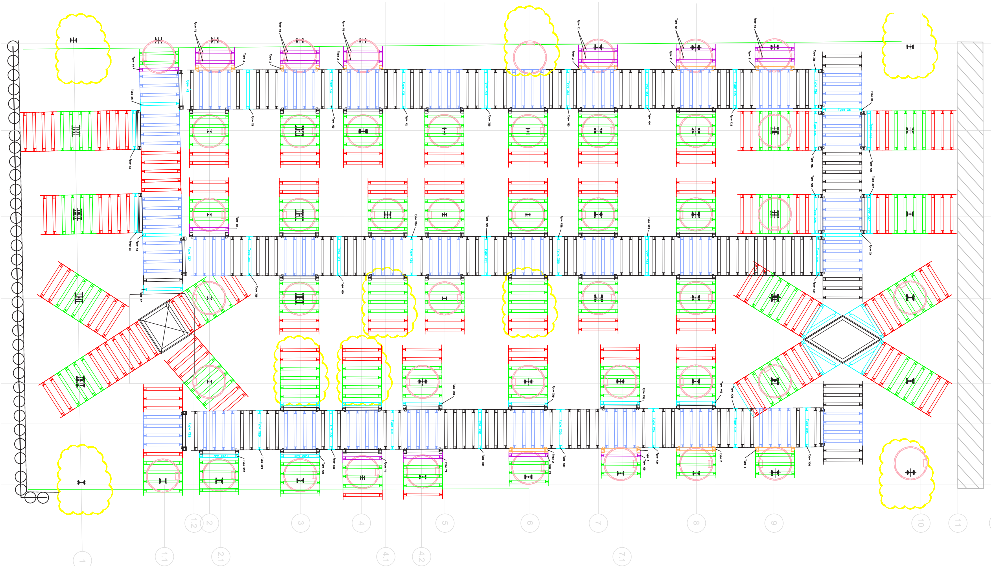
1: The five-storey basement was constructed under the 1920s Art Deco section of the hotel

2: All the machinery and excavated materials passed through a single window to the rear of the hotel



3.

3: More than 400m of horizontal tunnels were constructed in total

4: The shafts were hand-dug, with temporary steel liners installed by the miners

5: Basement level one was excavated directly below the 1920s raft slab

6: 3D model showing the foundations and columns, along with the first basement level

Pioneering solution
The client's aim was to create 5,500m² of extra space. The upper two floors of the basement were earmarked for a range of new offerings for hotel guests, including a gym, a spa and two swimming pools. The three lower levels were to be used for back-of-house facilities and plant. By moving some of the staff areas into the basement, this freed up space at lower ground floor level, which could then be used for luxury retail units instead. Relocating the roof-level mechanical and electrical plant areas to the basement would create the space for 40 new rooms, including penthouse accommodation on the top floor.

Arup's geotechnical, structural and advanced technology engineering teams worked closely with McGee to minimise the significant ground and structural risks inherent in constructing a basement under a heritage building. They initially spent six months carrying out site trials, material tests, and geotechnical and structural analysis to demonstrate that the proposed basement construction methodology was workable. There was no precedent for such an ambitious project.

The design team developed a solution that involved coring through the existing basement raft slab in a single 2m x 2m location, and from there constructing horizontal tunnels (more than 400m in total) under the slab to below each of the 61 columns requiring support, with four additional columns supported on new transfer structures. Vertical shafts 1.8m in diameter were then hand-dug beneath each of the columns. These needed support to depths of 30m in order to form caisson foundations. A five-storey reinforced concrete column was built within each shaft up to the underside of the existing raft to provide vertical support to the superstructure above. Once complete, the basement area was excavated around the new columns to create the basement space. All 25,000m³ of excavated material was removed through the one window at the rear of the building, with all equipment used in the excavation electrically operated to minimise noise, vibration and possible pollution.

4.

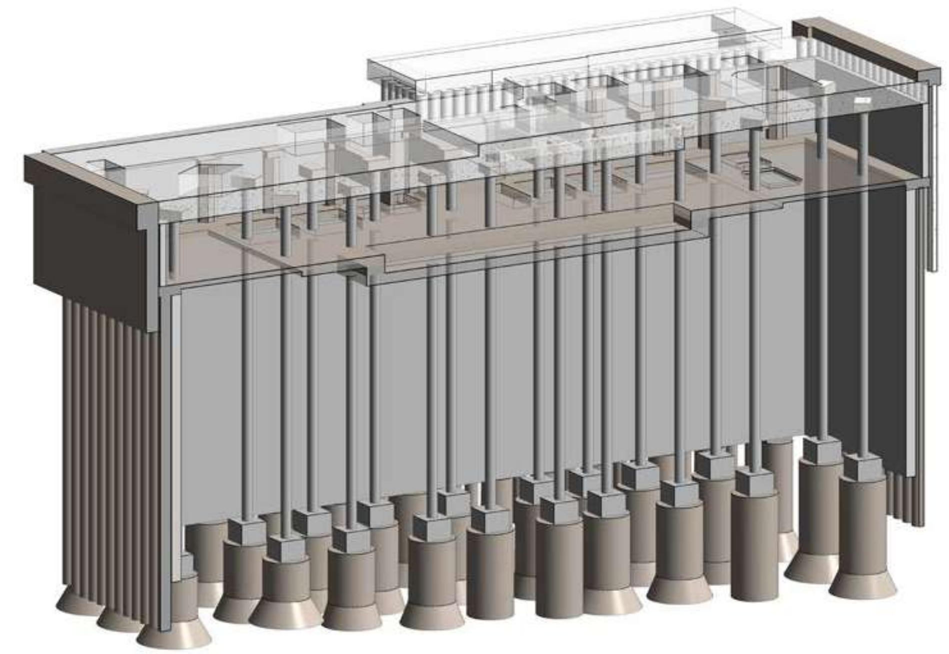
5.

This work required close collaboration between Arup, McGee and temporary works designer RKD, with Arup carrying out extensive analysis of the existing building foundations to understand the load path from the building and determine its response through all phases of the work. Movement had to be limited, as excessive displacements would have had serious consequences for the structure, sensitive listed heritage features and – most importantly – the hotel occupants. A rigorous regime of movement monitoring and control was put in place during construction. Buildability drove the design; the work needed to be methodically planned, as construction was taking place in such a confined space and with access to the construction site so limited.

Raft slab investigation
Claridge's first opened in 1856 and, before the basement extension began, it was made up of two buildings – a Victorian-era seven-storey building constructed in the 1890s and an Art Deco building at the east of the site dating from the 1920s. The Victorian building was constructed with load-bearing masonry walls founded on an unreinforced mass concrete slab, making it unsuitable to excavate under.

The Art Deco section consists of a nine-storey steel frame with heavy perimeter load-bearing walls founded on a 50m x 25m x 1.1m deep concrete slab. With careful construction of a new supporting foundation system, this load-bearing raft slab could be converted into a suspended slab, thereby allowing the basement to be excavated below the slab. In order for this plan to be feasible, it was crucial to understand how the slab would behave at all stages of construction.

Arup needed to quantify the strength of the slab and determine the density of reinforcement within it to ensure it could span over the tunnelling works and safely transfer loads both during the tunnelling operations and when the new columns were in place. There was limited information on the slab – one of the only sources was a November 1931 article on construction of the Art Deco wing in *The Builder* magazine, which noted the overall quantity of reinforcement, as well as the difficult soil conditions. The slab is an early example of the use of a reinforced raft. As it did not meet modern codes of practice, one of the major challenges was understanding the raft's response to the movements from the proposed construction methodology.



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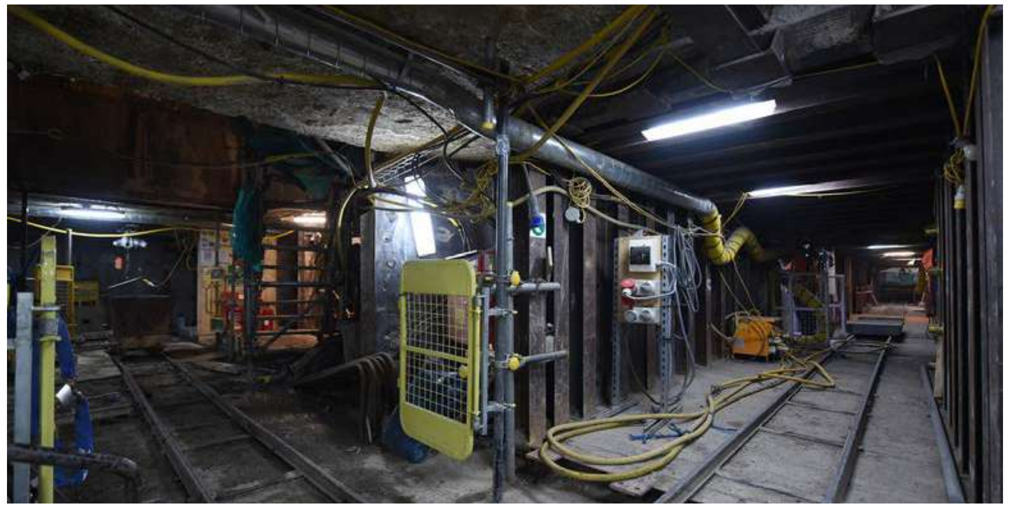
An 800mm x 800mm section was cored out to investigate the slab's concrete strength and reinforcement quantity. This section was lightly reinforced, matching minimum code requirements at the time of its construction. As access restrictions prevented investigations elsewhere, it was not possible to confirm whether any other areas of the raft had more reinforcement than this sample.

Using only the minimum 1920s code reinforcement as a conservative estimate, Arup carried out extensive analysis of the raft strength to inform the design and understand the construction-related movements that the building would experience. Deflections and settlements were analysed with soil-structure 2D and 3D finite element (FE) analyses. The staged geotechnical analysis modelled the various activities across the complete construction sequence to predict the load distribution in the slab, along with ground settlement and heave.

A separate 3D FE analysis investigated inelastic cracked behaviour of the raft and failure mechanisms, using a Continuous Surface Cap Model for the concrete material model that included each element of reinforcement. Hand calculations and non-linear FE analysis were also carried out, with Arup's Advanced Digital Engineering team modelling the concrete to analyse the crack pattern and associated concrete deflections at rupture. This combined analysis confirmed that the slab behaviour would remain acceptable, provided any deflections caused by excavation underneath were carefully controlled.

Challenging ground conditions
While the raft slab was being examined, a significant geotechnical issue was being investigated, one that had the potential to stop the project. Claridge's is located in the former course of the River Tyburn, and initial site investigations suggested that the raft was founded on combination sand and gravel material. After further analysis, it was determined that the raft slab was bearing on an alluvial clay silt deposit of varying depth (up to 2m) on layers of gravel above London Clay. In situ, the alluvial layer has high-bearing pressure, but it is very sensitive to moisture. The stability of this soil layer during excavation was a huge safety concern, as once disturbed and in contact with water it turns into a paste-like consistency, making it impossible to tunnel safely through and risking excessive building settlements.

A solution needed to be found to prevent this sensitive soft layer from turning into liquid during the mining operation. Options considered included ground freezing and grouting. However, ground freezing would have required extensive additional access within the hotel, and there was also the potential that this method would cause soil



7.

7: 152 UC steelwork sections were used to frame the tunnels on all sides. Excavation was carried out in small sections to minimise distortion on the slab

8: Some 61 of the building's columns required support, while four other columns were supported on new transfer structures

9: A 2m x 2m shaft was cut from the access room to allow tunnelling to begin

expansion that could damage the structure. Grouting would not work due to the high fines content of the soil. The solution, designed in conjunction with WJ Groundwater, was to dewater the alluvial layer using vacuum wells. This method sucked out the water to provide increased soil strength and stiffness, with the wells initially placed in the single 7m² room to the south.

However, the dewatering could only take place following the installation of perimeter cut-off walls, which would prevent groundwater from flowing back into the site. On the west side of the site, existing sheet piles used during the construction of the Art Deco section of the building already prevented water from entering, and on the east side adjacent buildings had either underpinning or secant piles providing a similar cut-off.

A new secant pile wall was installed to the south, but on the north side a different solution was required. This area is not easily accessible, as it is below a busy road and the hotel's ballroom entrance. The solution was to construct a 1.2m-wide x 1.8m-deep water cut-off beam 25m in length. In a 'hit and miss' underpin method, a trench was excavated in front of the raft, within the lightwells in the pavement outside the hotel. This trench was then filled with concrete to form the cut-off. Three vacuum dewatering wells were sunk on the south side of the hotel, with another two sunk to the north. Once the dewatering process was complete, it was safe to excavate in the alluvial layer.

Tunnels

To allow the tunnel construction to commence, a 2m x 2m vertical shaft was cut through the basement slab from the construction access room. Three main 2m x 2m tunnels were initially built midway between the main column grids, with shorter

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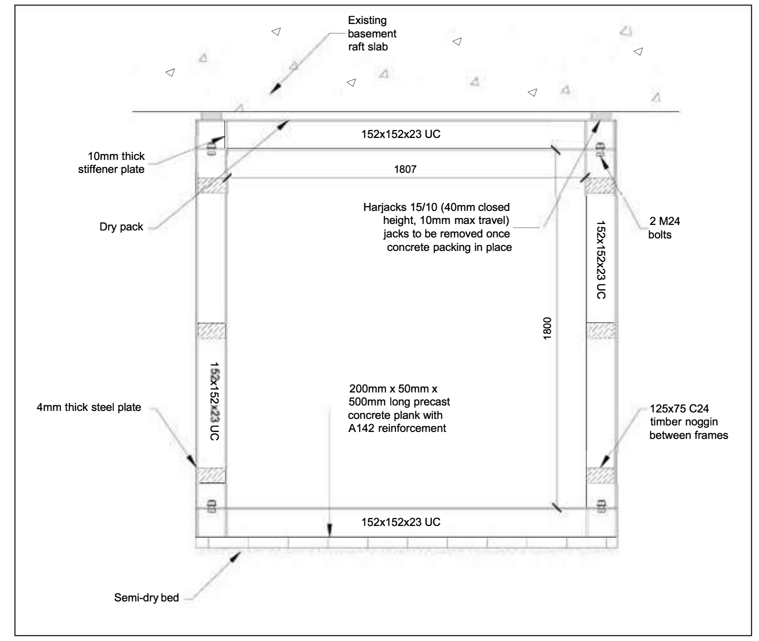

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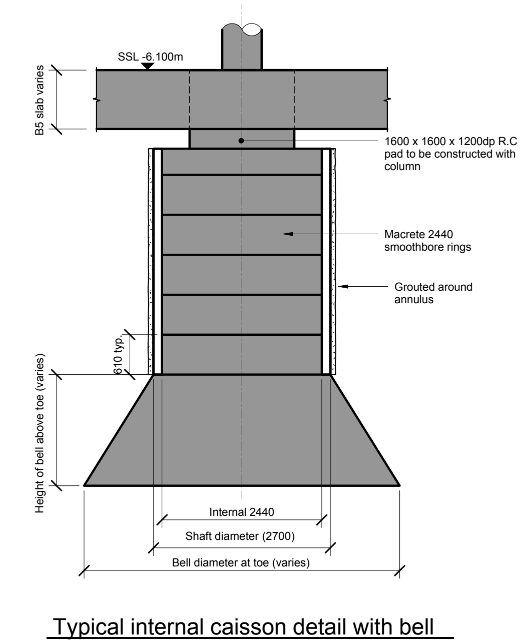


11.

passages mined from the main tunnels to locations below the steel columns supporting the hotel. The size of the tunnel was a balance between being large enough for the miners to safely work in, but also small enough to ensure the raft above was adequately supported while maintaining a load path through the tunnels into the ground below.

The tunnels were hand-dug in 500mm sections, with 152 UC steelwork sections used to frame the tunnel on all sides. The steel was light enough to be put into position, bolted and assembled on site. The frames were placed at 500mm centres, with steel plates inserted between the side frames and the voids grouted behind to control movement. The top of each frame was jacked and dry packed against the underside of the raft to minimise raft settlement. Carrying out the excavation in such small sections meant any imposed distortion on the existing slab was reduced. The tunnelling was carried out by a team of 15 experienced miners, mostly from Donegal, using hand-held pneumatic spades.

