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Contents

Left: Caesars Entertainment's LINQ development at Las Vegas, with the *High Roller* at the eastern end (photo: *Mary Ferguson*).

The Vegas *High Roller*

Location
Las Vegas, Nevada, USA

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Setting the scene

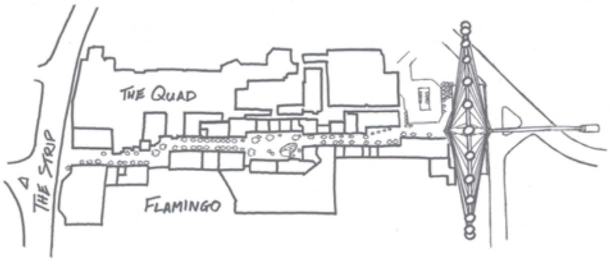
The *High Roller* in Las Vegas, Nevada, is now the world's tallest observation wheel. It opened to the public on 31 March 2014, concluding five years of design and construction in which Arup was involved throughout, from the early concept stage to completion. The project drew upon the expertise of numerous Arup staff from around the world, demonstrating the value of the firm's global networks, and many of the design challenges also required close collaboration with contractors, fabricators, suppliers and other consultants.

Without the willing participation of all these parties, the *High Roller* would not be the technical success that it is.

The *High Roller* is the anchor attraction of Caesars Entertainment's new LINQ development at the heart of the Vegas Strip (Las Vegas Boulevard). The LINQ comprises a high quality retail, dining and entertainment area, replacing an under-used alley extending east from the Strip (pp2–3 and Fig 1), previously occupied by an old casino and multistory car park. The LINQ connects directly with several adjacent casinos owned by Caesars.

Caesars initially engaged The Hettema Group (THG), an attraction design consultancy, to develop ideas for an iconic feature. Historically, Las Vegas developers intent on creating landmarks have opted for replicas of famous structures such as the Eiffel Tower, but Caesars and Hettema decided on a large and distinctive observation wheel.

Arup was engaged in June 2009, on the basis of its involvement with two previous record-breaking giant wheels, the *London Eye* and *Singapore Flyer*[1], to start the process of engineering the creative vision into a buildable reality.



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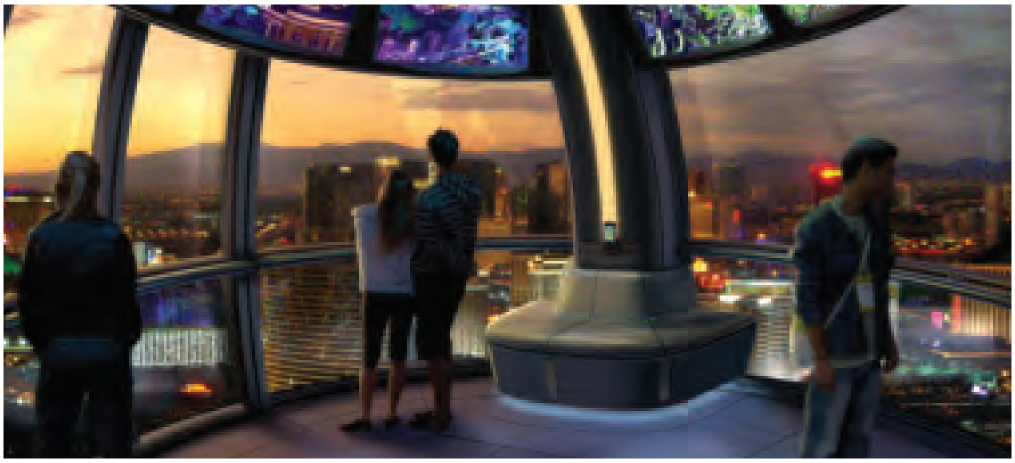

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1. Sketch plan of the LINQ development (see previous pages).

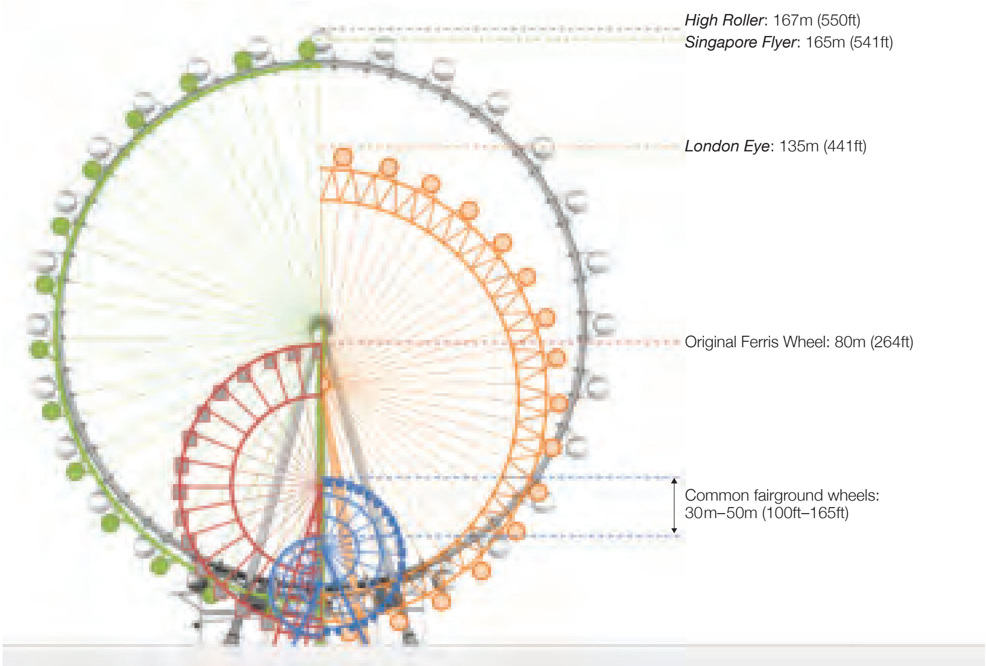
2. The Hettema Group's concept for the cabin experience.

The first stage was to develop alternative structural concepts in keeping with the desired aesthetic of the wheel (Fig 2) and the significant footprint constraints of the proposed site, but Arup's role developed progressively as the project proceeded, and almost every aspect of the completed wheel was designed by, or heavily influenced by input from, Arup.

A brief history of observation wheels

Images of small observation wheels can be found in documents dating back centuries, but it was George Ferris's wheel, built for the 1893 Chicago World Fair, that really brought such rides to a wide public. The original Ferris Wheel was an 80m (262ft) tall engineering marvel enjoyed by hundreds of thousands of passengers, and other similar wheels quickly followed, in London (1895, 94m/308ft), Blackpool (1896, 61m/200ft), Vienna (1897, 65m/213ft) and Paris (1900, 100m/328ft), all inspired by Ferris's landmark design. These wheels had railcar-like cabins hung from the rim, using gravity to stabilise them. They would pause as each cabin passed the loading area to allow passengers on and off.

With the exception of Vienna's *Wiener Riesenrad*, all these giants of the late 19th century have now perished. During the 20th century, smaller Ferris wheels continued to proliferate around the world as staples of fairgrounds and amusement parks, typically ranging from 30m–50m (100ft–165ft) in height (Fig 3).



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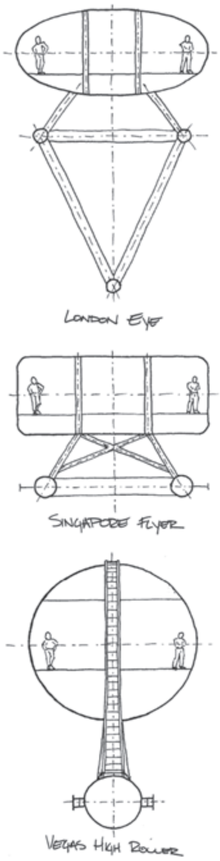

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3. Size comparison of observation wheels through history.

4. *The London Eye*.

5. Comparison between standoff and structural systems of the *London Eye, Singapore Flyer* and *High Roller.*

In the late 1980s and 1990s Japan embraced observation wheels and constructed the *Cosmo Clock 21* (Yokohama, 1989, 113m/370ft), the *Tempozan Ferris Wheel* (Osaka, 1997, 113m/370ft) and the *Daikanransha* (Odaiba, 1999, 115m/377ft). Up to this time, such wheels typically used heavy truss structures, or radial compression struts with tensioned circumferential elements. These were ideal for fairgrounds, being simple to fabricate and easy to erect, but this form limited the maximum size that could be economically achieved.

The year 2000 saw the realisation of a real technical leap forward with the opening of the 135m (443ft) *London Eye*, designed by Marks Barfield Architects and originally engineered by Arup (Fig 4).

Its structure is exactly like that of a colossal bicycle wheel, with tensioned spokes holding a rim in compression (interestingly, the same system used in the first flurry of wheels, including Ferris's own), and enabling it to be much larger than any previous wheel.

The rim of the *Eye* comprises a fully braced tri-chord steel truss, and the cables are arranged to provide lateral stability as well as carry the weight of the wheel. Arguably even more importantly, the *Eye*'s cabins are positioned outside the rim and do not rely simply on gravity to stay level. Instead, they are captured in two slewing bearings and are rotated by an active stability system.

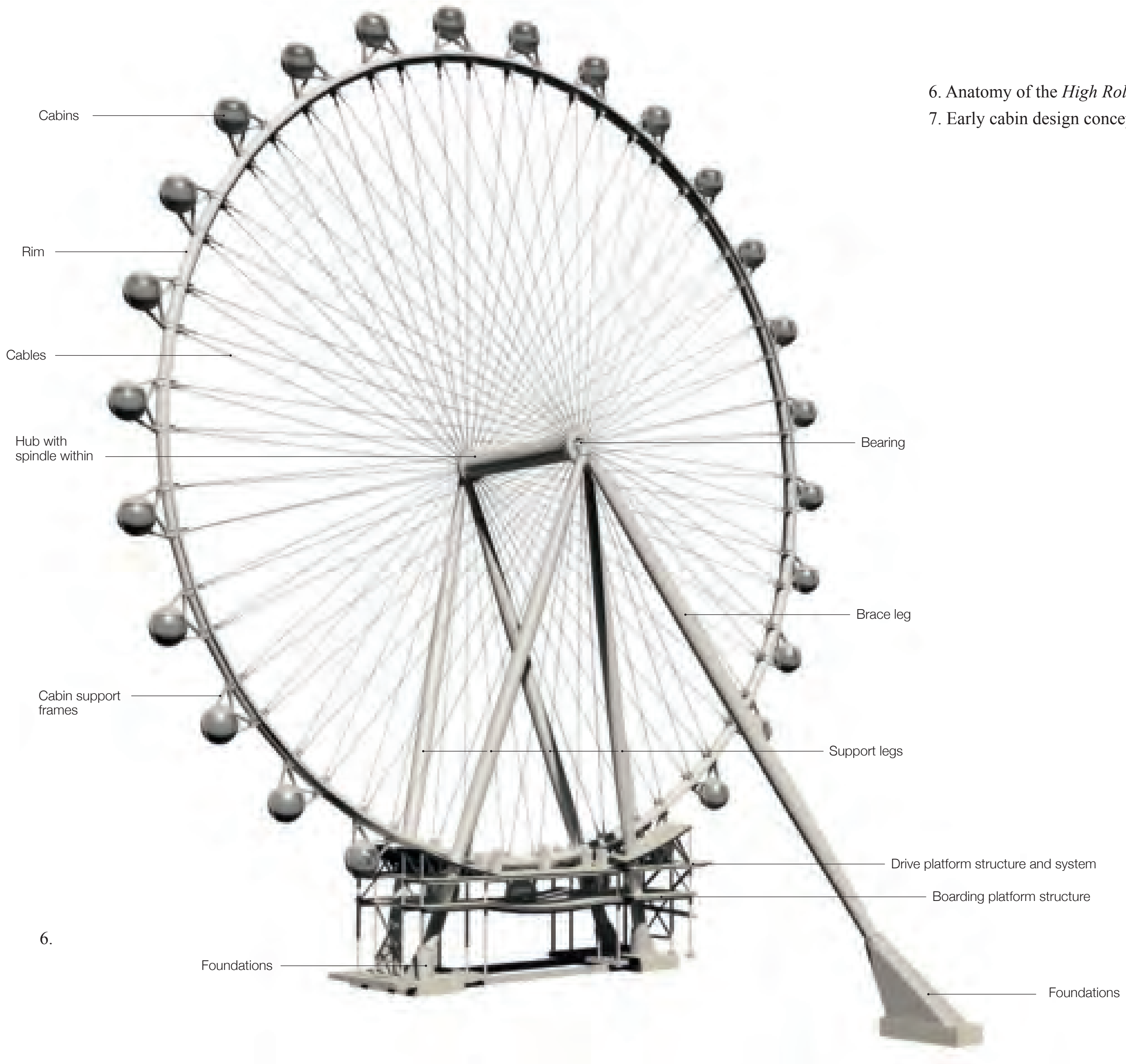
While this innovation certainly adds complexity, it gives passengers a more "stable" ride and a much more open view, particularly at the apex.

