Issue 2 2017

The Arup Journal

Contents

Front cover:
Queensferry Crossing, Scotland
Photo: *Graeme Peacock.*

Left:
Queensferry Crossing, under construction
Photo: *Paul Baralos.*

1.

Queensferry Crossing

Location
Firth of Forth, Scotland, UK

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Introduction
Shortly before 2am on Wednesday 30 August 2017, northbound traffic was diverted from the Forth Road Bridge onto the new Queensferry Crossing. Now the UK's tallest bridge, this 2.7km structure has entered the record books as the world's longest three-tower, cable-stayed bridge. It is also by far the world's largest to feature cables that cross at mid-span, providing strength and stiffness to the slender towers and deck. The length of the balanced cantilever during construction, which measured 650m tip to tip, was another world record, and the method of installing it was an engineering innovation.

But there is more to the Queensferry Crossing story than impressive statistics. Planning and managing the authorisations and approvals, design and construction of this project presented a unique set of challenges, not least the time pressure exerted by the deterioration of the existing road crossing. This was a race against time, successfully run, against a backdrop of high political and social expectations and tight budgetary constraints. The unpredictable waters, difficult ground conditions, busy existing road and rail links, and notoriously changeable weather conditions that prevail in the Firth of Forth, added to the complexity. It demanded all the ingenuity of the Jacobs and Arup joint venture (JAJV) partnership that guided the project through its planning stages between 2008 and 2011, and the six years of construction that followed. The detailed research, planning, consultation and investigations that preceded construction, and are detailed in this article, were key to success. The outcome is an elegant, strong bridge that carries the M90 motorway across the estuary between Lothian and Fife. It provides new options for managing traffic on this important road artery which is essential to trade and industry in Scotland, as well as being an important link between local communities in the region.

Why a replacement?
In 1964, when it was first opened, the Forth Road Bridge was the longest suspension bridge in the world outside the USA. It was designed for four million vehicles per year, but by 2007 it was carrying 24 million, with heavy goods vehicle (HGV) weights trending upwards to a projected 44 tonnes at that time.

A weight monitoring system, together with regular inspections, enhancements and repairs, was introduced to keep the bridge operational while the Government considered whether to reconstruct or replace it. The eventual decision to replace it was timely. By 2016, the condition of the bridge meant it had to be closed for several weeks for urgent repair, causing widespread disruption.

The challenge
The Scottish Government first promoted a new road bridge across the Forth in the mid-1990s when it became clear that the existing Forth Road Bridge (FRB) was unable to cope with increasing weight and volume of traffic. The initial plan to supplement the bridge with a new crossing subsequently foundered, but the feasibility of an additional crossing had been established and much of the land on which it would make landfall had been acquired. It was only a matter of time before events conspired to make a switch from the 'make do and mend' strategy unavoidable, and the critical juncture turned out to be a comprehensive inspection in 2006 of the main suspension cables supporting the FRB. This showed substantial deterioration of the wires forming the cables: the cables had lost about 10% of their wires and the worst case projection of continuing decay meant the bridge would have to be closed to traffic by 2017.

Although, in theory, staged rehabilitation of the FRB was an option, the time this would take, and the disruption to the Scottish economy it would entail, made it unrealistic. So, in 2007, Transport Scotland commissioned the Forth Replacement Crossing Study to examine options for a new bridge or tunnel at various locations along the Forth, with the Government ultimately deciding to adopt a bridge in the same location as its 1995 proposal. Concept designs had been prepared in the mid-1990s for a suspension bridge at this location, but in the intervening 20 years bridge technology had developed such that a three-tower, cable-stayed construction, using the island of Beamer Rock for its central tower, was the most economical solution, and this was the configuration chosen.

1. Queensferry Crossing viewed from the north shore of the Firth of Forth.

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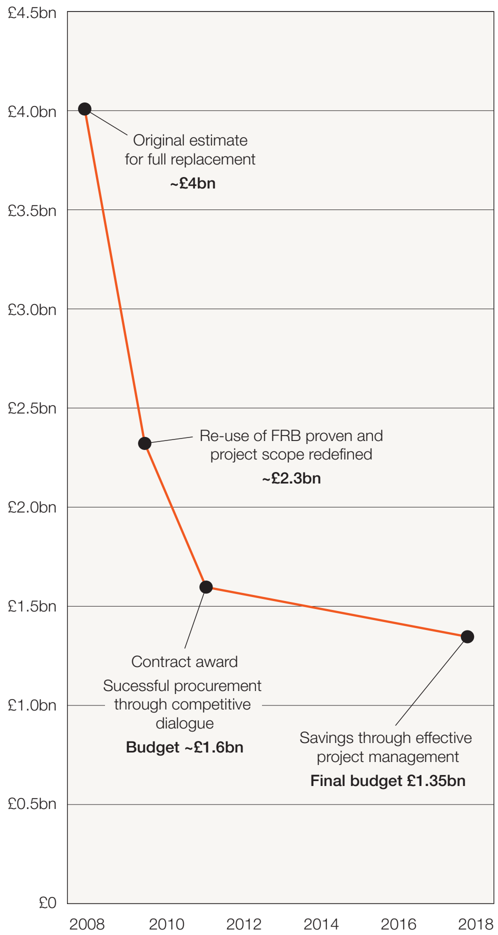


3.

Official opening ceremony

Her Majesty The Queen opened the Queensferry Crossing on Monday 4 September, exactly 53 years to the day after she opened the Forth Road Bridge.

Royal connections on this stretch of the river reach back more than 1,000 years. In the 11th century, Queen Margaret of Scotland introduced a ferry to carry pilgrims across the Forth, giving the communities on either side of the Firth their name.

More than 35,000 votes were cast in a public ballot to name the new crossing and the Queensferry Crossing emerged as the winner.

2. The new Queensferry Crossing over the Firth of Forth. This aerial view, from South Queensferry, shows how the cable-stayed design of the new bridge complements the suspension bridge opened in 1964, and the cantilever rail bridge completed in 1890.

3. How the out-turn cost of the project was more than halved compared with initial estimates.

4. Road connections north and south were reconfigured as part of the project.

Project overview

In addition to the bridge, the scope of the Forth Replacement Crossing (FRC) project included all road connections to the north and south. Jacobs and Arup established a joint venture to tender for the project delivery role, bringing together Arup's international design and construction experience on several similar large bridges (including Stonecutters Bridge in Hong Kong) with Jacobs' experience on its portfolio of Scottish highway projects. In early 2008, Transport Scotland, on behalf of the Scottish Government, appointed JAJV. The commission included developing and assessing the project proposals; cost, programme and risk management; concept and specimen design of the bridge and road networks; preparing an environmental statement; assisting in procurement and authorisation of the project; and administering and monitoring construction. The individual work packages were undertaken at the offices of the JV partners, with the design of the bridge predominantly in Arup's London and Hong Kong offices.

4.

Initial estimate more than halved
When the bridge was officially opened, the final out-turn cost of the overall project stood at £1.35bn, substantially less than the original estimate had been in 2007. Achieving this outcome was critical to success because the project inception coincided with the global financial crisis of 2008. At that stage, estimates for the crossing were very broadly between £3.2bn and £4.2bn, an amount the Scottish Government could not fund from its resources in 2008, and with the feasibility of external funding models in doubt because of the crisis, this estimate had to be reduced. Radical reassessment of the client's brief, coupled with a targeted engineering research programme, identified substantial potential reductions with three significant amendments contributing most of the savings.

Firstly, it was demonstrated that with maintenance the existing FRB could be used for public transport, pedestrians and cyclists; this meant the public traffic corridor, both on and off the new bridge, would not need to be built, so it could be substantially narrower.

Secondly, using crossing cables at mid-span on a narrower bridge would mean that the bridge foundations, deck and towers could be reduced in size without reducing the bridge stiffness.

Thirdly, by introducing comprehensive Intelligent Transport Systems (ITS) better use could be made of existing highways, considerably reducing the requirement for new road construction.

In combination these measures, which were adopted, reduced the estimated cost in 2009 to the range £1.7bn to £2.3bn, which was just within the self-funding capability of the Scottish Government, as justified by the business case.

The urgent need to deliver a new integrated solution demanded a swift completion programme. The target for opening was 2017, but this could not be achieved via the conventional sequential process of acquiring authorisation and approvals before seeking tenders for the works. An added complexity was the requirement for an Act of Scottish Parliament because of the scale and functionality of the project. So the Parliamentary Bill and tendering processes were run in parallel, with tenderers given protective assurances in the event the project did not proceed. This approach made the 2017 project contract date achievable.

The procurement process was marked by a high level of engagement with prospective tenderers: a marketing campaign, coupled with extensive bilateral discussions, followed by prequalification leading to a competitive dialogue tender process. The success of this approach can be gauged by the fact that the contract was awarded £300m below estimate, and without challenge.

Planning and management
Transport Scotland and JAJV spent three years managing, designing and procuring the project through to Royal Assent for the Forth Crossing Act in January 2011, and the scale of work done during this stage of the project enabled Transport Scotland to award construction contracts shortly afterwards.

From the outset, the management and governance structure was clearly defined. The project's management team, called the Employer's Delivery Team (EDT), comprised Transport Scotland and JAJV staff. This lean integrated team was key to the success of the project because it meant communication and reporting lines were short. There was no duplication of Transport Scotland and JAJV activities and the thin governance structure was geared to making early and durable decisions. Key staff in the EDT remained in place from appointment to project delivery in 2017, providing essential continuity. The EDT was small, with key discipline leaders drawn in only as required.

The Programme and Budget Team (PBT), established the cost, programme, procurement and risk functions required to manage the project, supported by specialists from EC Harris who audited cost data and undertook the assessment of historic inflation indices. The lean governance structure comprised just two levels of oversight: the Project Board that confirmed key strategic decisions; and the Project Management Board (later the Construction Management Board) that directed day-to-day management of the project. Subsequently, to further streamline the working of the Project Board, a sub-board focused on finance and risk was formed. The Project Board was chaired by

5.

- **2007** Forth Replacement Crossing Study concludes, decision to build a cable-stayed replacement bridge announced.
- **2008** Concept design, project planning, specimen design. Procurement documents drafted.
- **2010** Forth Crossing Bill passed.
- **2011** Construction contract awarded to Forth Crossing Bridge Constructors (FCBC).
- **2012** Cofferdam and caissons arrive on site.
- **2013** Queensferry Crossing is chosen as the name of the bridge in a public ballot. Tower foundations completed.
- **2014** Steel deck sections arrive in Rosyth and starter sections are lifted.
- **2015** South approach viaduct completed. Tower construction completed.
- **2016** North approach viaduct completed.
- **2017** Bridge structure completed with lift of final deck section. The bridge is opened to the public.

6.

the Independent Decision Maker, the chief civil servant for transport, who reported directly to the government minister responsible for the project. This lean structure led to effective communication and decision-making, and the continuity of membership of the boards resulted in decisions that were durable and consistent.

Transport Scotland wanted a high level of cost assurance before tendering the design and build contract, to avoid the inevitable delays caused by a subsequent cost reduction exercise. So a major challenge at this stage was making a precise estimate of the cost of the bridge. With no reliable database of comparable costs (such projects are unique, cost is driven by location, environment, ground and marine conditions, construction methodology and logistics), the PBT produced a bottom-up time and resource estimate based on a detailed specimen design and programme, supported by an analysis of construction sequence and logistics. This represented significant commitment and investment by the client compared with traditional tendering approaches, but it proved beneficial because the design and construction information created was shared with tenderers to enable them to understand the scope, material content, project logistics and the risks involved. The tenderers' designs were largely developments of the specimen design and construction sequence, and the resulting tender prices were comfortably below budget demonstrating their confidence in their understanding of the project and its risks. The PBT also provided information to support the project business case, including analysis of the long-term operational and maintenance costs for both the FRC and the FRB.

The master project programme (design, consultation, Parliamentary Bill process, procurement and construction) underpinned the completion date of 2017 and was important in determining cash flow, which was essential to the Scottish Government in confirming that its available funding matched the demands of the project. This was crucial in tendering the works as it enabled a cash flow limiting model to be included, which meant tenderers could plan their construction sequence accordingly. During the construction phase, the PBT continually reviewed the contractor's design and construction programme, which evolved in stages as methods of construction were developed, and conducted monthly reviews to keep cash flow on track.

Assessing risk on a project of this scale is complex: careful analysis is required to avoid setting the budget too high or providing insufficient contingency. Developing a quantitative risk analysis process was pivotal to analysing the risk profile of the project and the subsequent apportionment of risk between client and contractor. For example, the Scottish Government decided to take 90% of the price inflation risk after contract award, partly to increase the competitiveness of the tenderers' pricing, partly to increase industry appetite for the project. But in order to do this, the budget needed to allow for price inflation over a period of up to ten years. The trends in 16 different component indices over a historic 20-year period were examined and forecast forward, the components of each index reflecting the relative costs within the base price, for example materials such as steel, concrete, timber, labour, supervision and plant. These forecasts were aggregated separately for the main crossing and network connections and estimates of low, medium and high inflation were made. Inflation allowances between approximately 3% and 8% per annum were added to the base price to give a cost range for the project out-turn cost but in the event, during the course of the project, inflation did not exceed the lower range.

Procurement

Discussions were held with prospective tenderers in late 2008 to gauge industry appetite and initial views on packaging and procurement routes. The findings fed into the EDT's analysis of funding options, contract packaging and form, and procurement process. The 2008 financial crash had significantly affected funding choices owing to the high cost and limited availability of external finance. Public-private partnership, and direct and shadow tolling, were both considered but it was decided that capital funding would offer best value for money and highest delivery certainty. This approach, combined with a lump-sum design and build contract, provided Transport Scotland with the high level of price certainty that was required for direct finance from the Scottish Government. Analysis of contract type options concluded that the FIDIC Silver Book form best represented the risk distribution desired, and was a contract type with which international contractors would be familiar. Contract packaging was also directed at ensuring the project provided opportunities for local participation, with early contracts specified to improve traffic flows on the network prior to construction of

5. The cantilever on the central tower was the world's longest and the JAJV and FCBC teams received a certificate for its entry in the *Guinness Book of World Records*.

6. Some of the key milestones during the ten-year planning, authorisation and construction process.

7. A view of the bridge prior to its connection to the North Approach Viaduct.

8. How speed of delivery was increased by running tender and statutory processes in parallel.

7.

Tender process		**Statutory process**	
Scottish Minister announcement			Dec 2007
Appointment of JAJV	2008	Bill	Nov 2009
Prequalification	Dec 2009	Stage 1 debate	May 2010
Competitive dialogue	Sep 2010	Stage 2 debate	Oct 2010
Outline proposal	Dec 2010	Stage 3 debate	Nov 2010
Tender submission	Jan 2011	Royal Assent	Dec 2010
Quality evaluation	Feb 2011		
Parliamentary announcement			Mar 2011
Opening of bridge			Sep 2017

8.

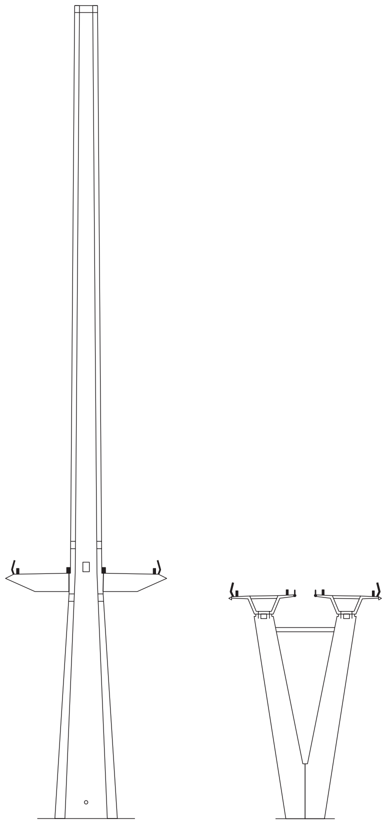
the new bridge. This meant the main works were split into three packages.

Procurement began early in 2009 and an industry day that included presentations and tour of the proposed bridge location attracted more than 60 prospective tenderers. Further bilateral discussions with prospective tenderers were held, in line with the requirements of the procurement regulations, followed by issue of the Contract Notice in July 2009. Two contractor consortia subsequently prequalified for the main crossing. Within the rules of procurement regulations only the competitive dialogue procedure could adjust to the changing requirements arising from the Parliamentary process happening in parallel. Additionally, this procedure proved beneficial because the dialogue enabled participants to fully understand the client's requirements.

Invitations to Participate in Dialogue (ITPD) were issued on 4 December 2009, along with a draft Invitation to Submit Final Tender and Instructions to Participants; and Contract. Employer's Requirements were issued on 18 December. Unusually, to recognise the risk that a parallel statutory process posed, participants were offered capped partial tender cost support to be paid to the unsuccessful tenderer, and capped full costs to be paid to both tenderers should the project not proceed. The dialogue period continued until September 2010, during which time structured meetings were held with each participant as they developed their proposals. Simultaneously, preparations were made for the procurement of the M9 J1a and Fife ITS contracts.

A noteworthy feature of the proposed contracts was the linking of key performance indicators to participants' quality statements. The procurement team researched how best to secure economic and social benefits for communities local to Queensferry, engaging with the Scottish Government Procurement Directorate, Public Contracts Scotland and Construction Skills, among others. These consultations resulted in the Community Benefits Project Strategy, complete with draft clauses to be incorporated into the contract. The successful participant was expected to embrace the concepts of sustainable development and community benefit and to work with the Scottish Government to deliver local training and employment. The strategy was subsequently successfully implemented, with more than 21 apprenticeships and 179 targeted employment opportunities created between 2011 and 2017.

In early 2011 the main crossing preferred bidder was announced. It was Forth Crossing Bridge Constructors (FCBC), a joint venture comprising Hochtief, Dragados, American Bridge Co. and Morrison Construction.



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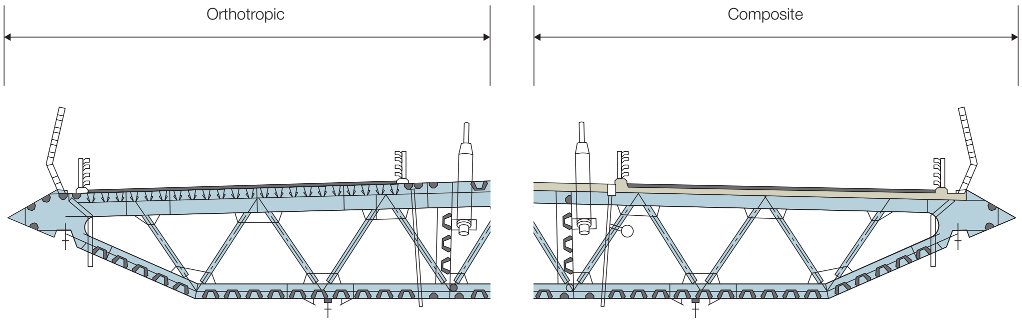

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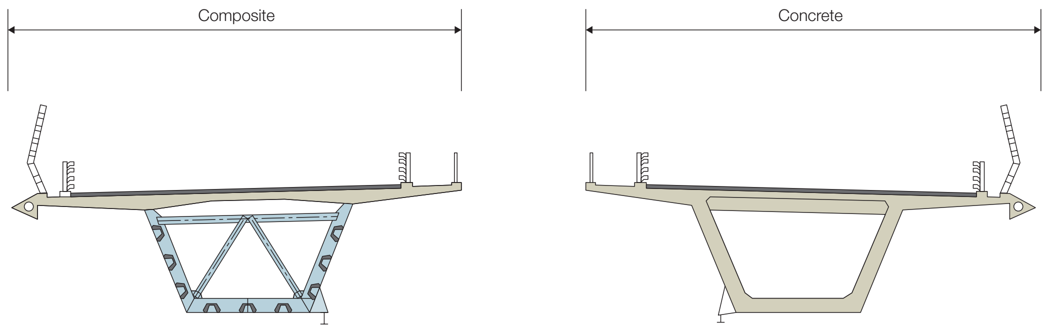

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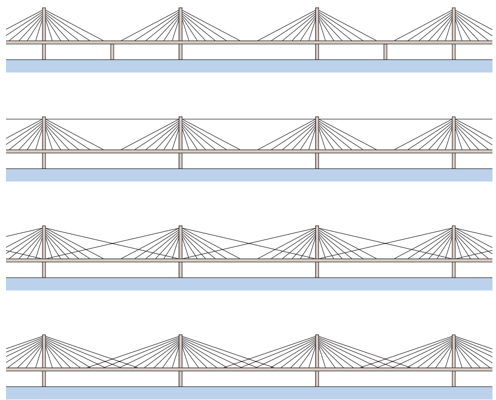

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Specimen design

The setting of Queensferry Crossing is uniquely interesting: the adjacent crossings – the famous cantilever rail bridge, completed in 1890, and the FRB suspension bridge – are Grade A listed, so the design for the new structure had to complement and not visually dominate them. The proposed alignment took the route across the estuary where Beamer Rock separates the Forth Deepwater and Rosyth navigation channels, the rock supporting the central tower of a three-tower, cable-stayed bridge, with two main spans each of 650m.

A major challenge to address was the stability of the central tower. As this would not be connected to a stiff back span, out-of-balance live loading on only one of the main spans could cause significant sway of the tower, resulting in large deflections of the deck and large bending moments in the tower. This is a well-known issue in multi-span, cable-stayed bridge design, and several configurations can be adopted to stabilise the internal tower. The simplest solution is a stiff deck, and very stiff towers, but this would have looked heavy and out of place at Queensferry and would have required substantial foundations. Alternatively, connecting additional stay cables at the top of the central tower to the the side towers or their connection points with the deck was an option. But the massive cables required for the 650m spans would have sagged very visibly. The solution chosen was to extend each cable fan beyond the mid-span so that adjacent cable fans overlap. Parametric studies carried out for this project showed that as the extent of overlapping is increased, the structure becomes stiffer and the bending moment in the tower reduces. Once the overlapping zone is approximately 25% of the span length, deck deflections are equivalent to a single main-span bridge, with the peak tower bending moments reduced to about two-thirds.