Shafts and caisson foundations

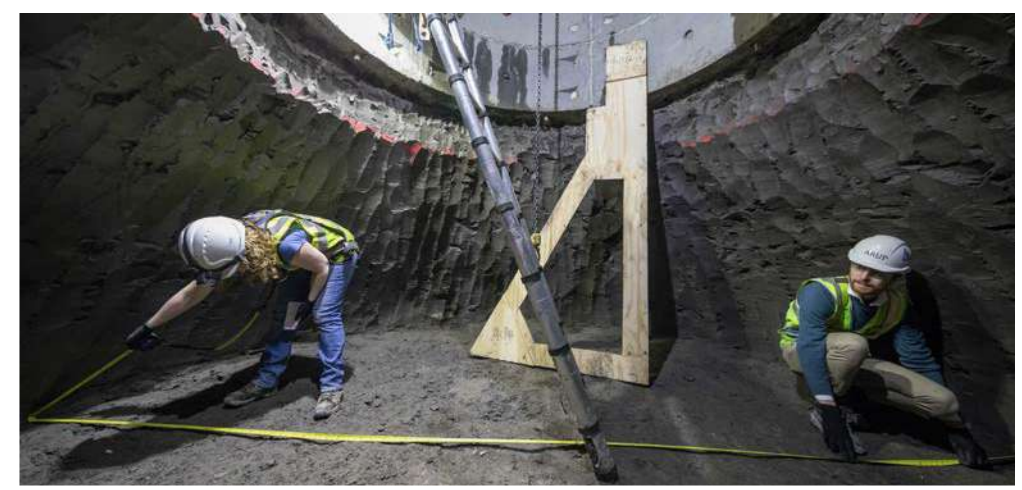
Vertical shafts, 1.8m in diameter, were constructed below the 61 building columns that needed support, with a reinforced concrete collar used to frame the top of each shaft. Miners worked 24 hours a day across two 12-hour shifts. Three separate teams worked on a shaft each, with no two adjacent shafts excavated at the same time, in order to minimise any raft disturbance. Two miners hand-dug each shaft using pneumatic spades and, as they excavated, installed 1m-deep temporary steel liners manufactured specifically for the project. To speed up construction, a second access point through the raft was constructed. This allowed shafts to be sunk from both sides of the site, with 1,800m of vertical shafts excavated in total.

When the steel-ringed shafts reached to below the lowest basement level, 22m beneath the raft, they were enlarged to form a caisson foundation 2.7m in diameter. At the bottom, the caisson sizes were further increased up to a maximum diameter of 4.6m to provide a wide base for the foundation, at a depth of up to 30m in places below the raft. Each caisson was inspected by McGee and Arup staff prior to concreting, as it was essential the shaft dimension was correct and that the bottom of the base was founded in the London Clay layer. The concrete caisson rings were then filled with unreinforced concrete up to the underside of the new basement level five.

10: Section showing the supporting steelwork in the tunnel

11: Beneath the lowest basement level, the shafts were enlarged to form 2.7m diameter caisson foundations

12: Some 30m below the raft, under the most heavily loaded columns, the foundations were widened to 4.6m in diameter



12.

Avoiding having to fix reinforcement prevented any delay that might have caused softening of the base of the foundation.

Concrete columns

Reinforced concrete pads (each measuring 1.6m x 1.6m, and 1.2m in depth) were constructed on top of the concrete infilled caissons. Internal columns 600mm in diameter were then built to the underside of the raft from inside the 1.8m diameter shafts. This column diameter was the largest that could be accommodated within the shafts while still allowing safe access for construction. The column reinforcement was made up of 2m lengths with coupler connections, making the reinforcement easier and safer to handle and reducing rebar congestion in the column. The couplers were placed at waist height to enable the reinforcement to be fixed more readily. Self-compacting C60/75N concrete was used in each column, ensuring good quality concrete in zones of congested reinforcement and avoiding the need to use a vibrating poker to compact the concrete in the small access shafts. Steel shutters were used for the formwork to provide a high-quality concrete finish, with the added advantage that they could be reused across the site during construction. To prevent buckling, temporary struts were used to stabilise the columns in the 22m-deep shaft until the basement floors were built.

The columns at the edge of the building form part of the retaining wall and are subjected to eccentric loads from above. These columns are 1.2m in diameter and located to one side of the 1.8m-wide shafts. Offsetting the edge columns in this manner freed up space in the excavated basement at each column location. Using a 1.2m diameter column also provided sufficient space during construction for workers to fix the column reinforcement from within the steel reinforcement cage.

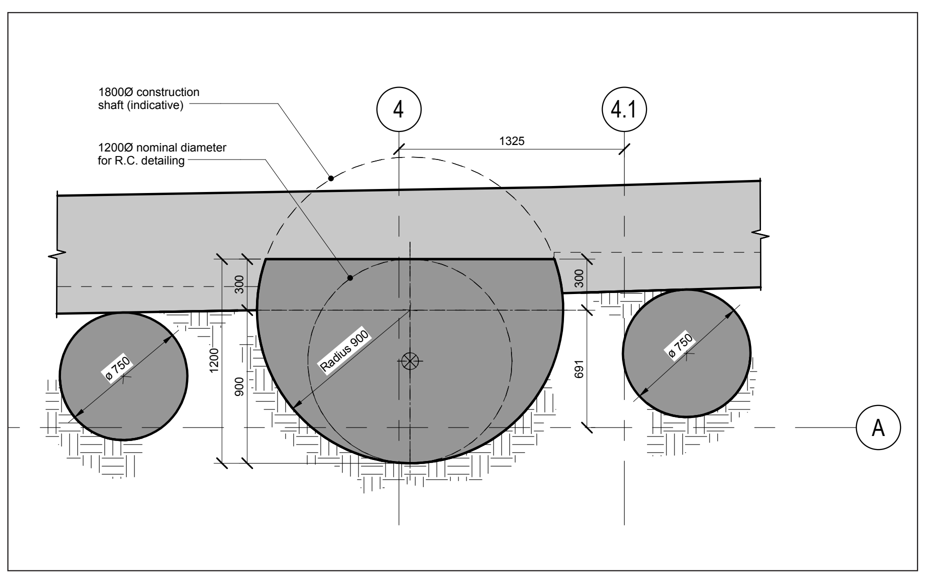
13.

All the columns were cast to the underside of the existing raft. The column heads were cast with twin hydraulic jacks installed on top of them and beneath the raft. These were to engage the column, so they could take the superstructure load from above and control raft movement.

The tunnelling works, shaft excavation and construction of the columns took 18 months. Once all the columns were built and preloaded, the tunnel steelwork could be carefully dismantled and the ground beneath the existing raft removed. When the first basement level was fully excavated, it created space to construct a 750mm diameter, 19m-deep contiguous pile wall around the basement perimeter. A modified electrically powered piling rig was used for this work to avoid diesel fumes and reduce noise. The rest of the basement was excavated and built using traditional top-down construction, with each basement level taking two months to excavate and construct.

Service shafts below Victorian wing

Two service tunnels were constructed underneath the Victorian section of the hotel to provide building services routes into the basement, along with a lift and stair core. The new access core serves the first three basement levels, providing a shorter route for hotel guests and staff into the new facilities. The tunnels were built to provide services access to the lowest level. These works were all carried out at night, with the excavated material removed in wheelbarrows through the hotel corridors. The 4m diameter vertical shafts were built first, with the 3m diameter horizontal tunnels then constructed from the basement to reach the shafts. These shafts, tunnels and connection chambers were as logistically challenging as the main basement.



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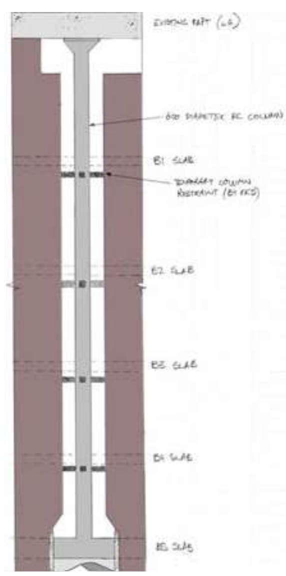


15.

13: Twin hydraulic jacks sit atop each column, to transfer the load and help control raft movement

14: The edge columns form part of the retaining wall

15: The internal columns measured 600mm in diameter – the largest possible size that would still allow safe construction access

Movement monitoring and control

During construction, extensive movement monitoring of the building took place. Monitoring mechanisms were installed to assess movement of the existing raft and the building overall. Real-time movement monitoring was put in place on all columns, inclinometers were placed internally on all retaining walls, and precise level studs and 3D targets were positioned externally. Liquid levelling sensors enabled movements to be displayed in the site office in real time.

The hydraulic fluid-filled flat jacks at the top of the columns allowed for the control of raft movements (ground settlement and heave) and for adjusting the distribution of loads going into the new columns. The measurement systems allowed for the actual loads from the superstructure to be determined. These confirmed that the actual building loads were within design tolerance. At the end of construction, the hydraulic fluid was replaced with cement grout, locking the building into its final position.

Building the impossible basement

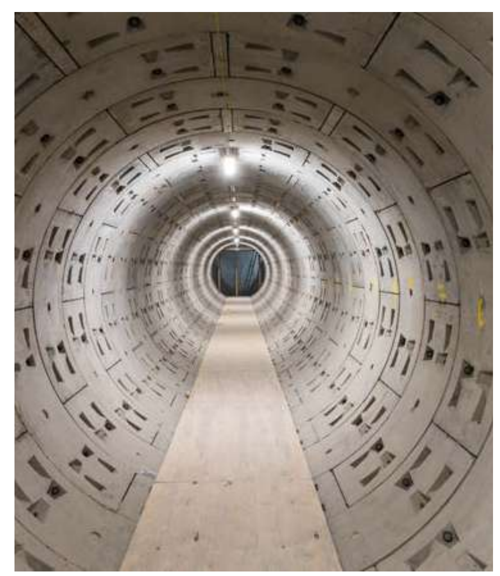
The successful completion of this project would not have been possible without close collaboration between McGee, Arup and RKD, which collectively drew on their extensive technical knowledge, skills and experience to overcome the significant challenges in creating a five-storey basement below this Grade II-listed building.

With construction taking place beneath an operational hotel, in such confined space and with such limited site access, the design process was governed by what could be practically and safely built. Each element of construction required meticulous planning. The £37m basement works were delivered on budget, four months ahead of programme and carried out while the hotel remained fully operational at all times, with guests oblivious to the feat of engineering that was going on below their feet.

17.

16: Two service shafts were constructed under the hotel's Victorian wing to provide building services routes to the basement

17: Claridge's remained fully operational throughout the basement extension, with guests barely noticing the works taking place beneath them



16.

Awards

Council on Tall Buildings and Urban Habitat
Geotechnical Engineering Award of Excellence (2020)

Concrete Society Awards 2019
Highly Commended

Ground Engineering Awards 2019
Editor's Choice

UK project with a geotechnical value over £3 million: Highly Commended

British Geotechnical Association
Fleming Award (2018)

Authors

Alice Blair led the structural design delivery on the project. She is an Associate in the London office.

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Dinesh Patel was the Project Director. He is a geotechnical engineer and Director in the London office.

Andy Pye was lead structural engineer on the project. He is an Associate Director in the London office.

Project credits

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Design and build contractor McGee
Jim Mackey – Project Director
Temporary works designer RKD Consultant
Geotechnical engineering, tunnelling, hydrogeology, structural engineering and BIM Arup: Paul Bailie, Samila Bandara, Alice Blair, Chris Brewis, Tristan Ferguson, Orlando Gibbons, Rupert Gibson, Sarah Glover, Rosemary Judd, Marialina Klokidi, Doreen Lu, Frank O'Leary, Dinesh Patel, Anton Pillai, Barrie Porter, Andy Pye, Darryl Tanner, Bryen Vieira Commins, Dunshun Yang.

Image credits

1, 6, 11, 14, 15: Arup
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3: McGee
4, 12: Nick Carter
5, 7: Daniel Imade/Arup
10: RKD Consultant

Taking flight

Beijing Daxing is the largest airport in the world and acts as a new gateway for the Chinese capital

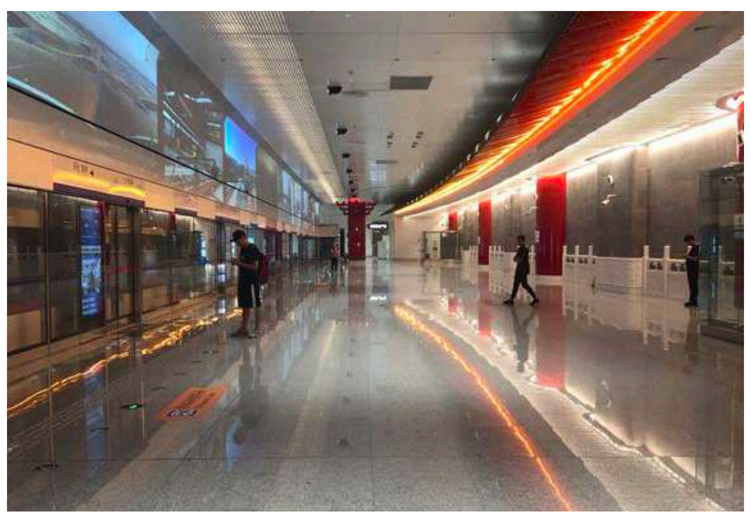
Authors Robert Feteanu, Ming Li, Fangzhou Su, Kelvin Wong and Vala Yu

The spectacular starfish-shaped Beijing Daxing International Airport is one of the biggest single-structure terminals in the world, measuring 1.2km from end to end. Covering more than 700,000m², it is the largest airport (in terms of size) globally. It opened in September 2019 and currently handles 300 take-offs and landings an hour and 42 million passengers per year. This will eventually grow to 100 million passengers annually.

Working closely with Beijing Institute of Architectural Design, Arup designed a number of innovative solutions for this project. The firm provided fire engineering, passenger and logistics simulations and structural peer review services. This work has resulted in significant material and cost savings, and carbon emission reduction. Successfully integrating the ground transportation centre with the terminal building, for instance, has helped to save at least 1.6 million hours for nearly 30 million passengers every year.

Fire safety design
The airport's vast size, the high footfall and the terminal's flowing interconnected form present a significant number of design challenges, particularly in relation to the fire strategy. At the heart of the airport, there is a single 500,000m² central space, spanning from the fourth floor to two levels below ground – this is one of the largest unseparated fire compartments in the world.

The eight-platform transportation hub below the airport makes travel to and from the terminal convenient for passengers, but from a fire safety point of view adds further complexity, as the space for emergency discharge of occupants to the outside is limited. Arup took the lead in providing the fire safety design solutions and coordinating with the various clients, operators and approval authorities in order that a consistent fire design, agreed on by all stakeholders, was approved. The firm overcame these challenges by deploying an innovative performance-based fire design strategy.



1.

2.

1: The transportation hub beneath the airport provides access to high-speed rail, intercity trains and the airport express

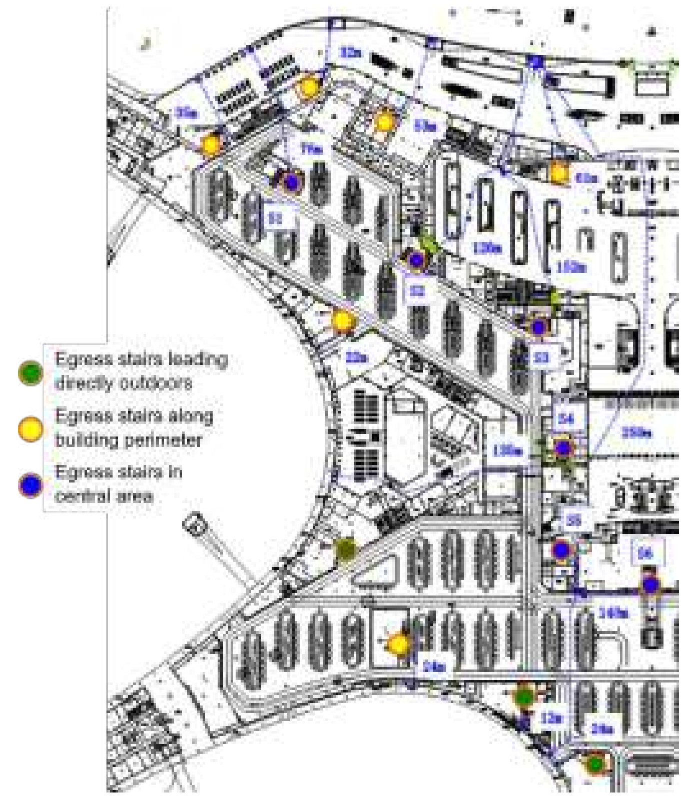
2: The airport is arranged around a large central space and measures 1.2km from end to end

There were four main aspects to this strategy:
• means of escape;
• smoke extraction;
• interface with the railways; and
• fire protection for the roof.