The completion in 2006 of China's *Star of Nanchang*, designed and built by Nanchang Star Entertainment Ltd, set a new height record of 160m (525ft), using the traditional compression strut system together with gravity-stabilised cabins. Just two years later the Arup-engineered *Singapore Flyer* opened with an official height of 165m (541ft). The *Flyer* has a similar structural system to the *Eye*, but with a two-chord ladder truss instead of the *Eye*'s tri-chord, stabilised in its weak axis by the cables.

Developing the reference design

Caesars Entertainment's vision for its new wheel had aspirations of lightness, freedom and an unforgettable passenger experience in every respect — to achieve something magical. Thus motivated, the Arup/Hettema design attempted to push the boundaries to make the most of a 360˚ panorama of Las Vegas and its spectacular surrounding desert environment.

This led to the development of a narrow, single tube rim supporting 32 large spherical cabins (changed to 28 as built), each with a single slewing ring, standing further out from the rim than is the case on either the *London Eye* or the *Singapore Flyer* (Fig 5). This minimises visual obstruction and maximises the panoramic views and sensation of free flying as it revolves.



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6. Anatomy of the *High Roller*.
7. Early cabin design concept.

When initial concepts for the *High Roller* (Figs 6–7) had been selected by the client, Arup was commissioned to develop a detailed reference design, in collaboration with THG, to enable the client to take this unconventional project to the construction market with a high degree of definition. The reference design was fully multidisciplinary, and its scope included:

- structural design of the wheel, supporting structure, and passenger loading building
- wind engineering and occupant comfort assessment under wind-induced motions
- geotechnical engineering and foundation design
- the mechanisation, including the drive and control systems
- cabin design, including structure, façade/glazing, HVAC, doors, controls, communications, and stabilisation systems
- utility and emergency (back-up) electrical power distribution for all systems including attraction lighting
- fire and evacuation engineering, including development of emergency response planning, means of access and escape, emergency power definition, and back-up safety systems
- acoustic and noise consulting
- preliminary FMEA (failure modes and effects analysis) documentation for permitting.

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8. Each *High Roller* cabin hangs from a V-shaped support frame.

9. The support structure under construction, showing the canting inwards of the main legs, and the brace leg angling outwards from the spindle.

Reference structural design

Design basis

The design of most aspects of the *High Roller* followed a performance-based approach. While existing codes of practice and design specifications offer solid methodologies for buildings or bridges, they are not fully applicable to unusual structures such as giant observation wheels.

One primary code used for the project covers the design of amusement rides[2], and this was selectively supplemented with portions of other codes, and bespoke methodologies developed by Arup. Where appropriate and feasible, the results of these analyses were verified with physical testing.

Support structure

The site constraints were a major driver in developing the form of the wheel support structure. The site is bounded to the west by a raised monorail, to the east by a road, and to the north by a road and an underground storm culvert. This left only a narrow footprint for the wheel to sit on with some additional space to the east — in a parking lot on the other side of the road — if needed for some lateral stability structure.

The four main steel tubular legs supporting the hub which carries the weight of the wheel are inclined to form two A-frames in the north-south direction, which also provide lateral stability in that direction.

However, both frames have to be canted inwards (from a maximum separation at the hub) so that their foundation plinths at the north and south extremes of the site fit within the site's restricted width.
A single tubular steel brace leg, from the east end of the spindle over the road to a concrete plinth in the parking lot, provides out-of-plane stability (Fig 9).

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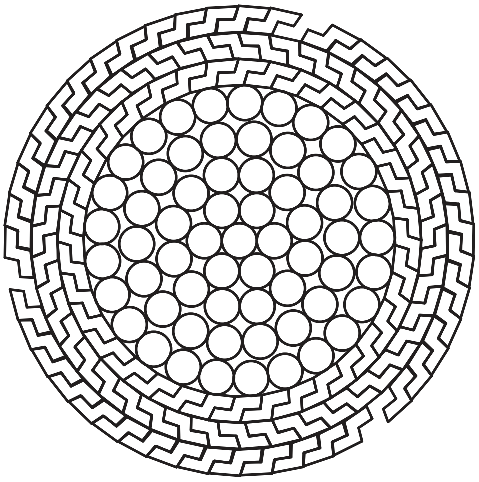

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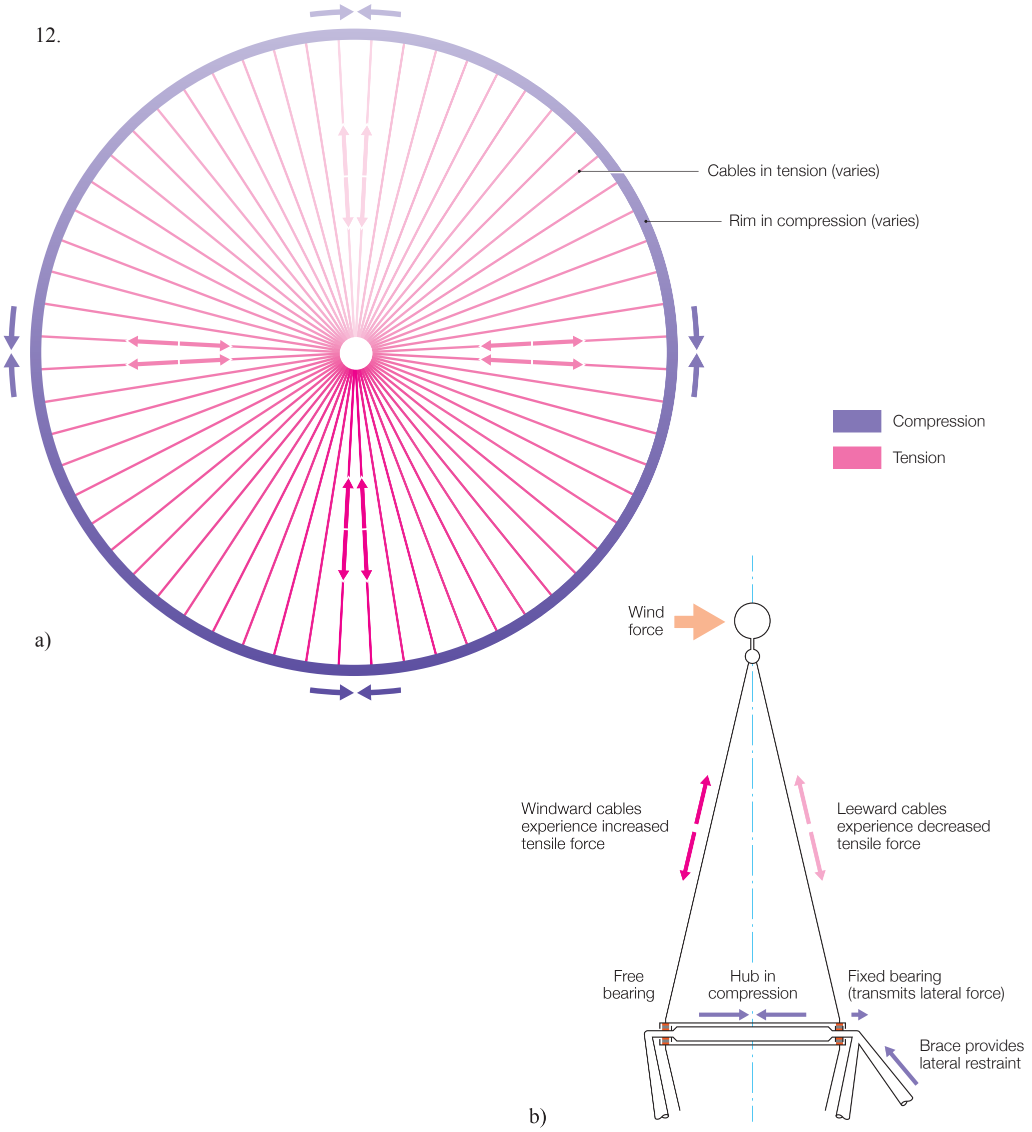


Rotating wheel

The structure rotating about the fixed spindle is essentially an oversized 128-spoke bicycle wheel. The spokes comprise 75mm (3in) diameter locked coil cables (Fig 10), because they provide the best stiffness–to–diameter ratio. This compactness reduces both the visual impact and the wind loading; an added benefit is that the interlocking “Z”s that form the outer layers of the cables offer better weatherproofing than spiral strand cables (Fig 11). To protect against vortex shedding, one Z-strand is removed from each cable, creating a helical groove up its length, similar to the helical strakes often seen on tall chimneys. Locked coil cables were also used on the *Eye* and the *Flyer*.

The cables are an essential part of the wheel structure, providing all the support for the rim and cabins. Though all the cables are set to the same length initially, gravity loading results in those at the bottom of the wheel carrying a higher tension than those at the top. Similarly, the overturning moment of the wheel caused by lateral wind loads is resisted by an increase in tension in half of the cables and a decrease in the other half (Fig 12).