The deck of the bridge is continuous over its 2,638m length. The majority is cable stayed, with a twin-box, multi-span viaduct to the south, and a short, twin-box viaduct to the north. Longitudinal fixity is provided by a monolithic connection at the central tower on Beamer Rock with transverse support at all towers and piers. Early cost estimates showed very little difference between an all-steel orthotropic box girder for the main spans and a composite version with a concrete slab, the cost penalty of additional steelwork fabrication balanced by savings in stay cables and foundations. The twin-box approach viaducts could have been either pre-stressed concrete boxes or composite boxes, so to avoid making a decision too early, scheme and specimen designs for all variants were prepared. The towers are in reinforced concrete located in the centre of the deck with two planes of stay cables anchored centrally in the shadow of the towers between the carriageways. The deck is a streamlined box girder and stay cables are of a multi-strand type. Visual continuity with the approach viaducts is achieved by maintaining the same constant 4.9m structural depth, which suits typical spans ranging from 80m to 90m.

13.

A particular aspect of the structural analysis was to determine a feasible sequence of stay cable tuning during the construction stages. The overlapping stay cables in the completed bridge share load but act individually in the final stages of cantilevering. Careful tuning of the staged stay cable stressing was required to avoid increasing the size of cables just for the temporary condition, without resorting to too many incremental stages of stressing. As well as structural analysis and verification, developing the specimen designs included ship impact analysis, wind studies and wind tunnel testing, consideration of construction methods and provision for access facilities for ongoing inspection and maintenance of the bridge.

Tendering contractors were given the freedom to optimise the specimen design proposals to suit their construction methods. The main span lengths were fixed within a few metres. Symmetry of the main spans was required, but the southern viaduct span arrangement could be varied. The overall section shapes of towers, piers and deck had to follow the specimen design, but ranges were defined for key dimensions to allow sufficient variation without compromising the overall look of the bridge. Arup had adopted a similar approach, with success, on the well-known Øresund Bridge project, completed in 2000 (see *Arup Journal Issue 1, 1996* and *Issue 3, 2000*). FCBC's tender-winning proposal adopted a composite box girder for the main spans, and twin composite box girders for the approaches, with the same continuous edge detail.

Ease of maintenance was a high priority for Transport Scotland. So to combat the unpredictable and often severe weather conditions that affect the Firth of Forth, a combination of design features was specified. These included the use of multi-strand stay cables that permit replacement of individual strands as part of routine maintenance, leading to longer cable life. To minimise maintenance, the road surface is a conventional construction laid onto a non-fatigue-sensitive concrete slab forming the upper flange of a smooth welded box with minimum external surfaces, expansion joints only at the bridge abutments nearly 2.7km apart. A dehumidification system inside the deck prevents condensation and consequently corrosion of steelwork.

Steel and concrete

Statistics compiled between 2007 and 2017 demonstrate the magnitude of the bridge superstructure. Quantities of key materials are approximately:

- 35,000 tonnes of steel
- 150,000 tonnes of concrete
- 23,000 miles of cabling

It took 15 days of continuously pouring concrete to complete the foundations of the south tower of the bridge: a world record for the longest continuous underwater pour.

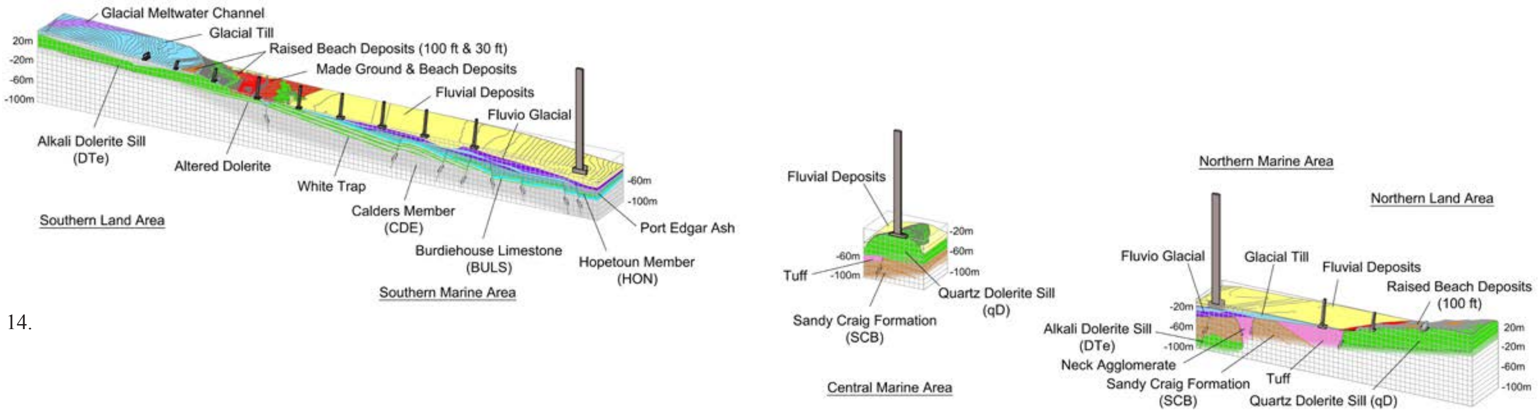
9. Tower and pier elevation.

10. Typical single-box deck.

11. Typical twin-box deck.

12. Possible configurations to stabilise towers of multi-span, cable-stay bridges.

13. The main crossing under construction.



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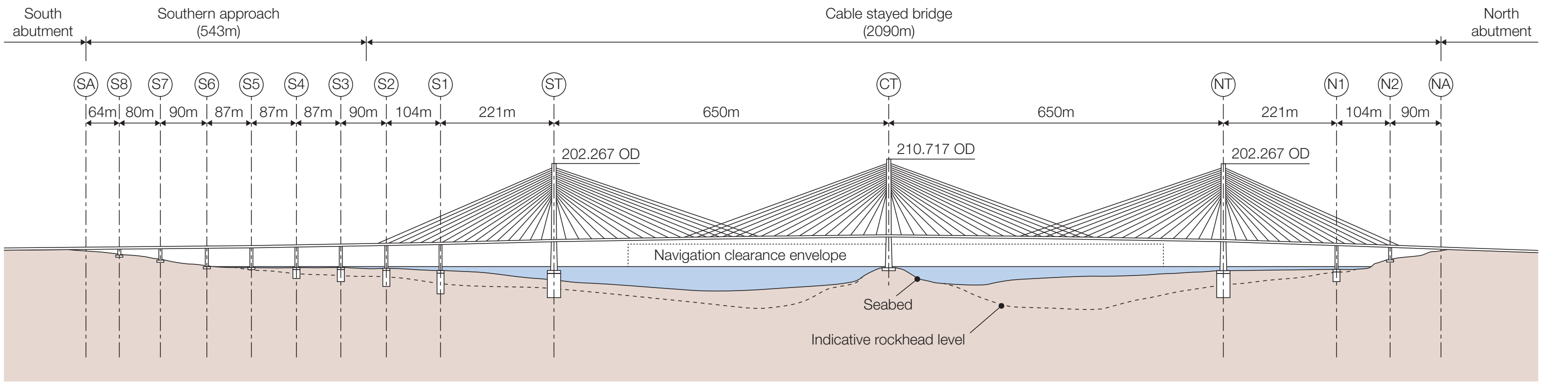

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14. The complexity of the geology is evident from this ground model of the site.

15. The foundations: from the gently shelving south shore to the steep bank on the north shore.

16. Marine foundations under construction.

17. The cofferdam on Beamer Rock.

Ground investigation

The geology of the Forth Estuary at the crossing location is complex: sedimentary rock with abrupt volcanic intrusions form the steeply sloping sides and it is this setting that largely dictated the shape of the bridge and its design features. It was recognised from the outset that the geological structure and variable ground conditions presented significant risks, so a multi-phased ground investigation was carried out. Existing information was supplemented by four phases of investigation to develop a robust ground model and obtain geotechnical data specific to potential foundation locations. Phases 1 and 2 were carried out prior to tender; Phase 3 during tender to enable participants to input into the scope and obtain experience of the ground conditions; Phase 4 was post tender award to add specific detail. The minimum acceptable ground requirements per foundation location were specified in the Employer's Requirements.

Foundation design

Queensferry Crossing has 15 foundations: ten in the estuary, five on land. The specimen design developed a foundation solution of spread and piled foundations capable of carrying the huge bridge loading down to rock in a challenging marine setting through up to 25m of boulder-rich glacial soils. The proposed solution for the foundations in the estuary included off-site construction of caissons/pile caps, floated to site and sunk onto blasted rock, dredged prepared marine formations, or receiving piles. The process of developing the specimen design, coupled with experience on similar projects, made it possible to assess difficulties the contractor could encounter and as there were clearly many challenges, tenderers were directed to develop solutions and procedures that could be tested and quality-assured, before use on site. This was included in the Employer's Requirements. In addition, tenderers could propose foundation designs of their own.

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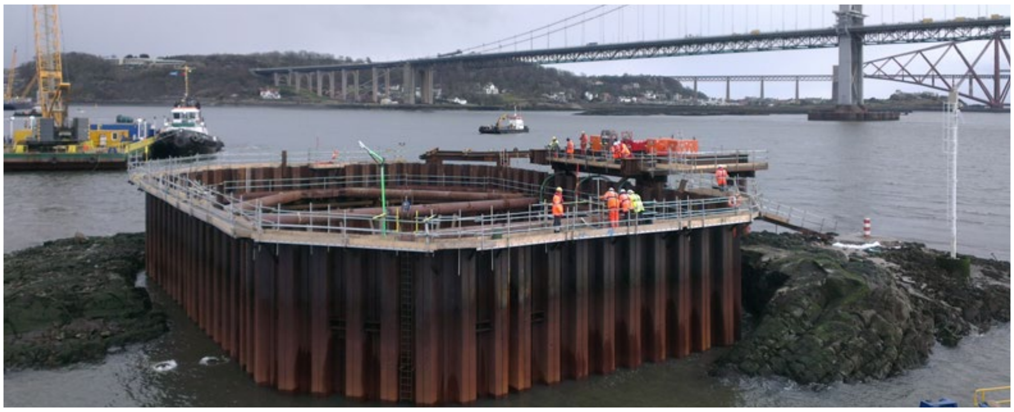

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The specimen design also provided a benchmark for Environmental Impact Assessment (EIA) of the project. As the site is within a protected marine environment, sufficient detail was required to enable consenting bodies to consider the impact of the scheme on sensitive ecosystems that include wintering birds, migratory salmon, benthic communities and marine mammals. Marine noise, and sediment plume impact from dredging and blasting, were among the effects modelled for specimen design. In the contractor's detailed design phase, the sub-sea foundation proposals were considered by consenting bodies against the EIA.

FCBC's marine foundation scheme included spread footings at all locations, with varying temporary works solutions. Mass concrete pours were required below water in the marine environment. The central tower foundation comprised a bespoke segmental prefabricated steel sheetpile and concrete base cofferdam founded in a blasted pocket on Beamer Rock. The north and south tower foundations, in deeper water, adopted large diameter temporary works caissons sealed around their base by rings of grout-injected piles and spread footings bearing on competent rock. The pier foundations used cofferdams of varying geometry: a solution developed during the dialogue process to confirm feasibility, albeit one that was not without risk from boulders in the glacial till and uneven rock head. These risks were successfully mitigated in FCBC's alternative marine foundation scheme.

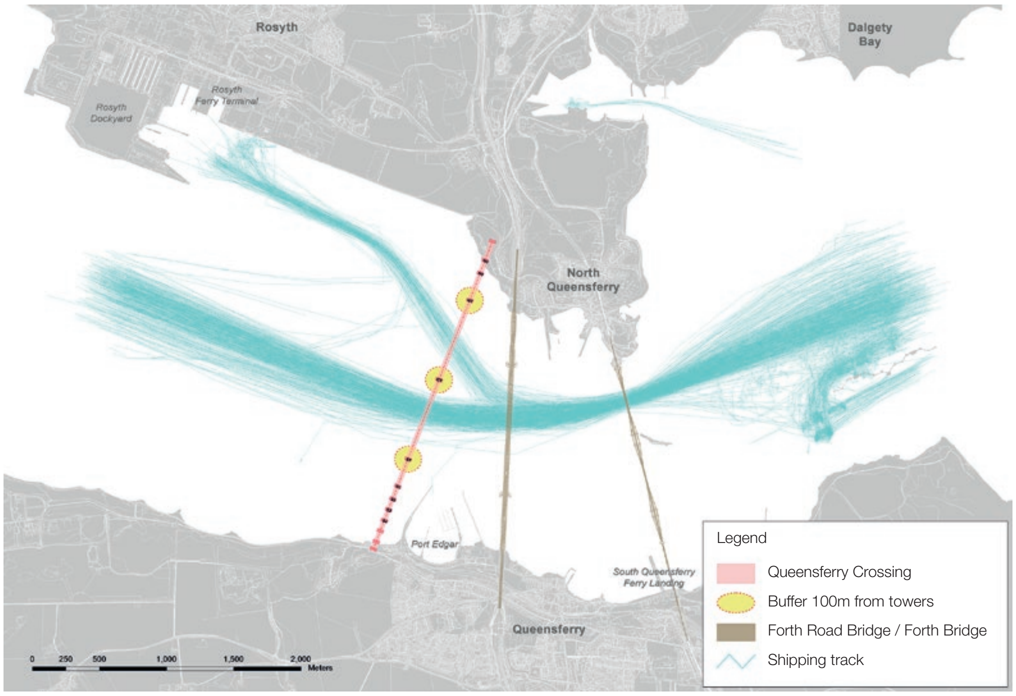
18. Scale models were built to test the design in a wind tunnel.

19. Shipping lanes: an innovative strategy was devised to determine impact risks.

20. Lighting plans were developed for marine and aviation safety (top) and to provide comfortable driving conditions on the bridge at night (bottom) without over-illuminating residential districts either side of the river.

21. Road and river traffic flowing over and under the bridge.

18.



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Specialist studies

The final design of the bridge depended on much research and development in areas of specialist engineering including wind, ship impact, lighting and structural health monitoring. The following sections describe a summary of these studies and, where appropriate, references are given in which further detail may be found.

Wind studies

Before design could begin in earnest, the meteorological conditions unique to the Firth of Forth were assessed. The area is known for high winds and bad weather. Historic wind data was used to determine a site-specific wind climate. Data from measurements was analysed, along with calculation models to account for the local terrain. This included wind records measured on the Forth Road Bridge, wind records measured at Edinburgh International Airport, and wind climate information provided in various codes, particularly the UK NA to BS EN 1991-1-4 [4] and BS6399-2 [5].

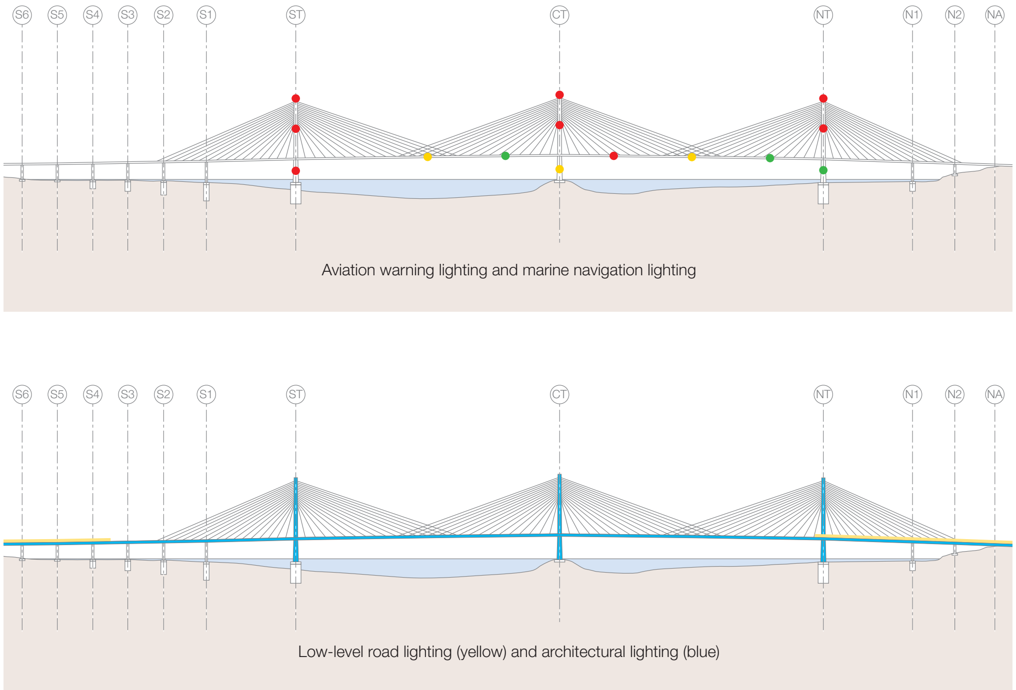
Analyses based on the resulting design wind climate helped determine suitable cross-sectional shapes for the deck and towers, and the associated aerodynamic properties. They also helped to identify the form of effective wind shields and to confirm the aeroelastic stability of the bridge. Preliminary computer simulation of the response to wind was followed by extensive preliminary tests in a wind tunnel. Different types of deck sections were tested at Politecnico di Milano at 1:50 scale to investigate the aerodynamic stability and force coefficients. At the early stages, ladder beam decks were included in the investigation because they might have provided a cost-effective solution. But the mitigation measures tested to improve stability, including edge fairings and partially open central vents, did not eliminate the risk of aerodynamic problems, so they were not progressed beyond the preliminary stage.

Traffic restrictions and occasional closure due to strong winds has frequently affected the FRB. To reduce similar disruption on the new bridge, wind shielding was developed for the edges of the deck to protect vehicles without increasing beyond reasonable levels the forces the structure must carry. Performance criteria were set to select wind shields that would achieve conditions on the bridge no worse than those to be expected on typical approach roads around the site. A wide range of shield geometries were tested on a 1:40 scale model of the deck section and this resulted in the selection of shields that were 3.44m high, with six horizontal slats of 300mm, achieving approximately 50% porosity. This provided the required level of protection for the critical design vehicle, a double-decker bus. Near the towers, a varying height barrier reduces the sudden impact of the wind shadow effect caused by the towers,

Tests at 1:30 scale were conducted to confirm the deck was aerodynamically stable up to and beyond the critical wind speed expected at site. Cut-outs in the corners of the towers were found to greatly improve the aeroelastic behaviour of the towers, and to obviate the observed galloping-type response. A very large 1:170 scale model of the bridge was used for the full aeroelastic tests. Key stages of construction were investigated, including the balanced cantilever deck erection around the central tower, as well as the completed bridge in smooth and turbulent wind flow. The contractor subsequently carried out comprehensive wind tunnel testing to confirm the adequacy of the final design.

Ship impact

The Firth of Forth is a busy shipping lane. The southern main span of the new bridge crosses the Forth Deepwater Channel, and its towers and piers lie just outside the shipping channels that serve the refinery and petrochemical plant at Grangemouth, and the docks and shipyards at Rosyth. Tankers, ferries and container vessels pass under the bridge and several of the new piers are in sufficient depth of water that large vessels passing under could feasibly collide with the structure, resulting in very significant impact loads.



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Forth Ports maintains comprehensive records of ship movements on the Forth. The typical annual movements, by size of ship, show that while vessels greater than 42,000-tonnes displacement do pass under the bridge, the number of transits is very few. The traditional deterministic design approach bases ship impact load on the largest ship travelling at a predetermined speed without considering the likelihood or feasibility of those impacts actually occurring. But on this project, an innovative risk-based approach demonstrated that lower ship impact forces could be adopted than those used for traditional deterministic design, while maintaining acceptable risk levels. Ship impact loads were derived using a probabilistic approach based on existing vessel transit data combined with assessments of future changes in usage and vessel type. For every segment of every transit the probability of aberrance, and its consequence, was assessed in terms of the frequency of collision with a bridge support and the resulting load: the data set was analysed to discount vessels that would ground before reaching the support.

A ship impact design load and probability profile was established for each support to establish a probability of collapse acceptable to the client based on the principles of 'As Low as Reasonably Practical' (ALARP) risk. The approach resulted in a substantially more efficient design.

Architectural lighting

After dark, the lighting design aims to subtly transform the bridge into what looks like a blade of light floating on the water, the effect enhanced because there are no road lighting columns on the bridge. Roadway lighting is required only towards the ends, near the junctions, where low-height lighting units integrated into the vehicle restraint barriers throw wash-light across the road. The design priorities in the selection of the lighting elements were driven by the desire to be energy efficient, achieve neat integration, and offer ease of long-term operation and resilience. The luminaires that were specified do not need external wiring, are unobtrusively sized, and are dimmable for maximum flexibility in use. Cowls are specified, where necessary, to minimise spill light and glare.

The blade effect of the deck is created by a continuous 2.7km row of LED strip lights integrated into the wind shield on each side of the bridge. These lights illuminate the topside of the bridge deck.. Each lighting unit consumes 55W, resulting in an installed load of 145kW. The design for the tower lighting is based on metal halide lamps, comprising 172 narrow-beam 1kW/2kW projectors, mounted above and below the bridge deck.

Where provided, the road light levels were selected in compliance with British Standards, with a ME specified target luminance of the road surface illuminated to 1.5cd/m^2. The luminance of the architectural lighting was designed to achieve an appropriate balance of night-time impact against a dark ambience backdrop of the night sky. As a result, target luminance ratio of 10:1 has been set against the brightness of the road surface. This translates into a minimum design luminance of 15cd/m^2 on the bridge towers, for white light. These levels ensure that the lighting effect is noticeable at a distance of about 1.5km, the primary viewing condition for the bridge at night.

Structural health monitoring

To enable forward planning of major maintenance, rapid response to incidents, and early interventions to keep maintenance costs sustainable, a structural health monitoring system was designed for the bridge. It incorporates approximately 2,000 sensors that measure environmental actions, bridge actions and bridge response. Databases of structural capacities, design load effects and baseline conditions, combined with advanced data analytics, mean that reports correlating monitored actions and responses with the design data are generated automatically. Cloud computing enables the operator to maintain and update records and provides Transport Scotland with detailed oversight of the condition of the bridge and its operational and maintenance budgets.

22.

22. The world's longest balanced cantilever was built on the tower founded on Beamer Rock.

23. Beamer Rock, formerly the site of a mid-channel lighthouse, was blasted to create the foundation for the central tower.