Means of escape
Arup divided the airport's public space into 30 zones, each spanning between 2,000m² and 48,000m². Rather than a conventional solution of zones separated by solid walls, a mix of flexible shutters and doors were used so that the spread of fire and smoke could be contained and safe spaces created without affecting passenger circulation during normal operational times. The higher risk areas with high fire load were, however, constructed for full fire containment. These were limited to a maximum area of 2,000m² and equipped with two-hour fire-rated construction elements and 1.5-hour fire-rated floors.

In the event of a fire, people can leave the zone where there is an immediate threat and take shelter in a safe space nearby. The decision can then be taken to either evacuate occupants further if the fire escalates or allow them to return to the area if it is safe to do so.

There are 11 escape staircases in the large central area; these shorten the escape distance to the building perimeter. Arup provided different exit strategies for the central zone based on the fire location. If a fire is detected on the ground floor, for example, the egress stairs in the central area will be closed and occupants on other floors in the building will be directed by smart signage towards egress stairs along the building perimeter. Should a fire be detected on other floors, then all stairs are made available to allow rapid evacuation of people close to the fire. Arup performed simulations for both scenarios to make sure they were acceptable and in order to gain the approval of the expert panel.



3.

3: Depending on the location of a fire, there are various egress stairs and exit strategies

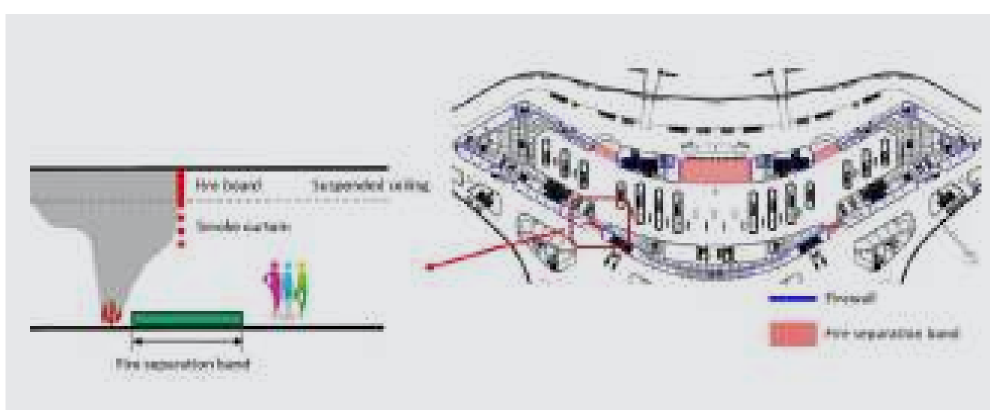
4: The airport is divided into six smoke control zones

5: Arup used several techniques to prevent fire from spreading from one zone to another, including fire separation boards and passive vents in the roof and downstands

Smoke extraction
The second element of the fire safety strategy was smoke extraction. This is vital to minimise the risk to building occupants and reduce potential damage to the building. China's building codes assume much smaller rooms than those present in Beijing Daxing. Because of the airport's vast open space, smoke could potentially fill a larger area without being obstructed. The smoke extraction is directed at both helping people escape and preventing smoke spreading and affecting other areas of the building. It is rare that an airport needs to be fully evacuated during a fire; more often, the fire is localised, people move away from it and normal activity resumes. Arup needed to consider comfort and operational continuity as a major part of its strategy.

The terminal was divided into six smoke control zones – the central zone and five piers. Downstands were installed within the perforated ceilings to prevent smoke spreading from one zone to another, so that if a fire occurs in one pier, the other four can remain operational. To extract smoke from the building, Arup made full use of the roof, incorporating passive vents between its metal and glass elements. The building was designed so that smoke is directed upwards; that way, it can be diluted by the sheer volume of the atrium space and then removed through the vents.

4.



5.

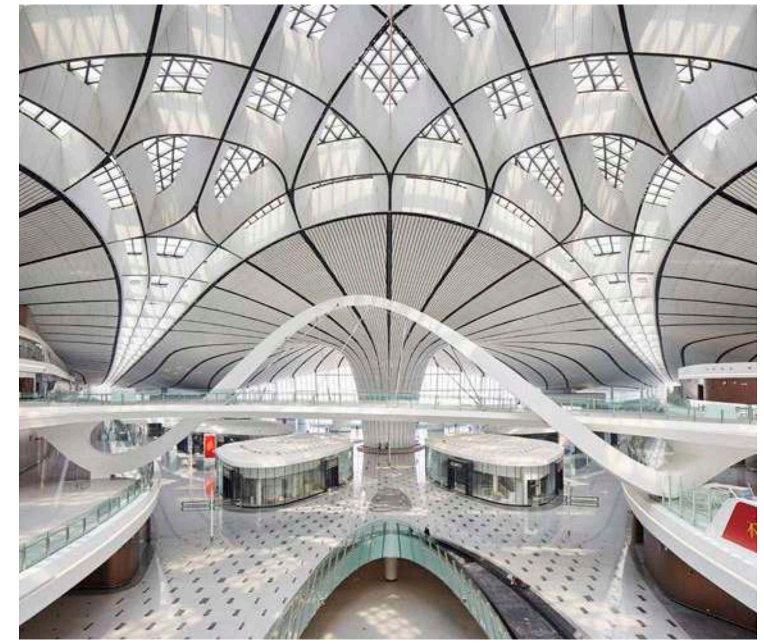
Arup conducted simulations to ensure the design was optimised for smoke extraction and that people would be able to escape. These tested what would happen if some vents failed to open or if smoke rose high into the ceiling, stratified, spread out, or lost its drifting power because of the heat. The results of these simulations were then used to refine the placement of vents and other measures. Arup also developed augmented reality tools to visualise the smoke simulation.

Interface with the railways
Below the airport terminal is the 80,000m² underground transportation hub for high-speed rail, intercity trains and the airport express to Beijing city. There are three underground stations, eight platforms and 16 tracks for five railway lines. The platforms are located on basement level two and the concourses on basement level one.

Arup liaised with both the railway and airport authorities to develop a strategy. Normally, fire safety plans in such cases are developed separately, but given the interdependency between the two in this case, that approach was not practical.

Arup developed a proposal that was accepted by the airport and railway approval authorities as well as the national fire expert review meetings. The firm proposed using the transportation interchange hall that connects the railway areas and the terminal as a main circulation space. This hall is designed as a safe area. It has features such as an opening towards the roof, sufficient means of escape to the outdoors and no high fire load use, such as retail areas or fuel storage. This significantly reduces the required number of egress stairs directly extending from the concourse level to the ground. It also means that during an evacuation, passengers can remain in a familiar, comfortable environment.

Fire-proofing the roof
Finally, the fire safety engineers had to consider the large-scale steel-framed roof structure. Under China's building code, steel structures need to be protected by fire-proof paint to make sure they achieve the required level of fire resistance. Arup's performance-based model looked at the worst-case fire scenarios and analysed their impact on the roof structure. The results showed that only roof trusses within a 6m to 9m distance above the floor needed to be fire protected. The majority of the roof structure did not require additional protection, as its height meant that it would be sufficiently far from any ground-level fire. This finding led to a cost saving of several million renminbi.


6.

6: The building's design means that smoke is directed upwards; the huge central atrium space at the airport's heart allows smoke to be diluted naturally

7: MassMotion helped to size and locate the vertical circulation elements such as lifts and escalators

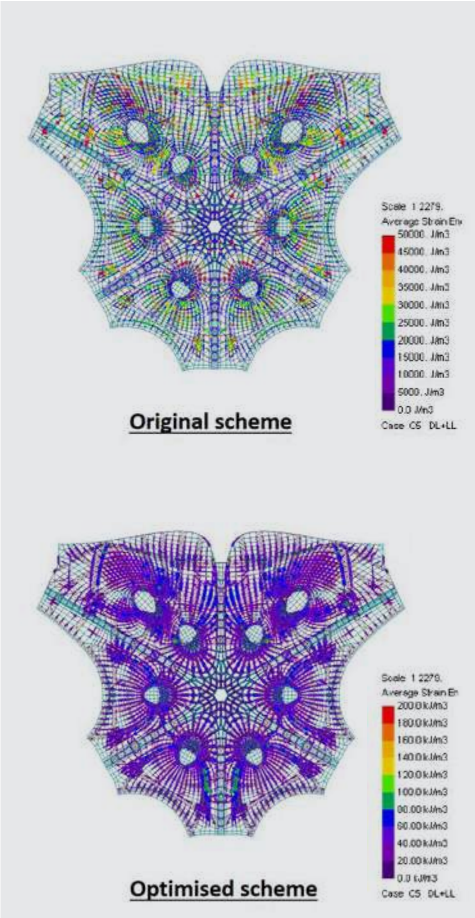
Terminal simulation and analysis
Beijing Daxing is expected to handle up to 72 million passengers by 2025. Arup used a series of simulation tools that combined airport schedules and passenger flow data to optimise the airport's design so that it can accommodate both the current and expected number of passengers. This was the first time an airport in China was fully simulated before construction and also the first project on which Arup integrated these two types of data and two different software packages, Simio and Oasys MassMotion.


7.

The detailed passenger flow outputs from the simulation tools enabled Arup to demonstrate the effects of suggested design modifications at a stage in the project when they were relatively inexpensive to implement.

Every aspect of the airport has been designed around passenger experience, which includes the provision of passenger processing facilities and sizing of corridors to prevent excessive passenger congestion. Passenger processing facilities include boarding gates, aircraft stands, check-in counters, bag drop areas, security checkpoints, passenger holdrooms, inbound and outbound border control, bag reclaim and washrooms.

Passenger flows were particularly complicated. Most international airports have departure and arrival areas split across different floors, but Beijing Daxing takes this even further, with domestic and international flights occupying separate floors. The main passenger flow therefore spans over four floor slabs. In addition, a separate check-in and security screening area in the basement is planned; this will serve flights at the proposed satellite building, which will be located away from the main terminal. All passenger flows needed to be connected to the roadways and the ground transportation centre. This meant that the analysis had to incorporate a complex set of vertical circulation demands spanning six floors in order to identify potential bottlenecks at different times of the day based on flight arrivals and departures.



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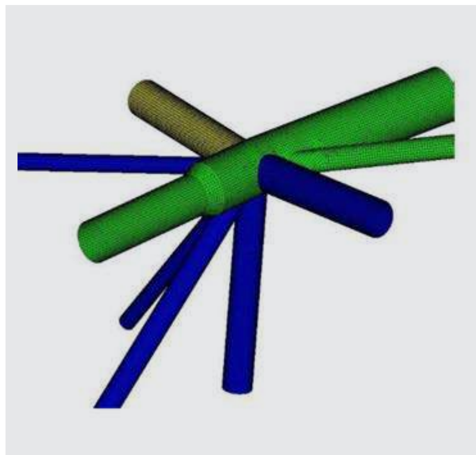
9.

8: Arup optimised the truss pattern scheme used in the complex roof structure using several analysis tools

9: In order to reduce the roof's weight, Arup recommended that some of the spherical joints on the longer spans be replaced by tubular joints

10: The roof is a continuously flowing dynamic shape


10.

The simulation was based on the flight schedule. It followed every passenger's movement through the airport's facilities to identify shortfalls or over-provision. The detailed simulation model, built in Simio 3D, helped decision-makers and stakeholders to visualise the airport's future performance. The passenger congestion model built in MassMotion informed the design, particularly with regard to the sizing of critical corridors. It helped to avoid the creation of geometric chokepoints, as well as inform the size and location of vertical circulation elements such as lifts and escalators.

Trolley simulations were also carried out to analyse the management of passenger trolleys both air-side (beyond security) and land-side. A Simio model was used to demonstrate how trolleys circulated from land-side car park to curb to check-in, and from arrival piers to reclaim carousels at air-side. The model allowed Arup to indicate the minimum trolley numbers in each storage area and to advise the client on how many operational staff would be needed and on the timing of trolley collection throughout the day. This helped the airport operator to optimise work procedures and reduce unnecessary trolley purchases.

Engineering the complex roof structure

One of the most important aspects of this project was the engineering of the roof, designed by Zaha Hadid Architects. The roof covers a 350,000m² area and is a continuously flowing dynamic shape supported by giant C-shaped columns. It has more than 170,000 steel members. Arup's role was to carry out a peer review and value-engineering exercise on the hyperboloid steel grid structure. This work was done when the construction drawings were almost finished, with a tight timescale to carry out the analysis.

Arup set up a computer model to analyse the structure within a week and completed the evaluation and optimisation in three months, in order to meet the deadline for the steelwork tendering schedule.

Arup used a wide range of analysis tools, including GSA, Sap2000, Strand 7 and LS-DYNA to carry out the elastic analysis, connection FEM analysis and non-linear analysis. Arup's extensive experience in long-span steel structure and structural optimisation tools enabled the firm to develop alternative designs. These resulted in a saving of more than 4,000 tonnes of steel (with the value of around RMB54 million) and a large reduction in carbon emissions.

A total of 420 load combinations were considered and 38 different cross-section sizes were employed in the superstructure. Through its review, Arup determined that about 1% of the steel members had exceeded their limits for deflection and required strengthening. More than 90% of the members had a stress ratio of less than 0.5. The team proposed various optimisation strategies to improve the roof truss patterns and reduce structural depth and member sizing.

The radius of many of the compression steel members was reduced, as they were already well below the slenderness ratio limit set by the expert review panel. For circular hollow sections that had slenderness ratios close to the 120 limit but with excessive margin in their strength and stiffness, their thickness was reduced to minimise self-weight. These strategies were most effective in the concourse wings; they achieved a 40% steel reduction in the north-west wing.

Single horizontal braces in the roof truss were replaced with higher tension cross-braces so that their sizes could be safely reduced. This led to a 70% reduction in bracing steel. In addition, the original scheme used a large number of spherical joints, with diameters ranging from 300mm to 900mm. Using finite element analysis, Arup recommended that for larger spans some of the spherical joints be replaced by tubular joints to reduce the structure's weight.

A new gateway for China

Beijing Daxing International Airport opened on 25 September 2019, with its first commercial flight landing the following day. The project is a new gateway for the capital and China as a whole, paving the way for the country's continuing economic growth.


11.


12.

11: A simulation model was used to predict every passenger's movement around the airport and optimise design accordingly

12: Ultimately, the airport is expected to handle 100 million passengers annually

Authors

Robert Feteanu led the passenger simulation and analysis aspects of the project. He is an Associate Principal in the Toronto office.

Ming Li was the Project Manager on the structural peer review. He is an Associate in the Beijing office.

Fangzhou Su worked on the passenger simulation and analysis aspects of the project. He is a senior analyst in the Toronto office.

Kelvin Wong was the Project Manager for the fire engineering design. He is an Associate in the Shenzhen office.

Vala Yu worked on the fire engineering elements of the project. She is an Associate in the Beijing office.

Project credits

Clients Beijing New Airport Construction Headquarters, Beijing Institute of Architectural Design (BIAD)
Joint venture partners ADP Ingeniérie, Zaha Hadid Architects, BIAD, China Airport Construction Co Ltd
Fire engineering, structural design peer review and optimisation, and passenger and logistics simulation and analysis services Arup: Najim Afzalzada, Jing Chen, Emo Chiou, Robert Feteanu, Jian-Yun Han, Clement Ho, Rita Ho, Karen Lai, Abby Li, Ming Li, Kevin Liu, Ling-Tao Liu, Peng Liu, Shirley Liu, Vincent Liu, Mingchun Luo, Daley Mikalson, Aarshabh Misra, Fan Qi, Bert Su, Fangzhou Su, Wei Sun, Yong-Shan Wan, Jolin Wang, Ryan Wang, Shiny Wang, Kelvin Wong, Michael Wu, Emily Yang, Young Yang, Flora Yao, Kim Yong, Vala Yu, Jin-Ai Zhang, Leo Zhang, Cong-Ming Zhong.