10. Cables.

11. Cross-section of the 75mm (3in) diameter cable.

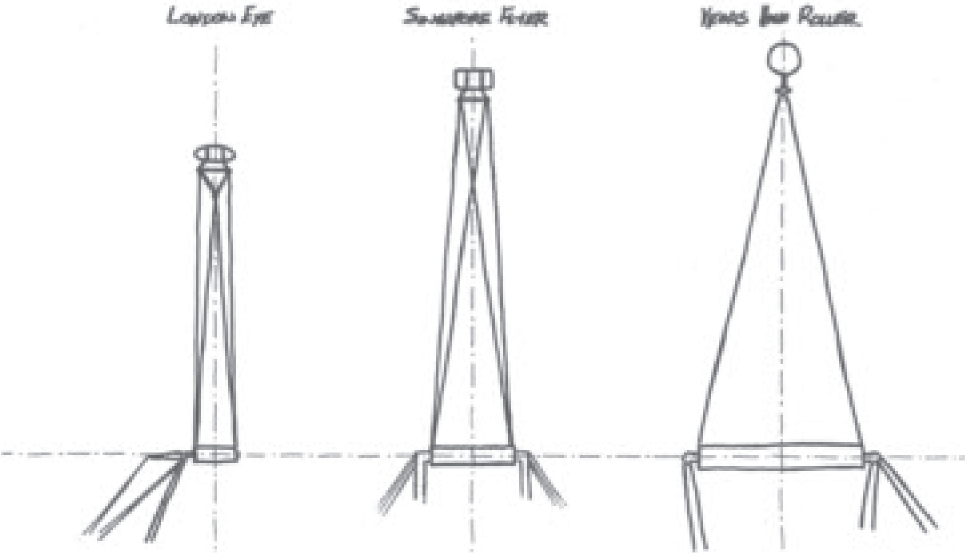
12. The forces on tension wheels: a) gravity; b) wind.

13. Comparison of hub lengths and cable angles on the *London Eye*, *Singapore Flyer* and *High Roller*.

14. The hub.

The choice of a single minimum diameter steel tube for the rim required the cables to provide more lateral stability to it than the wider “truss” designs for Arup’s previous wheels. The *High Roller*’s single 2m (6ft 7in) diameter tube rim, constructed of 56 straight segments, is relatively flexible compared with the *London Eye*’s 8m (26ft) wide tri-chord truss, so the necessary stability was achieved by aligning the cables with greater inclination in the lateral direction, necessitating a longer hub.

The hub on the *Eye* is just 8m (26ft) long, partly limited by the flexibility in its cantilevered spindle. The *Flyer* took advantage of having support for its spindle at both ends and increased the hub length to 16m (52ft), while the *High Roller*’s hub is almost twice this at 30m (98ft) (Figs 13–14).



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Fatigue

Observation wheels like the *High Roller* are not just structures, but machines. Additional considerations arising from a wheel's rotation include the need for drives and bearings, the importance of fatigue in the design process, and wear and maintenance. Fatigue is a deterioration of structural capacity due to the growth of cracks in materials subjected to many reversals of loading.

Static resistance of the weight of the *High Roller* requires the tension in the cables at the bottom of the wheel to be far greater than that in the top cables. Correspondingly, the compression in the rim varies from high at the bottom to low at the top.

As the wheel rotates, each structural element moves from a bottom position to a top position, and therefore passes through these zones of high tension/high compression and low tension/low compression — one stress cycle per revolution. The stress cycles can induce fatigue damage in the cables, their attachment points to the rim and the hub, every hole and bracket on the rim, and every weld.

During the intended operational life of the wheel, all the elements in the rotating part of the structure will experience over 650 000 cycles of primary load fluctuation due to rotation, so in the reference design fatigue was considered for all of the rotating steelwork. Members were sized and details were developed to minimise fatigue susceptibility. Load reversals due to rotation do not arise in the stationary parts (the spindle, the legs, and the brace leg).

Cable fatigue

Design against cable fatigue is one of the more challenging problems for observation wheels. Not only does the tension in a cable vary during each wheel rotation, but the cables are subject to cyclic bi-directional bending due to the need to support their self-weight in the varying orientations.
In the plane of the wheel it is evident that the cables will experience maximum sag at the three o'clock and nine o'clock orientations, and no sag when they at the top or bottom.

However, the cables are also inclined out of the plane of the wheel, so when at the top the cables sag inwards; at the bottom they sag outwards. At the three o'clock position, the cables sag clockwise; at nine o'clock the sag is counter-clockwise.

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This bi-directional bending action is particular to giant observation wheels. The literature on cable fatigue is based primarily on research for bridge applications, dealing almost exclusively with axial load fluctuations only.

The Arup team therefore "deconstructed" the axial fatigue guidance and developed an analytical model for axial + bending fatigue in cables. The key to achieving long fatigue life is minimising detrimental bending effects (imposed moments and curvatures at the ends), and the following design measures were adopted for the cable ends:

- low-friction spherical plane bearings to reduce the moments at the cable ends at the hub and rim (Figs 15–16)
- extra-long clevises (U-shaped fasteners) between the cable end and the bearing to minimise the moment at the cable end itself.

Because of the uncertainty around cable fatigue, particularly due to bending, Arup commissioned physical testing to validate the assumptions in its analysis. This was done at Bochum University in Germany and showed that the selected bearing friction met the specification, and that the fatigue performance was in line with the predictions.

The Bochum tests also gave information about long-term elongation of the cables during repeated cycling, which enabled Arup to predict the loss of tension in the cables during the first few years. Just like a bicycle wheel, the *High Roller* needs its spokes re-tensioning.

15. Cable connections to the hub.

16. Cable connections to the rim.

Structural steel fatigue

Fatigue damage is caused by the propagation of a crack from an initiation point such as an inclusion in the parent steel, or a stress riser generated by a geometric discontinuity and/or a weld. Once a crack has started to form, the rate of propagation is affected by the toughness of the material.

The weld details on the rotating portion of the wheel were selected for their fatigue performance. All welds were detailed as complete joint penetration (CJP) welds, which typically experience much lower levels of fatigue damage than partial joint penetration (PJP) or fillet welds.

The weld procedures were specified to conform to AASHTO (American Association of State Highway and Transportation Officials) procedures for fracture-critical elements, which demand a higher level of inspection and better post-weld heat treatment, among several additional requirements. To control the rate of crack propagation should fatigue damage start, Arup's specification called for ASTM *A709*[3] Grade 50 steel, a bridge steel tougher than those used for buildings.

Tougher steel with verified through-thickness properties was also necessary to permit welding of cruciform connections without tearing the centreline of the plate.

17. Rendering of the hub and spindle.

18. The spindle has one fixed and one floating bearing.

19. Rendering of the fixed end of the hub and spindle.

20. Hub end forgings, in which the bearings are located.

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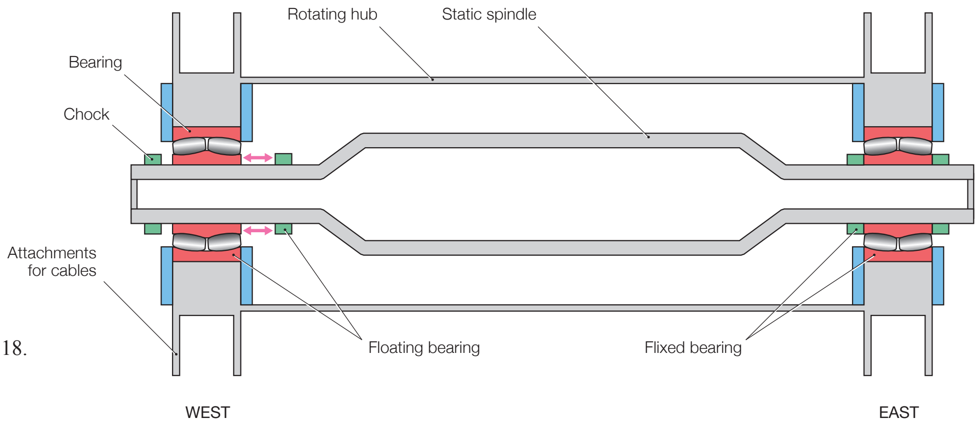

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Hub/bearings/spindle

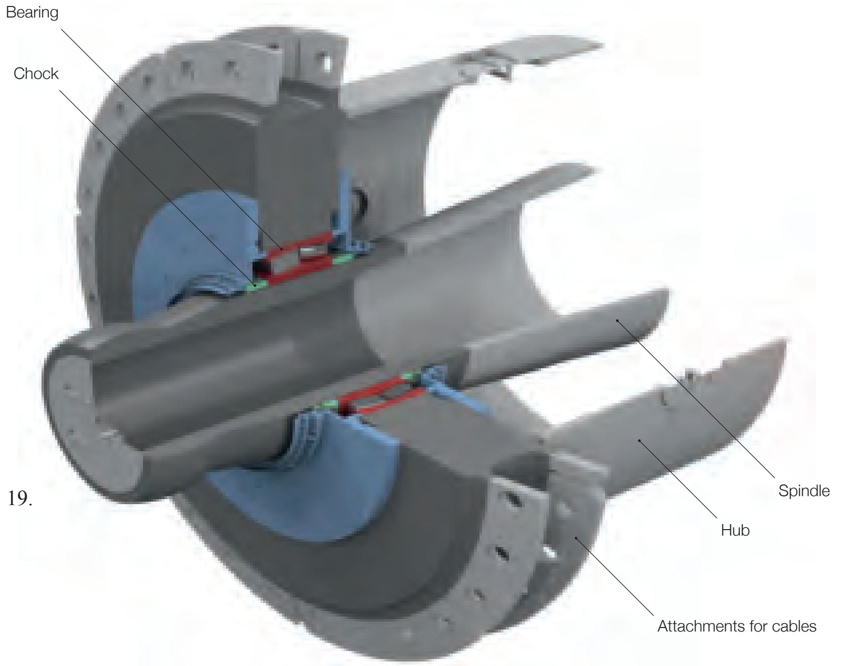
General arrangement

The rotating portion of the wheel interfaces with the static support structure by means of a hub rotating on a fixed spindle via two bearings, one at each end. To best suit this particular application, the design team chose spherical roller bearings, with the following main requirements:

- capable of carrying large radial and axial loads to cope with the wheel's huge weight and the significant wind loads that it attracts
- able to accommodate misalignment of their inner and outer rings without experiencing pinching on the rollers; as loading conditions on the wheel vary, the hub and spindle undergo different amounts of bending, resulting in angular misalignment between the hub and the spindle at the bearing locations.

Thermal loading on the structure can lead to differential expansion of the hub relative to the spindle. The bearings must be able to transfer axial loads, but they also have to be arranged so as to prevent build-up of large internal forces. These dual requirements led to the east bearing being axially fixed to both the hub and the spindle, allowing it to transfer axial loads, but with the west bearing left free to slide on the spindle (Figs 17–19).

The bearings themselves were supplied by SKF based on a performance specification developed by Arup. Each bearing weighs around nine tonnes and is designed to survive the wheel's full 50-year life without having to be replaced.