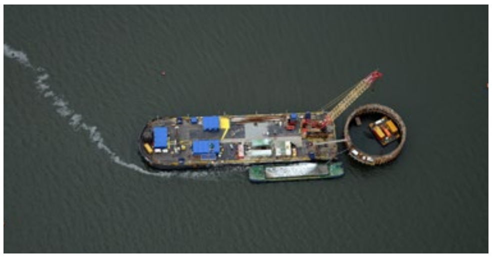
24. Caisson delivery to site on semi-submersible barge.

25. Caisson excavation and base cleaning.

26. The interior of a caisson after underwater concrete placement and dewatering.

23.

24.



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Construction: 2011–2017
With the award of the contract in April 2011, JAJV transitioned from its role in creating and defining the scheme to assuring quality delivery. The works were underpinned by the 'Code of Construction Practice and Environmental Assessment' that was incorporated into the construction contracts. FCBC implemented the code so successfully that for every year on construction it won Gold in the UK construction industry's Considerate Contractor Awards.

To ensure assumptions made in design were achievable, targeted construction trials were carried out to examine, among other things, the effects of underwater blasting, the accuracy of underwater inspection techniques, and the evaluation of large underwater concrete pours. Robust and rigorously controlled quality assurance procedures for design compliance reviews provided opportunities for clarification and, if necessary, rectification before construction, to avoid any omission or misinterpretation. Communication was based on an archive and project collaboration system (called Business Collaborator) that was used during the procurement process and the construction phase to maintain a consistent flow of information between the EDT and FCBC. This comprehensive filing structure and document control register made contract information easily searchable during the project, and will be available retrospectively.

Foundation for the central tower
Beamer Rock is an outcrop of dolerite. As there was huge demand on the load capacity of the foundation of the central tower during construction, it was essential for 90% of the area of the post-grouted precast concrete base to have intimate contact with intact dolerite. To ensure the integrity of the foundation, trial blasting to determine the depth of fissuring of the rock was carried out, together with off-site base grouting trials to prove the methodology to achieve the required contact. Holes were drilled to verify complete coverage had been achieved.

Caissons for the flanking towers
The flanking towers sit on circular caissons that had to be positioned accurately in tidal waters up to 22m deep in which competent rock is overlaid by approximately 25m of soils including boulder-rich glacial soils. The wet caisson technique was used: the caissons remained filled with water to ensure internal and external pressures were approximately equalised during sinking.

Double-skinned steel permanent caissons, the largest being 31m diameter, topped with smaller 10m tall temporary caissons to allow below-water construction, were delivered to site on semi-submersible barges. To sink them, a mechanical grab emptied out materials such as soil and boulders, while water, followed by concrete, was injected between the two skins to increase the weight. When the caisson edge arrested at the high point of the rock-head, a curtain of jet grout columns on the outside of the caisson was used to bridge the gap between the cutting edge of the caisson and the rest of the rock-head. The area within the caisson was then excavated, cleaned and plugged with concrete. The south tower holds the world record for the largest continuous underwater concrete pour by marine supply: 16,869m^3 over 15 days supplied by a flotilla of barges. Final dewatering of the completed caisson allowed construction of the required foundations for the superstructure above.

Trials and inspections included: building jet grout columns on the south shore of the estuary where there are materials similar to those found in the deep water; underwater inspection with a freshwater-filled, diver-operated, camera dome for fissure mapping in turbid water; and building a trial cofferdam to prove underwater concreting methods.


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Concrete tower construction
The concrete bridge towers rise 210m above their bases. To ensure a smooth and even finish, jump-forming of the concrete pours was mandated to avoid the risk of unplanned construction joints. This meant creating 4m-high hollow concrete tower segments, then jumping the formwork up to mould the next pour on top. The concrete, single sourced to ensure uniform colour, was delivered by a combination of pump and crane. In the upper levels of the towers, the inner shutter of the walls was formed by the steel boxes forming the anchorages for the cable stays.

Again, this process was meticulously planned prior to execution. Proving trials were carried out on land before construction commenced, to replicate the eventual highest concrete pour at 205m and provide confidence that the mix design would not have to change. The concrete mix designs and testing included determining chloride diffusion rates and modelling thermal behaviour. GGBS (ground-granulated blast-furnace slag) mixes were specified to provide protection against both sulphate attack and chloride attack. In the splash zones of the towers and marine piers, extensive use of stainless steel reinforcement was made.

Cable-stayed bridge deck
FCBC chose to fabricate the majority of the deck steelwork, the stay anchor boxes within the towers and the primary temporary works in China. To supplement the fabricator's and the contractor's inspections, JAJV provided a team to oversee the fabrication in Shanghai and Yangzhou to ensure that process, procedure and product were correct at prototype stage, and in the manufacturing process, rather than discovering corrective measures were necessary on receipt. The local team was supported by regular visits from experts in fabrication and corrosion protection who provided clear guidance on specification interpretation and requirements.

The steel deck segments, generally 16m in length, were delivered in large shipments direct to the FCBC Marine Yard in Rosyth where the concrete slab forming the top flange of the deck box was added in an assembly line arrangement; of particular note is that the deck required transverse pre-stressing to control cracking to maintain the torsional stiffness of the box. The units were fitted out with as much secondary steelwork and mechanical, electrical and plumbing services as practicable before transport to site on barges. The completed lifted units were up to 850 tons in weight.


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The starter deck segments surrounding each tower were supported on temporary trestles, placed by a 1,200-ton floating crane. After securing the starter deck units, erection gantries at the tip of each cantilever lifted the units that followed to form the balanced cantilever construction at each tower. The balanced cantilever around the central tower was the longest ever constructed before its final closure to the adjacent flanking tower cantilevers. Methodology, out-turn geometry and loadings were reviewed throughout each stage, and quality and compliance were monitored. The process was sensitive to wind and tide so it took approximately four hours to lift each section approximately 50m to

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27. The concrete towers were built by jump-forming concrete pours, the crane climbing upwards as construction progressed. The form was adjustable to deal with the tapering width and length of each section.

28. The deck steelwork was delivered to the FCBC's Marine Yard at Rosyth.

29. Floating crane places temporary support trestles and starter units.

30. Flags representing the nations of the FCBC partners – Hochtief, Dragados, American Bridge Co. and Morrison Construction – were hoisted on the last piece lifted to complete the structure.

31. Erection gantry lift of deck segment. A total of 111 segments were lifted to complete the bridge.

32. Multiple-strand stay cables permit individual replacement of strands to lengthen the service life of the stay.

33. Vibration tests to confirm the loads on the stays.

deck level. The sections were held in place by the traveller gantry while cable stays were attached, tensioned, and the section was welded in and the top slab secured with concrete.

Cable stays

Historically, durability, fatigue life and maintainability of stay cables have been problematic on cable-supported bridges.
So a multiple-strand system was specified for Queensferry Crossing that allows individual replacement of strands to maximise the service life of the stay cable. The corrosion-protection system comprises a multi-layer barrier of high-density polyethylene (HDPE) on the outer stay pipe and HDPE-coated strands consisting of seven galvanized and waxed wires. The anchorage, the most vulnerable part of a modern stay cable in terms of durability, was put through rigorous fatigue and water-tightness testing to demonstrate that there was no ingress of water through the nested corrosion-protection system, particularly the water-tightness of the connection between the strand sheathing and the anchorages. The corrosion protection within the anchorage is additionally maintained by a flexible gel filler injection. Control of load involved length control and load measurement both of individual strands and whole cable bundles. Vibration tests to measure natural frequencies confirmed the as-installed loads.

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Approach viaducts
The viaducts were manufactured at Cleveland Bridge, Darlington, UK, and ZPMC, Shanghai, China.

The South Approach Viaduct (SAV) was delivered to site in half box sections and was constructed by a push-launch technique: a king-post arrangement avoided the need for temporary supports at ground level and over the mudflats. The boxes were assembled into 90m lengths then attached to the rear of the launch, pushed forward to allow the next section to be placed, before the process was repeated. The deck was concreted after the total length of the push-launch was completed.

The process for constructing the North Approach Viaduct (NAV) was different because the steep bank at the north shore prevented access from beneath. The entire 6,500t, 220m length of the NAV unit was assembled behind the north abutment, launched forward horizontally to Pier N2, then pivoted to provide the 3.9% final gradient of the deck, before being pushed over Pier N1 to connect to the cantilever deck.

Finishes and wind shields
To minimise maintenance requirements and provide a continuous conventional low-noise road surface, there are movement joints only at each end of the 2.7km crossing, but this results in large movement demand at each end (2,360mm at the south approach and 2,100mm at the north approach). Each abutment is close to people's homes, so to minimise the noise of wheels passing the joint, sinus plates were attached to the lamellar beams of the joint to spread wheel contact over multiple beams.

The innovative wind shields installed at the deck edges protect traffic from strong winds (see 'wind studies' section above), and high containment barriers on each side of the carriageway were validated through crash testing to BS EN 1317. The efficacy of a reduction in working width from 1,000mm to typically 800mm around the towers was proven through numerical modelling.

The wearing course of the carriageway was laid in echelon pattern to avoid longitudinal cold joints and maximise the life of the road surface.

Mechanical, electrical and plumbing (MEP) services
MEP services comprised essential lighting, a dehumidification system, lifts in the towers, fire detection, cleansing water, security and the building management system. Lightning protection was installed to safely conduct up to 200,000 amps to earth, with side-strike protection for the top 40m of the towers because of their height. The first permanent MEP works on site were containment (cabling and connections) for lightning protection through the foundations as part of the groundworks.

Cable trays and ladders were installed into completed units of the bridge deck in the marine yard at Rosyth from February 2015, prior to float-out and lifting. This pre-assembly minimised the time needed after completion of the deck structural works and reduced the need for working at height inside the deck segments. Large equipment and fittings were also placed inside the completed units prior to float-out, ready for moving and fixing into their permanent locations after being lifted into position.


37.


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The electrical load of all the equipment on Queensferry Crossing is similar to that of a 15-storey office building. Power supply is via electrical substations on each side of the bridge, with essential services backed up by a generator and uninterruptible power supply system in each abutment, or local batteries. The length of the deck, and its consequent expansion and contraction, requires all cabling to be supported by drag-link systems, like a big bicycle chain, crossing the movement joints at each abutment and each flanking tower.

The dehumidification system, designed to prevent corrosion, has two main parts: a ventilation system to continuously circulate a small amount of air around the box section voids; and a desiccant wheel dehumidifier that injects dry air into the ventilation. There are eight dehumidification zones in total, including one for each of the towers. In cross-section the deck has three cells, one in between and one each side of the cable stay anchorages. Air is supplied down one cell and drawn back along the other two. The largest spans are 650m so the air in the dehumidification systems travels over 1km before returning to the circulating fan.

The supervisory, control and data acquisition (SCADA) system and building management system (BMS) for MEP systems in the deck, towers and abutments are combined into one control and management system. Alarm, control and supervisory systems are accessed at work stations in the south abutment and also in the Bridge Control Room adjacent to the FRB, from where the bridges and the local road network are managed.

Summary

Completion of Queensferry Crossing not only meets the practical need to provide a fast, reliable route that is designed to stay open in most weather conditions, it also makes Queensferry a unique location where three technologically different bridges, from three different centuries, sit side by side within a magnificent landscape. Its graceful elegance inspired Jackie Kay, the Scottish Makar (Scotland’s poet laureate), to compose the poem overleaf that she recited at the opening ceremony: a fitting conclusion to a project that will become renowned the world over.

34. South Approach Viaduct: assembly of steelwork boxes at rear of launch and progression of launch.

35. North Approach Viaduct (NAV): assembly of this 220m-long structure behind the north abutment.

36. Start of the NAV launch: the 6,500t total weight, including the concrete slab, acted as counterweight at the tail of the launch.

37. Wind shield and vehicle restraint system as installed.

38. Carrying out finishing works to seal the cables from the weather at the tower tops. This allows air within the tower to be dehumidified to prevent corrosion.

39.

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Matt Carter, Leader: structural scheme design, including ship impact, and involvement in conceptual design proposals.

Kenneth Chong, Leader: mechanical, electrical and plumbing services design.

Mike Glover, Technical Director and Project Manager. He is an Arup Fellow.

Richard Hornby, Technical Manager, construction and logistics of the main crossing. He is an Arup Fellow.

Stuart Hunter, Programme and Budget Manager, including risk and procurement.

Naeem Hussain, Main Crossing Design Leader: bridge design, developed the specimen design and crossed cable solution. He is an Arup Fellow.

Steve Kite, Leader: bridge design team, analysis, scheme design, wind tunnel testing.

Paul Morrison, Leader: geotechnical team.

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Project credits

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39. The new bridge was designed to complement both the Forth Road Bridge (right) and the Forth Rail Bridge (far right).

Queensferry Crossing

If you were a ship you would sail and be gone,
But you are the bridge that will stay
You are the ship that does not leave,
That breathes in the sky, night and day

Queensferry Crossing

If your fitters and your welders, your joiners and engineers,
Surveyors, scaffolders, concrete finishers and crane operators
Across Scotland had a dream o' ye –
It would be to see you on this opening day,

Queensferry Crossing

Raising your harp and playing your strings
At every return, every going away,
Back and forth, Firth of Forth
North to South, South to North

Queensferry Crossing

Like a great cormorant, perfectly still,
And lifting your wings out to dry,
In snell winds or high,
Come driving rain, come shine,

Queensferry Crossing

You glint, you glimmer, are ne'er the same twice
Your cables shimmer, disappear in the chittering light
Mystery crossing, here one minute, gone another,
In dreich mist, in the haar, in twilight,

Queensferry Crossing

Along St Margaret's marsh, where the pilgrims once were ferried,
by the banks of the Forth
Across time's estuaries, life's vagaries,
Its ups and downs – here you are, arms outstretched

Queensferry Crossing

Three bridges; three centuries; one life.
Be safe, be bold, be kind!
A girl crosses the old red in a crimson dress,
An old man walks the suspension;

Queensferry Crossing

Cars of all colours will drive across the Queensferry
Like the Queen's car did today.
The urge to build bridges runs deeper
than the great rivers they ford

Queensferry Crossing

You're the bridge in the sky, the high hope,
You're the wingspan of centuries, the future's story.
If you were a ship you would sail and be gone
But you are the bridge that will stay,
You are the ship that does not leave
That breathes in the sky night and day

Queensferry Crossing

Queensferry Crossing

Queensferry Crossing

V&A Exhibition Road Quarter

Location
The Victoria & Albert Museum, London

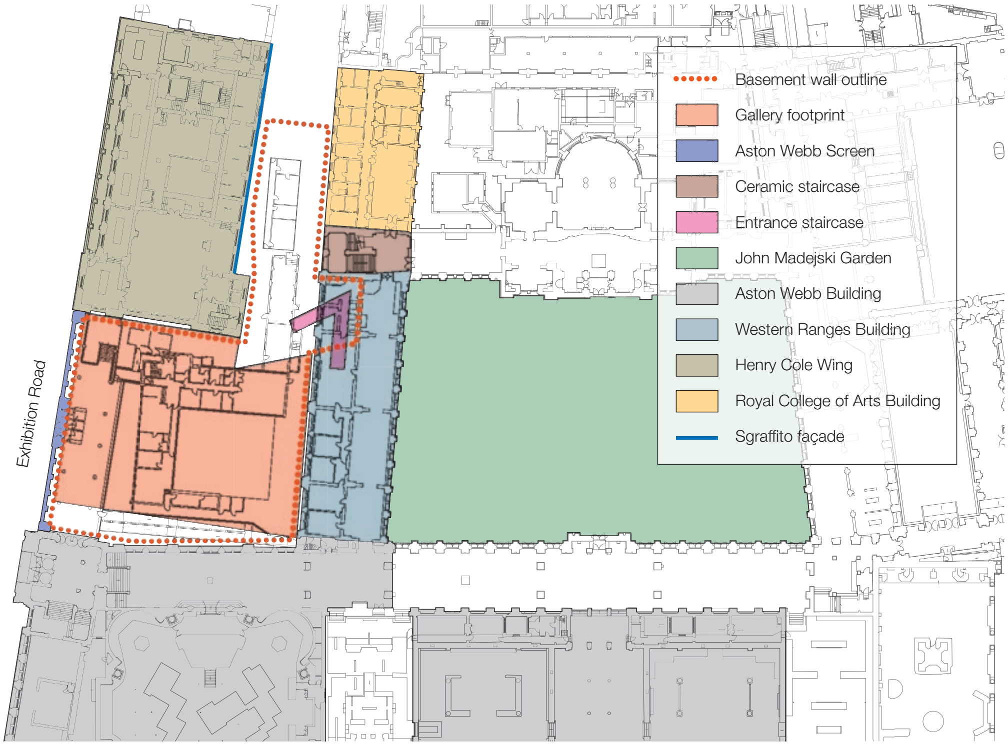
Authors
Mel Allwood Carolina Bartram Alice Blair Ed Clark Rachel Harris


1

1. The entrance courtyard lies behind the Aston Webb Screen built in 1909. This was originally a semi-solid structure, now permeable through gates that provide public access and views into the courtyard from Exhibition Road.

2. A map of the site showing the close proximity of the basement walls to the existing buildings. The site is an 'L' shape: the gallery shop and servicing access are in a narrow gap off the courtyard.

3. Boilerhouse Yard before work began: various utilitarian buildings occupied the courtyard and the façades of the surrounding buildings were largely obscured.



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3.

Introduction

Designing deep basements for buildings in historic city-centre locations is always a challenging proposition. The Exhibition Road Quarter at the Victoria & Albert Museum, London, was no exception. The V&A's new Sainsbury Gallery for temporary exhibitions is 15m deep and it is on a site bounded by Grade I and II listed buildings that have unusual and fragile façades. Artefacts sensitive to movements and vibrations are housed in these buildings, and the museum had to remain open throughout the works. The roof of the gallery is a 'folded plate' steel structure spanning 36m across the width of the site. Expressed steel transfer beams and columns support an existing museum building as the main entrance staircase passes underneath. Access to the gallery is via a porcelain-tiled entrance courtyard, now known as the Sackler Courtyard. It is the world's first public space to be paved in this way.

Sophisticated 3D analysis, digital design and optimisation methods, together with early considerations of buildability and construction sequence, were important to understanding the structural actions, and reducing the risks, during construction of this ambitious project. These techniques allowed the structural design to be visualised, understood and communicated in a way that enabled architects, engineers, the client and contractors to participate in its development. The project also provided the opportunity to further develop low-energy and sustainability initiatives at the museum. Working with Amanda Levete's architectural practice AL_A, Arup provided multidisciplinary design services from competition stage through to completion of construction.

Competition brief

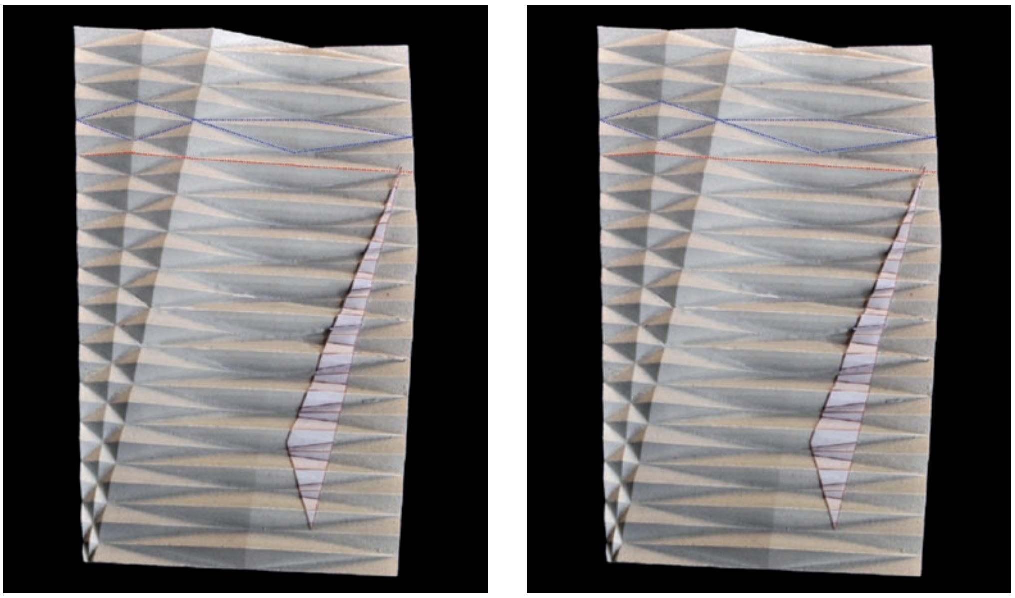
The gallery is in what was known as the Boilerhouse Yard. Sir Aston Webb, who designed the principal museum buildings, intended this to be a courtyard but when the museum's boilers were located there instead, he designed a solid rusticated wall, with Portland stone columns and an entablature above, to hide this area from neighbouring Exhibition Road. The 'Aston Webb Screen' continued to divert attention when the area later became a servicing hub and various utility buildings were built there. The site slopes in both directions and buildings on and around it were founded at levels that varied by up to 6m.

The V&A's design competition brief asked for a large, column-free gallery on this site, with a minimum floor to ceiling height of 5m within a scheme that would reveal the façades of the surrounding buildings to visitors. This meant the gallery and associated facilities would have to be largely underground. AL_A's winning scheme comprised a courtyard, café and shop at ground level, with the gallery one level below this, together with back-of-house spaces for preparing objects for exhibitions.

At competition stage various configurations, materials and systems were considered for the gallery roof and the eventual choice was a folded, almost origami-like structure, spanning over the exhibition area, defining the architectural character of the space. This versatile geometry was developed to reconcile the differences in levels across the site, and it creates the significant structural depth to span the 36m site and support the courtyard above. The geometry provides soaring headroom, yet integrates the services strategy generating simple lighting routes and space for low-energy air extract. A large oculus perforates the courtyard to let daylight penetrate the basement areas and create views upwards to the surrounding façades.

The Aston Webb Screen was opened up, the columns and entablature retained, and the solid wall removed to leave individual columns between which are gates to allow easy access to the courtyard from Exhibition Road.

4.