Image credits

1, 3–5, 8, 9: Arup
2, 6, 7, 11: Hufton + Crow
10: Zhou Ruogu Architecture Photography
12: Xinhua News Agency

1.

1: Stretching 3.4km, the bridge crosses the Saint Lawrence River and the international shipping channel, which links the Atlantic Ocean to the Great Lakes

Bridging the gap

Arup's expertise meant an essential piece of infrastructure was delivered two and a half years earlier than originally planned and within the project budget

Authors Douglas Balmer, Jo Balmer and Matt Carter

In June 2019, Montreal celebrated the opening of the 3.4km Samuel De Champlain Bridge, one of the largest and busiest bridges in North America. Crossing the Saint Lawrence River and its international shipping channel, it is a vital thoroughfare for both goods and people, accommodating in excess of 50 million crossings and facilitating CAD$20 billion (around £12 billion) of trade every year. Built through a public-private partnership (PPP) between the Government of Canada (via Infrastructure Canada) and the Signature on the Saint Lawrence Group, it is a landmark structure forming a gateway to the city of Montreal.

The construction of the bridge was part of the CAD$4.24 billion New Bridge for the Saint Lawrence Corridor Project, a major urban highway improvement project in the Montreal metropolitan area and one of the largest infrastructure schemes in North America. The project also encompassed the construction of the 500m Île des Sœurs Bridge and the renewal of 8.5km of highway; there is a dedicated public transport corridor incorporated, as well as an enhanced network of pedestrian and cycling paths throughout the corridor.

Arup's challenge was to define and enable procurement of a durable yet architecturally pleasing new bridge before the ageing original Champlain Bridge reached the end of its useful life. Drawing on its global knowledge of PPP procurement on major infrastructure projects, Arup provided comprehensive technical advisory services, and engineering and procurement strategies to the Government of Canada.

Transport linchpin

The Samuel De Champlain Bridge crosses the St Lawrence River on a broadly east–west alignment and connects the City of Montreal with the municipality of Brossard on the south shore. It has an asymmetrical cable-stayed main span of 240m, supported by a single, elegant 160m pronged tower, with elevated approaches on either side. Gradual horizontal and vertical curves along the length of the structure provide an ever-changing view for everyone who crosses over or passes by the bridge. The resulting bridge is visually spectacular and built for the long term. It has been designed so that it can adapt to the changing transport needs of the region and has a lifespan of 125 years – significantly longer than the 75-year period normally required of such infrastructure in Canada.

Arup was selected to be the owner's engineer, providing Infrastructure Canada with full engineering and coordination services for the bridge. These included civil, structural, bridge, geotechnical, highway, mechanical and electrical engineering, as well as security, fire, threat mitigation, life and sustainability consulting services. The firm also provided expertise in programme and project management; asset management; acoustics, aviation, lighting, operational and maintenance requirements; economic and cost estimating; and procurement advice. Arup's streamlining of the procurement process was crucial to the successful completion of the project.

The need for a new bridge

In Canada, infrastructure is generally the domain of provincial governments, but certain international or critical assets are managed by the federal government. The Champlain Bridge is one such asset due to its strategic value. It crosses the Saint Lawrence Seaway international shipping channel that links the Atlantic Ocean to the Great Lakes, connects Quebec and Ontario to the United States, and links to three major highways (Autoroutes 10, 15 and 20).

Arup's initial appointment in 2012 was to help develop the business case for this bridge for the Canadian government. The existing bridge required significant structural strengthening and ongoing maintenance costs owing to its exposure to extreme winter weather and a harsh schedule of de-icing salts. These had led to irreversible corrosion, which was further compounded by large increases in traffic using the route.

Arup was tasked with developing a range of technically viable bridge options in order to understand the costs and practicalities for each bridge scheme, before taking the project

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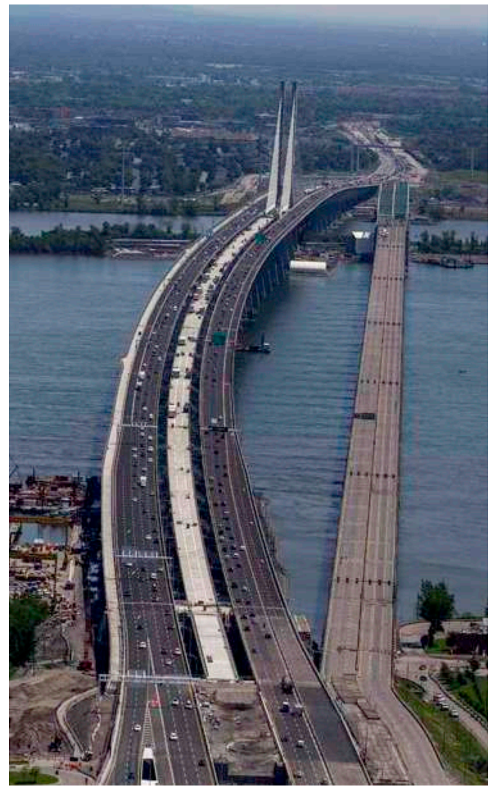

3.

forward to the procurement stage. The government had already spent hundreds of millions of dollars to keep the old bridge operational, so Arup had the foresight to develop two timelines for the project; one where it would progress in a business-as-usual scenario, aiming for completion in 2021; and an accelerated schedule taking into account the deteriorating condition of the existing bridge so that the new bridge could be opened by the end of 2018.

Through a two-stage screening process, a long list of bridge options was reduced to three preferred alternatives. Based on Arup's recommendation, one of these was selected as the base case design for carrying out more detailed cost estimates and quantitative risk analyses to determine the viability of the project, the procurement method and the required budget. During the summer of 2013, when it became apparent that ongoing maintenance problems on the existing bridge were more acute than anticipated, Arup was asked to move ahead with the accelerated timeline and was awarded a contract to get the new structure to market as quickly as possible.

An aesthetically pleasing design

As well as being a strategic section of the region's transport infrastructure, the bridge was required to be a landmark piece of architecture for Montreal. Arup led an integrated team of engineers and architects (Danish architects Dissing+Weitling and local architects Provencher_Roy) to deliver this. The design comprises three corridors, with the bridge's cable-stay span supported by a 160m tower in the shape of a tuning fork, flanked by an elegant harp of cables.

The total length of the bridge is 3.4km from the west to the east abutment, with a navigation clearance to 38.5m above the Seaway channel. The vertical alignment of the western approach smoothly rises over the width of the river. This option was considered to be preferable from both an aesthetic and operational perspective, and was a change from the older bridge, which had a relatively low and flat section over the majority of the river before starting an abrupt, steep gradient to climb over the Seaway channel.

From the beginning of the process, the provincial government stated its aspiration to eventually replace the planned bus services that crossed the bridge with a light rail system. However, there was no specific timeline for this plan, so the three decks were created with this eventual transition in mind. The idea was that, at least initially, the two outer decks would be used as highways, while the central one would be reserved for bus transit. When the shift to a rail system began, the plan was for buses to use a temporary reserved bus lane on each of the highway decks, while a light rail corridor would be built down the middle deck.

Connecting communities

The abutments on either side of the bridge serve four primary functions: providing vertical and lateral supports for the east and west approach structures; retaining the adjacent embankments that support the roadway; housing the mechanical and electrical equipment necessary for bridge operation and maintenance; and providing architecturally novel features at the entrance and exit points of the bridge.

During the development of the business case, the west abutment was set to be located to the west of Boulevard René Lévesque, a road that passes beneath the bridge close to the shore. However, a subsequent study indicated that a preferable placement for the abutment was on the east side of this road, next to the river. Although this required a small amount of reclamation in the river, it had the major advantage of providing maximum flexibility for the future construction and urban

2: The original Champlain Bridge was opened in 1962

3: Arup's initial appointment was to help develop a business case for the new bridge

4: The 240m main span is supported by a 160m-tall pronged tower

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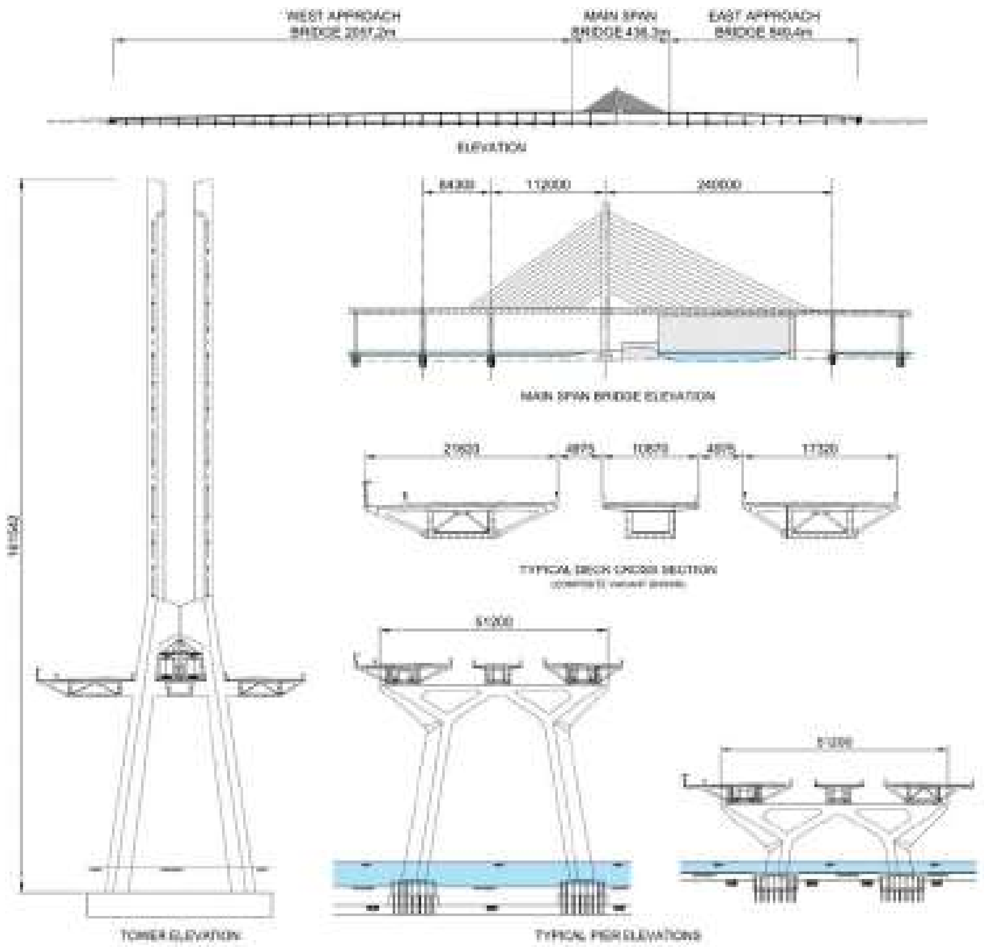

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5: The design process included a programme of architectural reviews with a panel of local engineering, architectural, urban planning and heritage professional bodies

6: Longevity has been built into the design by using stainless steel and concrete

7: The width of the highway decks was increased to accommodate bus lanes

8: The bridge is made up of three separate box girders

9: Built for the long term, the bridge has a lifespan of 125 years

integration of a transit station if the bridge was converted to carry light rail on the central deck. The abutment placement also had the benefit of shortening the length of the main bridge by approximately 70m, so this was the option that was ultimately selected. To allay concerns regarding views to the river, the span of the bridge that was required over Boulevard René Lévesque was significantly increased to maintain as many sightlines as possible.

As Arup further defined the scheme, it proposed that the spans be increased for the sections carrying the reconstructed highway over local roads, to both help reconnect communities and provide space for pedestrian and cycle paths, thus promoting active transportation. To further enhance the community connections, a 3.5m-wide multi-purpose path was constructed on the north side of the new Samuel De Champlain Bridge to provide a direct pedestrian and cycling connection over the St Lawrence Seaway and River. As the project progressed, Arup undertook studies to assess the viability of keeping the link open as much as possible


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during the harsh winter months, which led to the Minister of Infrastructure and Communities being able to declare that the multi-purpose path would be open year-round.

Defining moment

Arup's considerable experience in designing long-span bridges (including the Queensferry Crossing in Scotland and the Oresund Bridge that links Malmo in Sweden with Copenhagen in Denmark) meant the team had the expertise to ensure that architectural aspirations were mandated through contract documentation. The approach required the use of a 'definition design' within the PPP procurement process, a first for the North America market.

The definition design that Arup developed clarified the intentions in terms of aesthetics, ensuring that all bidders would consider the technical and visual dimensions of the design when submitting their bids, thus safeguarding the bridge's architectural integrity through to the final stages of the project. In order to arrive at a definition design, it was necessary to first generate a preliminary design for the bridge that was compatible with both the architectural vision and all other project constraints. Then, critical dimensions and tolerance allowances were identified to form the definition design requirements, which ensured that the design was preserved during the procurement and construction process by mandating certain geometric elements in the project requirements.

Given the prominence of the new bridge, and the public interest, this design was not developed in isolation but included a programme of architectural reviews with an Architectural Quality Review Panel (AQRP) that consisted of representatives from the local engineering, architectural, urban planning and heritage professional bodies, and the City of Montreal. Animations and renderings of the bridge were produced in 3D, which helped to respond to any concerns and explain how the project would improve the built environment in a sustainable way. For example, belvederes were incorporated into the elevated bridge design on the north corridor. Along with a viewing platform below the bridge, these provided vantage points for the public.

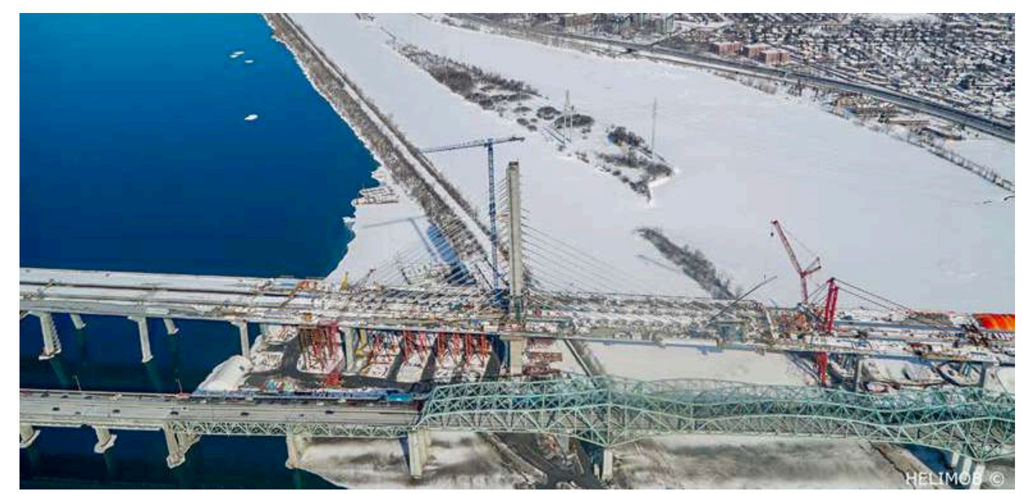
This AQRP consultation process meant that the design was developed with the cooperation of local stakeholders, with the finalised architectural design received well by the public. It also permitted the Minister of Infrastructure and Communities to announce the design of the bridge, and legitimately declare that "what you see is what you will get".

Because the definition design integrated all the constraints included in the technical requirements, while still allowing flexibility in terms of materials and methods of construction, the bidding proponents were able to save significant time in elaborating their proposal.

Accelerated programme

Shortly after the project team completed the business case for the new bridge, it became apparent that the condition of the existing bridge that served the route was rapidly deteriorating. Despite the costly repairs and maintenance that had already been implemented on the 1960s structure (and others that were planned), the bridge was deemed to be living on borrowed time. Arup's team recommended and implemented strategies to accelerate the preliminary design and procurement process. Arup produced the procurement documentation in eight months, enabling the PPP project to reach financial close in June 2015. The bridge was then constructed in a mere 48 months. This was two and a half years less than the original timeframe, while remaining within the government's original budget.