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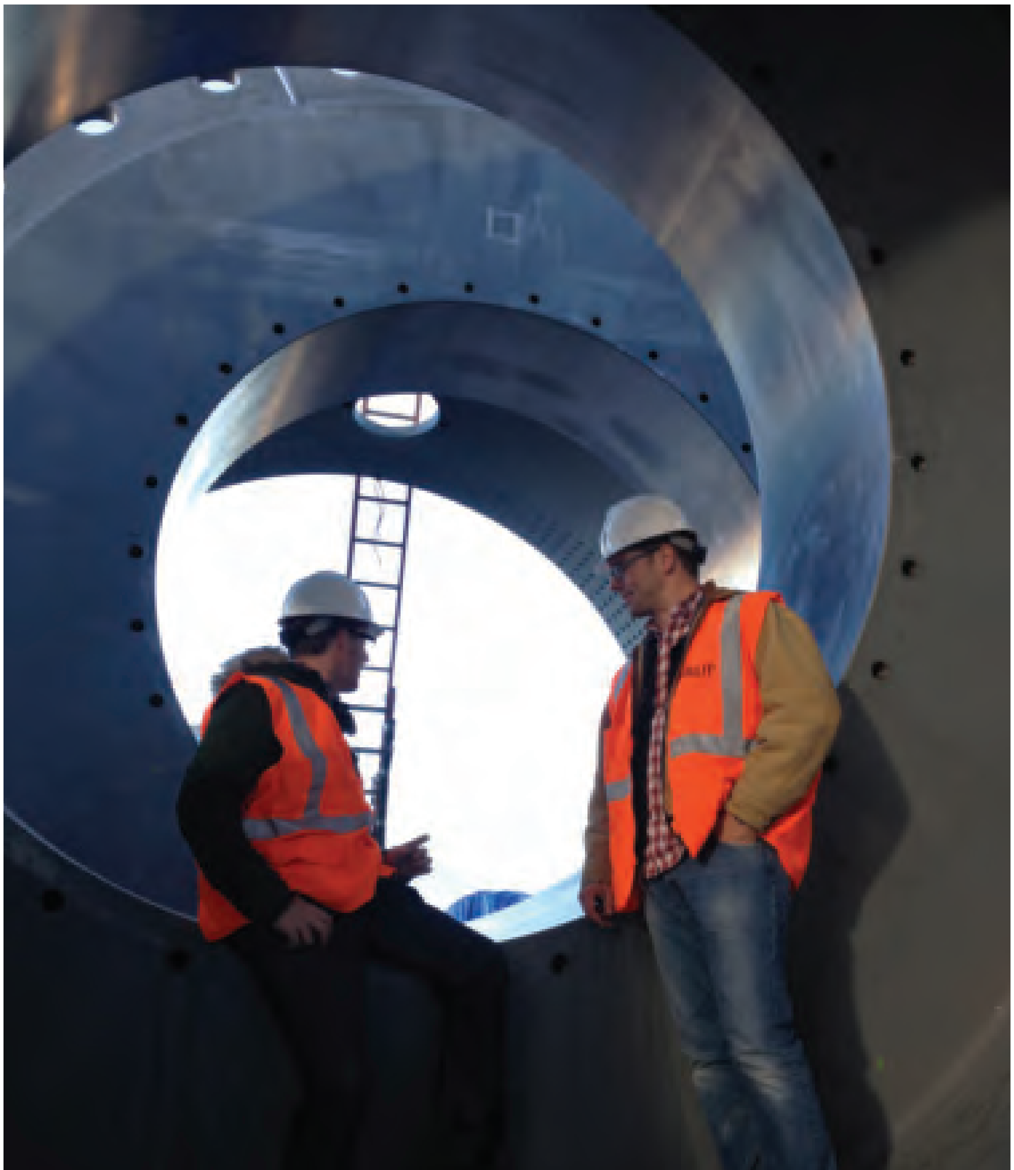


Each bearing is tightly located in the hub using a tapered collar sitting around its outsides. At the interface between the bearings and the spindle there is a clearance fit, and a ring of chocks on either side of the bearings. For the fixed east bearing, the chocks are located firmly against the bearing's inner ring; at the west bearing, they are set back to allow axial movement.

The hub supporting structure

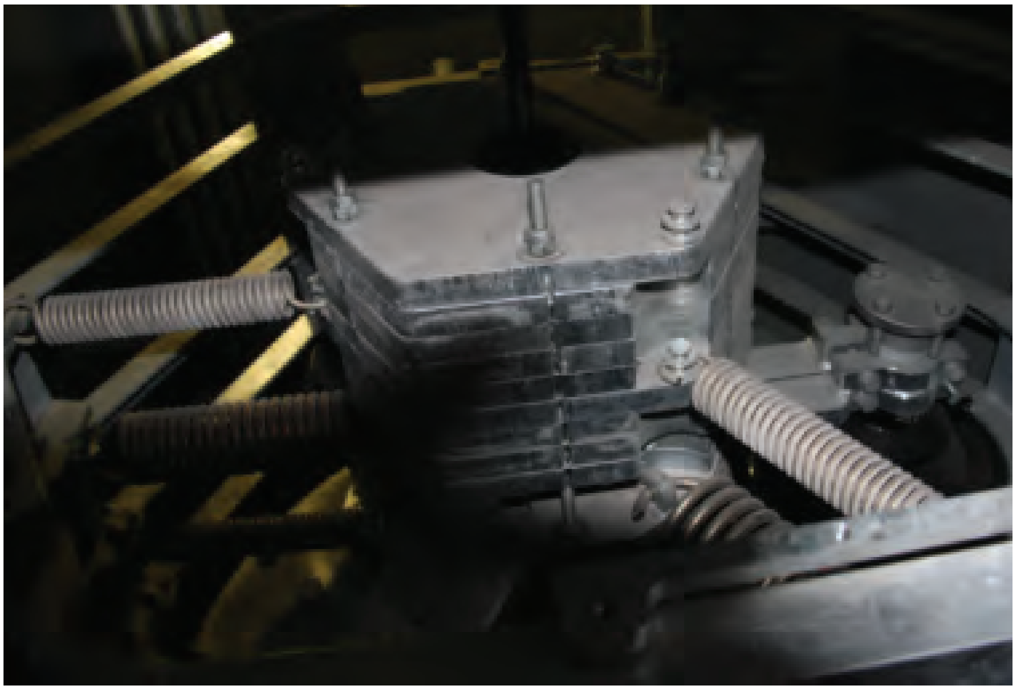
For the bearings to survive the 50-year design life, the structural housings must provide uniform and very stiff support. Any hard spots or excessive flexibility in the structure around the bearings would transfer a disproportionate share of the overall load into individual rollers as they pass. The hub and spindle were therefore specified as thick forged rings, manufactured by Japan Steel Works (JSW) (Fig 20).

While the bearings are designed to last the full life of the wheel, provision has been made for them to be replaced if premature degradation does occur for any reason. This is a major task, and would involve building a truss between the support legs below the hub. This would allow the hub, supporting the weight of the rest of the wheel, to be jacked up from this truss, relieving the load on the spindle.

The top of the legs would then be removed, and the end of the spindle extracted from the hub, taking the bearing with it. This is certainly a challenging process that should never have to be executed, but allowing for it was essential to guarantee the *High Roller* meeting its design life.

Achieving adequate bearing life also depends on keeping the grease needed for lubrication and sealing free from wind-blown sand and other contaminants. Each bearing is protected by steel cover plates bolted to the hub, minimising the gap to the spindle, and triple-layered rubber seals close the gap between the static spindle and the rotating parts.

Pressurising the cavities between the layers of seals with grease ensures a constant outward movement of grease and prevents the ingress of any contamination, whether particulate or fluid. Grease is also pumped into the bearing itself, entering between the two rows of rollers and moving outward, thereby flushing out any contamination.



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Wind

Although wind-induced motion is common to many tall structures, the *High Roller*'s light weight and low natural frequencies make it particularly susceptible to this type of dynamic response, both globally and locally in individual elements.

The aeroelastic stability of the cables was checked for vulnerability to vibrations from vortex shedding, galloping, flutter and rain-induced vibration, and in the design, allowance was made for Stockbridge dampers (small dumbbell-shaped tuned mass dampers) to be included on the cables if the vibrations were larger in practice than expected. These, however, have not as yet been required. The tubular members forming the support legs and the brace leg were predicted to be susceptible to vortex shedding excitation, and tuned mass dampers were incorporated in them (Fig 21) to control the potential response.

The team used a combination of analysis and wind tunnel testing to predict the dynamic wind response of the wheel as a whole. Site-specific desktop studies estimated the wind climate for the wheel, based on local airport wind records. The drag characteristics of the rim and cabins were initially estimated from code coefficients, and were then checked for several orientations relative to the wind direction by means of wind tunnel tests (Fig 22).

Static wind loads with a selection of patch loading scenarios to consider non-uniform gust distributions were used for the strength design of the wheel, but more sophisticated approaches were required to predict the wind-induced motions that passengers might experience.

Though there are now recognised vibration acceptance criteria for many types of structure, nothing existed specifically for giant observation wheels. Acceptability of vibration is a matter of perception, and the context is crucial. Arup developed bespoke criteria based on an amalgamation of the available guidance and previous experience.

The dynamic response of the wheel under service winds was predicted with spectral analysis, using purpose-written spreadsheets to account for gust correlation across the unique spatial distribution of the wheel elements. It was found that perceptible motions in the cabins would be generated over 10 natural modes of the wheel with frequencies between 0.4Hz–2.5Hz.

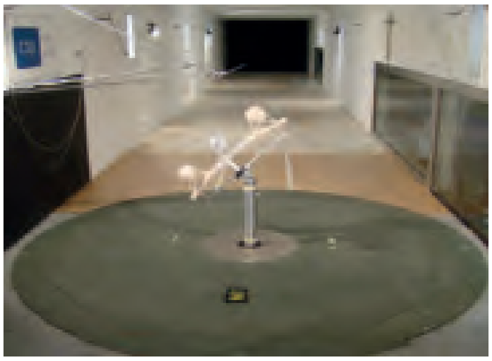
Unfortunately, all wind motion acceptance criteria are expressed on the assumption that a single frequency dominates in each direction (as is invariably the case for tall buildings where the problem is most usually encountered). There was therefore no clear way to establish whether or not a given multi-frequency response would prove acceptable or not.

For this reason, it was decided to set up a physical demonstration so that the client and design team could experience the predicted motions under various wind conditions on a motion platform. A series of time history wind response analyses were performed to develop simulated motion histories to apply to the test platform.

Arup's wind team in London produced sets of wind force time histories based on incident wind spectra to apply simultaneously to multiple loading points on the wheel, accounting for spatial correlation of wind gusts of different sizes. The response analyses were performed for different wind speeds using the design team's LS-DYNA model of the entire wheel, and for cases with and without supplemental damping.

The general consensus from the physical test was that a level of supplemental damping was needed to provide acceptable comfort in a one-year wind — the agreed target return period for continuation of normal operation.

The necessary level of damping could be provided by incorporating viscous dampers in the lateral guidance units at the drive platforms, although provision was also made in the steelwork to add tuned mass dampers at each cabin support in future if deemed necessary.



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21. Tuned mass damper in one of the support legs.

22. Wind tunnel test.

23. Platform structure.

24. At the boarding platform.

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The platforms

Passengers approach the *High Roller* through the wheel building where the tickets are sold and pre-show entertainment flashes information about the ride to come.
The wheel building connects to a four-storey platform structure that straddles the wheel, from which passengers can enter and exit the cabins (Fig 23). The platform is curved to match the arc of the rim, and the cabins move by at 0.25m (10in)/sec — slow enough for boarding while the wheel is in motion (Fig 24). It takes about 1.5 minutes for a group of up to 40 passengers to exit the wheel to the east and a new group to enter from the west.