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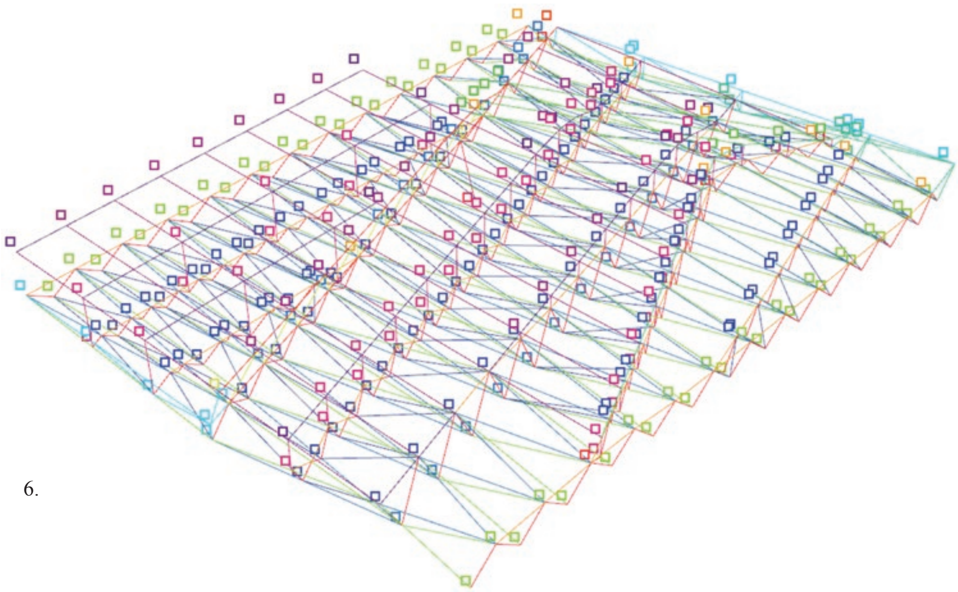

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Concept design

At concept stage, the client and design team explored the brief and design in detail to clarify the fundamental elements of the project, balancing the architectural scheme and client brief against pragmatic and economic requirements. The folded plate roof was a fundamental part of the competition scheme, so developing this efficiently and economically was critical. It became clear that to maximise the internal floor area of the gallery, the structural and geotechnical design must specify construction of the basement walls as close as possible to the façades of the existing buildings. As the basement had to extend under the existing Western Ranges Building to create the new entrance stairs, early consideration of construction sequencing was essential to limit the effect of ground movement on the existing building and to ensure the museum could remain operational throughout the works. The goal of achieving a BREEAM Excellent environmental rating meant making key decisions early, particularly with regard to the impact of the brief on energy use in the space. The network of existing services and plant in Boilerhouse Yard area had to be unravelled and a services diversion contract was implemented. This enabled the rest of the museum to function during the main construction contract and permitted the strategic upgrade of key elements of the existing infrastructure.

Courtyard roof design

The structural design for the courtyard that developed during concept stage introduced a deep primary truss along the side wall of the mezzanine, providing intermediate support for the folded roof. This allowed the depth of structure under the mezzanine to be minimised, and since this was the pinch point for height, it also minimised the excavation. After exploring various options, a series of 3D steel trusses was chosen because they were lightweight (compared with deep steel or concrete beams), simple to connect on site, and provided the most flexible solution for integrating lighting and other high-level services into the gallery ceiling. The mezzanine and courtyard floor slabs, on metal deck, span over the trusses.

At concept stage, simple models were used to review the efficiency of structural options with different geometrical parameters – from the lean of the main truss off-vertical, to the depth and different potential geometric forms of the folded plate. The concept design was then developed further, through

a full three-dimensional interactive geometrical process with AL_A, in order to coordinate and examine the geometry. This was done via a shared Rhino model that used the Grasshopper plug-in to adapt the folded plate geometry (depth of structure at various locations, widths of trusses). The model was brought into the Oasys GSA for structural analysis, which in turn linked to an Excel optimiser for steel member sizing.
The GSA analysis had to take into account both vertical loads and also the lateral loads the structure had to resist to prop the retaining walls. Due to the slope of the site in both directions, and large openings in the courtyard slab for daylighting, there was no simple continuous horizontal diaphragm to resist these loads. The initial geometry that required complex sequencing, or significant temporary propping, was also adjusted in favour of a geometry that allowed for the fabrication of fully stable elements that could be delivered to site in one lift.This design and optimisation process saved approximately 40% of the steel weight of the original concept design, and the saving was achieved without using an excessive number of section sizes, which would have complicated fabrication.

Basement design and sequence
The brief asked for 1,100m^2 of exhibition space; achieving it was dependent on the thickness of the perimeter basement wall and how close it could be to existing buildings. Control of ground movements was critical because settlement behind the retaining walls due to wall deflection could result in damage to the surrounding masonry buildings, which were heavy, yet fragile, having very fine joints, decorative plaster details, and ceramic and terracotta elements.

Pressure from the existing foundations due to the weight of the masonry walls close to the top of the new retaining walls was a key consideration in the way the basement walls were designed. A hard/firm secant pile retaining wall was selected, constructed using rotary bored piling rigs with temporary casings toed into the London Clay through the water-bearing terrace gravels. In the main courtyard area, the wall was formed from 880mm nominal diameter male piles. In the final condition, these piles span vertically up to 11m. In the constrained spaces of the smaller leg of the 'L' shape and under the Western Ranges, the wall thickness was reduced to 600mm. Arup developed a good understanding of what were the tightest possible limits by combining information from measured surveys of the façades, and trial pits to find the existing footings, with pre-construction advice on clearances required by likely piling rigs. This also meant a high level of detail for tender could be produced so that contractors were fully aware of the risks and the care they would need to take. When work began on site, the piling rigs operated to within 300mm of the

7.

8.

4. A render shows the 'origami-like' steel visible in the gallery ceiling. The ceiling was painted grey when it was built (see picture 21).

5. Physical models were used to explore various configurations of the 3D geometry for the folded plate roof.

6. The final structural model of the roof.

7. Supporting the secant pile wall during construction of the basement.

8. Erecting the roof steelwork.

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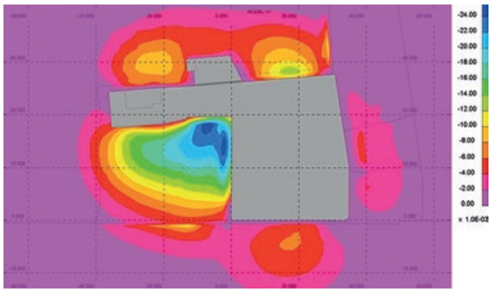


12.

9. Piling rigs operated to within 300mm of the existing buildings.

10. A semi-top-down construction sequence reduced cost and risk.

11. Work within the façade of the historic Western Ranges Building to create the entrance stairs to the basement.

12. The soil behaviour model in LS-DYNA®.

13. A comprehensive lighting, heating and ventilation strategy was devised in pursuit of the highest possible environmental performance ratings.

14, 15. Detail of how the approach to daylighting and associated heat gain was developed.

16. The modernity of the basement staircase, with a skylight above, is in striking contrast to the Victorian buildings above ground.

buildings at their limits (foundations and cornices) and the basement wall was successfully constructed to the Arup tender setting out without change.

In the courtyard area, a semi-top-down sequence was proposed and adopted for the basement excavation to minimise cost and risk. Temporary steel props were installed at the top of the retaining walls. This was followed by excavation to gallery floor level, construction of the gallery floor slab, and a final level of excavation below the gallery floor to formation level. The gallery floor slab provided a stiffer prop to the retaining walls during construction than would have been feasible with temporary steel props and so helped to control ground movements. In the dog-leg area of the site, basement construction was bottom-up with four levels of props.

A staged 3D finite-element geotechnical model was created at scheme design stage to refine the temporary propping arrangement and excavation sequence, and predict ground movements in more detail. The model was created using the geotechnical software LS-DYNA®, with the advanced BRICK model (Simpson, 1989) representing the soil behaviour. The model showed that the movement of the existing buildings was affected not only by the basement wall design, but also by heave, particularly in the courtyard area where the heave effect under the base slab from the 18m-deep excavation is significant, especially as there is minimal gravity load to counteract it. Heave board or sub-slab drainage to reduce pressures under the base slab were ruled out as they increased the predicted settlements of the surrounding buildings. Instead, a piled raft with heave-reducing tension piles to control deflections was adopted, the tension piles extending 32m below the raft. The 12 tension piles are located on a grid of 8m–9m centres, with plunge columns installed on each pile to support the 300mm-thick gallery floor slab.

The 3D finite-element model was used to consider all aspects of the basement geometry and model key construction stages to predict building movements, and from these to predict crack widths and the potential for damage. Because the model showed how important the wall stiffness and levels of the temporary props would be, Arup designed all the piles and defined the assumed construction sequence, stiffness, strength and levels of temporary props in the tender information.

Arup specified a detailed system of movement monitoring that included surveying the buildings using 3D prisms on façades and levelling studs within the buildings, extensometers in the ground and inclinometers in the secant piled wall. These were all monitored regularly throughout the construction process and tracked against pre-set trigger levels at each location for each stage of construction.

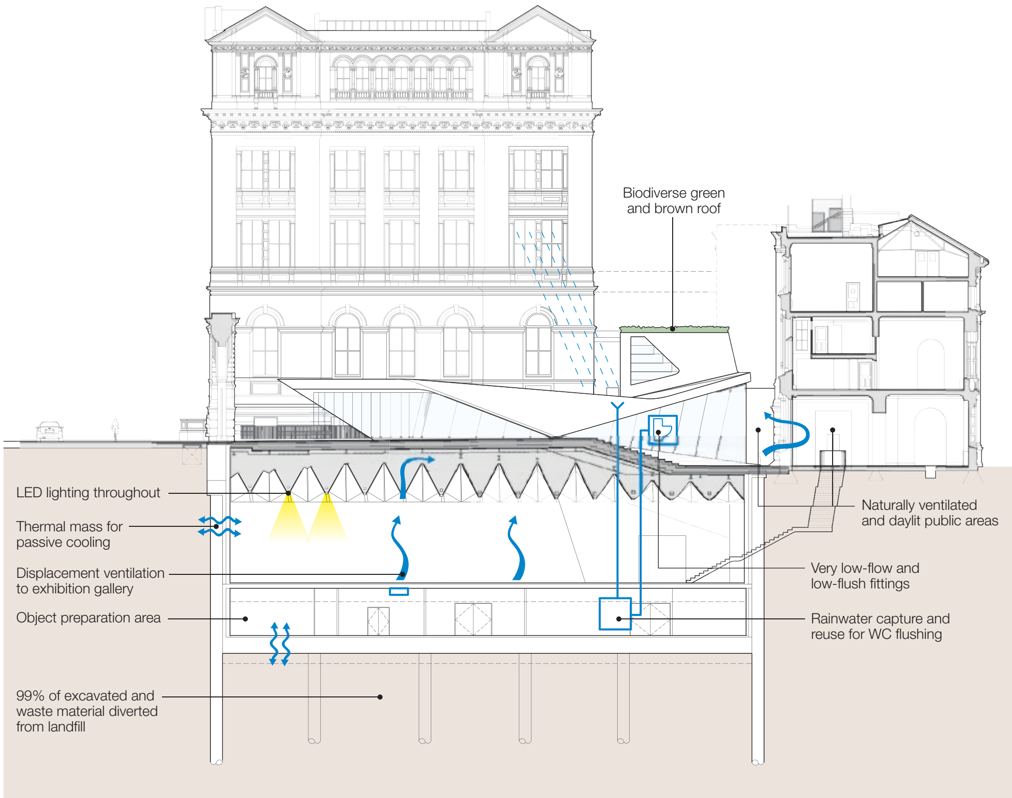
The entrance staircase

The staircase to the gallery is designed to admit light and afford views of the sgraffito façade and the dome of the Aston Webb Building. To avoid encroaching on the gallery space, this staircase (and a passenger lift) is accessed from a two-storey basement beneath part of the Western Ranges Building,

Understanding heave
In collaboration with the Centre for Smart Infrastructure and Construction (CSIC) at the University of Cambridge, the heave effects from beneath the V&A Exhibition Quarter basement will be measured as part of a long-term research project. Fibre optic monitoring systems have been installed in two of the tension piles and within the basement raft. The development of tension in the piles and bending in the raft will be monitored and calibrated against the 3D models to achieve a better understanding of the phenomenon of heave.

connected to the rest of the basement through the original façade line. Major temporary works and a specific construction sequence were needed for the stairwell because of the requirement to support the load-bearing wall of the building above, and the restricted working space. A low-headroom piling rig and temporary plunge columns were used. The plunge columns supported temporary steelwork that in turn supported the three-storey masonry façade, internal floors, and walls of the Western Ranges Building from ground level upwards during excavation. The permanent structure consists of four steel transfer beams, which span between two sets of four double-height steel columns and the basement walls. The contractor's preferred sequence was to install the beams early, and support the building on extensive temporary works during excavation, until the columns could be built. Temporary transverse propping of the retaining walls was also needed and threaded through circular holes cut in the webs of the transfer beams.

Sustainability
From the outset, sustainability was implicit in the design. The project's target rating was BREEAM Excellent, ambitious for a building that is largely underground, is surrounded by listed buildings, and requires precise internal environmental conditions for the conservation of exhibits. The goal was a reduction of carbon emissions by 25% more than the Part L baseline (a building regulation in England that sets standards for the energy performance of new buildings). The strategy for achieving this was to reduce energy demand as much as possible and improve the efficiency of energy supply.



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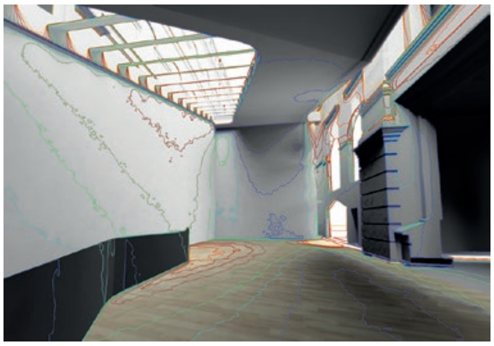
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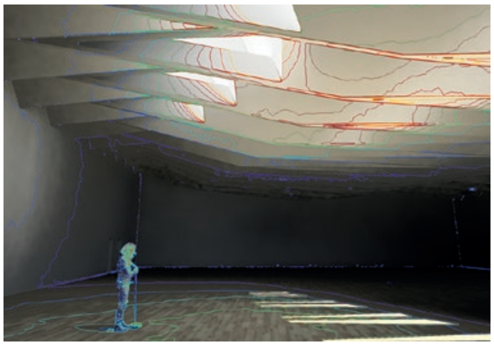
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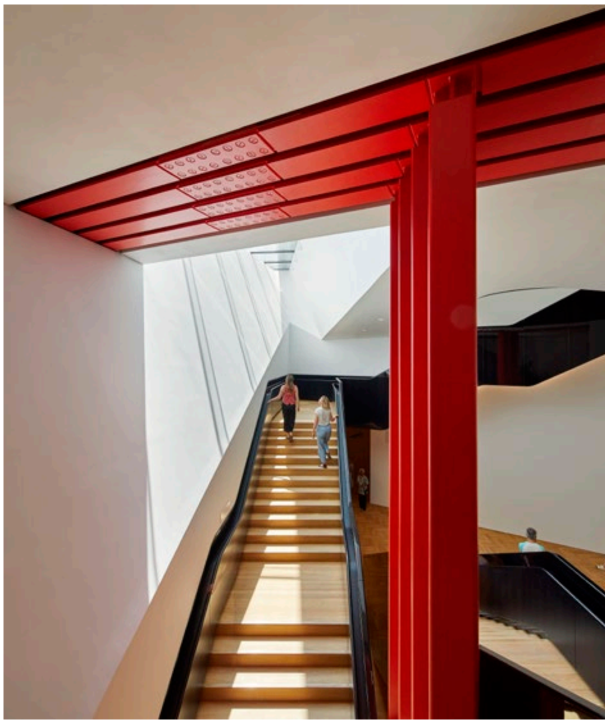
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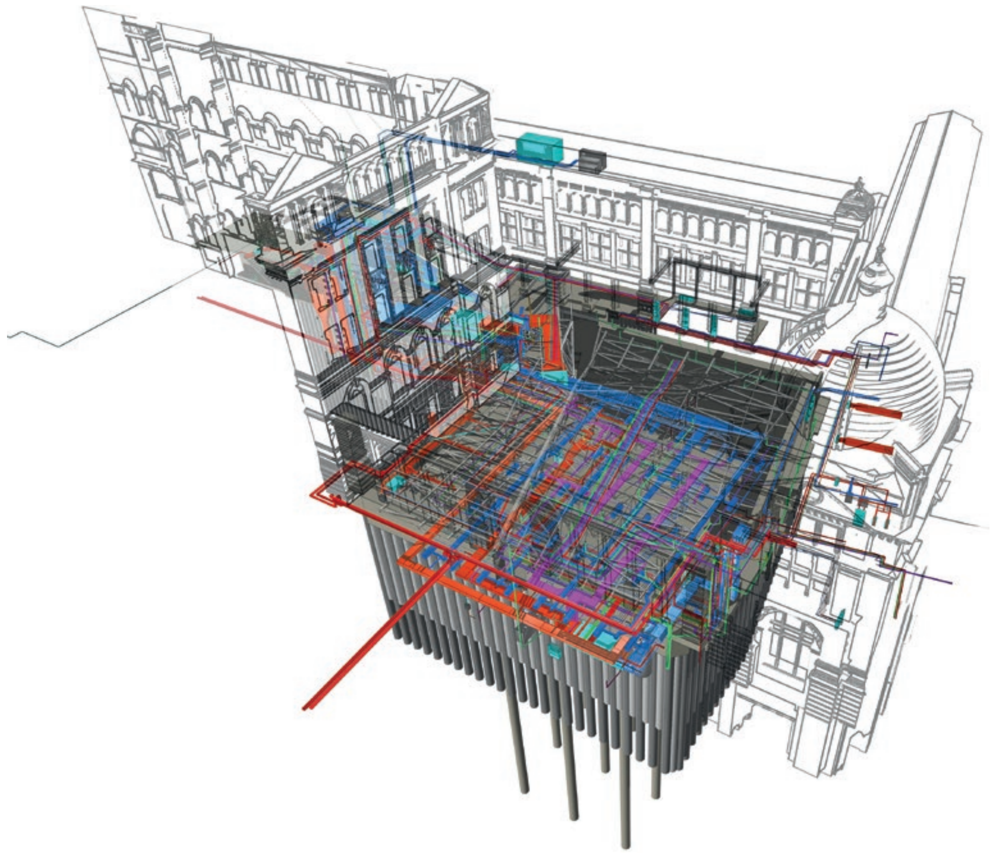

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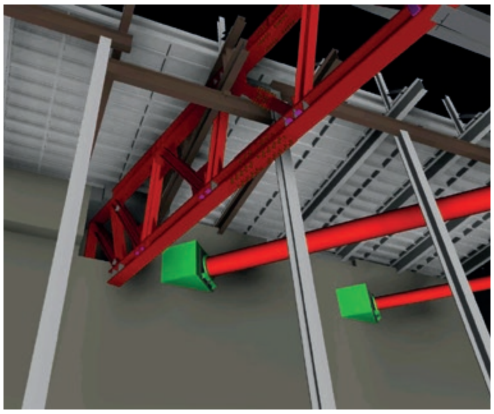

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Arup has worked with the V&A over a number of years to develop innovative, low-energy solutions for the environmental control of galleries, and the Exhibition Road Quarter project is a culmination of that work. The museum has pioneered a progressive approach to environmental control that accepts a wider band of temperature and humidity ranges within the constraints of exhibit conservation, while limiting daily and seasonal change. In the Exhibition Road Quarter, Arup created a sequence of spaces, from the naturally controlled lobby areas, through to intermediate buffer zones, to the more closely controlled gallery and object preparation areas. The design exploits the thermal mass of the structure to create a stable environment for the exhibits and provide passive cooling. A low-level displacement air supply is used in the gallery space; the height of the gallery ceilings complements this servicing strategy, allowing warmer air to stratify at high level.

Further energy efficiency measures implemented included the use of LED lighting and variable volume air supply, controlled with feedback from CO_2 sensors.

Carbon savings were also achieved by connecting the museum to the district heating system in the adjacent Natural History Museum.

All of this work on energy solutions, carried out early in the project, was critical in identifying the limits on design flexibility for the team. It set out where there were conflicts between energy performance and architectural aspirations, and how the unusual site could contribute to the overall energy-saving strategy.

Other sustainable measures to minimise the impact of the project included a small green/brown roof, planted with native and adaptive species. Water use in visitors' toilets was minimised through the use of low-flush and low-flow systems. Rainwater harvesting was implemented wherever possible.

A single point of contact for monitoring progress throughout the site phase ensured that the sustainability strategy was executed as it had been intended. Reviews were tied to the procurement process so that the best-performing products and materials could be selected. By developing a sustainability strategy early, and maintaining focus on implementation in line with design development, the completed project is a clear demonstration that sustainability need not compromise an architectural vision.

Sharing a BIM model

Using a single federated 3D BIM model, initially owned by the design team, then by the contractor, was fundamental to delivering the project given the tight site and complex geometries. The coordination of temporary works with the permanent steel and concrete structure would have been very difficult without use of the model, which incorporated a 3D survey of the existing buildings as well as the new construction.

The model was refined at various stages of the construction process, enabling review of the large temporary props, their relationship to the trusses and other elements of structure at different stages, and making it possible to model how they would be removed; the steelwork design for the courtyard meant that the steel structure itself required minimal temporary support (only to the

17. 3D coordination of the structure and services interfaces with the existing museum systems.

18, 19. Coordination of the primary mezzanine truss with the props and the working platform in a BIM model and as built.

20. The porcelain-tiled courtyard, the world's first public space to be paved in this way; the entrance staircase is within the partially glazed structure, the skylights for the gallery below neatly enclosed and an artwork in their own right.

21. The dramatic effect of the skylights in the gallery.

20.

21.

large primary truss). By combining the process of optimisation with a review of construction methodology, the concept stage structure – which had at one stage seemed complex to build – became one for which fabrication, structural action at all stages of construction, and installation, were well understood. This greatly minimised risks and increased speed of delivery.

Services for the building were integrated closely with the structure and architecture, with key routes modelled at the design stages to ensure coordination at pinch points and also to maximise areas that could be more 'loose fit' in their approach, allowing for simpler installation. Knitting together the existing museum services infrastructure and the new installation was a complex task and the BIM model proved a useful tool for showing the resulting key services routes, and describing how to access and maintain them, to the V&A and its facilities management team.