Arup drew on lessons from its past projects, including the Tappan Zee Bridge in New York, to bring the project rapidly to market, compressing the procurement preparation period. The firm refined the reference design, amending as appropriate to accommodate the outcomes from stakeholder consultations, and also to incorporate Arup's own assessments on how to improve the lives of those who lived and worked close to the highway and bridge corridor. The reference design served



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10: To support the three separate box girders, a W-shaped system of supports was used

11: The bridge was constructed in just 48 months

12: Arup drew on lessons from its past projects, including the Tappan Zee Bridge in New York, to bring the project rapidly to market

to help define the project's technical requirements, and thus inform the cost and schedule estimates. It was used to demonstrate that the design was technically viable and achievable within the proposed budget and timeframe.

The main objective was to open the new bridge as soon as possible, without compromising the safety and security of workers or the quality of work. For some of the most important aspects, especially those relating to durability and the need to achieve a 125-year design life, the specifications developed by Arup were more prescriptive than usual. For example, they stated that stainless steel reinforcement, rather than regular steel, should be used in critical areas, so the bridge was more likely to realise the durability criteria. This also took away the potential for protracted approval discussions during the delivery phase.

The bridge's durability was a key concern. A layered approached was adopted, working on the principle that if something was important, it needed to be specified in the contract. If there was the possibility that one form of protection could fail, due to issues with design, construction or maintenance, a secondary measure provided an additional layer of protection. Given that the team was working to stricter standards than officially required (aiming for a 125-year lifespan rather than the legally mandated 75), emphasis was placed upon adopting tried and tested solutions that would help to achieve the required design life.

Realising the vision

To support the three separate box girders, Arup proposed a W-shaped system of supports, almost with the appearance of fingers supporting the highway and central public transport decks, all supported on two sloping piers. There are 37 W-shaped frames in total, each weighing approximately 450 tonnes and measuring 51.2m x 11.4m x 3.3m. These were installed on 74 separate pier footings of approximately 11m x 11m x 2m, each weighing between 600 and 1,000 tonnes. Of these, 38 footings were prefabricated on site and 36 were constructed in situ.

The tower supporting the cable-stay main bridge span comprises two tapered concrete legs connected by a tapered concrete cross beam. This tower was constructed adjacent to the seaway dike that frames the navigation channel. A berm, at the base of the tower, was added to aid construction and retained as a permanent feature to serve as a maintenance and work platform for the bridge and to provide a viewing platform. About 200,000 cyclists per year use the cycle path on the dike, and the platform offers an excellent vantage point from below the bridge of the sculptural piers supporting the deck, the bridge's curved alignment and the river habitat.

Either side of the bridge, the highway and four interchanges have been reconstructed. Arup consulted, assessed and documented in the PPP contract the requirements that needed to be met. For example, the presence of a major sewer alongside Highway 15 required detailed analysis and optioneering to improve the eventual solution. Owned by the City of Montreal, it provides drainage for about a third of the city. Due to its location and limited construction records, it was not possible to fully inspect and assess the sewer's condition before construction of the bridge commenced. Part of the challenge was to develop a process that would not have an impact on the sewer. The design-build contractor adopted a solution similar to that foreseen in the Reference Design, which used polystyrene (lightweight fill) embankments to minimise the imposed load on the sewer during construction.

Looking to the future

The bridge opened in June 2019, saving two and a half years on the original schedule, while staying within the planned budget.

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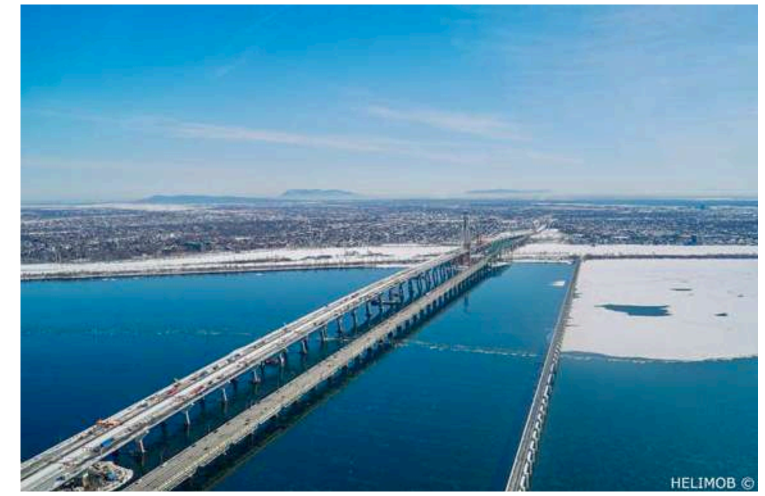

12.

Longevity was built into the design by the use of robust materials, including stainless steel and concrete; modifications to standard concrete mix specifications; and requirements for protection against ice abrasion as well as a comprehensive structural-health monitoring system. Arup prescribed such measures in the design that went to tender, to ensure the design-build contractor included these important features in its construction.

Since the original design was devised, the provincial government has decided to go ahead with constructing the light rail scheme across the bridge. This means that buses will not run along the middle deck, so the foresight to increase the width of the highway decks to accommodate temporary bus lanes is already benefiting road and bus users.

The provision of this new and more efficient public transit system has advantages for the local environment and improves accessibility for the local population. The combined pedestrian and cyclist pathway provides an invaluable alternative form of transportation, which is proving particularly useful for the previously poorly connected communities in the area, and the viewing points mean that the bridge is a tourist attraction in its own right. Arup has also completely redesigned an interchange that bisected two parts of the city. In addition, in several nearby areas, roads have been reconfigured to make them greener, cleaner and quieter, enhancing community connections and promoting physical activity.

All this was made possible by the client and project team always keeping in mind the twin focus of improving the lives of the local populace and creating an iconic new landmark in Montreal.

Authors

Douglas Balmer was the Project Director. He is an Associate Principal in the Montreal office.

Jo Balmer was the Project Manager. She is an Associate in the Montreal office.

Matt Carter was the bridges lead on the project. He is a Principal in the New York office.

Project credits

Client 2012–14 Transport Canada 2014–20 Infrastructure Canada and Public Services and Procurement Canada
Architects Dissing+Weitling Architecture and Provencher_Roy + Associés Architectes Inc.
Traffic modeller Loctrans Inc.
Road and environmental design services Groupe S.M. International Inc.
ITS and tolling IBI Group
Electrical and lighting Roche Ltd, Consulting Group
Private partner Consortium Signature on the Saint Lawrence Group
Design build contractor Signature on the Saint Lawrence Construction
Infrastructure design, bridge, civil and geotechnical engineering Arup: Aidan Archer, Andrew Armstrong, Mahsa Azad, Stephen Baldrey, Douglas Balmer, Jo Balmer, Pouya Banibayat, Abeera Batool, Maxime Bellefeuille, Ken Bontius, Clifford Bouchereau, Jean-Claude Bourque, Matt Carter, Mei Cheong, Sarah Cholloux, Pierre-Louis Cons, Anthony Cortez, Sebastien Cote, Margaret Cowie, Gary Crisp, Sebastian Cumpatescu, Ankit Desai, Joseph Digerness, Bob Donker, Chris Donovan, Jelena Durovic, Juan Echague, Casey Eckersley, Georges El Chammas, Corey Fan, Adam Finkin, Matthieu Galland, Ahmed Ghazi, Javier Gonzalez, Steven Gresk, Eric Guerra, Dawn Harrison, Sylvana Hochet, Martin Hooton, Vicki Hope, Aidan Hopkins, Evan Hughes, Sayed Kadiri, Tim Kaiser, Gerard Keogh, Amjad Khan, Martin Landry, Rebecca Lasry-Legault, Anthony Lefour, Diana Lubniewski, Bill Maddex, Sanjeev Malhotra, Bryan Marsh, Peter Matusewitch, Keith McCall, Colin McCreath, Andrew McNulty, Omar Metwally, Maria Mingallon-Villajos, Kelvin Moneypenny, Omar Moussa Shehata, Guillermo Munoz-Cobo Cique, Dimitrios Niarchos, Ryan Nolan, Louise O'Neill, Chuck Ormsby, David Orta, Ralph Otrembiak, Mariona Pahisa, Nicolas Pawlonka, Adrian Pena-Iguaran, Francisco Perez, Paolo Perugini, Lana Potapova, David Pratt, Audrey Provost, Louise Ann Quevillon, Isabelle Raymond, Mark Roche, Léonard Roussel, Francisco Rueda, Laurent Rus, Marina Saez, Dan Saville, Lauren Scammell, Nicole Scanlon, Juanma Serrano, Will Sims, Jelena Sisko, Jordy Tang Hon Yue, Daniel Tarantino, Graham Thomas, Assumption Uber, Monica Valls Marquez, Carmen Venegas Perez, Yannick Vintila, Jeff Walter, Nicole Washington, Paul Wilson, Christopher Wong, Roger Wood.

Image credits

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2, 4–8, 10, 11: Arup
9, 12: HELIMOB

1.

1: Guoco Tower consists of two towers that offer residential, hotel, office and retail space

2: An urban park in front of the building provides a green public space in the heart of this humid city

3: At 290m, the 64-storey tower is the tallest building in Singapore

2.

An oasis in the city

The construction of these geometrically complex towers was achieved at great speed and with minimal disruption to the surrounding area

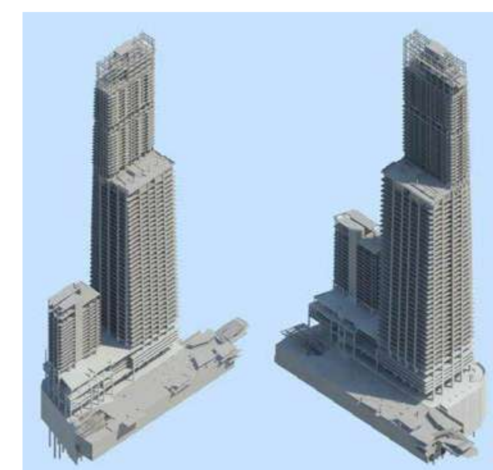
Authors Dion Ananditya and Jason Tan

Guoco Tower is a 156,000m² mixed-use development consisting of premium office, residential, hotel and retail space. Named after its occupant and owner, property developer GuocoLand, it sits at the heart of a neighbourhood that is swiftly being transformed into Singapore's next business and lifestyle hub. Working in conjunction with US architectural practice Skidmore, Owings & Merrill, Arup was responsible for civil, structural and façade engineering, and sustainable building design.

The development comprises two towers; the taller, at 290m, is the tallest building in Singapore. It is linked to the smaller 105m tower by a podium that offers 10m column-free, ceiling-to-floor views across the area.

Part of the brief for Guoco Tower was that the development should attract people, becoming a vibrant centre of activity amid Singapore's central business district. In order to provide an area the public could enjoy, a 14,000m² urban park was created in the space in front of the buildings. This is a rare patch of shaded outdoor public space in hot and humid Singapore, where recreational areas generally tend to be indoors and air-conditioned. Amid this lush greenery is a 15m-high canopy that creates a sheltered 'city room'. This can host activities all year round and provide relief from the often stifling heat of the city.

Further ensuring that the development will attract people, the centre connects directly to the Tanjong Pagar Mass Rapid Transit (MRT) metro station via three basement levels, which are 18m deep in total. This proximity to an integral piece of urban infrastructure created challenges for the design and construction of the scheme. The Guoco Tower site is also surrounded by small roads, historical shophouses and buildings with shallow foundations, further adding to the complexity of the construction process.



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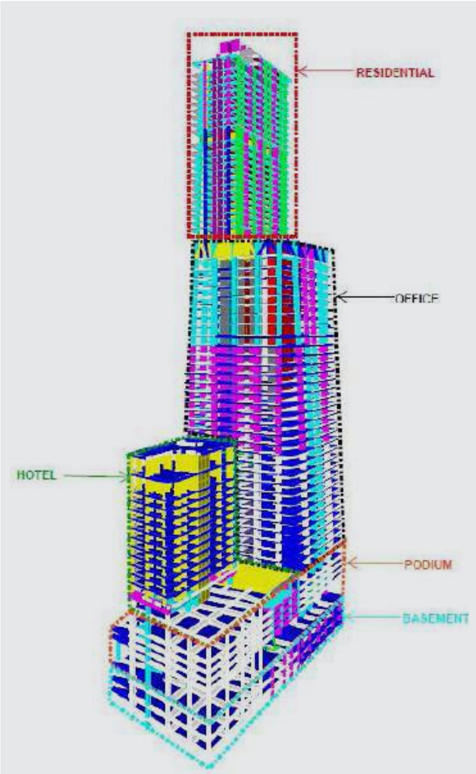

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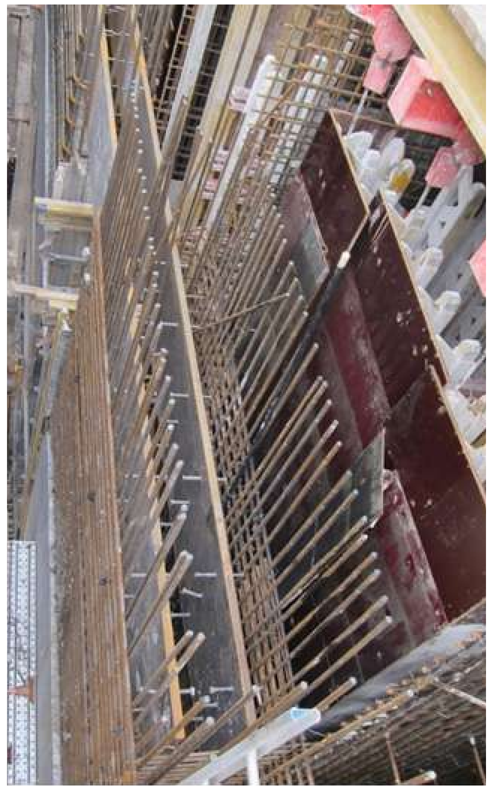


5.

To create the open space within the podium that links the two towers, Vierendeel steel frames are used from levels two to five, spanning 26.4m. Transfer beam structures are located within 2.5m-deep reinforced concrete at level seven of the hotel tower, transferring weight to the composite columns below.

To allow for the angular shifts in the shape of the 64-storey tower, outward-sloping southern perimeter columns have been installed from level one and inward-sloping northern columns have been put in place from level 26. The horizontal 'kick-out' forces where the sloping columns change direction at level six – as well as on the floors just above and below these transition points – are resisted by steel floor beams that act as tying structures, as well as by steel connectors that direct loads to the core walls through the steel columns and beams at level six. At level 39, additional stability is supplied by transfer beams acting with perimeter belt trusses. These transfer loads from the walls/columns of the residential section of the taller tower to the office floors below.

Geometrical complexity

The two towers are connected by a public-facing six-storey podium at their base. The 64-storey tower contains office space on its lower 37 levels and a mechanical floor at level 38, with residential space taking up floors 39 to 64. At the western end of the site, the 21-storey 105m tower contains a six-star hotel from levels 5 to 20, with a mechanical floor on the top level.

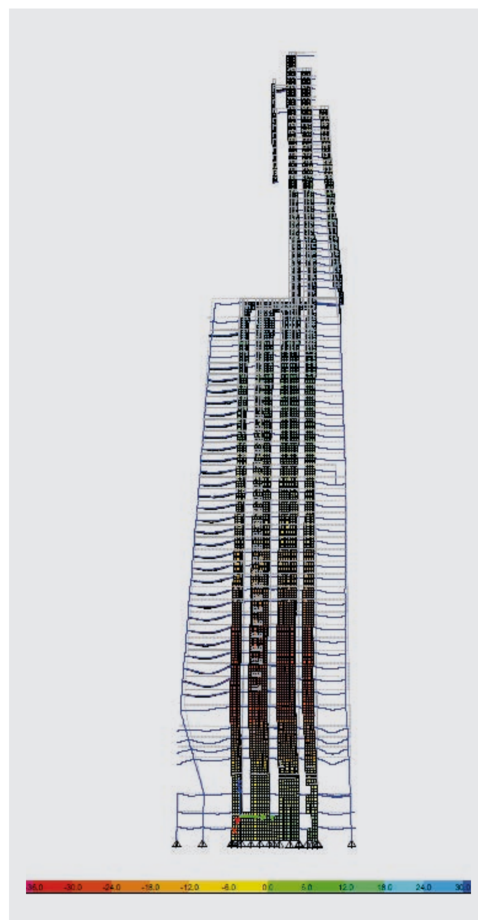
The structure is characterised by its elegant form – two tapered towers with angular shifts at several levels that create intriguing dips and turns. The scale and unusual shape resulted in significant engineering challenges, as these angular changes create opposing forces at different levels that had to be accounted for in both the design of the buildings and the construction process. At level six, for example, the tallest tower slopes on its southern side, and the floorplate is reduced dramatically above level 39, with weight shifting to the northern side. The result was that this tower was predisposed to lean southwards at its base, while the counterweight from the higher levels would move it towards the north.