The positions of the platform edges have to allow for variation in the positions of cabins as they enter the platform zone. Variations arise from movements of the rim of the wheel due to wind loading, thermal expansion, and contraction under the extreme temperature range of the Nevada desert and differential solar heating causing the whole wheel to lean slightly one way or the other.

There is also potential differential settlement between the platform foundations and the wheel foundations, and finally, despite stringent erection tolerances, the as-built geometry of the platform and wheel will not be perfect. All these factors had to be taken into account and controlled so that the required gap would be small enough for passengers to comfortably step into the cabins, but large enough to accommodate potential movements and construction tolerances.

In operation the cabins can move laterally under wind and thermal loading, but viscous dampers eliminate any sudden jerks as passengers enter and exit. The mechanisms that drive and control the wheel are designed to track along the rim and move laterally and radially to match its movements.
To minimise the effect of construction tolerance, the platform edges were installed after the wheel was finally “trued”, so that they positioned to the as-built rim geometry.

Finally, the edge of each cabin was fine-tuned to match the finished platform.
Under extreme events, such as earthquakes or winds exceeding the design return period, the lateral restraints will lock off to limit excessive rim movements and thereby prevent damage to any of the sensitive mechanisms or cabins.

25.

The cabins

The *High Roller* carries 28 cabins each accommodating up to 40 passengers. By comparison, the 32 cabins of the *London Eye* and the 28 of the *Singapore Flyer* each accommodate up to 25 and 28 passengers respectively. Each cabin is a complex entity in its own right, somewhere between a building and an automobile in terms of design considerations.

As well as having to provide an entertaining and pleasant experience with excellent day and night views and the sense of being "on top of the world", they had to be engineered to function in what is essentially a desert environment.

The original THG concepts were based on the almost ellipsoidal *London Eye* capsule design, but the Arup team, through its early involvement, was able to suggest a simple yet elegant alternative – a spherical cabin – which was quickly adopted. The basic structure is formed around two hemispherical steel frames connected to the slewing bearing that sits within a structural steel ring mounted to the wheel rim (Figs 25–26).

Glazing

Developing a viable glazing system was a key factor in the reference design, and achieving both the highest visual quality and the highest solar/thermal performance of the glazing was essential to the design's success.

The type of glass and chosen solar control significantly impacted the thermal performance and the size of the heating, ventilation and air-conditioning (HVAC) system. Steps were taken at concept stage to reduce the cooling requirements by minimising the extent of overhead glazing, but the amount of glass necessary for panoramic views required further steps to reduce the cooling loads.

The glazing also needed to satisfy other safety issues associated with extreme summer temperatures in excess of 40°C (104˚F) — such extreme heat could easily make surfaces in the cabin too hot to touch (the solar gain on single-glazed units in the Las Vegas sun can cause surface temperatures to rise beyond 70°C/158˚F).

It was quickly established that double glazing was needed to handle the temperature extremes, but the challenges of differential thermal expansion of the two glass panels and the air gap remained. Expansion and contraction of the air would generate varying pressures within the double glazing, and Arup's façades team determined that this could lead to cracking at the supports.

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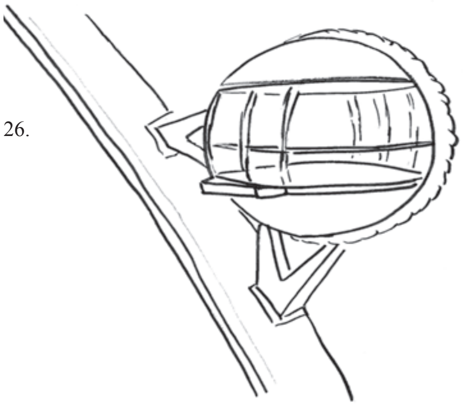

A vent in the double glazed cavity was therefore included in each panel, accommodating the expansion and keeping stresses in the glass at acceptable levels. The air gap also included a desiccant, to avoid problematic condensation.

At the temperatures that can occur in Las Vegas, re-radiation into the cabin also becomes problematic, so it was essential that most of the glazing be insulated. The design team considered deployable external shading, but the sun's intensity at low altitudes made this unviable.

The outer glass layer has a simple absorptive coating, selected for its balance of optical qualities, but again this had a side-effect of causing the outer layer to heat up, so this needed to be dealt with, as described above. The coating is non-reflective, providing clear views from the cabins and enabling higher quality photos through the glass. It also has low transmissivity to reduce the amount of solar heat entering the cabins.

In the reference design the main space of the cabins — that portion accessible to the passengers — is fully glazed using large laminated double glazed units (Fig 27). Eight glazed units per cabin are used, each doubly curved to follow the spherical form. The doors are single glazed, to reduce the weight on the door mechanism.

Cabin HVAC

Even after optimisation of the glazing system, a large HVAC system (around 25kW of cooling) is still required in each cabin, housed in the belly below the passenger floor (Fig 28). Cooled air is passed to the top of the cabins through ducting close to the structural ring, and released around the perimeter of the ceiling. This allows cool air to flow down the glass, preventing it from getting uncomfortably hot to touch.


27.

25. One of the 28 *High Roller* cabins.

26. Cabin concept sketch.

27. Close-up of cabin glazing.

28. One cabin being assembled, showing the internal arrangement.


28.

This air, now slightly warmed, is then extracted downwards through vents under the seats and used to cool the HVAC and electrical equipment beneath. Finally the air is reintroduced to the cooler and circulated back into the cabin at the top. Fresh air enters the system through intakes, as well as from deliberate leakage from the outside environment into the belly.

The passenger space is kept slightly pressurised relative to the outside environment, so that at any locations where air can pass in or out, there is cool air flowing out rather than hot air flowing in.

Electrical power is supplied to the rim at platform level using several collector shoes sliding on conductor rails (busbars) on the moving rim. Since the cabins rotate relative to the rim, a similar system is required to transfer the power into the cabins.
The transistor box in each cabin generates a significant heat load, which contributes to the required size of the HVAC system.

Each cabin has an uninterrupted power supply in the form of a high capacity lithium battery with over six hours' running time, so that life-critical systems can continue to operate if the main power supply fails.

Stability and safety

The orientation of each cabin is controlled with an active rack-and-pinion stability system. This is backed up by a battery-powered secondary stability system also installed under the floor, which provides continuity of function if the primary system fails. The cabins are stable (will not overturn) in fully passive mode even if all power fails, though achievement of precise orientation would be compromised.

Many other features are included to maintain a safe passenger environment, and developing these formed a large part of the FMEA for the cabin systems undertaken throughout the development.

If the HVAC fails, a fan provides continued ventilation; though not particularly comfortable, this gives adequate cooling in an emergency situation. The interior finishes of the cabins were selected to minimise combustibility and reduce the risk of fire, compliant with *NFPA 130*[4]. Further safety features are discussed later in this article.

29.

Mechanisation/electrical/communications

Arup's reference package included an engineered design of all these systems, together with performance specifications for a design–supply–install–commission contract. Five main systems comprise the mechanisation: the primary drive, the backup drive, the lateral restraint (and damping), the electrical distribution, and the communications distribution.

All of these cross the interface between the rotating structure and the static structure, and must accommodate differential movements between the two due to the rotation itself, the faceted form of the rim, thermal and wind loads, and fabrication tolerances.

Primary drive

The primary drive system is based on those for the *Eye* and the *Flyer*, using individually-driven truck tyres to grip the rim and rotate the wheel (Fig 29). Electrically controlled actuators provide the contact force between the tyres and the drive rail, a welded steel box on the side of the main rim tube.

Each tyre is driven by a hydraulic motor with a small gearbox, which fits neatly within the drive unit arms (Fig 30). Hydraulic motors were selected for their compactness and good torque profile at low speeds. Electric motors could have been used, as on the *Flyer*, and they have some advantages, but the substantial gearing needed adds weight and takes up space.

The four tyres and motors on each drive unit are mounted on the top bar of a four-bar linkage which leans against the rim, supported by a nylon roller running on the side of the drive rail and held in contact by its own weight. A hydraulic cylinder across the diagonal of the four-bar linkage is used to retract the drive units for maintenance.

Backup drive

Though the primary system has 100% redundancy, an independent backup drive system can rotate the wheel should primary drive fail totally. The backup has its own diesel-powered hydraulic power units and three clamps that engage with the drive rail in a similar manner to a disc brake.

The clamping blocks can be extended and retracted along the rim to haul it round. In a storm, the backup drive system can be used as a "hand brake" to prevent rotation of the wheel.

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Lateral restraint and damping

The rim passes between two pairs of lateral guidance units at the drive platform level. Load-balanced nylon rollers apply a force to the side of the drive rail, which is controlled by hydraulic cylinders. These cylinders can operate in different modes, fully locking off lateral movements of the rim (during a storm, for instance), or providing damping during normal operation (Fig 31).

29. Layout of the mechanisation systems on the drive platform.

30. Drive unit engaged on the rim.

31. Lateral restraint.

32.

Electrical distribution

Supplying power to the cabins and the wheel lights requires electrical distribution right round the rim, via a busbar system. Collector shoes at the drive platform engage with five continuous conductive rails around the rim. The electrical distribution system has 100% redundancy of the shoes and, if a break were to occur in the conductive rails, power can travel in either direction around the rim, ensuring that all cabins continue to have power.

Communications distribution

The transfer of communications signals from the rotating wheel to the static structure occurs at the hub and spindle (Fig 32). Communications cables span (supported by messenger cables) from the rim to the hub, where the signal is transferred across the rotating-static interface using “leaky coaxes” (coaxial cables with gaps in the outer conductor to allow the signal to leak into or out of the cable along its entire length). These are housed in the hub, which protects them from weather and contamination, as well as malicious interference.

Safety

Since the wheel can hold over 1000 passengers at any one time, and there is no direct emergency escape route from the cabins, incorporation of safety features was a major design driver from the beginning. From an overall structural perspective, the structure has minimal redundancy, and with multiple non-redundant elements.

The design was approached by using a FMEA, standard practice in the design of many mechanical engineering projects from commercial airplanes to rollercoasters. This enabled the team to identify potential failure points and their consequences, and design of mitigation measures including increased resiliency of elements, incorporating additional redundancy, and development of emergency response plans. A comprehensive list of natural hazards, accidental incidents and system malfunctions or failures was assembled, and a mitigation or response strategy was developed. Satisfactory solutions to every eventuality were required as a condition of licensing the wheel for operation.

Safety design features

The following were incorporated:

Drive mechanism: The primary drive system has 100% redundancy, ie the capacity to rotate the wheel with just half the drive units operational. Each set is powered through separate electrical circuits and, in the event of utility power loss, there is an emergency power supply. The primary drive can also rotate the wheel at double speed and in reverse to allow emergency evacuation of a particular cabin if required.

Drive backup: In the event that all power fails there is a separate backup drive, incorporating a “sloth-like” system (Fig 33). This is not incorporated in either the *London Eye* or *Singapore Flyer*.

Cabin stability: The cabins have to rotate relative to the rim as the wheel operates so that the floor remains horizontal (otherwise the glazed walls quickly become the floor). In the *High Roller* stability is maintained by a doubly-redundant active system in each cabin. A gravity mode still exists as a final system for maintaining an upright cabin (Fig 34).