Summary

This was an ambitious project from the outset, but the design intent and brief from concept stage were very clear. Best practice use of automation and optimisation and collaborative digital processes helped the team to successfully understand, design, coordinate and construct this complex building on a challenging site. Movement monitoring and cutting-edge research gave a clear understanding of construction movements and the real effects of ground heave on structures.

This approach minimised risk during construction, and combined detailed and complex geometry and analysis with care, pragmatism and understanding to exploit the site to its full potential.

Authors

Alice Blair, Senior Engineer, Project Structural Engineer, managed construction coordination and delivery of the structural design.

Mel Allwood, Sustainability Assessment Team Leader.

Carolina Bartram, Associate Director, Structures.

Ed Clark, Project Director.

Rachel Harris, Lead Building Services Engineer.

Project credits

Client: *Victoria & Albert Museum* Architect: *AL_A* Main contractor: *Wates Construction* Basement propping and Western Ranges temporary works design: *Wates Engineering* Piling: *Keller Foundations* Specialist low-headroom piling: *Martello Piling* Demolition, groundworks and substructure: *Toureen Group* Structural steelwork: *Bourne Steel*. Arup – *Mel Allwood, Francesco Anselono, Tim Barker, Carolina Bartram, Alice Blair, Phil Borowiec, Ken Carter, Steve Chapple, Jake Cherniayeff, Ed Clark, Tara Clinton, Lizzie Davies, Jim Deegan, Andrew Duncan, Ken Eaton, Zeena Farook , Claire Feng, Lee Franck, Mark Freeman, Sam Frith-Salem, Peter Griffiths, Graeme Hanshaw, Stuart Hardy, Rachel Harris, Kate Hibner, Sarah Hooton, Jade Kang, Matthew King, Lee Kirby, Leonora Lang, Andrew Lerpiniere, Maike Lorenzen, Mei-yee Man, Shane O'Riordan, Petra O'Sullivan, Jean Parker, Dinesh Patel, Dan Pook, Xiangbo Qiu, Richard Reid, Ed Sayce, Dave Seager, Andrew Sedgwick, Glen Swinney, Darryl Tanner, Nick Troth, Christoforos Tsiaousis, Rick Wheal, Colin Winant, Mike Yap, Jeff Yuen.*

Image credits

1, 16, 20, 21 *Hufton+Crow*; 3, 8 *Victoria and Albert Museum, London*; 4, 5 *AL_A*; 2, 6, 7, 9, 10, 12, 13, 14, 15, 17 *Arup*; 11 *Stephen Citrone*; 18, 19 *Wates*.

Woltersum Church, Groningen

Location
The Netherlands

Authors
Ben Arents Daniele Dozio Richard Sturt

1.

Introduction

Groningen, a province of the north-east Netherlands bordered by the North Sea, has experienced earth tremors in recent years thought to be caused by the extraction of gas: a phenomenon known as induced seismicity. Arup has been appointed by Dutch gas exploration and production company Nederlandse Aardolie Maatschappij B.V. (NAM) for consultancy services that include induced seismic hazard and risk assessments and the design of structural upgrading measures for buildings in the region. Arup's work on this project relies to a large extent on advanced nonlinear finite-element analysis. This type of analysis, using LS-DYNA® software, is well established at Arup. However, only recently has the firm examined how it can be used to assess unreinforced masonry buildings that are not designed to resist earthquakes, but may nevertheless be exposed to them.

Work continues at Groningen and further details of Arup's project with NAM will be the subject of a future article in *The Arup Journal*. At this stage, however, recently completed work on historic buildings in the region provides useful insight into appropriate seismic strengthening options that can be proposed. This article examines the approach taken at Woltersum Church, a building that dates back to the 18th century. An interesting facet of this project has been the extent to which virtual reality (VR) and augmented reality (AR) techniques have proved valuable. It is becoming clear that as solutions are developed at Groningen, digital technologies will play an increasingly important role. The VR and AR output has been useful for communicating how proposed structural strengthening options might look when built.

Seismic activity at Groningen

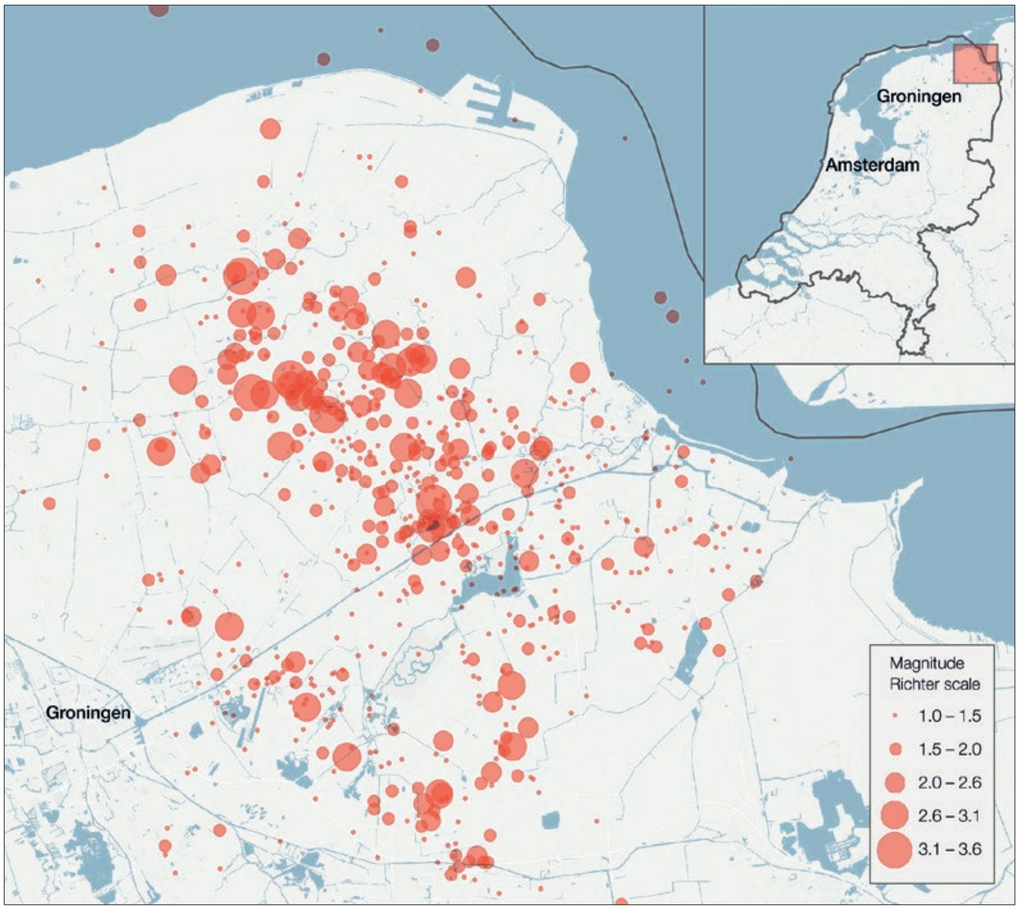
Gas was discovered in the Groningen region in the 1960s but it is only in more recent years that its extraction has been linked with induced seismicity. The strongest earthquake ever to hit the region was in 2012 and its peak ground acceleration was 0.085g. The seismic upgrading proposals for Woltersum

1. Woltersum Church, Groningen, is a pilot project for examining structural strengthening options that can be proposed for unreinforced masonry buildings, based on seismic assessment Arup has performed using LS-DYNA®.

2. Seismic activity in Groningen province between 1992 and 2017.

3. The walls of the church are built from clay bricks.

4. The interior of the church.



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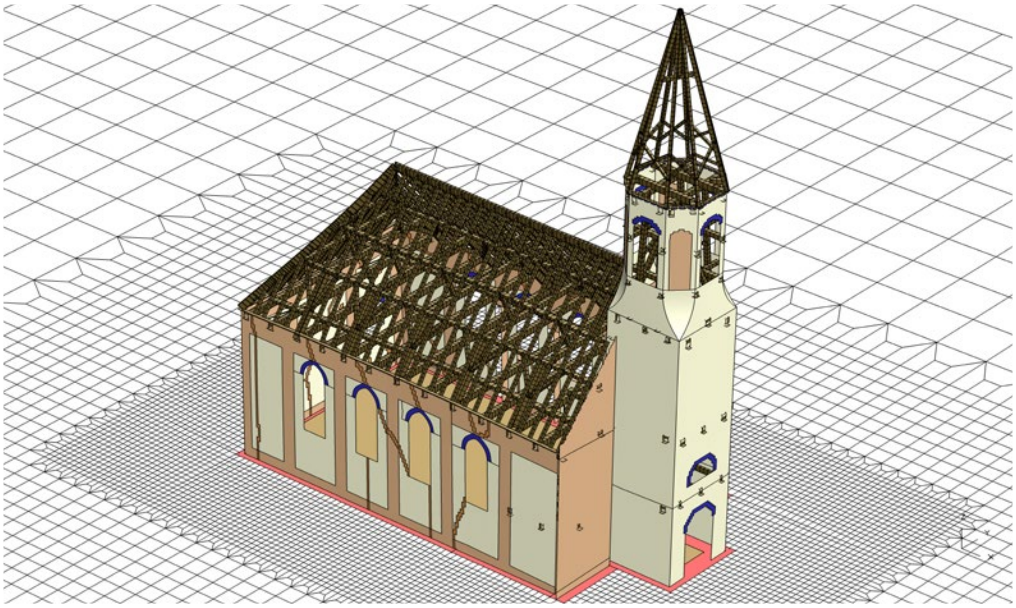
Church have been developed against the backdrop of this recent seismic event (though there has not been any seismic activity of similar magnitude since then), and NAM has already taken steps to moderate future gas production from the region. A suitable target performance level was set for developing the upgrading options.


4.

Woltersum Church

Selected by NAM as a historic buildings pilot project in 2013, this is a prime example of a traditional village church. It is located on a terp mound: an artificial hill typical of this low-lying area, created to provide safe ground during high tide and river floods. The nave is 11m wide, 18.5m long and approximately 17.5m high to the top of the timber roof. A bell tower at the eastern façade is approximately 4m by 4m in plan and 25m tall. All walls are clay brick masonry supported on strip foundations, and the two main building phases are apparent in the use of different types of brick. The elevations of the main western body of the nave are built from small 18th-century brick. The eastern extension of the nave and the bottom part of the bell tower are made from reused medieval brick (or ‘kloostermoppen’). Two buttresses were added just over 100 years ago to strengthen the north façade.



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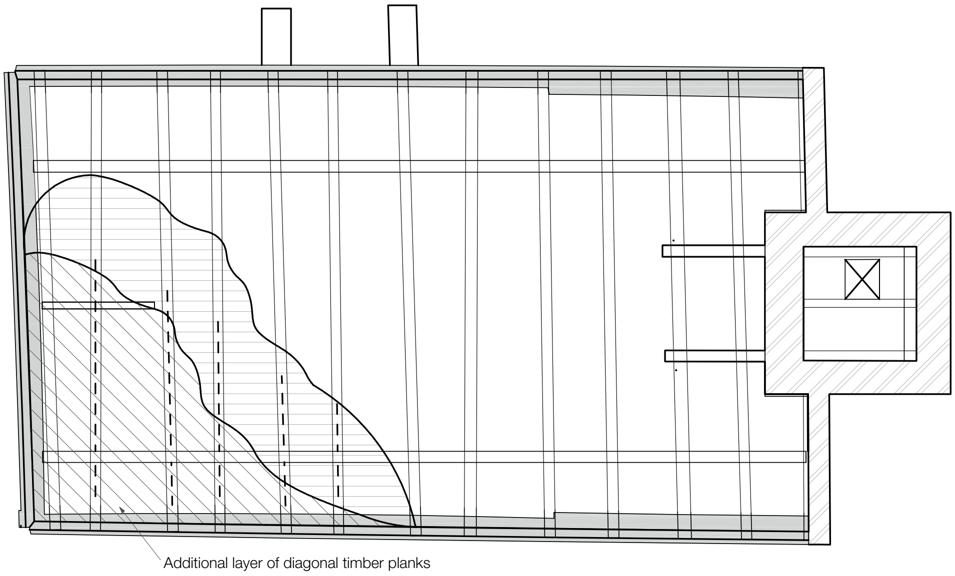

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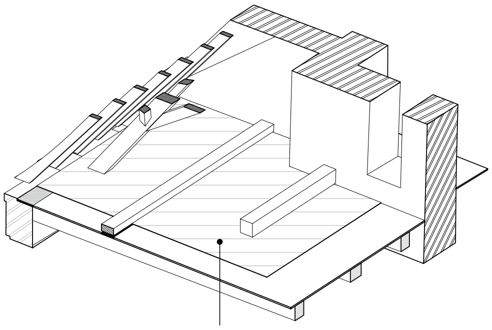

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Assessment method

After first carrying out detailed historical, geometric (3D laser scan), material and condition surveys, Arup conducted a seismic assessment of the church in its existing deformed condition. Assessment of the seismic performance of existing buildings can take many forms, ranging from qualitative procedures such as surveys by experienced engineers, through quantitative procedures such as spreadsheet calculations based on codes and standards, to the use of a variety of computer simulation techniques. For Woltersum Church, detailed finite-element simulation was performed using LS-DYNA®. It takes considerable time and effort to perform this type of analysis but it can prove the most cost-effective approach because simpler methods may be over-conservative and lead to unnecessary spending on remedial measures. This becomes particularly relevant for historic buildings, where a balance between seismic retrofit and preservation should be pursued. A further benefit lies in the fact that simpler analysis may require the engineer to make assumptions about how the structure will resist seismic loads, whereas detailed finite-element models can test out those assumptions and may sometimes lead to a different understanding of the building. This is especially the case when considering structures that were not designed to resist tremors because the mechanisms by which seismic actions may be resisted, and the fragilities that limit them, are not always obvious.

Model description

The masonry walls of the church were modelled using the techniques described in this article. Derivation of material properties for this centuries-old masonry, with varying degrees of degradation evidenced from survey, was challenging. Limited non-destructive testing was possible, providing estimates of compressive and shear strength. Other required properties were derived by scaling from destructive tests on similar types of masonry. Settlement-induced cracking is visible on the exterior of the building, and the most significant cracks were included in the model by means of elements with pre-weakened properties. The model includes other significant structural elements such as the roof timbers, which are joined to each other using connection elements with pre-defined strength and ductility. Where timber elements bear on the masonry over a limited contact length, the ability of the timber to fall off the wall is included in the model.

Superficial deposits can affect the horizontal components of ground motions (site response). Deformations of the soft soil on which the building is founded are expected to influence the response of the structure during a seismic event. Local rocking modes, differential settlement and sliding can lead to an increase of damage, or alternatively may help isolate the building from ground motion (soil structure interaction). For these reasons, a block of soil was included in the LS-DYNA® model. Properties were determined by Arup's geotechnical team based on site investigation results.

Proposed strengthening solutions
A variety of proposals for retrofitted structural strengthening were developed and LS-DYNA® was used in relation to the three described below to ensure they could effectively meet a target performance objective. The proposals are currently being considered by local heritage organisations so full details remain confidential at this stage. All the options described here included strengthening the existing attic floor in the nave to improve the three-dimensional response of the whole structural system. This would be done by adding a second layer of timber planks diagonally to the existing planks to increase in-plane stiffness and strength, then connecting the strengthened timber diaphragm to the top of masonry walls (figures 6 and 7).

Proposal 1: using a GFRP mesh
Devised to minimise aesthetic impact on the outer clay facing brickwork as much as possible, this proposal aims to increase the out-of-plane bending capacity and in-plane shear capacity of the masonry piers (and spandrels) by strengthening the existing masonry walls of the nave. If chosen, it would involve substituting existing inner plaster from the nave with a fibre-reinforced cementitious mortar (FRCM) of similar thickness, interleaved with a glass-fibre-reinforced polymer (GFRP) mesh, inserting inclined GFRP bars into the masonry piers (figure 8), and the structural repointing of masonry spandrels by adding GFRP bars into the outer bed joint mortar.

Proposal 2: inserting a seismic isolation system
Seismic isolation is a technique to shift the fundamental natural period of a structure to the long period range by placing horizontally flexible isolation devices at its base to physically decouple it from the ground. If chosen, there are various ways this could be implemented, all of which would involve minimal upgrade to the superstructure.

The isolator system was made up of a double grillage of reinforced concrete (RC) beams: one supporting the superstructure and installed on isolator devices; and the other one on micro-piles, placed on inner and outer sides of the existing masonry foundation beams. Another possibility would be to keep two rows of piles outside the building footprint (figure 10) and use a combination of RC and steel beams for the top grillage to make it lighter.


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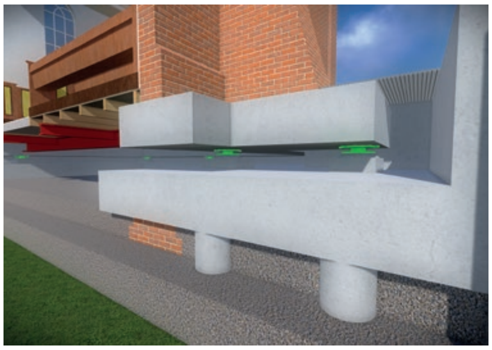
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5. The LS-DYNA® finite-element model of Woltersum Church on the soil block.

6 and 7. Attic floor strengthened by an additional layer of timber planks.

8. Proposal 1: FRCM replastering, and diagonal GFRP bars inserted into holes drilled around window openings to provide strengthening at these points of weakness.

9. Proposal 2: using flexible isolation devices to separate the base from the ground.

10. Detail of the proposed base isolation system.

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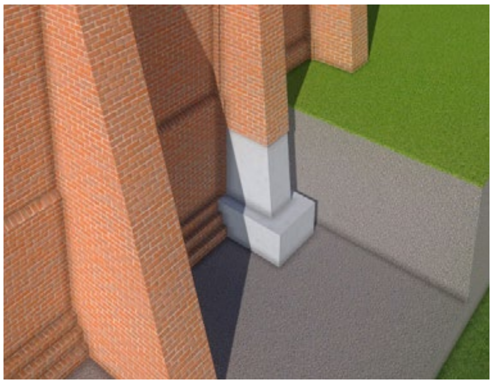

13.

11, 12 and 13. Proposal 3: details of the external buttressing system.

14. Augmenting virtual reality images on site, within a headset, enabled designers to visualise proposed buttressing.

15. Preventing damage or disturbance to historic graves and headstones was an important consideration.

Proposal 3: external buttressing

The design intent of this proposal is to replicate a uniform language of slender buttresses around the perimeter using the existing structure as far as possible for resisting the required seismic demand. The new buttresses would work as reinforcing piers to the current masonry rather than being designed as vertical cantilevering elements to provide lateral resistance to the entire building. This proposal could be implemented by using RC tapered external buttresses on pad foundations coupled with the existing masonry through bolts fixed to an internal steel plate (figures 11 to 13).

Virtual reality and augmented reality

Proposed structural upgrading measures, particularly for a large building, are traditionally communicated to clients and other stakeholders through drawings and buildings information modelling (BIM), as has been done in this article. But on this project, Arup is also using virtual and augmented reality, which have the benefit of providing an immediate visualisation, at the project site, of how proposed alternatives might look, if adopted.

At Woltersum Church, wearing a Microsoft HoloLens headset enabled the designer (or anyone who wanted to see the design proposals) to bring a 3D model of proposed buttressing into the real world and change it virtually. As well as being able to assess the aesthetics, it became possible to spot potential problems quickly. In this instance, it became clear that using external buttressing (Proposal 3) would need to be meticulously planned to avoid resting on the historic graves surrounding the building.

Summary

As work is ongoing, the full simulation results for Woltersum Church cannot yet be published. But it is fair to say that detailed finite-element analysis has shown itself to be a practical option for assessing the seismic performance of historic, unreinforced masonry buildings in the Groningen region. Work at Groningen has underlined how this analysis technique provides useful input for decision-making in risk management and mitigation in any situation where unreinforced masonry is subject to earthquake, whatever the cause.

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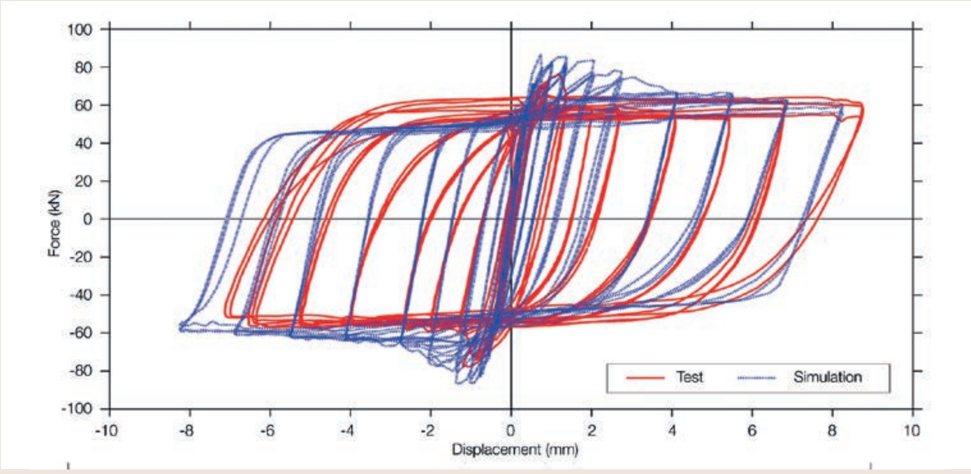
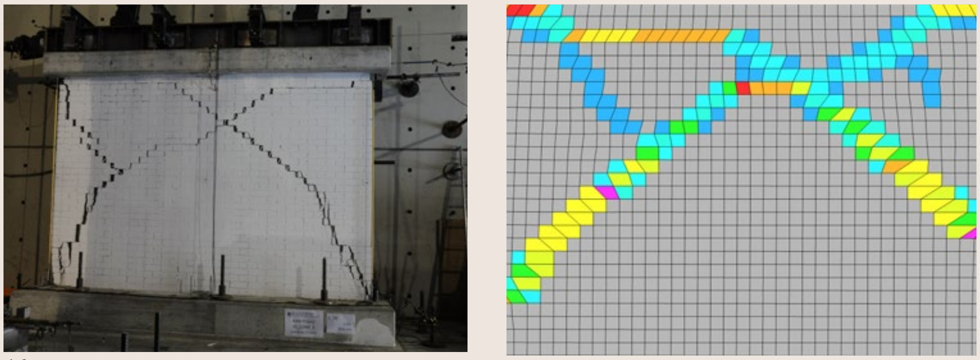




16.