Working with the architect, Arup's task was to take this ambitious vision and develop the design without compromising the building's structural integrity. Crucial to this was creating lateral stability via a central core wall made up of cast-in-place reinforced concrete, into which large steel plates with enormous shear studs were embedded at the points of greatest tension. At level one, reinforced concrete beams transfer horizontal forces to the core wall in the basement. To provide further stability, reinforced concrete links and coupling beams are located above doorways and corridors, and additional shear walls have been installed around stairways and mechanical rooms, as well as passenger and service elevators.

4: The two towers are linked by a podium level. The taller tower offers office space up to level 37, and residential space from level 39 and above

5: To create lateral stability, the central core wall was made of cast-in-place reinforced concrete with embedded steel plates

6: The tapered towers have angular shifts that create opposing forces



6.

Awards

Council on Tall Buildings and Urban Habitat
Urban Habitat – Single-Site Scale – 2019 Award of Excellence

FIABI Singapore Property Awards 2019
Mixed-Use Development Category (Winner)

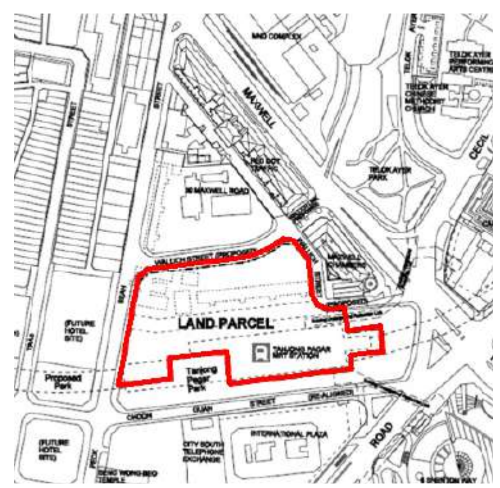
Land Transport Excellence Awards 2019
Best Design for Land Transport Integration Award (Winner)

The Institution of Structural Engineers Singapore Structural Awards 2018
Supreme Award for Structural Engineering Excellence
Tall or Slender Structures category (Winner)

Association of Consulting Engineers Singapore
Design Excellence Award 2018 (Winner)

Building and Construction Authority
Design and Engineering Safety Excellence Award 2018 (Winner)
BIM Award 2015 (Gold)

7.



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At the transfer floor on level 39, where the tower changes from office to residential use, an innovative 1.3m-thick transfer composite steel and concrete floor plate was created directly below the columns in the residential levels. This was to circumvent the difficulties of installing falsework and scaffolding at such a height, and with such heavy loads involved, and to reduce the amount of labour involved in construction. This floor plate acted as temporary formwork, doing away with the need for propping.

Speeding up the construction process

Constructing a building in the middle of Singapore's central business district adjacent to an operational metro system meant that speed was essential. Arup was charged with finding engineering solutions that could contract the construction process to fit within the tight project timeline. Essential to this was the adoption of a top-down basement construction process, which meant that the superstructure could be constructed at the same time as the basement levels. To enhance productivity at basement level, steel was used for the basement and podium construction.

The construction process was refined to be as fast and efficient as possible. Materials were procured three months ahead of schedule. The cutting and drilling of segments was carried out with the utmost precision to ensure that each component was fabricated accurately and was easily identifiable throughout the fabrication process. The components that were made of 100% steel were fabricated off-site, where quality could be best controlled. Off-site construction also meant less overall disruption to the neighbourhood around the construction site, which as a result was safer and experienced less noise, dust and vibration.

In order to reduce the number of temporary supports needed for the erection of the floor structures in the office levels of the taller tower, steel decks forming concrete ribbed slabs were adopted. These steel decks spanned up to 8m across the post tensioned (PT) beams as ribbed slab formwork, supported in turn by temporary supports at the PT beams. The permanent structure was formed after pouring concrete over the deck, with the steel profiled sheet serving as permanent formwork.

The engineering team and the contractor, Samsung C&T Corporation, spent a lot of time planning the project to ensure it ran efficiently. The team studied all possible site access, storage space and cranage capacity available before deciding how the segments would be fabricated. Wherever possible, bolted connections were used for floor beams, in order to maintain an efficient construction and installation process. This efficiency was further extended with the use of automated cutting and welding machines for the built-up concrete and steel sections.

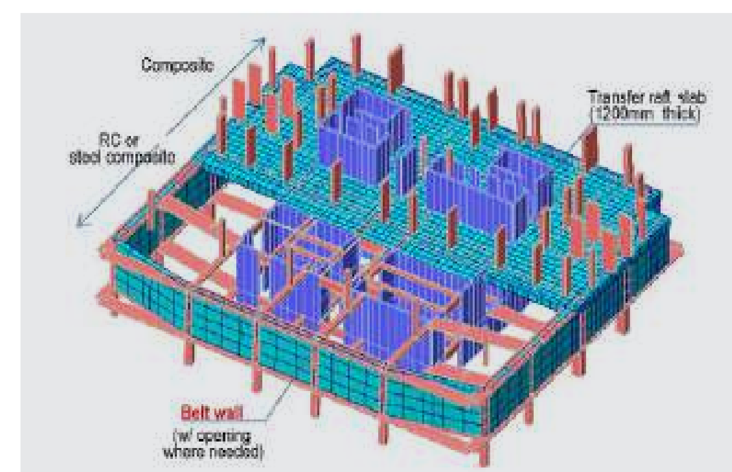
The benefits of steel

The use of steel, rather than reinforced concrete, on the basement and podium levels was also essential to speeding up the programme. This was an unconventional move – the building was one of the first hybrid concrete and steel structures to be built in Singapore. Even though steel is more expensive than reinforced concrete, the benefits of expediting the process by using the material were deemed to be worth the extra cost.

7: Steel plates with shear studs were embedded at key tension points

8: The towers are located in a crowded area containing many adjacent structures and differing soil complexities

9: At level 39 of the taller tower, a transfer raft plate was installed to act as temporary framework



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10: Speed was essential in the construction of the towers, which are located in a busy area of central Singapore

11: A 15m-high canopy in front of Guoco Tower provides a cool, shaded 'city room'

11.

Steel floor frames and composite slabs on the basement levels and podium meant that temporary formwork and scaffolding were not required. Due to the lighter self-weight of the steel structure, compared with the concrete structure, five additional upper floors were constructed during the top-down construction of the basement and podium levels – this would not have been possible in a fully reinforced concrete structure. As a result of this strategy, the structures were completed two months earlier than scheduled.

Steel's lightness meant the components could be easily transported to the site. In general, construction with steelwork is much faster compared with other materials, because steel allows for a more efficient and safe sequencing of a construction programme.

Accommodating the MRT station

Guoco Tower is located immediately adjacent to an MRT station that is supported by raft foundations. As such, one of the biggest challenges was to control the movement of the MRT structures, as well as of the two other buildings founded on shallow foundations less than 20m away from the development.

Arup undertook careful mapping and 3D modelling of the movements of the two buildings to understand the impact that excavation works and their long-term settlement would have on these existing structures. It began by using 2D analysis to size the wall elements and predict ground movement behind the new basement structures. Due to the complexities of the soil and existing adjacent structures, 3D modelling was used to study the effect of excavation and long-term settlement of the structure itself.

The 3D models were used to analyse the phasing of the project to better control the wall deflections of the MRT station. Arup worked with the contractor to phase the construction so that the basement levels doubled as supports to the retaining walls, thereby meaning there was minimal disruption to the station's usual operations. These analyses also informed the approach to the design; for example, the decision to keep the building's base slab at the same level as the existing raft foundation of the MRT station. This also translated into a 30% saving on creating piled raft foundations and a reduction in the number of piles required. The main tower is founded on a 4m-thick raft supported on 1.8m-diameter bored piles, extending approximately 40m below the base of the raft.

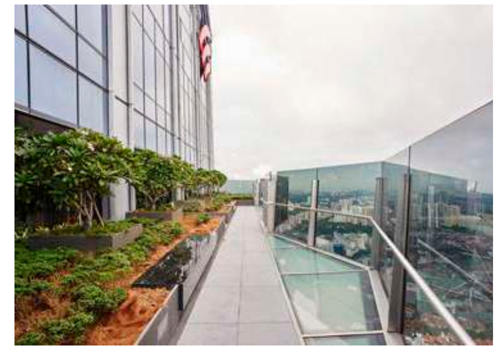
A sustainable high-rise

Guoco Tower has been awarded Green Mark Platinum rating and a LEED Platinum certification for its office and commercial spaces, as well as a Green Mark Gold^{Plus} for its residential elements. It is one of very few buildings in Singapore to achieve such high standards of environmental sustainability. This was achieved through a combination of energy- and water-saving strategies, as well as the provision of ample public green space.

One of the most innovative aspects of the project's sustainability plan relates to water conservation. Owing to rainwater harvesting facilities on its rooftops and water storage facilities in the building's basement, there is almost zero stormwater run-off when it rains. This recycled water is used to irrigate the greenery that surrounds the building and for flushing the lavatories, which means the building's water usage is half that of a conventional building that meets current local environmental codes.

For the residential areas, natural ventilation is provided through operable windows. Fresh air is delivered to the interior office spaces at a rate that is 30% higher than a conventional office building. This is complemented by shading on the façade that controls the amount of sun that reaches inside the building and heats it up.

Materials were also chosen with sustainability in mind. For example, all the



12.

13.

wood in the building is Forest Stewardship Council certified, and recycled steel and concrete were used as far as possible. The use of steel in particular was crucial to meeting environmental goals, as it produces less dust, noise and carbon emissions during construction than other options, and can be reused and recycled.

Photovoltaic (PV) panels have been placed on the rooftops and the canopy in the public plaza. Placing them in this latter space was challenging, because of the dual need to create shade for people and maximise the amount of sunlight received by the PV panels. Arup carried out thermal modelling to ensure the plaza space was designed in such a way that it was both sheltered by Guoco Tower and also well ventilated, meaning it is comfortable to use year-round. The use of PV panels and energy-efficient building services systems is estimated to contribute to 31% energy savings compared with similar buildings. Studies of thermal comfort criteria informed the design of the canopy, including its glass roof. The PV panels on its surface allow soft light to filter through while capturing the energy from the sun.

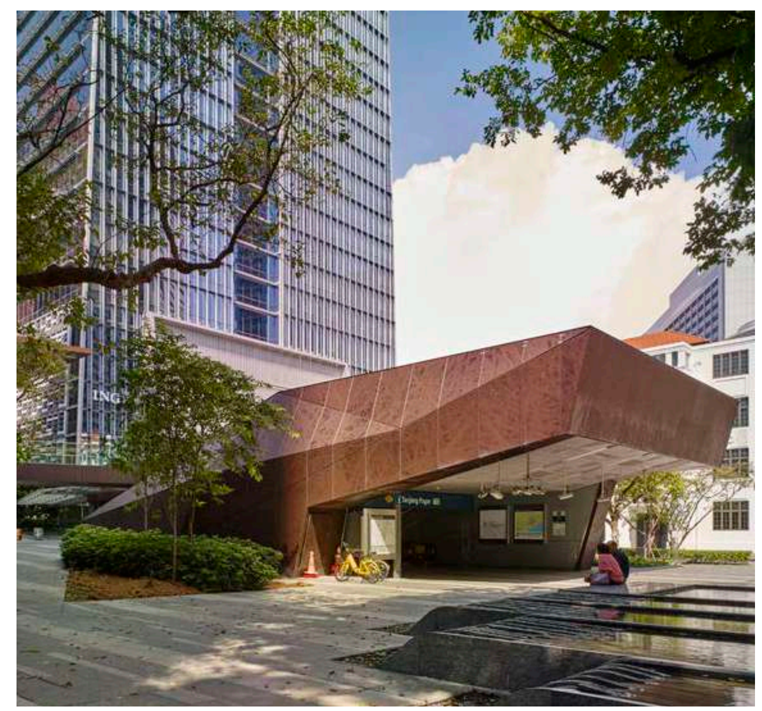
A blueprint for sustainably constructed buildings

Since its completion, Guoco Tower has won several awards for its design, engineering and innovative use of materials. The apartments at the top of the skyscraper have become among the most highly coveted slices of real estate in the city. Perhaps most crucially, the building is at the forefront of sustainable construction and engineering and will act as a model for future mixed-use developments across the region and beyond.

12: Rainwater harvesting facilities on the rooftop assist with reducing stormwater run-off

13: PV panels have been installed on the plaza canopy

14: Guoco Tower connects directly to the Tanjong Pagar MRT station



14.

Authors

Dion Anandityo leads the sustainability team in the Singapore office.

Jason Tan was the Project Manager and one of two Professional Engineers responsible to the local authority for the design and overall project supervision. He is an Associate Principal in the Singapore office.

Project credits

Client GuocoLand Group
Architect Skidmore, Owings & Merrill LLP (SOM) in association with architects 61
Main contractor Samsung C&T Corporation
Steel fabricator TTJ Design & Engineering
Civil, structural and façade engineering and sustainable building design Arup: Ivy Abo, Alexander Agung, Liyana Ahmad, Joseph Amores, Dion Anandityo, Christine Ang, Serene Ang, Christopher Anoso, Eddra Ardentiana, Jenny Austin, Sandar Aye, Renuga Chandra, Wei Cheng, Henry Chia, Wah Kam Chia, Dominic Chong, Shiao Teng Chow, Russell Cole, Shane Collins, Majal Dag, Gino De Castro, Feng Gao, Gladys Goh, Liana Hamzah, Eric He, Subash Kathiresan, Min Kyi Myo, Lukki Lam, Phuong Le, Jia Le Ngai, Wong Lei Lei, Keithson Liew, Jia Yuan Lim, Lip Boon Lim, Julius Limanjaya, Siaw Ling Hiew, Bee Choo Lloyd, Geena Loke, Sin Ching Low, Kimberly Lu, Farong Luo, Tim Lyon, Nur Farah Mazlan, Wing Sze Mo, Jon Morgan, Mitchell Mulvey, Daniel Mulyawan, Scott Munro, Sabariah Norman, Nilo Ola, Azri Omar, Jimmy Pang, Sam Peart, Sujesh Piillay, Jason Poon, Ronilo Portugal, Virgilio Quinones, Nizar Abdul Rahim, Jerr Ricafort, Ei Sandar, Jamie Scott-Toms, Heng Seng Lee, Daniel Simmonds, Benjamin Sitler, Seng Siong Soh, Vilia Soelaeman, David Sum, Evi Susanti, Richard Tai, Elaine Tan, Jason Tan, Rohan Tariq, Jee Wei Tay, Andra Thedy, Shi An Ting, Mart Umali, Dino Van Deijzen, Leo Waible, Berlina Winata, Kah Chou Wong, Wendy Wu, Xiaofeng Wu, Joelle Xiong, Wesley Yeo, Jing Zhang, Ning Zhang, Xiangjing Zhang, Dianfeng Zhao, Zhi Qin Zhou.

Image credits

1, 2, 11–14: Ying Yi Photography
3–10: Arup

Building to match the spirit of the Scottish Highlands

A state-of-the-art distillery and visitor centre created to meet growing demand for Macallan Scotch whisky

Authors Jim Deegan, Susan Deeny, Paul Edwards, Adam Jaworski, Stuart Jordan, Bob Lang and Alistair Murray

1.

The new Macallan Distillery and Visitor Experience is located in the Easter Elchies estate in the Scottish Highlands, where it is set into the landscape so that it blends in with its surroundings. The building's double-curved grass-covered roof is one of the largest timber grid-shell roofs in the world.

Working in collaboration with architects Rogers Stirk Harbour + Partners (RSHP) on the £140m project from concept through to completion, Arup carried out the structural, building services, fire, acoustic and civil engineering design, along with providing environmental and transportation advice for the new facility.