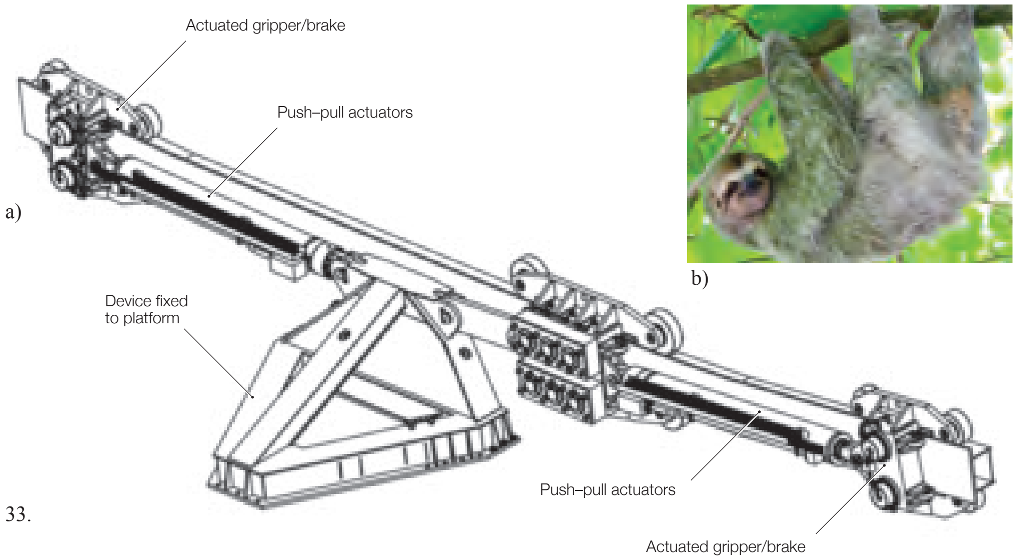
Other cabin features: Each cabin is equipped with water and other emergency supplies, as well as having communications back to the control office. Smoke detectors and cameras allow the control staff to monitor activities in the cabins.

Fire: The cabins contain minimal flammable materials, and emergency ventilation will operate should smoke extraction be required.

Lightning protection: While lightning storms are uncommon in Las Vegas, a direct strike on the wheel may cause both electrical and mechanical damage. For this reason, a special lightning conductor slip ring was incorporated to prevent a lightning strike crossing through the main bearing, damage to which could prevent rotation of the wheel.

Evacuation: In the extremely unlikely event of the wheel being unable to rotate — failure of either all drive systems or the main bearings — there is an evacuation plan, involving a combination of high reach equipment and rope rescue. For cabins near the top, rescue staff from the local Clark County Fire Department Heavy Rescue team worked with Arup to develop methods of access via ropes, ladders and other features. Some modifications were necessary to the rim design to make this possible (Fig 35).

Earthquake: Las Vegas is in a region of moderate seismicity. The wheel is designed to remain operational after a major earthquake (allowing evacuation while rescue services are busy elsewhere), so the structure was designed to be fully elastic during the 2475-year return period seismic event. As a precaution, “fuse” details were included in anchor bolts at the bases of the legs to allow a ductile mechanism to form in the case of even more extreme loads (Fig 36).



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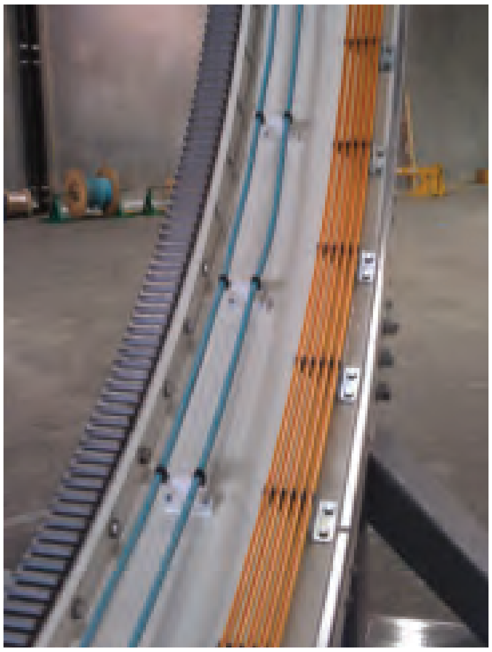

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35.

32. The hub contains and protects the communications distribution system.

33. The “sloth-like” backup drive system.

34. Cabin ring showing stability system and electrical distribution.

35. Cabin access ladder.

36. Tightening anchor bolts in the support legs.


37.


38.

37. Brace leg plinth.

38. Shear key, before installation.

Foundations and geotechnical design

The wheel is supported by three main foundations — for the north legs, the south legs, and for the brace leg. Each steel leg attaches to a giant concrete plinth via an assembly of embedded anchor rods. The two north plinths sit on a common pile cap, as do the two south plinths. The brace leg lands on a plinth with its own pile cap (Fig 37).

The connection between the legs (including the brace leg) and the plinths comprises a shear key (Fig 38) to locate the steel relative to the concrete, a stiffened base plate, and an array of unbonded anchor rods that connect to a plate embedded within the plinth. The heavily reinforced, cast-in-situ concrete plinths transfer the loads from the support legs into the pile cap. Each plinth was poured monolithically; special concrete mix design and means of placement were adopted for the very hot weather pours necessary in Las Vegas.

The 2.4m (8ft) thick pile caps are connected by grade beams and supported by 0.9m (3ft) diameter drilled shafts that extend 10.7m–13.7m (35ft–45ft) deep. Each pair of main support legs is supported by an 18-pile group, while the brace leg is supported by an eight-pile group.

The piles pass through several layers of alluvial deposits and caliche, a hard calcareous deposit commonly formed near major washes in the Las Vegas Valley. Over geological time, carbonate minerals were transported from the surrounding mountains and dissolved into the groundwater, and their precipitation in the arid Valley climate resulted in a cemented soil mass. Because of its erratic deposition, caliche varies greatly in its thickness, hardness, cementation and lateral continuity.

The ground investigation focused on identifying the variability in caliche thickness, stiffness and persistence, as well as the strength and stiffness properties of the softer alluvial layers underlying the support leg foundations. In situ P– and S–wave suspension velocity logging[5] and pressuremeter testing was used to supplement preliminary borings and refine understanding of the subsurface stratigraphy.

Arup's pile design was confirmed by high-strain dynamic load tests on two production shafts. Both achieved total shaft capacities of over 8800kN (2000 kips), more than four times the design service load.

39.

Procurement and construction

Introduction and contractual setup

There is no "standard" procurement process for giant observation wheels, and one of Arup's earliest roles was to advise the client on the options. Following the precedents of the *London Eye* and the *Singapore Flyer*, the original proposal was that Arup would develop a reference design for the *High Roller* that would be released for a complete design–build contract.

Towards completion of the reference design Arup assisted the client in testing the market for potential design–build contractors but, despite concerted attempts, it became apparent that there would be no takers for a single turnkey contract, and that the project would have to be let as a series of contracts managed and co-ordinated by the client.

The main contractor selected for the wheel itself — American Bridge Company (AB) — submitted a bid that was limited to the supply and erection of the main wheel steel and its ancillaries. AB's proposal excluded responsibility for the Construction Documents (CD) design phase, and for any aspect of the foundations, boarding platform, drive equipment, and cabins.

Construction of the foundations and platforms was let to Richardson Builders; the cabins and their V-shaped support frames were developed as design–build items by Leitner-Poma of America (LPOA), and were lifted onto the wheel (Fig 39) by AB. The mechanisation systems were let as a design-build contract to Schwager Davis Inc.

Extended Arup role

In the absence of a full design–build contractor the client asked Arup to develop the reference design of the wheel, the structure, the platforms and the foundations to the CD stage and take on the construction administration throughout. This extended the firm's role for multidisciplinary services that included structural, geotechnical, fire, electrical, and plumbing engineering, and blast resiliency.

Arup also took the main role in design co-ordination, working with the client's small project management team, because the *High Roller* was a project in which there was no architect leading the design team as with a conventional building project. THG was involved through the reference design, but did not take on a co-ordination role. Local entertainment architecture specialists Klai Juba Wald developed the architectural components of the platform design, but again without any overall co-ordination role.

A further consequence was that Arup had to consider the minutiae of access requirements and design in detail the related components. Access through the wheel includes ladders up every leg to the hub and spindle.

Doors in each end of the spindle (Fig 40) allow east–west movement without climbing down 70m and then back up again. There is access, through an opening in the floor of the spindle, to the inside of the hub. Here, a complex of ladders and platforms allows maintenance staff to inspect the bearings, collect grease rejected by the bearings, and exit through external hatches to stand on the hub for cable inspection.

Arup's role co-ordinating the interfaces between the various contractors included building (in *Navisworks*) an integrated model of all the wheel systems that was used for clash detection and to aid communication. This incorporated 3-D model data from the design–build cabin and mechanisation contractors, the architects and other sub-consultants, and included all drive equipment, the connection of the cabins to the main wheel structure, the power to the cabins, the lighting equipment, and cabin communication — every bolt, bracket and piece of conduit on the project.

40.

The decision to go down this route was a wise one. Many elements of the wheel, being fabricated by different companies, had to fit together with fine tolerances, and field alterations — welding, drilling, cutting — were particularly undesirable because of the implications for fatigue performance.

The success of this approach can be measured, in part, by the number of requests for information (RFIs) Arup received related to attachments to the rim — just four. On site, (almost) everything simply fitted perfectly together.

This was the first time Arup had taken responsibility for this level of design and construction of a wheel, and so this was a great opportunity to help fully deliver one of these rare projects.

39. Cabin being installed by American Bridge.

40. Spindle end door.

Structural design for Construction Documents phase

The CD design of the wheel structure was a major co-ordination challenge in incorporating the fabrication and erection methods and schedule of the AB contract. Fabrication was undertaken in Shanghai by AB's subcontractor ZPMC (Shanghai Zhenhua Heavy Industry Co Ltd).

Many aspects of the design finally executed involved balancing multiple requirements for structural integrity and performance with the constraints associated with the way that AB wished to fabricate and erect, the capabilities of fabricators and requirements of manufacturers, the lift capacities of the cranes, etc.

For example, the design of the hub, spindle and bearings was strongly driven by requirements associated with the bearings supplied by SKF. To mobilise their full capacity, the bearings had to be housed within smooth supporting structures with a 73µm (0.0029in) tolerance and hardened surfaces. The ends of the hub could not be manufactured to these requirements by ZPMC, and ultimately JSW was engaged to produce forged end pieces machined to this tolerance (limited only by the accuracy of its measuring tools) and provide the hardened surface.

JSW also managed to develop a weld procedure that gave acceptable performance for the welds between the forgings and the structural steel, which had to meet the fracture critical toughness requirements. The hub/spindle assembly needed to be designed with two fully bolted splices so that AB could lift it in three pieces, each at the full capacity of the largest crane in Nevada.

Arup as engineer needed these components to transmit the structural loads and was ultimately responsible for ensuring that the design balanced everyone's requirements. This was done in very close collaboration with the other three companies, including developing an installation method that was validated with dynamic finite element analyses (conducted by Arup and SKF) to simulate the insertion of the tapered collars that capture the bearings.

On site, installing each bearing took just a couple of hours and the whole complex process went precisely to plan (Fig 41). This was a huge testament to the success of this collaborative process.