Authors

Daniele Dozio, Senior Structural Engineer, was lead engineer from the start of the project.

Ben Arents, BIM Manager, virtual reality and augmented reality work on the project.

Richard Sturt is an Arup Fellow. He reviewed the analysis work on the church and developed the LS-DYNA® modelling methods.

References

LS-DYNA® is registered trademark of LSTC.

Project credits

Client: *Nederlandse Aardolie Maatschappij B.V. (NAM)*
Owner of Woltersum Church (permitted the inspections and tests, and provided advice on historical matters): *Jur Bekooy, Stichting Oude Groninger Kerken*
Structural engineering, geotechnical engineering, LS-DYNA modelling, CAD, augmented reality, virtual reality: *Arup – Ben Arents, Brian Austin, Daniele Dozio, James Go, Michail Kalogerakis, Boy Lamein, Agostino Lampariello, Chiara Mainardi, Carlos Merino, Hilde Millekamp, Alasdair Parkes, Erik Siemer, Ronald Stoter, Richard Sturt , Claire van der Wielen, Pepijn Vermolen, Michael Willford.*

Image credits

2. *Arup, using data from KNMI (Koninklijk Nederlands Meteorologisch Instituut): the Royal Netherlands Meteorological Institute*; 16. *Arup/EUCENTRE (Pavia, Italy)*; All other images *Arup.*

LS-DYNA®

LS-DYNA® is a versatile three-dimensional nonlinear finite-element analysis program, owned and developed by Livermore Software Technology Corporation (LSTC). Arup has collaborated with LSTC in its development, particularly for building and civil engineering applications.

The behaviour of masonry could not be reproduced accurately with the pre-existing LS-DYNA® capabilities that are normally used to model, for example, concrete structures. Arup therefore developed a purpose-written material model to capture key behaviours of masonry (such as preferential cracking directions, the 'interlock' between bricks in adjacent courses, and the degradation of strength and stiffness under cyclic deformation), without the need to model the fine detail of the individual bricks and mortar. The modelling method enables rapid model preparation and solution times while retaining the required accuracy and the ability to include other relevant components of the building in the model.

Validation against experimental data is vital and NAM has commissioned a laboratory testing campaign that to date comprises around 25 wall specimens loaded cyclically, some static and others dynamic; three shake table experiments on full-scale masonry house specimens; two further cyclic static tests on full-scale masonry structures; and companion material tests that characterise the basic properties of the specific types of masonry. An example test and the equivalent LS-DYNA® model is shown. The validation of the models covered the initial resistance of the structures and their hysteresis behaviour, their ductility and eventual collapse mechanisms.

Microgrids in Nigeria and Kenya

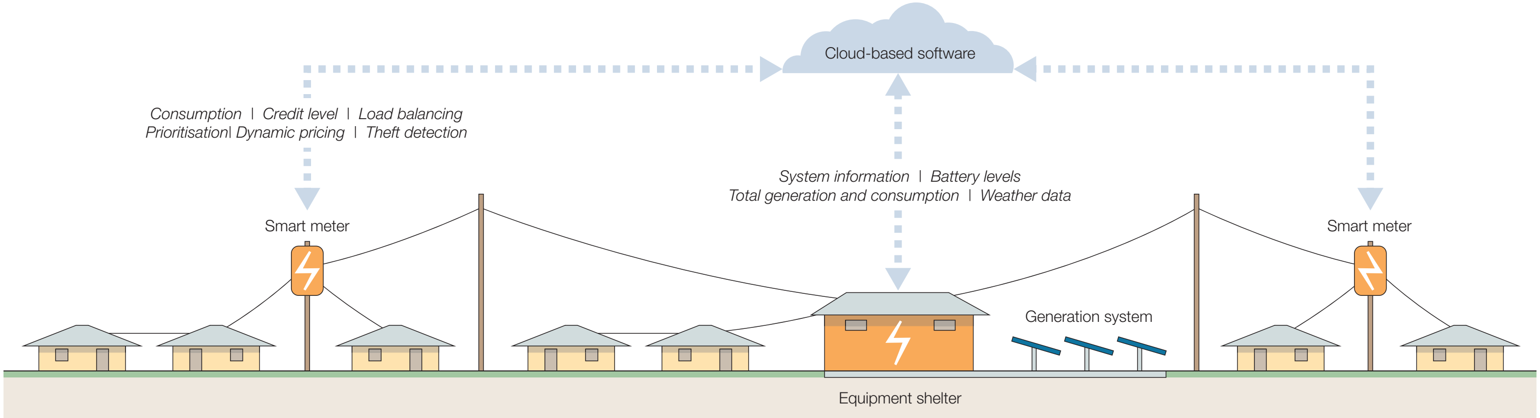
Location
Nigeria and Kenya

Authors
Kwame Adu-Asomaning Chris Brosz Justin Wimbush

1.

2.

Introduction
According to International Energy Agency statistics[1] approximately 1.1 billion people worldwide had no access to electricity in 2016. A substantial proportion of these people live in sub-Saharan Africa, and more than 600 million of them could still be without electrical power in 2030. Yet this situation could be improved: reductions in the cost of renewable energy generation and electrical energy storage over the past decade, particularly using solar photovoltaic (PV) technology, mean that villages without a grid connection can now leapfrog solutions based on fossil fuels and move directly to microgrids, a process that can be eased by effective cost analysis to make the systems viable and robust. In Nigeria and Kenya, Arup is working with Powerhive, a microgrid technology and project developer, to design projects that will bring secure, sustainable microgrids to remote villages that might otherwise be unable to access electricity.



3.

How a microgrid operates

The terms 'microgrid' and 'mini-grid' are often used interchangeably to describe a self-sustaining independent energy system that manages various generation and storage systems to supply electricity demands. In the context of rural electrification, microgrids consist of two main parts: a centralised energy plant and the reticulation system. The energy plant is where energy is generated, stored and managed, so for PV-generation the plant contains the solar array, backup diesel generator, battery bank, and various electronics, such as the inverters and microgrid controller. This plant can be quite small because a viable solar array can comprise as few as 96 panels of approximately 10kW in size. The reticulation system that distributes energy to the customers is made up of the wires, poles, smart meters, and what are known as 'ready boards' – these are distribution boards pre-wired and kitted with main switch, socket outlets and bulkhead light.

Powerhive hired Arup in 2017 for consultancy services on projects in various stages of development and construction in Nigeria and Kenya. Using Powerhive's systems, customers use their cell phones to buy electricity credits in advance, as part of a pay-as-you-go approach that is common for microgrid developers. Smart meters, distributed throughout the reticulation network, communicate with a cloud-based management system that allows the microgrid operator to prioritise loads, and use various pricing schemes including real-time pricing. As energy theft from microgrids can be a problem, the Powerhive system is protected with several novel power theft detection algorithms.

4.

5.

1. Even a very small microgrid can produce viable quantities of electricity for a community.

2. The small shelter needed to protect the batteries and electronics necessary to run the microgrid.

3. Smart meters communicate to a centralised monitoring and control system for intelligent microgrid operation.

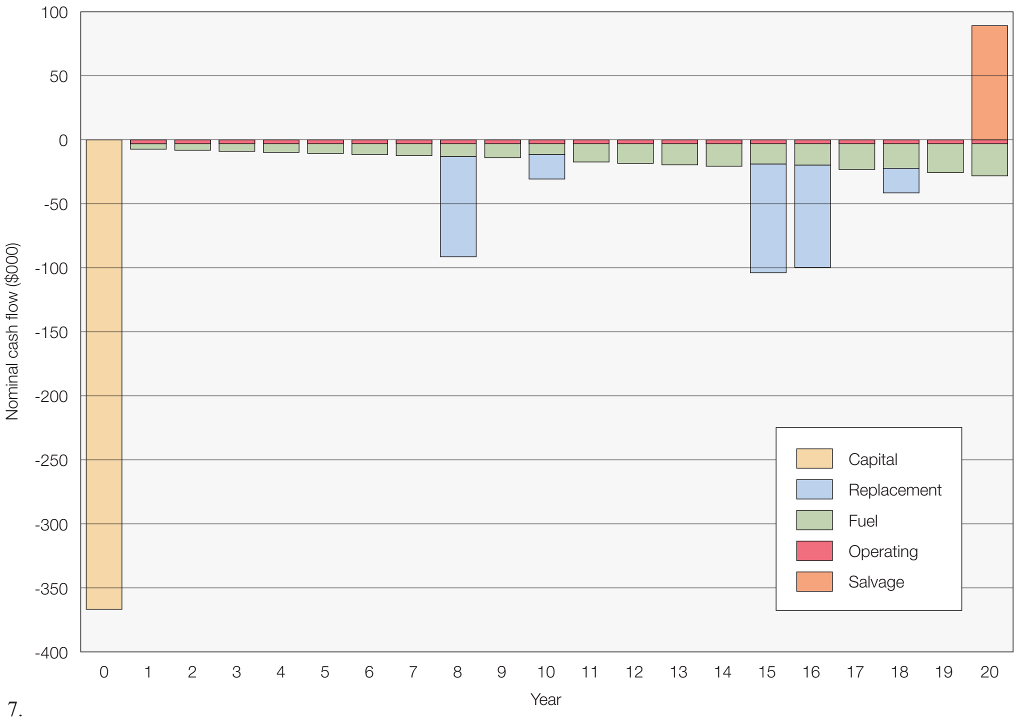
4. The moment is captured as a 'ready board' is energised and electric lights come on for the very first time inside a village home.

5. A smart meter is installed as part of the reticulation system that distributes microgrid electricity to customers.

6. An example of a reticulation design. This one was created for a village in Nigeria. Higher intensity users are shown with a red diamond, with residential dwellings shown with the brown circles.

7. For a typical microgrid project with a large solar PV array, batteries and a backup diesel genset, a cash flow chart of capital costs from start to end of system life (year 20) might look like this. Since most of the energy in the microgrid comes from the solar PV array, capital costs in year zero are high, but operational and fuel costs are low. Replacement of expired batteries, inverters and other components in later years is shown. A salvage or resale value is estimated to occur at the end of the system's life.

6.



7.

Nigeria

Arup is providing ongoing technical services for a microgrid currently under development to serve a rural community approximately 193km from Lagos. The firm has modelled the energy demands that will be made of this microgrid to optimise it and reduce its capital cost. It is estimated that more than 300 households, 30 small-to-medium business enterprises (SMEs) and various schools and health clinics will use power from this microgrid when it is completed. A telecommunications 'anchor client' will consume much of the generated electricity, lowering the average cost of household connections.

Arup modelled the energy demands that could be made of the microgrid, accounting for the diversity of operation of various electrical loads, weekly and seasonal variations, and projected energy growth rates. An optimisation study was then carried out using HOMER software[2] to determine the energy strategy optimised for life cycle costs. The resulting information enabled Powerhive to prioritise the financial variables to determine the optimised design for this microgrid. It is an approach that can now be applied to develop similar solutions for other villages.

When it came to considering the reticulation system for the village, Arup optimised it such that medium voltage (MV) was not needed, thereby obviating the need for the costly transformers that would otherwise be required at the energy plant and at points throughout the reticulation network. This kept capital costs to a minimum.

Kenya

Arup is supporting Powerhive with similar technical services on five microgrid projects in construction at various locations across Kenya. Senior electrical engineer Kwame Adu-Asomaning, who is based in the firm's Cape Town office, spent nearly two weeks on site in Kisii to review in-field construction methods, construction quality, commissioning procedures and acceptance tests and he was present as the ready board was energised for Powerhive's first customer in Kenya, lighting a home with electricity for the first time ever. There are already plans for an additional 15 projects in Kenya.

8.

9.

Summary

In its work with Powerhive, Arup is developing methodologies for assessing the energy requirements of communities in remote areas with the aim of improving the optimisation of microgrids and making the technology more accessible. This is helping Powerhive to build its business in Africa and assisting villages that would otherwise be without electricity to obtain microgrids that are likely to improve day-to-day living conditions and assist in economic growth.

Authors

Kwame Adu-Asomaning, Senior Electrical Engineer, Energy Projects.

Chris Brosz, Senior Engineer, Energy Projects.

Justin Wimbush, Renewable Energy Leader, Project Director.

Notes

[1] International Energy Agency's *Energy Access Outlook 2017*.

[2] The HOMER Pro® microgrid software is a simulation model for optimising microgrid design.

Project credits
Client: *Powerhive* Technical services: *Arup – Kwame Adu-Asomaning, Chris Brosz, Justin Wimbush.*

Image credits
1, 2, 4, 5, 8, 9: *Powerhive*; 3. *Powerhive/Arup/ Martin Hall*; 6, 7: *Arup.*

8. One of Powerhive's completed microgrids in Kenya.

9. Although some physical security is required in the form of a fence and gate, the cloud-based nature of the system means it is protected from power theft by an algorithm.

1.

Raffles City, Hangzhou

Location
Hangzhou, Zhejiang Province, China

Authors
William Chan Antony Ho Andrew Luong Gui-lan Zhao

Introduction

The twisting towers and curvaceous podium of newly opened Raffles City, Hangzhou, presented unique design and engineering challenges that demanded innovative solutions. The outcome was an interesting building that offers useful insights into how towers such as these, built largely from reinforced concrete, can be delivered most effectively in China. Sustainable design strategies to reduce energy consumption and carbon emissions meant the project also achieved LEED Gold certification.

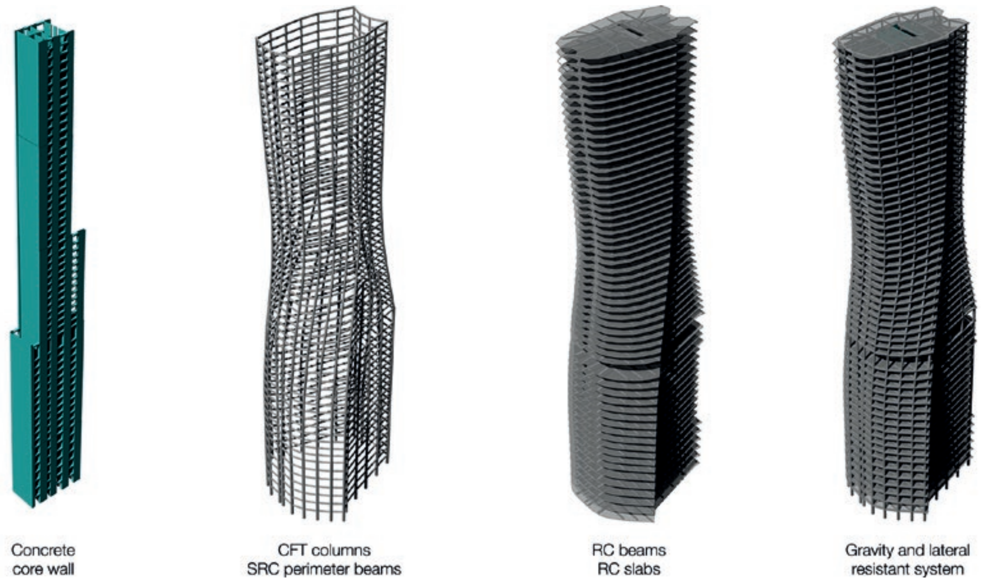
Situated in Qianjiang New Town, the fast-growing central business district (CBD) in the riverside area of Hangzhou, the development is the latest of CapitaLand's Raffles-branded commercial complexes to be built in China. Designed by architects

UNStudio, working with Arup, it comprises two 250m-high towers containing offices, apartments and a hotel, a 10-storey podium that houses retail outlets and restaurants, and a basement three levels deep where there is car parking and a direct connection to the metro transportation system. Arup provided integrated design and engineering services for the project including structural engineering, building services, sustainability strategy and fire engineering. The development obtained LEED Core & Shell 2.0 Gold certification, and won the Grand Award (Mainland/Overseas Projects) at the Structural Excellence Awards 2017 organised by the Hong Kong Institution of Engineers/Institution of Structural Engineers Joint Structural Division.

Twisting towers

From the outset, the structural challenge was to develop a structural system that responds to the twisting architectural geometry. It was decided that the building columns should follow the flow of the building shape, an approach that efficiently and naturally maximises the floor layout. The building stability system comprised an internal reinforced concrete core working with a twisting outer moment frame of two-directionally tilted perimeter columns that merge and bifurcate following the form of the building. Another key decision made early on was to adopt the same mirrored structural column arrangement for both towers, which are not identical but complement each other, and to promote a visual dialogue between the distinctly urban context in one direction and the green, landscaped areas nearby.

The design makes extensive use of reinforced concrete, which is comparatively cheaper than structural steel construction. The external twisted frame is comprised of concrete-filled steel tube (CFT) columns and steel-reinforced concrete (SRC) perimeter frame beams, but apart from these structural steel elements the tower is essentially of reinforced concrete (RC) construction. In the earliest days of the project, back in 2007, the original proposal had been for a predominantly structural steel building. This would have been quick to build, but much more expensive. A pause in progress at the time of the global financial slowdown in 2008 meant there was time to rethink this approach and Arup recommended the predominantly concrete building that has now been constructed. The design was optimised to accommodate the new choice of materials.



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3.

The development of Raffles City, Hangzhou, and other similar projects has enabled Arup to increase its extensive knowledge of the systems and structural materiality of buildings such as this one. Structural steel construction, which tends to be used for buildings above 300m tall, is not such an obvious choice for buildings between 250m and 300m tall in China: the efficiency and costs of buildings in this height range can favour concrete over steel construction depending on, among other factors, the local seismicity, wind conditions, and fluctuations in construction costs.

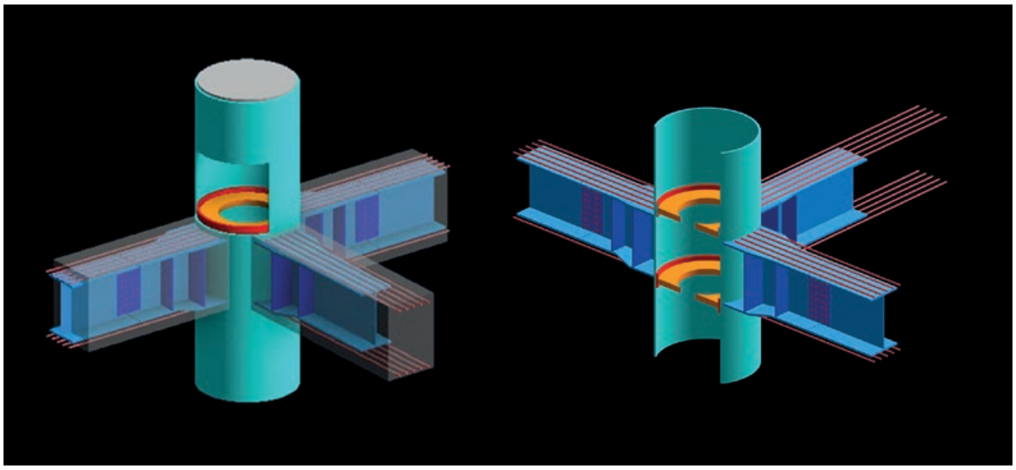
1. Raffles City, Hangzhou, has been widely admired for the creativity of its design.

2 and 3. How the structural system of the towers was developed to form the twists and curves of its geometry.

The innovative connection

The combination of perimeter steel frame (CFT columns and SRC beams) and the reinforced concrete floors struck a balance between the two materials' respective stiffness and ductility, and cost. Adopting the SRC beam enabled simplified connection detailing for the RC floor beams and slab supported by it. However, the SRC beam connection to the CFT column, a major connection that repeats along the perimeter and at every floor, posed major problems, both in aesthetics and in construction. The conventional ring beam composite joint detailing, as recommended in the Chinese codes, is too bulky and would have impacted on the local floor and ceiling detailing as well as the aesthetics of the towers, so Arup developed an innovative refinement to this repetitive perimeter CFT column and SRC beam connection detail. The solution was to enlarge the steel sections used in SRC and RC beams at the beam ends connecting to the CFT columns, and add stiffening plates inside the CFT columns. This approach removed the need for external stiffening plates to the CFT columns (as occurs in the standard code-recommended detail). It made the construction much easier and significantly reduced the construction cost. This simplified deviation from standard detailing received commendation at the Expert Panel Review approvals stage of the project.

4.



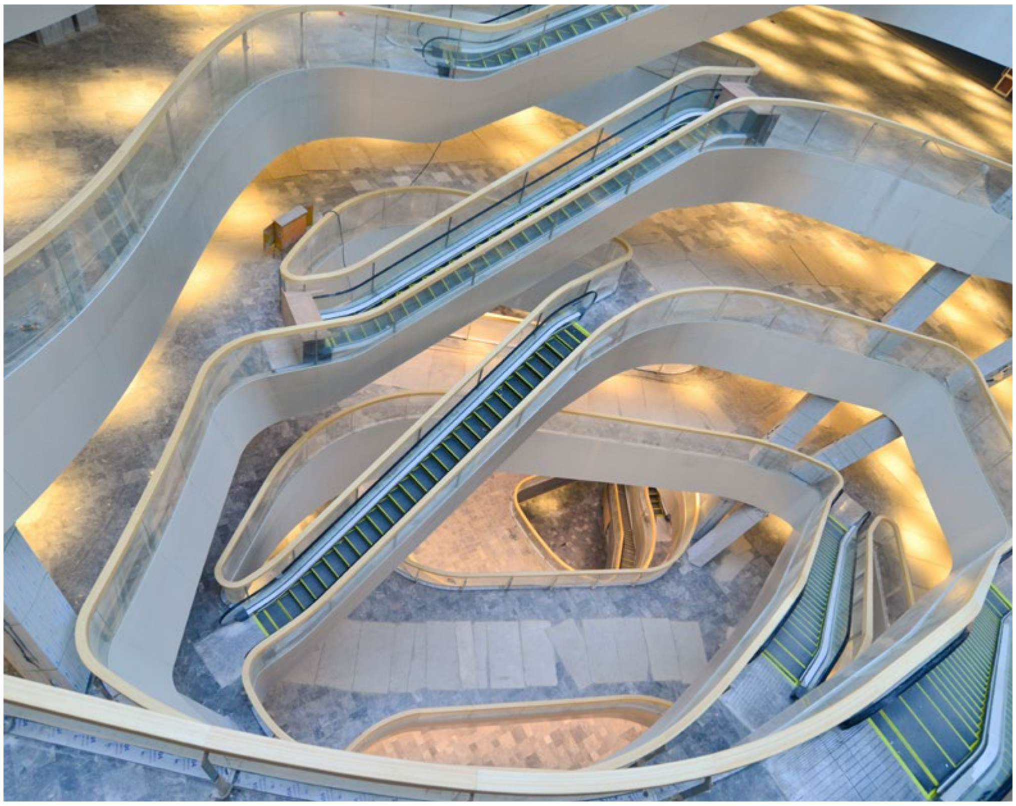
5.