The client wanted a contemporary distillery that would showcase the production of Macallan whisky and also be of the highest quality and craftsmanship, reflecting the company's values. In addition, they wanted it to respect the surrounding countryside. Arup's multidisciplinary approach has resulted in a 15,000m^2 building that meets this vision while also mitigating the fire risks inherent in the distilling process.

Distilling the building design

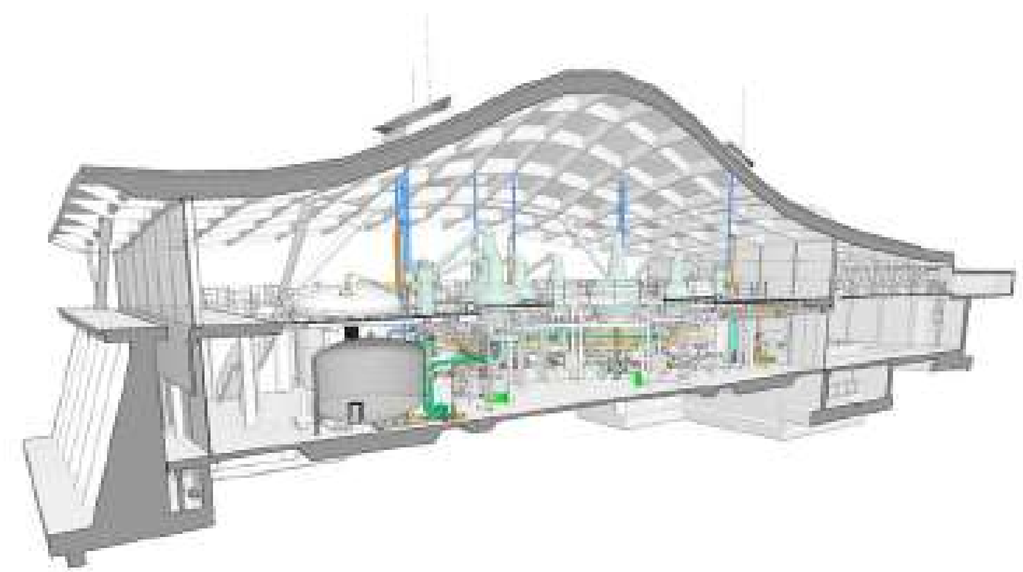
In its design brief, the client required a state-of-the-art facility in order to meet increasing demand for Macallan Scotch whisky. It also wanted a welcoming building for those looking to explore the whisky-making process and its heritage – whisky has been distilled in the Spey Valley since 1824.

Arup provided traffic and transportation advice and documentation in support of the planning application for the facility. The distillery is located in a designated Area of Great Landscape Value, meaning that it must not disrupt the character of the surrounding area. Arup assisted with the environmental and ecological aspects of the building's design and construction. This included technical support for the variation in the surface water abstraction and discharge licences associated with the distillery. The nearby River Spey is an important fishery habitat, and is also a source of water for production and cooling in the whisky-making process. Arup carried out analytical modelling and technical assessment, developing monitoring and mitigation measures to ensure compliance with the EU Water Framework Directive regulatory requirements.

The process of whisky distilling is presented in the facility in a highly coordinated space. Arup's building services engineers worked closely with the architect; the main contractor, Robertson Construction Group; and the process engineers, Forsyths, to ensure the striking roof form and soffits are clear of any visible services and to control the ventilation so that potentially flammable ethanol vapours produced in the distilling process are removed quickly and safely.

1: The new Macallan Distillery and Visitor Experience showcases the production of Macallan whisky

2: The curved timber grid shell allows the roof to flow over each still house in the distillery using a lightweight structure



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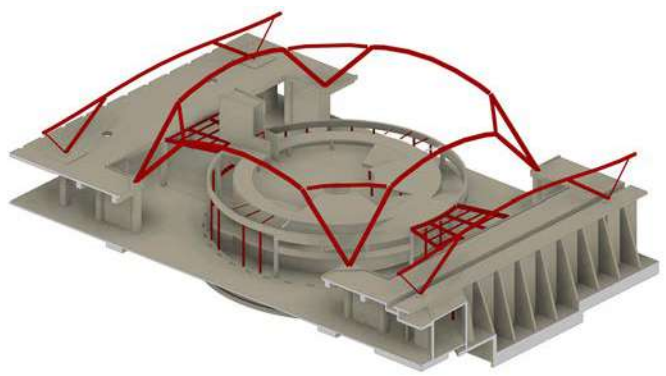

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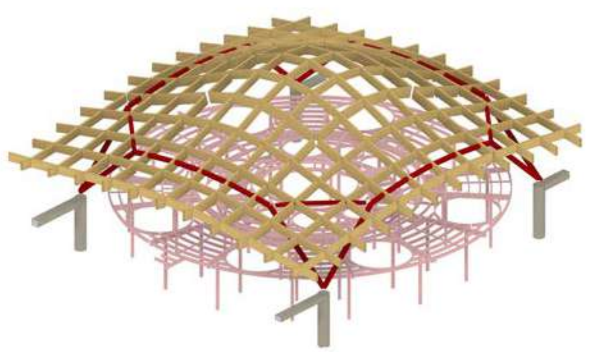

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3: The grid shell roof consists of steel portal frames that support timber beams and cassettes

4: A repetitive form was used to create the roof's complex shape

5: The roof domes have been designed to reflect the surrounding rolling hills

6 & 7: 3D models showing the steel and timber roof elements

Grid shell roof

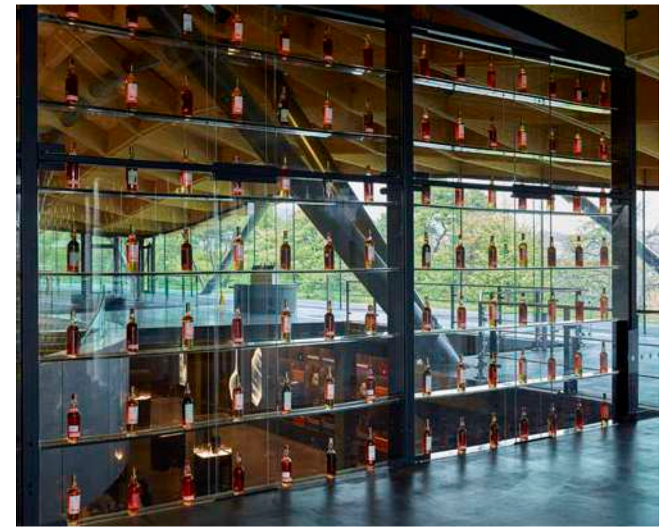
The distillery roof consists of five domes that reflect the rolling hills of the Spey countryside. The tallest dome encloses the main entrance and the Visitor Experience centre, where an exhibition and gallery introduces visitors to Macallan and its history. The four other domes enclose the mash house (where hot water is added to the dried malt grist as part of the distilling process) and three still houses (where the spirit is heated and distilled prior to casking).

The building is dug into the sloping contours of the site, reducing the above-ground footprint of the distillery and meaning that views across the countryside are not disrupted by its presence. Although the domed roof mirrors the adjacent sloping hillsides, the architectural vision was not for the distillery to disappear completely into the landscape but for it to be clear that it was a man-made, yet fully integrated, part of the environment. The roof has a network of aluminium channels that provide a service zone for lightning protection, rainwater run-off, safety fall restraint systems and power to serve vents in the roof lights.

The complex shape of the roof was rationalised by using a repetitive form. There are three main components to the roof structure: steel portal frames, timber beams and timber cassettes. The steel portal frames support the timber beams, with the timber cassettes spanning between the beams to form the roof deck. The timber grid shell allows the roof to 'flow' over each still house using a lightweight structure. Four of the domes are identical in shape, 11.5m tall and 36m in diameter.

The roof is separated from the ground and walls, meaning it supports vertical load only. Each dome contains one standalone four-sided steel portal frame supported on concrete buttresses. At roof level, the frame is octagonal on plan and is supported at the eight corners by V-shaped columns that meet the ground at four locations in each dome zone.

The portal frames support the timber roof elements by providing a vertical load path back to the ground and tying together the timber domes so that they can resist any horizontal load potentially caused by arching action within the roof. In order that they can efficiently resist both horizontal and vertical forces, the steel frames are made from circular hollow sections that pass directly through the centre of the timber



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beams. The steel sections are typically 16mm thick, but where required, in some isolated locations around connections, this thickness increases to 40mm. An additional perimeter frame that is of similar construction to the typical internal frames runs continuously along the glass façade of the building. Overall, 216 tonnes of steelwork were used in the roof.

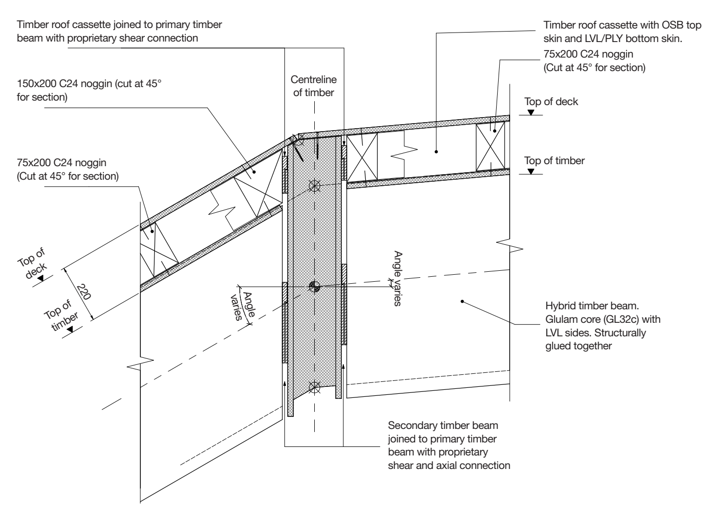
Timber elements

The timber beams are set out in a 3m x 3m grid on plan. The actual distance between beams varies depending on the slope of the roof, with the maximum distance being 3.7m where the roof slope is 35°. The timber beams form a two-way spanning structure. The geometry of the timber frame adds stiffness and reduces stresses by causing the timber to transfer loads largely through arching rather than bending. The roof beams are 200mm wide and 750mm deep, with 930mm-deep beams used in the area with the highest loads. The beams consist of a glulam core with laminated veneer lumber (LVL) boards glued to each side.

The top 'skin' of the roof structure consists of 200mm-thick prefabricated hollow timber cassettes. These are made up of a 9mm-thick top layer, 75mm x 200mm softwood joists and a 21mm-thick LVL soffit. They are triangular in shape, with two cassettes filling one panel of the beam grillage.

The cassettes are independent components and are not designed to be relied upon to provide any diaphragm action between elements. Approximately 85% of the timber cassettes simply sit on top of the timber beams that support them. Screws inserted from above provide a robust connection but are not frequent or large enough to engage the cassettes as a diaphragm. In the higher loaded areas, 930mm-deep beams extend up into the depth of the cassette and ensure that the bottoms of all the timber beams are located in the same plane. At these locations, the cassettes connect to the timber beams by means of small steel shear connectors fixed to the side of the timber beams running around the perimeter of the cassettes.

The construction required the timber and steelwork to be erected to very tight tolerances in the demanding climate of north-east Scotland. The roof construction started in March 2016 and the 13,620m² timber roof was completed within six months using 1,800 individual timber beams, 20 installers and two cranes that carried out 4,245 lifts.



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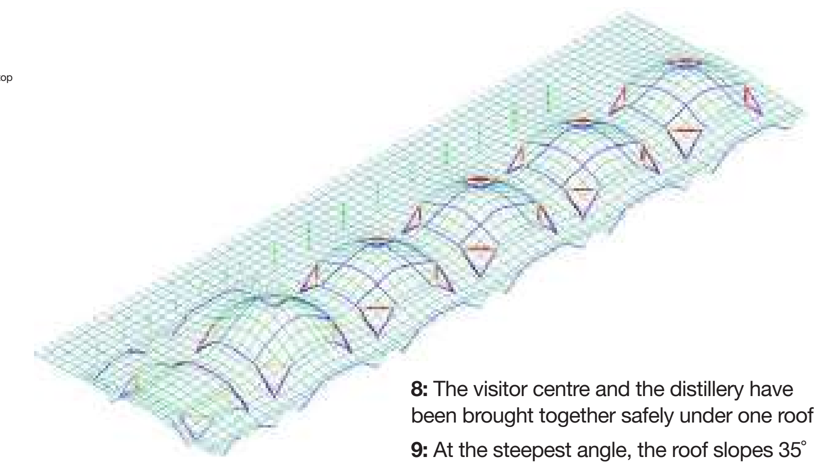


11.

8: The visitor centre and the distillery have been brought together safely under one roof

9: At the steepest angle, the roof slopes 35°

10: The timber beams have a glulam core and laminated veneer lumber boards on each side

11: Model mapping the roof axial forces

12: The smoke-detection system was tested on-site to ensure its efficacy

13: Due to the potentially flammable ethanol vapours produced in the distillation process, the distillery has a comprehensive fire-detection and action plan

12.

Fire engineering

Arup's Fire Engineering team were crucial in shaping the building's design, bringing innovative solutions to the project in addition to their considerable knowledge of local building regulations and the Scottish approvals environment. Typically, a building's design and construction fire safety is achieved by following prescriptive rules. The unique architectural design of the Macallan Distillery required a bespoke approach that demanded the subtle integration of fire safety concepts with all aspects of the building design.

By using an integrated design coordinated with civil engineering elements, Arup's fire strategy avoids the need for sprinklers and other equipment such as heavy fire curtains. This required careful detailing with RSHP and the structural engineering team to ensure that the roof remained isolated structurally. A third-party reviewer worked on behalf of the regulatory authority to review these elements of work, with discussions with the local fire service framing the design outcomes.

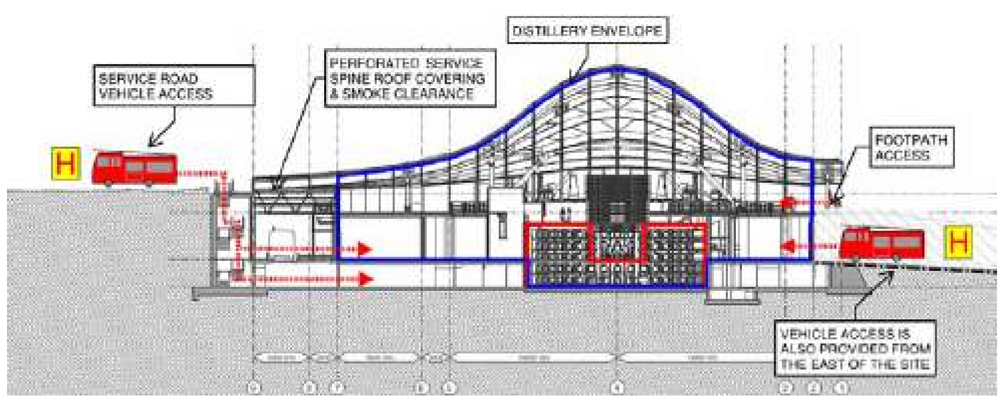
The distillery has an explosive gas atmosphere classification due to the nature of the gases produced in the distilling process. As such, it was a complex challenge to bring the visitor centre and the distillery together safely under one roof. Each presents a risk to the other. The typical solution would have been to provide heavy construction to separate the two, but this would have compromised the vision of having a strong visual connection between both parts of the facility.

Arup's solution was to develop a transparent fire wall, which was a first for a distillery. The fully glazed partition, 10m tall and 40m long, separates the visitor centre and distillery, with steel cantilevers keeping the glazed wall structurally independent of the timber roof. In a fire situation, a bespoke drenching system is deployed along the two-hour fire rated glazed wall. This creates a continuous film of water over the glazing surface to prevent it from shattering. A full-scale fire test was carried out on a 5m-tall sample of the wall to verify the design and demonstrate to the project team and the approving authority the system performance.

The fire detection strategy also minimised the visual impact on the roof. The system uses a combination of aspirating detectors as well as heat and flame detectors. An ethanol gas detection system was deployed at low level. This kept the roof clear of detection equipment and allowed maintenance of the system to take place at a low level rather than at height. Combined with heat and flame detectors at an elevated level, these alternative types of detection ensure reliable detection while minimising false alarms that would interrupt the distilling process.

Reviewing the process safety risk assessment with the client, it was noted that any spillage from one of the vessels needed to be dealt with quickly to reduce the risk of an escalating fire. Arup designed the floor so that it slopes towards high-capacity effluent ring drains that are linked to large underground tanks. Any spillage that is potential fuel for a fire can be evacuated from the building safely and quickly (up to 12,000 litres in less than 60 seconds) from both a fire and an environmental perspective.