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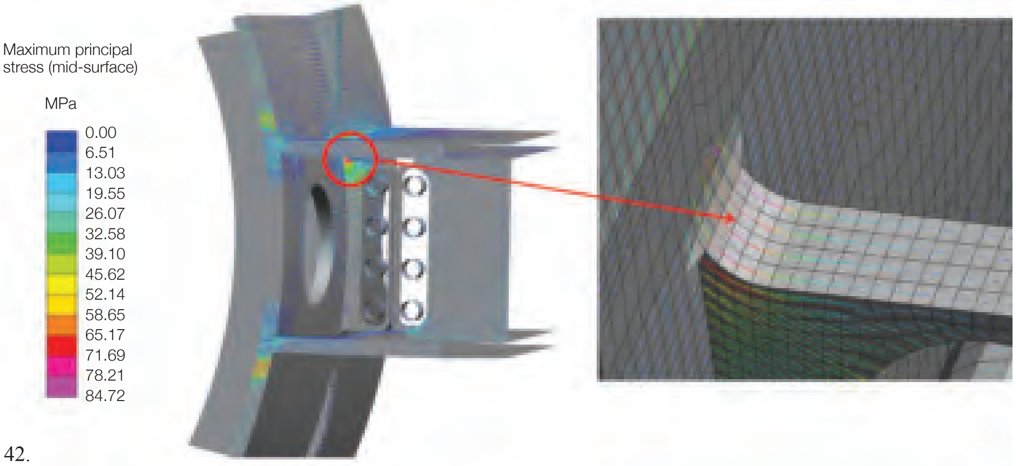

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Fatigue

As already noted, for the structural steel in the rotating part of the wheel, fatigue considerations affected every aspect of the design. All details were optimised to avoid fatigue; every hole and attachment to the rim was explicitly drawn, so that it could be fabricated in the shop to avoid on-site alterations. All components welded to the rim were aligned with the direction of the cycling stress, and profiled to reduce stress risers. Every penetration was assessed in relation to the surrounding geometry to ensure that the increase in stress that it generated would be acceptable. This level of thoroughness, while seeming, perhaps, excessive at the time, meant that only four alterations were required on site.

The team conducted fatigue analysis by various means depending on the complexity of the specific location. A finite element analysis using a relatively coarse shell mesh was used to determine the overall stress patterns. For simple connections, eg in-line brackets and holes, these stresses were used directly with the appropriate code fatigue classifications to determine the expected life.

For more complex geometries, such as the cable connection to the hub, a fine shell mesh was used to better assess the geometric flow of stress. The hotspot fatigue assessment method was used to calculate the expected life, based on extrapolated surface stresses, following the methodology in *BS7608*[6]. In a few locations, where the standard hotspot method was inappropriate due to the complex geometry, a very fine solid finite element mesh was built and a special assessment methodology developed to ensure appropriate application of the fatigue calculation theory (Fig 42).

41. Tapered collar being lifted into place, to fit around the bearing.

42. Solid mesh finite element fatigue analysis.

Welding

Particular challenges were presented by several details of the drive rail, which is attached all around the rim. These derived from the high cycling stresses, the complex geometries required to carry the longitudinal compression loads in the rim, and the radial compression loads from the drive system combined with the limited access for forming the required welds. While Arup's original geometry was technically possible to produce, the steel fabricator requested some detail changes to suit the proposed sequence of assembly.

Arup and AB went through an iterative process to converge on the final design: Arup would present an option to AB; AB responded with concerns; engineer and contractor discussed possible alternatives; Arup analysed the new design option, made adjustments as necessary, and presented the results to AB. Over weeks, this collaboration arrived at a solution that accommodated the contractor's assembly sequence and also met all the design requirements, most notably fatigue performance.

Owner's Engineer role

For those parts of the design for which Arup was not directly responsible — eg the drive systems and cabins — the firm took on the Owner's Engineer role, providing general reviews of progress and monitoring through detailed design and testing.

Construction

Two contractors

Two general contractors handled the project as a whole: AB for the wheel structure, and Richardson for the LINQ development, the foundations, and the platform. These scopes of work created several important interfaces between them, a critical one being at the concrete plinths of the foundations (Fig 43). As already described, the support legs connect to an anchor bolt assembly that is cast into the massive concrete supports — and the anchor bolt and shear key assembly was fabricated by AB and installed by Richardson. The foundation assembly required very tight geometrical tolerances because it set the position for the support legs, later installed by AB.

There were also many important interfaces between the platform structure and the wheel that required close co-ordination of contractors and fabricators. The platforms were built first, due to schedule constraints on fabricating the steel for the wheel. Several temporary "leave outs" were incorporated into the platforms so the support legs could be lowered carefully through the four-storey structure. After AB completed the wheel, Richardson connected the platforms to the legs and cast the slab edge to match the arc swept by the cabins.

Erection of the wheel

The erection process AB selected was similar to that for the *Singapore Flyer*. The support leg structure was constructed first, and then the hub and spindle were erected. Then the rim was assembled introducing each new element at the base and then rotating it to make space for the next section (Fig 44).

After Richardson completed construction of the foundations, it proceeded to the platforms, incorporating the leave-outs for the main legs of the wheel. Once Richardson handed over the site, AB needled the bottom third of the legs through the leave-outs and attached them to the plinths. Temporary trusses supported the legs as they were completed and capped off with the section known for obvious reasons as the "pants" (Fig 45).

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43. Interface between the plinths and the legs.

44. The rim half-assembled, showing temporary struts.

45. The legs completed by the "pants" being lowered into place.

The hub and spindle were split into three parts: two ends and a middle tube. The hub ends, bearings and spindle ends were assembled on the ground and then lifted into place, the west assembly first. Since the crane did not have the capacity to place the assembly directly into its final position, it was deposited on a sled on the temporary truss and jacked into place. The centrepiece of the hub followed, and then the spindle centre, which was loaded into the hub horizontally. Finally the east end assembly was brought in and attached to complete the central structure.

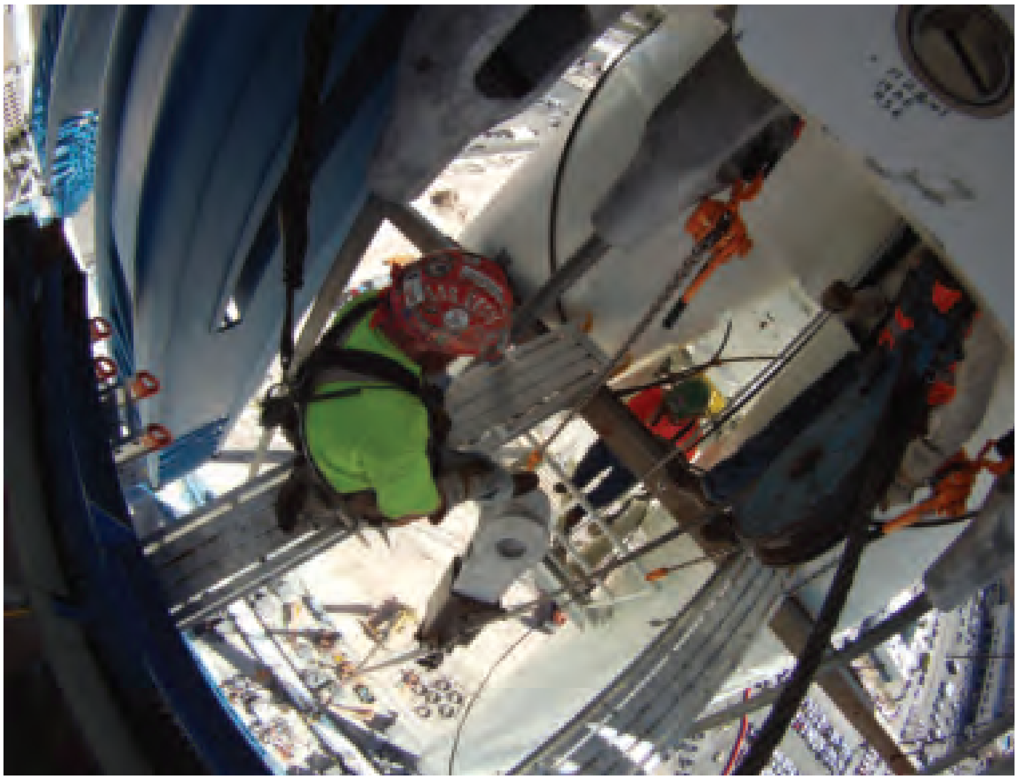
Chain falls from the hub were used to lift the rim sections into place at the six o'clock position (Fig 46). These were supported by temporary trusses from the hub and rotated to make space for the next rim element. As the partial rim was lifted round, the gravity loads were resisted by tie-back cables to temporary foundations to the north. On completion of the rim, the temporary trusses were removed and the cables added and tensioned.

Cable tensioning

Tensioning the cables is a lot less straightforward than it might seem. Even though they all have the same nominal pre-tension, in practice each carries a different load at any given time. Tension in the cables was also used to true the wheel, straightening out some of the fabrication tolerances to hit the extremely demanding ±30mm (1.2in) in any direction.

Having a rim that runs straight and true helps to minimise the gap that passengers must step across at the platforms, and allows the drive system to accurately track along the wheel. The cable tension was specified with a ±10% tolerance to allow for this truing. AB initially set the cable tensions based on length, tightening each clevis by a defined amount from a known slack position (Fig 47).

Once all the cables were set and the wheel trimmed, the final tensions had to be confirmed. This was all done at the six o'clock position, for consistency and ease of access. AB's method for determining the cable tension involved placing accelerometers on the cable, and then "plucking" it like a giant guitar string — done by one person shaking the cable by hand —and measuring the frequency.



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46. American Bridge workers lifting a cable to the hub.

47. The cables were tensioned with hydraulic jacks, and then the clevises rotated by hand.

Progressing the cabins

Detailed design and development

The LPOA design–build contract progressed with several changes to the reference design to accommodate specific requirements. The main proposal was to use a conventional roller slewing bearing solution for the single mounting ring. Arup's reference design had avoided this because of the long lead times to procure large-diameter bearings and the stringent deflection criteria this type of bearing needs for support housings. LPOA proposed a bearing sourced from China, and further analysis by LPOA demonstrated the bearing raceway deflections could be accommodated in the bearing support structure.

The design was also complicated by the cabins' large external diameter and transportation issues. Arup's reference scheme was to transport the cabin halves and assemble them in a clean facility on (or very close to) the site. Introducing the smaller slewing bearing made this more difficult, but the issue was resolved by LPOA moving the whole assembly activity to Las Vegas, foregoing its initial plan to manufacture and assemble at its home base in Grand Junction, Colorado, and transport completed cabin halves to Las Vegas by road.

Another change from the reference design was in the HVAC system. The detailed design changed this to two self-contained units that could be easily removed for maintenance. This came at the expense of additional weight and less effective filter systems, but overall provided a much easier-to-maintain design solution.

The design of the V-frames connecting cabins to wheel rim also varied slightly from the reference design. These were developed to include the power and control signal conduits running inside the welded box section with the electrical connections accessible via waterproof access panels on the inside faces of the V-frames.