The double-curved podium

The twisting signature of the architecture of the towers carries through to the podium structure that has a dynamic double-curved external envelope and internal spaces shaped by various funnelling atria. This complex design responded well to Arup's total architecture approach, with multi-disciplinary teams bringing together their expertise in structural, building services and fire engineering.

The structural solutions for the podium began with placement of seismic and expansion joints to allow the towers and podium structure to behave independently under seismic loading. In close coordination with the architect, the structural framing for the podium was developed to deliver structurally invisible long-span spaces, flexibility for future shop arrangements, and high ceilings. There are many spaces in the podium building with spans over 14m and cantilevers of 6m or more. With the exception of two pairs of V-shaped columns located diagonally at opposite points of the atria, the structural columns have been concealed: a combination of techniques were employed to achieve this, including transfers, hanging columns, kinked columns, and composite steel beams for very long-span spaces.

A performance-based fire engineering approach to the non-aligned, open and spacious podium atria used the podium architecture to good effect: smoke would ventilate naturally through vents in the roof should there be a fire. Fire dynamics simulator (FDS) models were used to help the architect locate the smoke vents and validate the performance of natural ventilation. The resulting design, without the need for exhaust ducts and fans, meant the architectural aspiration to create an undulated roof was maintained, and a functional roof garden was made possible. The simulation tool, STEPS (simulation of transient evacuation and pedestrian movements), was used to model pedestrian movements under emergency conditions.



6.

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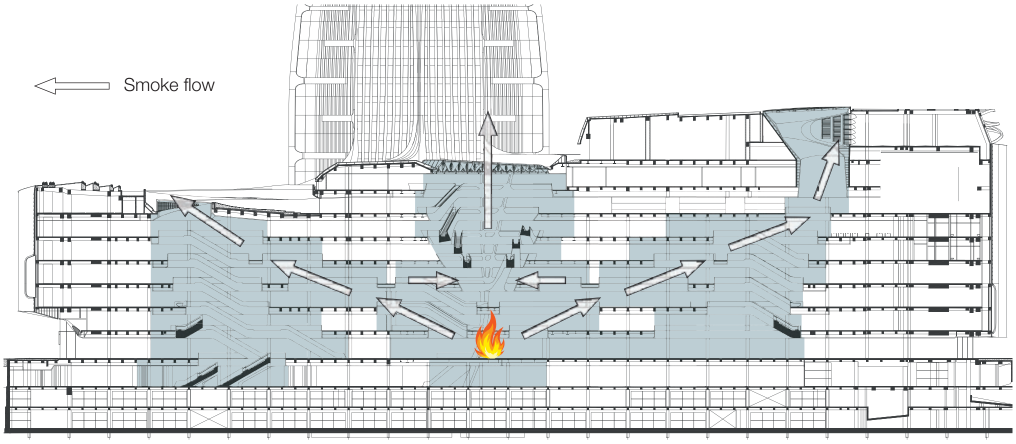
Link bridges
Four double-storey bridges connect the towers and podium in various formats, with the bridge end support and articulation details carefully chosen to isolate the towers from the podium during earthquake events. Rigorous footfall analysis throughout the bridges' design resulted in lightweight frames that provide the necessary functionality and comfort for users, yet are seamlessly integrated into the curving lines of the architecture.

Curved podium façade
During construction, and after the appointment of the façade contractor, Arup's structural team was asked to assist in developing the structure for supporting and forming the doubly-curved podium envelope to make it easier and less expensive to build, thus reducing the construction time required.

Various structural systems, including inclined wind posts and steel backing frames to form the double-curved façade backing surface, were used in the solution Arup developed, the breakthrough being the identification of a number of different types of structural support systems, depending on the inclination and curvature of the façade. These were developed through parametric



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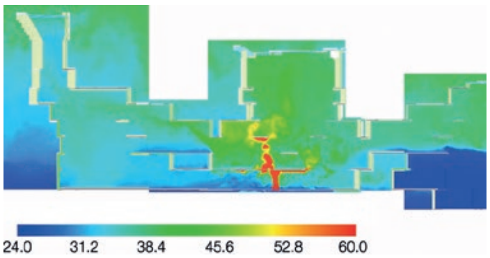

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4. The podium passes between the two towers, which mirror each other but are different in shape.

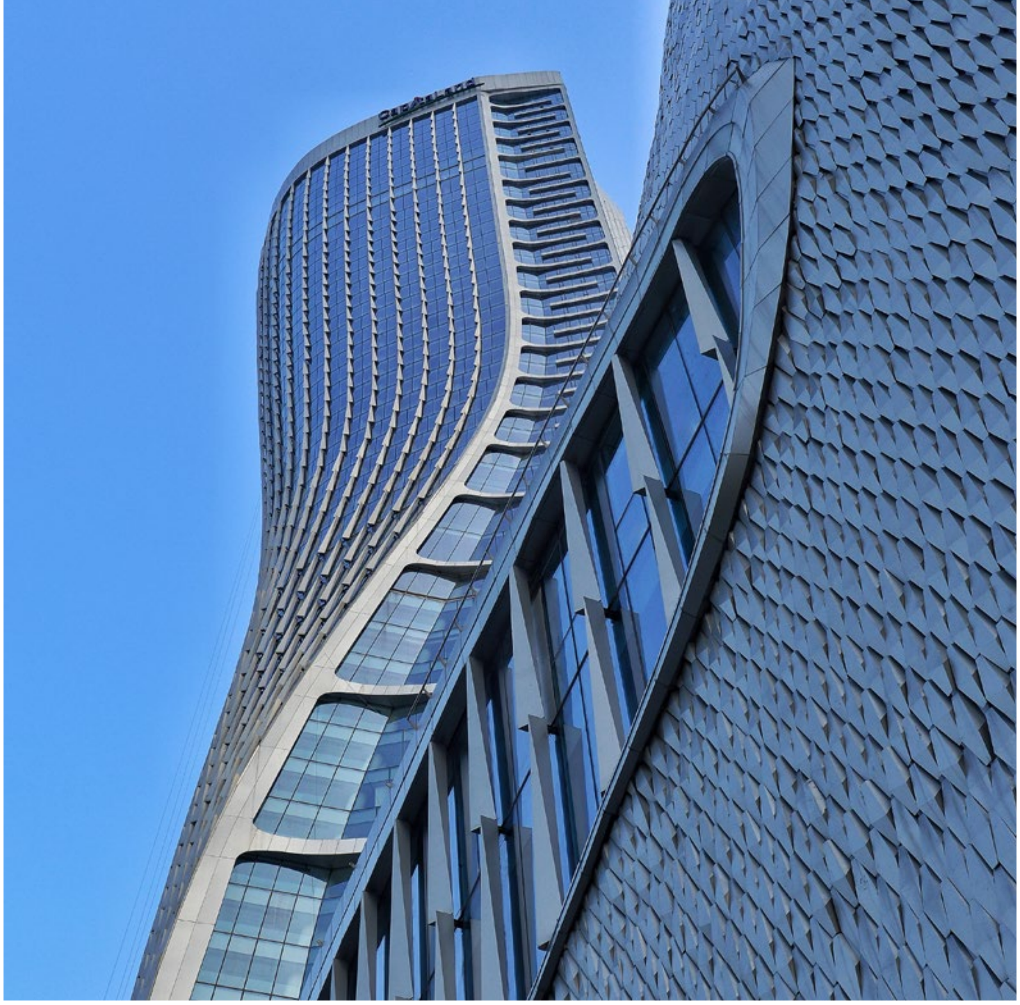
5. An example of the innovative connections that were developed for Raffles City, Hangzhou, making construction easier and cheaper.

6. The funnelling atria that are a creative facet of the design and were used to good effect in the fire engineering strategy.

7. The underside of one of the link bridges, showing the curves that are characteristic of the podium design.

8. How smoke would flow through the podium in the event of a fire.

9. Fire dynamics simulator models were used to locate smoke vents.



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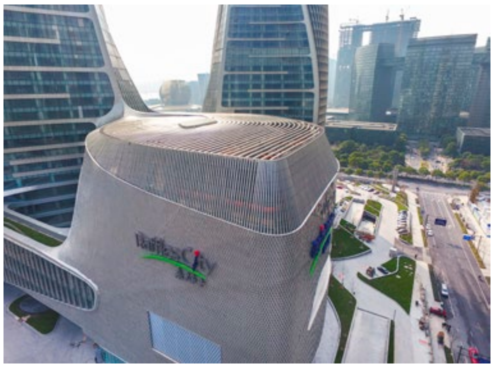

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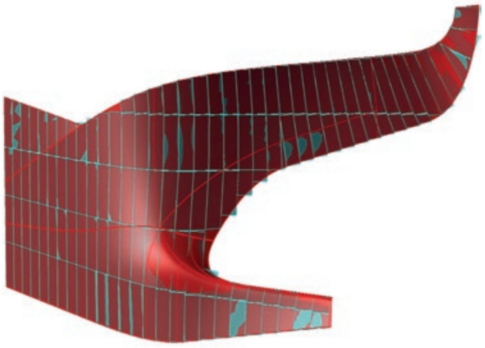


12.

and iterative analyses (using Grasshopper) of the podium double-curved surface; close collaborative working with the architect to slightly modify the envelope shape if required; and also with the contractors for their advice on 'buildability'.

Building services design

The twisting tower shape and façade features of the podium, together with the large-scale geometry and the variety of functions within the complex, posed challenges for building services design. The brief was for a sustainable building services strategy that met high standards for occupant comfort. As a result, the main system design is a combination of centralisation and de-centralisation. Different heating, ventilation and air-conditioning (HVAC) strategies were required to suit the different functions. Offices and retail spaces need a significant amount of cooling/heating by day, whereas hotel rooms, which are generally occupied from evening until morning, have different operations and load profiles. Therefore, the hotel has its own cooling and heating plants, while offices, retail space and apartments are served by one chilled and hot water system to save space and reduce cost.

The nature of tall buildings generally means that services need to travel long distances to reach their destinations, reducing the efficiency of heat/cooling delivery. By distributing the services through the towers, the distance travelled was reduced. Careful considerations were given to the unique local leasing market. In Hangzhou, the majority of the tenants are small-sized innovation and technology start-ups, rather than large company headquarters. So the system design focused on making it feasible to divide each typical floor into small units.

A variable refrigerant flow (VRF) system was deployed and chilled water storage technology was used as the main cooling source for offices, retail and serviced apartments to cut down the peak load and save on electric costs. Chillers and the chilled water tank are grouped in parallel to supply cooling during the peak summer months and water is stored in the tanks during low-load hours. Total capacity of the electrical system is reduced by this, and operating cost is lower due to the difference in peak and off-peak electricity tariffs. The water storage tank acts as a flexible cooling source in extremely hot weather. The water side balance of HVAC in the podium was verified by detailed calculation and optimisation of the setting of water valves. The distribution power loss is low and each terminal unit is efficient. As the building services consultant, Arup's work extended beyond systems design to testing and commissioning after the development was completed.

Sustainable design strategy

The project adopted integrated sustainability design strategies that were aimed at setting a new benchmark for the Eastern China region. Measures to minimise environmental impact, reduce energy consumption and carbon emissions, and reuse/recycle material were incorporated into the design process across disciplines. The result is a balance between sustainability, aesthetics and human comfort. A wide range of energy-saving strategies were incorporated, including free cooling, air-side heat recovery, demand controlled ventilation with CO_2 sensors, chilled water storage system, high COP chillers, natural ventilation, daylight sensors, high-efficiency luminaires, daylighting and sunshine-shading façade. The vertical transportation system uses level selection and other advanced systems to maximise core efficiency without compromising the performance. In combination, these strategies have achieved energy cost savings, as well as reduced carbon emissions.

13.

10. The podium façade (the side of one of the link bridges is shown in the foreground) is clad in a shimmering skin of aluminium tiles. The towers feature an outer layer of rotated, vertical solar shading fins, placed on top of the curtain wall system.

11. The podium viewed from the rear of the building, showing the landscaped gardens around the perimeter of the building.

12. The approximation of a double-curved surface using flat planes. Parametric modelling played an important role in developing the structural system solution.

13. Raffles City as seen from the neighbouring park.

Air quality has become a big issue for many large cities in China, including Hangzhou. To enhance outdoor air quality and healthiness, outdoor air delivery monitoring devices and high-performance air filters were installed in primary air-handling unit (PAU) and air-handling unit (AHU) plants. To enhance indoor air quality, the HVAC system is provisioned with an additional 30% capacity in fresh air volume over ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) standard. A particular issue that had to be addressed was the fact that more than half the podium tenants operate food and drink businesses. Traditional Chinese kitchens create a lot of kitchen exhaust air that carries grease and odour and some of the exhaust points on the podium are near offices. Simulation was carried out to address the zones likely to be affected by kitchen exhaust air, then ducts and shafts were adjusted to avoid any negative effects, with UV lamps and electrostatic filters installed on both the tenant system and the main system to clean the exhaust air. Outside the building, there are landscaped gardens around the buildings and on the rooftop of the podium. In fact, despite being located on a tight urban plot, the development has achieved more than 20% green coverage.

Summary

Raffles City, Hangzhou, is a busy and vibrant development that accommodates many different activities in a carefully considered arrangement of spaces: people can live there, work there, stay at the hotel, pick up groceries, enjoy a meal, do exercise or watch a film. It is well connected to the transit network, making it accessible, and it incorporates some of the latest thinking in sustainable development for communities in densely populated urban areas. Its distinctive appearance makes it a new landmark on the Hangzhou skyline.

Authors

William Chan, Associate Director in the Wuhan office, worked on the building services design.

Antony Ho, Associate in the Hong Kong office, worked on the building sustainability strategy.

Andrew Luong is a Director in the Shanghai office. He led the structural team from the design development stage through to construction, and was instrumental in the podium façade resolutions.

Gui-lan Zhao, Associate in the Shanghai office, worked on the fire engineering.

Project credits

Client: *CapitaLand China* Architect: *UNStudio* Associate design institute: *China United Engineering Corporation* Main contractor: *Shanghai Construction No. 4 (Group) Co., Ltd.* Structural engineering, building services, building sustainability, fire engineering, MEP engineering: *Arup – Carolina Bartram, Chao Cai, Han Cao, Hui-Ling Cao, Chris Carroll, Angela Chan, Frankie Chan, William Chan, Gang Chen, July Chen, Li-Juan Chen, Long Chen, Tian-Qi Chen, Xin Chen, Morgan Cheng, Vincent Cheng, Yan Cheng, Yu-Lung Cheng, Gary Cheung, Rosemary Cheung, Li-Bo Chu, Yan Cui, Jianhao Ding, Juan Du, Alex Edwards, Aaron Fan, Gavin Fei, Hui Gao, Wen-Qi Gong, Rong Han, Xiao-Juan Han, Shuqin He ,Antony Ho, Wing Ho, Johnny Hu, Shu-Hui Hu, Jie Huang, Linda Huang, Qing-Gang Huang, Sen Huang, Samuel Jiang, Chun-Yan Jing, Qi-Ming Kong, Michael Kwok, Jimmy Lau, Winnie Law, Martin Leung, Cui Li, Jian Li, Peter Li, Ren-Dong Li, Xiang Li, Xiao-Yan Li, Ze Li, Zhi-Jian Li, Zong-Cheng Li, Jie Liang, Qu-Ying Ling, Gang Liu, Li-Gang Liu, Zheng-Wei Liu, Ling Lu, Cheng-Yu Luo, Mingchun Luo, Andrew Luong, Riccardo Merello, Liu-Si Mo, Fumihiko Nakao, Jing-Hua Pang, Jenny Qu, Yi-Min Ren, Morgan Reynolds, Ying Rong, Pan Shen, Bi-Bo Shi, Karen Shi, Martin Simpson, Jacky Sin, Allen Sun, Jun Sun, Alex To, Chris Townsend, Iva Trifkovic, Chun-Lei Tu, Jue Wang, Ling-Fei Wang, Ya-Nan Wang, Yun-Jue Wang, CF Wong, Chang-Song Wu, Ren-Peng Wu, Xuchao Wu, Ze-Ling Wu, Ze-Ling Wu, Gao-Jing Xing, Dong-Lei Xu, Fan-Fan Xu, Penny Xu, Phoebe Xu, Sui-Hang Yan, Mars Yang, Xiao-Yong Yang, Yi-Lin Yang, Yi-Zhen Yang, Yu-Jing Yang, Nan Yin, Rachel Yin, Grace Yip, Fang Yu, Mei-Ling Yuan, Rojam Yuan, Brian Zhang, Ge Zhang, Hai-Peng Zhang, Ivy Zhang, Jenny Zhang ,Kevin Zhang, Kui-Wu Zhang, Yun-Qi Zhang, Gui-Lan Zhao, Matthew Zhao, Xue-Lian Zhao, Kuang-Yi Zheng, Lu Zheng, Wen Zheng, Guang-Yao Zhu, Han-Xiao Zhu, Jia-Jia Zhu, Jing Zhu, Jin-Lin Zou, Fu-Lei Zuo.*

Image credits

1, 11 *CapitaLand*; 2, 5, 6, 8, 9, 10, 12 *Arup*; 3 *Zhou Ruogu Architecture Photography*; 4, *Jin Xing*; 7, 13 *Hufton+Crow.*

Barangaroo South

Location
Sydney, Australia

Authors
Haico Schepers Paul Sloman Peter Tomlinson

1.

Introduction
Barangaroo South is a vibrant new commercial and residential precinct in Sydney that 'gives more than it takes' in its relationship with the environment. Strategies for efficiently managing water, energy, transport and waste contribute to the aim of a carbon-neutral development, the first in Australia at this scale. Designed in line with the principles of the C40 Climate Positive Development Program, it incorporates technologies and systems that mean operational carbon emissions can be monitored, measured and offset.

The three landmark towers of Barangaroo South – now known as International Towers Sydney – define the stretch of waterfront to the west of Sydney Harbour that was previously occupied by a container port. More than 16,000 people currently work there, its shops and restaurants attract thousands of visitors per day, and it is a popular place to live. The rest of the Barangaroo development comprises a new landscaped headland park, already open to the public, and commercial and residential buildings that will link the waterfront into Sydney's central business district (CBD). Barangaroo Central, is due for completion in 2023.

In 2009, before construction of the precinct began, the New South Wales (NSW)

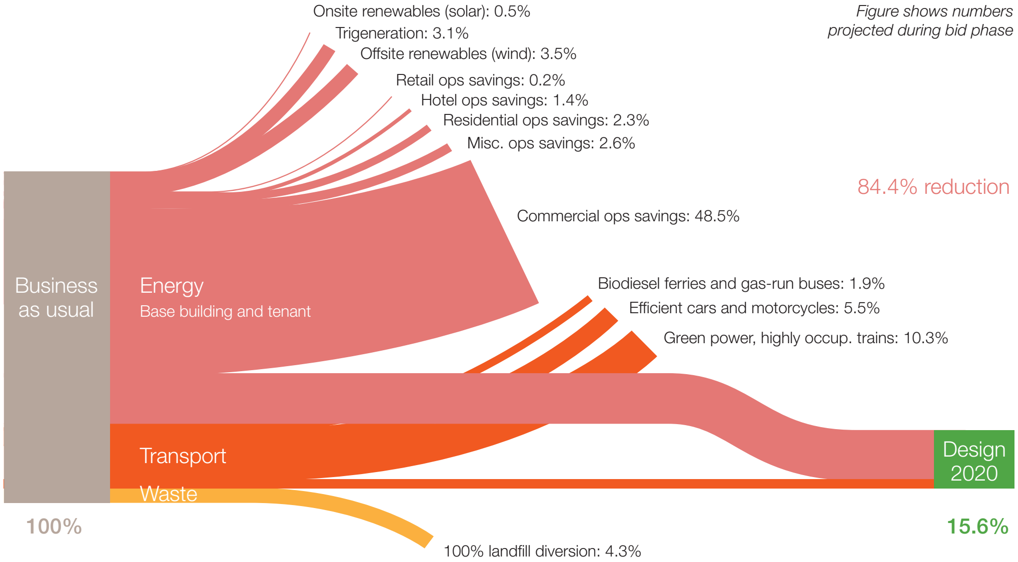
The C40 is a network of cities around the world, including Sydney, that is committed to addressing climate change. The C40 Climate Positive Development Program, supported by the not-for-profit Clinton Foundation, has a mission to encourage new models of sustainable development that will achieve net carbon-negative outcomes in energy, waste and transportation.

1. Barangaroo South urban regeneration precinct and its three landmark towers, now known as International Towers Sydney.

2. Strategic approach to achieving carbon net zero developed during the bid phase.

Government committed Barangaroo to the Climate Positive Development Program (see box above). The Barangaroo Delivery Authority included robust contractual mechanisms in all project development agreements and is working collaboratively with developers to ensure sustainability targets are implemented and achieved, both during construction and throughout operations over all 99-year building leases.

Arup has held multiple roles during the Barangaroo project. From the early days, the firm worked with Lendlease and Rogers Stirk Harbour + Partners (RSHP) to develop a sustainable masterplan for the Barangaroo South precinct in response to the sustainability targets the Barangaroo Delivery Authority had included in the development bid process. Lendlease, with Arup, developed sustainability commitments and design strategies for the Barangaroo South site that became part of a climate positive work plan and Arup was involved in multiple engineering and design scopes throughout. Under strict separation protocols, Arup was also separately engaged to act as an Independent Environmental Sustainability Certifier (IESC) overseeing the developer's delivery of sustainability outcomes, as required by the development contracts. At this time Arup relinquished other sustainability related work on Barangaroo South.