In the event of an emergency within the distillery, the effluent is purged into the effluent drainage system and, should the emergency continue, escapes via a high-level outlet into a specially lined effluent holding pond away from the distillery. This pond is capable of storing the combined contents of the whisky process and any spent emergency firefighting water. The overall design of the spillage evacuation system was a key factor in the building gaining permission to host visitors within the process hall.



13.

Civil engineering

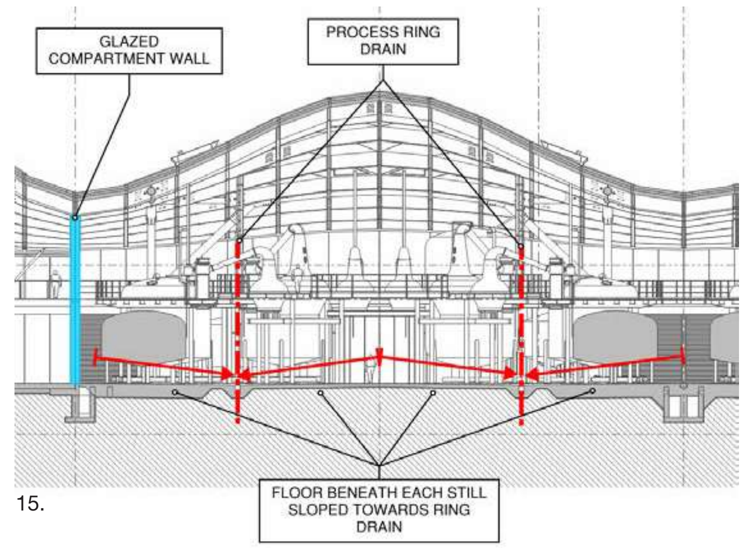
Arup's civil engineering design for the distillery also included the external sections of the foul and surface water, effluent and cooling networks, communications, electrical, steam, whisky and process water supply networks.

14.

14: The transparent fire wall (shown behind the copper stills) separates the distillery and visitor centre while retaining the welcoming and open feel of the building

15: Any potentially flammable liquid spillage is immediately expelled from the building

16: The green roof contains a service zone that provides lightning protection, safety fall restraint systems and power



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The building's buried nature meant that external drainage networks were up to 12m below ground, with specialist access manholes designed to provide safe access. Effluent from the distillation process is very aggressive (it has both high and low pH levels), highly flammable and potentially very hot. Coupled with the installation depths, pipe material selection required extensive investigation with support from Arup's Advanced Technology and Research team, resulting in specification of a specialist plastic product. The effluent drainage system is connected to the on-site treatment plant via a balancing tank where aeration and filtration are used to remove harmful pollutants. The waste is then combined with the cooling water network and discharged into the river.

Rainwater collected from the green roof is stored in buried tanks and used to irrigate the roof during dry weather. A sustainable drainage system has been put in place in order to protect the River Spey. Swales are used with flow restriction to attenuate initial rainwater discharge peaks. They also encourage the settlement of suspended particles before the water flows into pipes beneath the steeply sloped farmland to energy dissipation structures, prior to discharging into a grassed retention pond. This pond encourages the depositing of remaining suspended solids (and provides a variety of natural habitats) before discharging at a controlled rate into the river.

16.

Building services

Working closely with the process engineering designers, Arup provided the building services design for the distillery. Distilling is an energy-intensive process. Waste heat from distillation is recovered and

17.

18.

17: Development of the timber roof was carried out in conjunction with timber contractor Wiehag

18: The reinforced concrete air circulation ducts also act as structural ties as part of the building's stability system

19: The award-winning distillery blends into its surroundings while utilising state-of-the-art technology

Awards

2019
World Architecture Festival Awards
Completed Building Production, Energy & Recycling

RIAS Award
Doolan Best Building in Scotland Award
Special Category Award – Wood for Good/ Scottish Forestry Commission for the Best Use of Timber

RICS Scotland
Design Through Innovation Award

Structural Steel Design Awards
Merit Award

2018
Structural Timber Awards
Engineer of the Year and Winner of Winners

Scottish Design Awards
Leisure/Culture Building or Project

Wood Awards
Structural Award

used as the primary source of heating in the building through an underfloor heating system, and for domestic hot water in the visitor centre.

Steam power is used as the main energy source for the distillery. This is supplied by the Speyside Combined Heat and Power plant, which is located 2km away and is fuelled by sustainable low-grade harvested wood and draff – a biomass by-product from the distillation process. Two 10MW gas-fired boilers provide a back-up during any planned maintenance downtime.

The process ventilation has been engineered to dilute and remove potentially flammable ethanol vapours. This is critical, as parts of the building have potentially explosive environments. The air management system draws in air from a trench along the building's east side, with fans circulating the air throughout the building. An example of the coordinated design of the building is the 1m-wide x 1.6m-deep concrete floor ducts that are used for air circulation. These also act as a structural tie for the building between the buttresses that support the roof above.

The air circulation reduces the risk of accumulation of gas around the equipment and helps to moderate the temperature in the space. The air up to 3m above floor level is changed six times per hour. Above 3m, rising heat from the plant dilutes the ethanol vapour. Positive pressure is maintained within the building by the escaping ambient hot air; this also prevents dispelled process gases from recirculating back into the structure. As the expelled air contains concentrations of ethanol vapour, the zone just above the roof is classified as an ATEX Zone 1. The lightning-protection finials on the roof are raised above this zone.

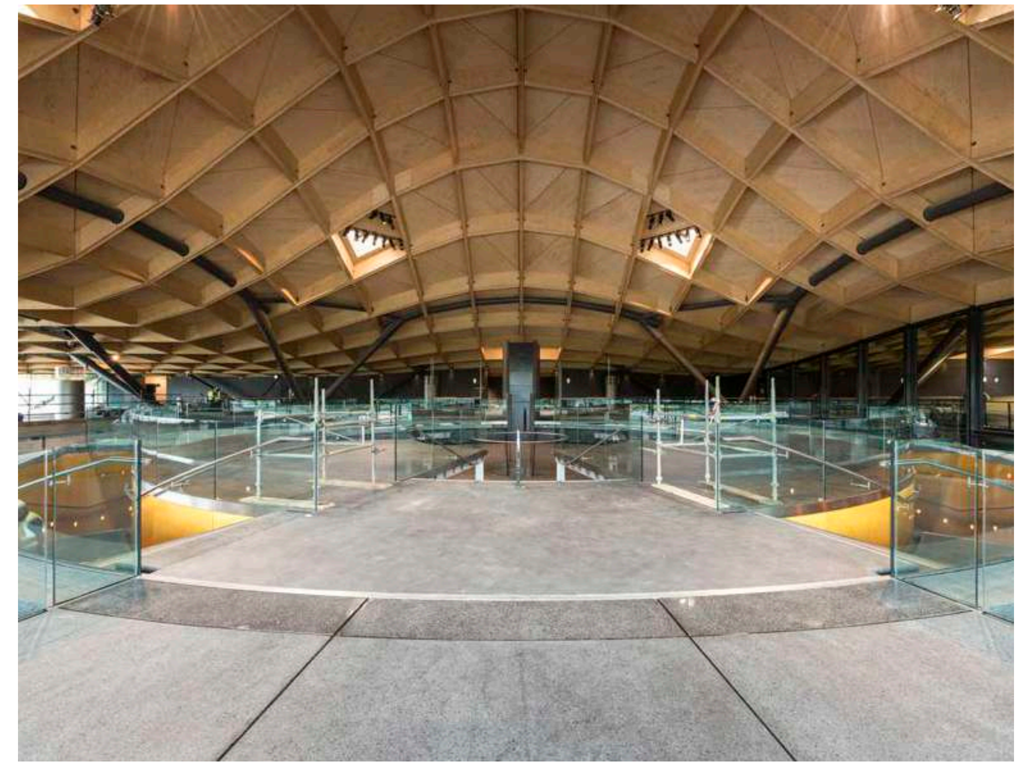
A small air handling unit (AHU) is used to condition the Cave Privée cellar space in the visitor centre. Here, 300 wooden casks of maturing whisky are stored. The temperature is ideally kept at 12°C with a relative humidity of 70% by mixing a portion of outside air with return air and re-humidifying to adiabatically cool the space. Low ambient temperatures allow these conditions to be maintained most of the year. It is accepted that some upward drift will occur in the summer months. The visitor centre does not require mechanical cooling. The main AHU for this part of the facility has a heat recovery wheel, with the operation running with 50% fresh air and 50% recirculated air.

Concrete elements

A 180m-long, 54m-wide basement structure forms the distillery's main operating floor. The excavation works for the building took place in an open cut without the need for any temporary sheet pile foundations for most of the retaining wall construction. The main 300mm-thick, 10m-high retaining walls were built free-standing and backfilled at a later date. The walls are supported at regular 3m centres by 300mm-thick counterforts.

This repeated wall pattern meant that the reinforcement cages could be prefabricated and lifted into position, allowing faster and safer working practices. The relative thinness of the wall panels reduced the effects of shrinkage on the long lengths of wall, aiding waterproofing, as this allowed the basement box to be constructed without joints. Early age shrinkage was controlled by leaving out one 3m-wide wall panel every 50m. This also benefited the contractor, as it could use these openings for working access into the basement zone during construction.

The steel-frame section of the roof is supported on concrete buttresses. These 8m-tall structures are the main stability elements of the building. Each pier is formed of two shear walls in the east–west orientation, and a moment frame and shear wall in the north–south direction. The shear walls receive the thrust coming down from the roof and transfer it, via their foundations, to the ground. These buttresses are tied together across the east–west axis of the building by the reinforced concrete ties below the floor slab that also act as the air circulation duct.



19.

3D design

The design team worked on the project in a digital 3D environment. Coordination was critical for the successful delivery of such a complex building design. Development of the design and detailing of the timber roof was carried out in conjunction with Austrian timber contractor Wiehag. Arup and Wiehag shared geometry and load cases in 3D, with all of the models checked independently so that they were aligned. Arup's structural analysis model was coordinated geometrically with the architect, with Wiehag developing its final analysis model from that before developing the fabrication geometry.

Working collaboratively, the project team has created a graceful award-winning industrial building that does not compromise the original concept, and respects the surrounding environment.

Authors

Jim Deegan worked on the mechanical aspects of the project. He is a senior engineer in the London office.

Susan Deeny led the fire engineering design. She is an Associate in the Edinburgh office.

Paul Edwards was the lead structural engineer and Project Manager. He is an Associate in the London office.

Adam Jaworski worked on the electrical aspects of the project. He is an Associate in the London office.

Stuart Jordan led the civil engineering design on the project. He is a senior engineer in the London office.

Bob Lang was the Project Director. He is a former Director and is currently a consultant with Arup.

Alistair Murray was the Project Director for the fire engineering design. He is the leader of Arup's fire engineering team in the UK and a Director in the Glasgow office.

Project credits

Client Macallan Distillers Ltd
Architect Rogers Stirk Harbour + Partners
Landscape architect Gillespies
Lighting consultant Speirs + Major
Main contractor Robertson Construction Group
Process contractor Forsyths
Project manager and quantity surveyor Equals Consulting
Civil, structural, fire, geotechnical engineering, building services, transportation planning and ecological advice Arup:
Matt Adams, Rodney Arnedo, Will Arnold, Endrit Badallaj, Rick Benjamin, Tim Brosnahan, Celine Cannam, Ian Carradice, Stuart Chambers, Tom Clack, Andrew Cole, Ricardo Costa, Jim Deegan, Susan Deeny, Tarun Devlia, Gordon Diamond, Paul Edwards, Chris Eliades, Angus Elliott, Sam Frith-Salem, Jonas Fuchs, Rob Gilbert, Mark Heath, Iain Herriott, Nicky Hilton, Afser Hussain, Adam Jaworski, Lidia Johnson, Stuart Jordan, Nikolaos Karamitsos, Mike Kong, Bob Lang, Andrew Lawrence, Rhodri Lea, Mark Lindsay, Tyler Little, Rena Maguire, Gavin Maloney, Mei-Yee Man Oram, Carlo Marras, Grant Martin, Fraser Maxwell, David McAllister, Matthew McCullough, Danny McVee, Paul Morrison, Alistair Murray, Tom Parker, Dan Pook, Hugh Quail, Morgan Rhodes, Eduardo Rico, Adriana Salgado Perez, Vera Sarioglu, George Scott, Andrew Sedgwick, Piotr Skowron, Clem Smoothy, Giulia Strallo, Katarzyna Tekieli, Con Therrios, Steven Thomas, Peter Toth, William Tung, Denis Venkov, Khyati Vinod, Colin Winant.

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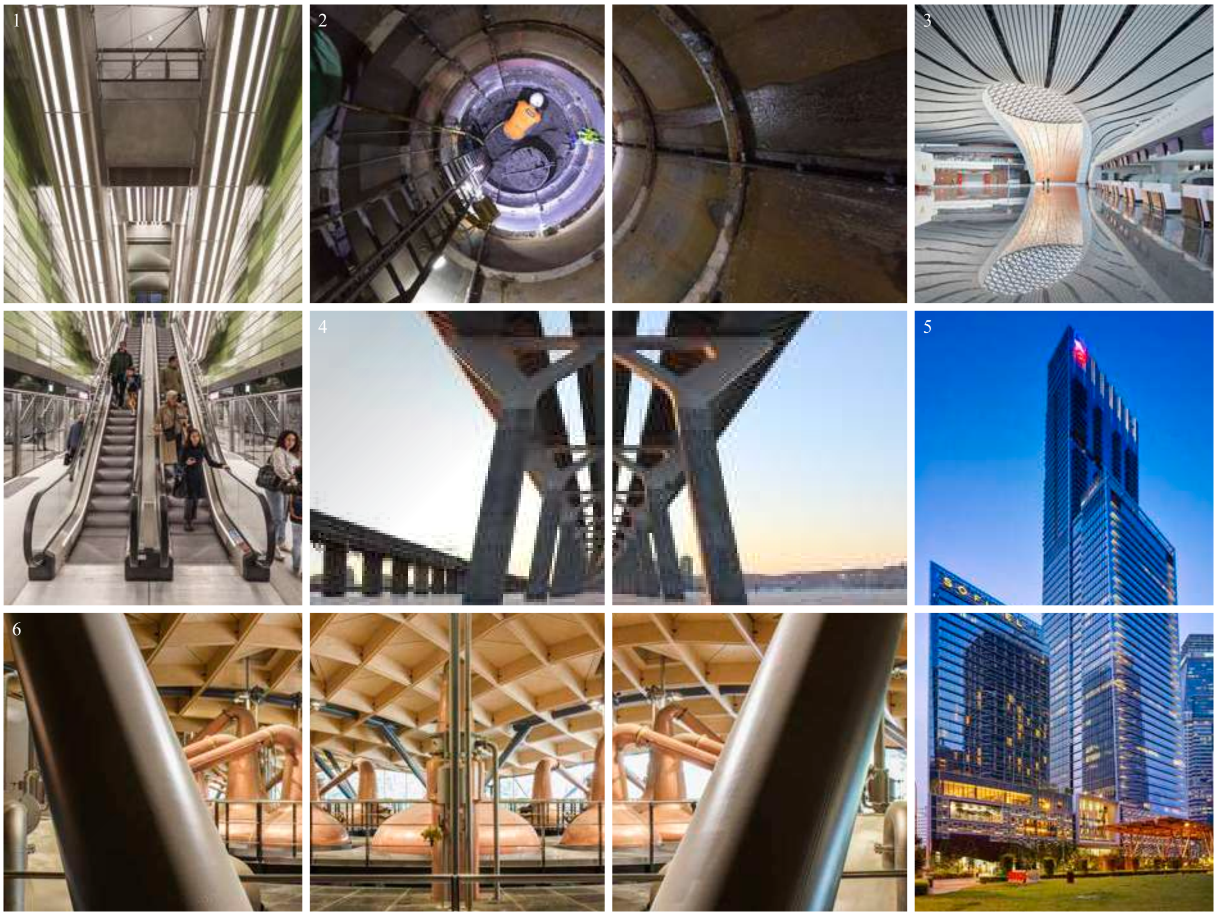

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