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Concept design and initial masterplan

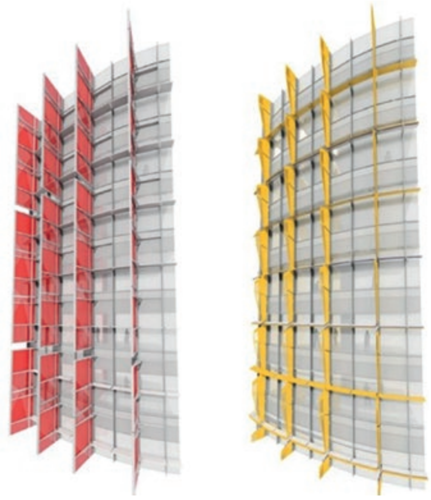
In 2005, the Sydney Harbour Foreshore Authority (SHFA, part of the NSW Government) held an international design competition to seek a concept for regenerating the 22 hectares of land that make up Barangaroo. It was won by Sydney based architects and urban projects practitioners Hill Thalis whose concept design and associated guidelines were used as the basis for developer-led bids for the site. The concept design consisted of a publicly accessible zone along the water's edge leading to a large public park on the former headland at the north end, with several large plots for commercial and residential development to the south. In 2007, developer-led bids were called for Barangaroo South, the commercial precinct, together with a cohesive masterplan for the rest of the site. Lendlease formed a team with Arup and RSHP to bid for the development, and was successful in winning it.

The Barangaroo Delivery Authority's original bid brief required the development to demonstrate 75% reductions in carbon and water use compared to a 'business as usual' (BAU) case and challenged the development team to exceed this outcome and achieve a carbon-neutral, zero-waste and water-positive outcome. This made a sustainability strategy the highest priority. So the project team carried out targeted site investigations and analyses during the 12-month bid phase to create an updated masterplan, concept designs for all proposed buildings, and strategies for construction sequencing, staging, and site decontamination. The outcome was that the team proposed to exceed the brief by targeting the carbon-neutral, zero-waste and water-positive response, using local ratings schemes such as Green Star and NABERS to demonstrate commitments.

Strategic approach

The Barangaroo Delivery Authority, formed by the NSW Government to deliver the development, accepted the Lendlease bid including the Arup Lendlease sustainability plan which set out the team's delivery of the four requirements: energy used on the site should be first reduced, then offset; more water should be recycled and exported than drinking water imported; waste should be minimised, with a target of zero, and diversion from landfill; and community wellbeing should be a priority.

A systematic approach was adopted to deliver this climate positive outcome. To form a baseline to work from, a full audit of carbon accountancy was performed against a BAU case. Each key sector's carbon use was accounted for – transport, waste, energy use and embodied carbon of materials, for example – then feasible reductions were evaluated and a specific plan was developed for each sector. Arup was subsequently, and separately, engaged to act as IESC to review the developer's delivery of the project against the climate positive work plan.



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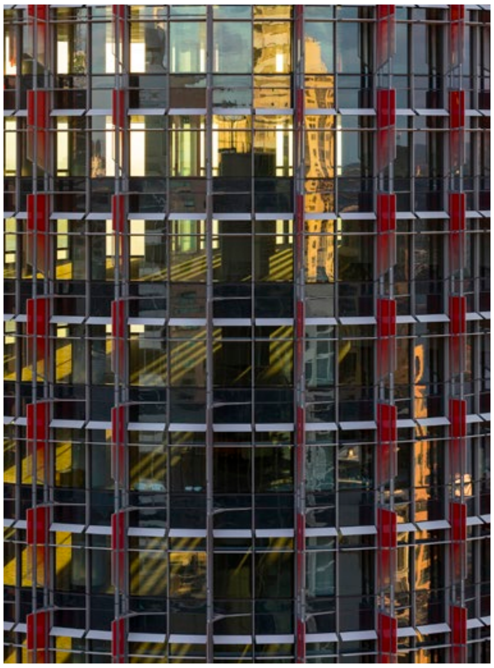
Reducing buildings' energy demand
Achieving reductions in the energy demand of Barangaroo's buildings was clearly going to result in the biggest savings in carbon emissions so this was the primary goal, closely followed by the development of on-site renewable generation. Leasing provisions to use carbon offsets sourced from renewables were developed for operational energy as the final part of the strategy. The diagram (figure 2) was produced during the bid phase to show how savings could be made. A combination of façade and services integration reduced the energy demand of the buildings by 75% compared with BAU.

An innovative glazing and shading strategy for International Towers Sydney achieved a substantial proportion of the saving. Much of the rest of the savings were generated by a central chilled water plant with harbour heat exchange, and the precinct's ventilation and air-conditioning. These systems were optimised for efficiency and control by Lendlease and Norman Disney & Young during design. Further savings were made by introducing energy-efficient systems – for lighting and vertical transportation, for example – and by encouraging tenants to become engaged in energy-saving best practice.

Glazing and shading
International Towers Sydney are carefully positioned on a radial geometry to maximise sunlight and views of Sydney Harbour. The challenge – and opportunity – for RSHP and Arup lay in how to develop and formulate three external façade systems that responded to this unique location, reduced façade thermal loads, yet maintained the harbour views. The goal was to provide each of the towers with an individual, low-energy façade that could be read as a cohesive whole across the precinct. This was achieved by developing detailed, engineered solar shading for each façade to create cohesion and provide legibility from city to human scale.

RSHP and Arup designed external sun screens of glass, aluminium tubes and folded plates for each floor of the towers. The sun screens were sized and located to provide uninterrupted views through very transparent glass while generating very low thermal loads. The design was achieved using a bespoke multi-variant façade optimiser software to locate and size the shading elements for each window bay. It combined a pattern search algorithm with automated analysis of each design iteration using the lighting and energy simulation reference software packages Radiance and EnergyPlus. EnergyPlus made use of a whole building model template underlying the simulation of the perimeter zone for each window bay. This allowed building effects, such as thermal lag of the concrete structure, to be taken into account in determining the effect of the shading arrangement on thermal loads. Daylight modelling using Radiance ensured a good depth of daylight penetration.

Optimal shading to each window bay allowed thermal and daylight goals to be achieved in response to the unique urban microclimate of each of the 6,000 individual panels. This added the benefit of minimising shading extent, removing and scaling back shading wherever possible, saving both cost



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and embodied carbon. It also allowed the towers to capitalise on self-shading and the varying degrees of exposure created by their close proximity to each other. Bespoke studies of daylight glare potential within the building and the estimated resulting blind-use were employed to evaluate different glass transparency options. The tallest tower has fritted and coloured-back glass on the shading fins. Reflectivity was studied through Radiance studies of both internal and external conditions.

The flexible floor plates sit at approximately 2,300m^2 within 270,000m^2 of premium office space. Across the three towers, the floor plates correlated with the optimised solar shading. The resulting space is highly flexible for the businesses that have chosen to move in and make their mark in creating agile and dynamic workplaces. Daylit lift lobbies, panoramic prows, 100% outdoor air, high ceilings and large open vertical spaces all form part of the overall carbon-neutral strategy. The design nevertheless enables large corporate clients who occupy the buildings to arrange their office spaces according to their unique needs.

The benchmarking, modelling, prototyping, testing, and delivery of these innovative façades with specialist consultants, façade engineers, fabricators and manufacturers was a rewarding experience that delivered new insights into low-energy façade solutions.

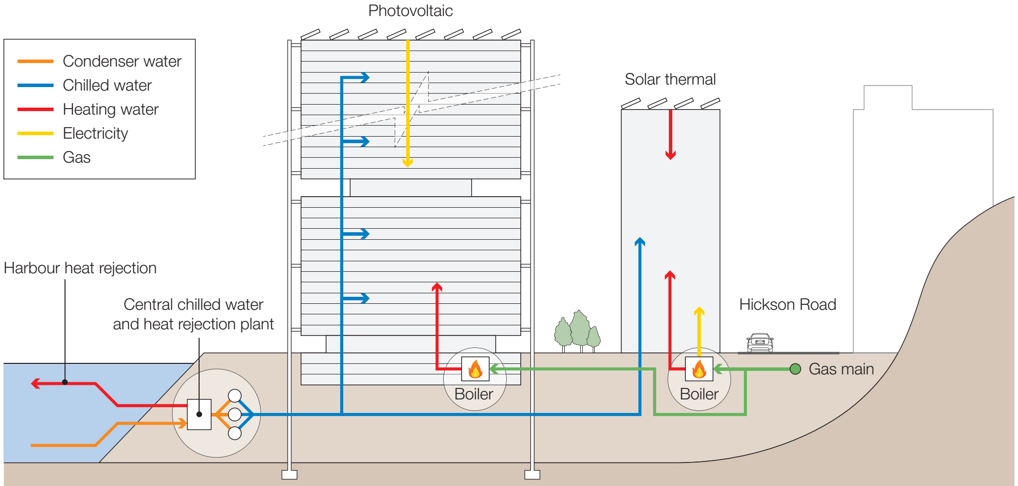
District cooling plant

As part of the Barangaroo South development a district cooling plant was proposed. The plant, designed by Lendlease, uses water drawn from Sydney Harbour for heat rejection. Energy and water savings are made by operating one centralised cooling system rather than separate systems for each building. The sea water passes through a series of screens, filters and strainers to protect and filter out marine life before it is used; and once it has passed through the cooling system it is returned to the harbour through injection pipes located below the waterline along the western waterfront. This minimises local heating of the harbour itself. The number of chillers used depends on the demand for cooling, which can vary on a daily, weekly or seasonal basis.

To reduce requirements for cooling, energy-efficient technologies were used throughout the development: examples include chilled beams, indirect evaporative cooling and heat recovery, efficient lighting, and energy reclaim lifts. Adopting these technologies reduced the base building energy, and energy consumed by tenant systems.

Vertical transportation

Together with Lendlease, Arup designed the vertical transportation for all of Barangaroo South – the most comprehensive vertical transportation project ever undertaken in Australia. All appropriate equipment types were considered including: single deck and conventional control; single deck and destination control service (DCS); and multicar solutions including double deck, with and without DCS, and twin lifts.



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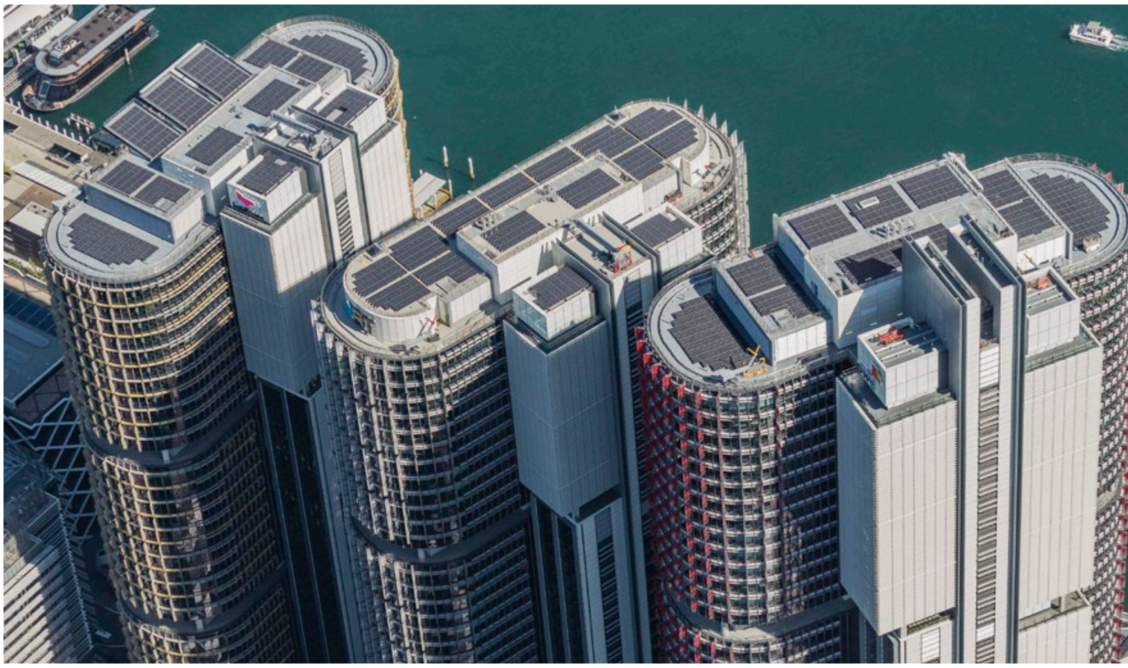

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To maximise the performance of the lift systems, DCS was used on all passenger lifts and integrated within security access barriers at the main lobby. This means the combined vertical transportation elements for all three towers can transport up to 3,645 passengers every five minutes. All lifts are fitted with the latest energy-saving technologies, including regenerative drives and high-efficiency permanent magnet lifting machines. These generate energy back into the building's electrical grid when the lifts' out-of-balance load assists with the direction of travel. Automatic sensors de-power car lighting, ventilation systems and destination control touchscreens when not in use.

3. Each façade panel and shading device was designed specifically for its unique microclimate on the tower.

4. A detail of the bespoke fins used to achieve optimal shading for each window bay.

5. The fins around the vertical villages (lift lobbies) in Tower One of International Towers Sydney.

6. How the fins contribute to the distinctive character of the towers.

7. Energy and water savings are made by operating one centralised system.

8. Solar photovoltaic panels on the roof of the towers.

9.

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9. Barangaroo Wharf, opened in June 2017, links the precinct to the busy ferry service around Sydney Harbour.

10. An aerial view of Barangaroo, showing the reserve on the headland to the left of the picture, and International Towers Sydney in Barangaroo South, just right of centre, and undeveloped Barangaroo Central in the middle.

11. Opportunities to relax and enjoy the view. The Barangaroo Delivery Authority is committed to community wellbeing.

Renewable energy

More than 6,000m^2 of solar panels are integrated into roof top locations where they are exposed to the sun. The green credentials of the on-site solar are used to offset the power used for the public domain, including public domain lighting and the recycled water treatment plant. The rest of the electrical demand for the site, calculated using certified carbon accounting methods, is subject to contractual agreements for certified offsets from offsite renewable power generation. These arrangements render the buildings carbon neutral.

Transport

Planning the movement of the 2,000 residents, 23,000 office workers and 33,000 daily visitors who will occupy Barangaroo South on completion was an important part of the project. So the development team worked closely with the Barangaroo Delivery Authority and other relevant government agencies to establish transport solutions for each mode of travel.

It was calculated that by 2018, total work-related trips by car to the area could be reduced to 4% of all transport modes. This meant on-site parking was restricted to only one space for every 45 workers, a measure that inherently encourages the use of other options including bus, train, ferry, bicycle and taxi. Bus and rail services are available at nearby Wynyard Station. To improve access from the precinct to this station, a new 180m tunnel called Wynyard Walk was built. New surface routes between Wynyard Walk and International Towers Sydney were also designed into the project and, in collaboration with Transport for New South Wales, new bus routes and services were established. Options for cyclists were enhanced: the City of Sydney has constructed cycleways on nearby CBD streets, and to improve access into Barangaroo South for cyclists there is short-term cycle parking in various locations around the precinct, including near the residential towers and food and beverage outlets. International Towers Sydney has 1,100 bicycle racks, the highest single-location density in Australia, together with thousands of individual lockers and a bicycle repair station. Ferry services run from a new wharf that opened in 2017 connecting Barangaroo with the western suburbs, lower north shore, eastern suburbs and Manly. Some routes from nearby Darling Harbour and King Street wharves were transferred to Barangaroo, making it Sydney's second largest ferry wharf.

Waste
A waste management partner for the precinct is committed to maximising resource recovery across all waste streams, with the aim of reducing greenhouse gas emissions from waste down to zero. In the first two years of operation, more than 2,000 tonnes will have been diverted from landfill. Tenants have been engaged to play a role in achieving this target. Lendlease actively monitors the process of separating waste into recycling and reuse streams to divert waste from landfill. They also source and provide feedback so that the process can be continuously improved. Retailers and suppliers are required to use compostable packaging, reduce waste and offer healthy food choices from local and sustainable sources. In addition, Barangaroo is a plastic bag free precinct.

Water
A variety of strategies will improve the way water is used. Potable water consumption is being reduced through the use of efficient fittings and fixtures. Harbour heat rejection is the technology selected for the district cooling plant, instead of the use of cooling towers. A treatment plant for black water (used water) will have the capacity to supply up to one million litres of recycled water annually. The output from this plant will be used in sanitary facilities across the precinct, with the plant being ultimately capable of exporting recycled water to other parts of the CBD. Rainwater captured in South buildings is used to irrigate the rooftop gardens.

Carbon footprint
Carbon footprint benchmark measurements were established and a stakeholder engagement plan was designed to bring businesses, residents, contractors and other agencies into the push to conserve natural resources, protect human health and ecosystems, and support local businesses. During construction, all buildings in Barangaroo South are subject to a target of 20% reduction of embodied carbon (compared to BAU).

Summary
By setting and widely communicating a clear strategic direction, supported by tactical targets and goals, including offsetting, Barangaroo South is working towards its carbon-neutral, water-positive and zero-waste goals.

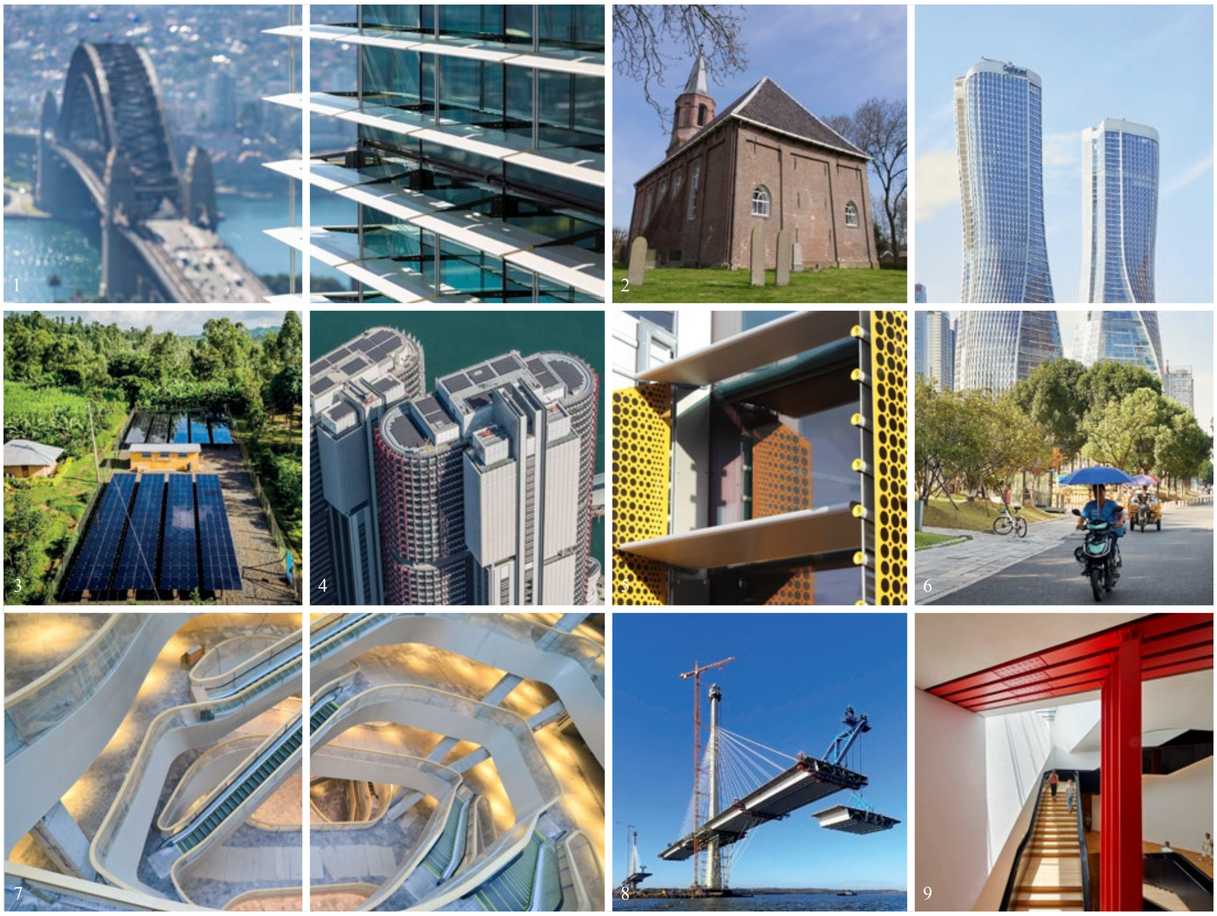
Authors
Haico Schepers, a buildings physicist, specialises in the sustainability of buildings.

Paul Sloman is a buildings engineer, also specialising in sustainability.

Peter Tomlinson designed the energy-saving vertical transportation system. Sadly, Peter died earlier this year. His legacy lives on in the work he has done to help shape cities around the world.

Project credits
Client: *Lendlease (Lendlease, also provided detailed design for the sustainability initiatives)* Project Owner: *Barangaroo Delivery Authority for the New South Wales Government* Architect: *Rogers Stirk Harbour + Partners* Environmental strategy development: *Arup – Tristram Carfrae, Alexander Hespe, Patrick Hespe, Andrew Hulse, Jorg Kramer, Josh Milston, Haico Schepers, Paul Sloman, Su-fern Tan, Sarah Tasic, Peter Tomlinson, Qian Wang. IESC: Natasha Connolly, Tim Elgood. Arup's other roles on the project to date have included: acoustic consulting, building modelling, façade engineering, geotechnics, maritime engineering, sustainable buildings design, vertical transportation design, building physics, master planning, transport consulting, structural engineering, wind engineering, building design, environmental consulting, sustainability consulting and urban design.*

Image credits
1, 4, 5, 6 *Lendlease*; 2, 7 *Arup/Martin Hall*; 3, *Arup*; 8, 10, 11 *Barangaroo Delivery Authority*; 9 *Transport for New South Wales*.



1, 4, 5 Barangaroo South, International Towers Sydney: *Lendlease, Arup*; 2 Woltersum Church, Groningen: *Arup*; 3 Microgrids in Nigeria and Kenya: *Powerhive*; 6, 7 Raffles City, Hangzhou: *Hufton+Crow, Arup*; 8 Queensferry Crossing, Firth of Forth: *Transport Scotland*; 9 V&A Exhibition Road Quarter: *Hufton+Crow*.

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