Prototype testing

The performance specification required prototype tests to be undertaken prior to starting production of the 28 cabins, and this was done in two phases during the early spring and summer of 2013.
The construction of the prototype cabins was used to determine assembly procedures and develop the assembly fixtures that would be used for the cabins assembled in Las Vegas.
The full range of development and acceptance tests for the stability systems and doors included rollover tests and detailed testing of the control systems for compliance with performance specifications, as well as the formal failure modes and effects analysis design approach used for the project (Fig 48).

Cabin and V-frame production

Following completion of the prototype tests, cabin assembly began at the Las Vegas location leased by LPOA, a large industrial unit that provided a secure, clean facility. It was also relatively close to the site (although transportation changed to a longer, more circuitous route to reduce difficulties). During this time additional testing of the HVAC units, waterproofing tests and several pre-determined factory acceptance tests on the bearings and control systems were completed at the facility (Fig 49).
The V-frames were subcontracted by LPOA to a fabricator in Kingman, Arizona, and these were delivered directly to site.


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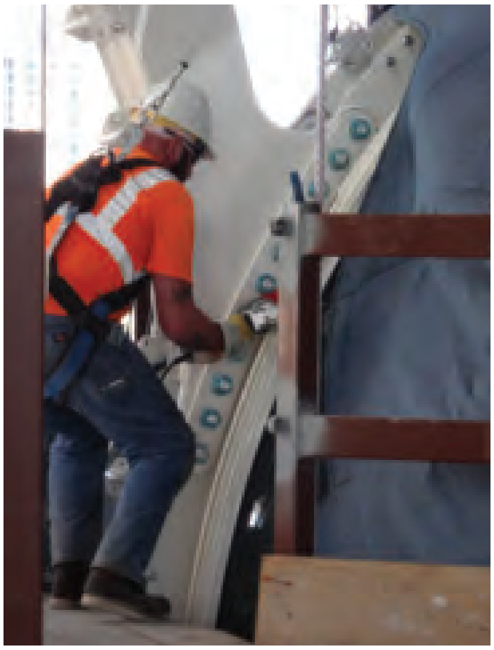
Cabin installation

The V-frames and cabins were installed in November and December 2013, attached in batches at an initial rate of one per day (Fig 50). First, the V-frames were attached to the wheel rim in a platform fixture moved into position under the rim, and then lifted using chain falls attached to the hub (the same as used to install the rim segments). Then the cabins were loaded onto the V-frames using a different set of temporary platforms rolled in to surround the cabins. This system proved much faster than originally planned, and the rates achieved for other large wheels.

Commissioning

The cabins were commissioned during January and February 2014, following operational readiness tests to verify the integrated ride control system (IRCS).
This brought together inputs from all 28 cabin control systems with the main drive for the wheel into a single integrated system in the control room. During this time the licensing permit was obtained from Clark County. This required a full set of submissions to the local authority for review, including 25 000 O&M manual pages.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48. Cabin prototype testing.
49. Cabin assembly, Las Vegas.
50. V-frame installation.
51. Uninterrupted views of
Las Vegas and beyond (overleaf).

“Vegas demands audacity and over-the-top. The *High Roller* is so much more elegant and beautiful than any other wheel. The creative intent was to have it appear to be lightweight, without a lot of structure...

The team is the most important thing. We needed people who were not intimidated by the large scale, not afraid of being part of something special that everyone is going to recognise.”

Greg Miller, Senior Vice President of development for Caesars Entertainment.

“It’s rare to be part of something this great.
At the same time it can be extraordinarily challenging.”

David Codiga, Executive Project Director.

“What could be more thrilling for an ‘experience designer’ than to design something that, perhaps from the moment it opens, will be an icon on the Las Vegas Strip, and a permanent fixture on one of the most famous skylines in the world? That’s a designer’s dream... One of the truly beautiful things about the *High Roller* is that spherical, pearl-shaped cabin on the outside of a tubular ring.”

Phil Hettema, THG.

“As a long-time resident of Las Vegas I could not be more proud of this project. The architecture team worked very closely with the engineers from Arup, and to see our vision come to life in such a gorgeous way is incredibly exciting. From the entry point, through to the interior design of the cabins, each and every detail has been beautifully realised.”

John Kasperowicz, THG.

“Even from afar, the *High Roller* is a delight, adding a playful ring of color to the Vegas skyline.”

Jorge Labrador, writing in the “Spotlight” section of *Las Vegas magazine*.

Conclusion

At an event hosted by Caesars Entertainment in the wheel building a couple of weeks after the opening on 31 March, 2014, an adjudicator from Guinness World Records officially announced that the *High Roller* is the world's largest observation wheel, and presented Caesars with the certificate.

Though its size is notable, the *High Roller*'s true value lies in its significance for Las Vegas and what it may represent for the future. Caesars' LINQ development has converted an under-used alley into a pleasant, pedestrian-friendly street of al fresco dining and artisan shops, with the *High Roller* towering at its end. Such a graceful attraction — clean, crisp, lit to delight, and arcing effortlessly over the city — is in marked contrast to the themed hotels and flashy cocktail bars elsewhere.

To enjoy their 30 minutes of encapsulated wonder, passengers are ushered into the discreetly air-conditioned cabins, quite comfortable despite the open doors on both sides for disembarkation and boarding.

Such a level of comfort was not easily achieved. The glazing is doubly curved, double laminated for strength, and double glazed for thermal comfort. Cool air from the HVAC equipment tucked away in the belly flows up through ducts and cascades down the inside of the glass, which would otherwise be too hot to touch. The coating on the glazing was selected for its near-perfect balance of optical qualities, sun protection, glare reduction, and minimal reflections at night.

As the cabin glides up, the ride feels smooth and stable, a testament to the damping system that reduces wind-induced vibrations, and the precisely controlled drive system. This feeling of security is no illusion; the drive system has 100% redundancy, as well as a completely independent backup system. In fact, the FMEA all but guarantees that the wheel will keep turning no matter what, but… if it cannot be rotated for some reason, Clark County Heavy Rescue will put its evacuation plan into action.

At the top, uninterrupted views stretch in every direction: the Eiffel Tower and Bellagio fountains; the glittering lights of the Strip; the vastness of the desert, and magnificent mountains east and west. A few other cabins and faint shadows of passengers behind the tinted glass can be seen, but the structure almost vanishes, thanks to Arup's unique structural system. The cabin extends far beyond the single tube rim, unobtrusive in its slenderness, and being held by just one bearing maximises the amount of viewing space and the feeling of lightness.

At the end of the journey the cabin lines up to the dauntingly narrow tunnel into the boarding platforms. The cabin in front squeezes precisely through with a hand's-width clearance on each side, yours follows, the doors open, and you disembark…

Even before it opened, Las Vegas was abuzz with chatter about the *High Roller*. Taxi drivers, concierges, bar tenders and guests could see it as a testament to a great city rising, excited for what it represents. Now, with the wheel already an iconic element on the Vegas skyline, reviews have been resoundingly positive. For locals, it signifies a revitalisation and a bright new future. For visitors, it is a fresh take on the uniquely Vegas experience.

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Project credits

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Image credits

1, 11, 13, 36–37, 41–42, 44 *Nicholas Christie*; 2 *Hettema Group*; 3, 5, 8, 16 *Brandon Sullivan*; 4 *Thomas Graham*; 6, 17 *Stephen Corney*; 7 *Hugo Mulder*; 9 *Courtesy, Caesars Entertainment*; 10, 14–15, 23–24, 29–30, 35, 40, 47 *Jason Krolicki*; 12 *Matt Reid*; 18 *Nigel Whale*; 19–20, 26, 31, 51 *Mary Ferguson*; 21 *Shaun Landman*; 22 *CPP (www.cppwind.com)*; 25, 28, 32, 38, 43, 49 *Adrian Crowther*; 27 *Elizabeth de Kleer*; 33a, 34, 48, 50 *John Lyle*; 33b *Flickr, Henry Allen*; 39, 45 *Denise Truscello*; 46 *American Bridge Co.*

Enabling renewable energy projects

Location
South Africa

Authors
Nic Bailey Auret Basson Andrew Bowden Paul Cosgrove Pedro Reis Neto
Vivienne Roberts Richard Stanford Thinus Van As Justin Wimbush

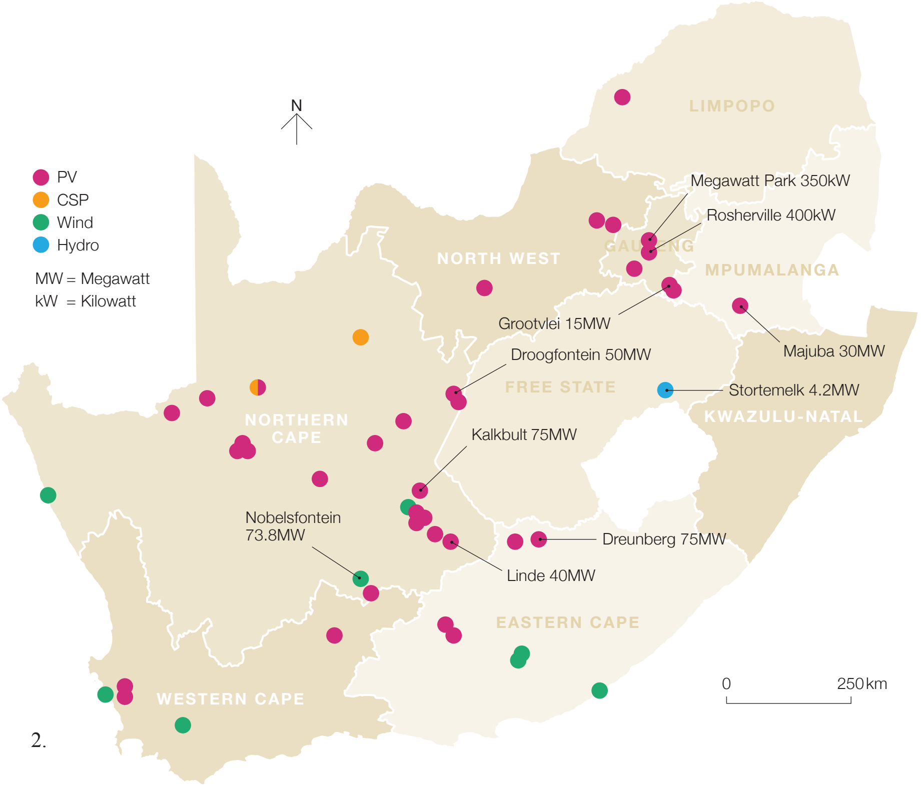
1.

Introduction and context

Although South Africa has extremely good wind and solar resources, as of 2010 more than 90% of the country's electricity was generated by coal[1]. Before 2008 it could supply the lowest electricity prices in the world (at R0.25/kWh[1], then equal to $0.0275/kWh), but in that year an energy supply shortfall was experienced, with demand exceeding supply. This resulted in load shedding (forced power cuts), which prompted Eskom, the government-owned electricity utility, to embark on a new energy expansion plan. This involved returning to service some mothballed coal plants, creating new coal-fired capacity at Medupi and Kusile in Limpopo and Mpumalanga provinces respectively, and the Ingula pumped storage hydroelectric scheme in the Little Drakensberg range.

In addition, the Department of Energy (DoE) initiated its Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). This obligated Eskom as system operator as well as the dominant utility to enter into Power Purchase Agreements (PPAs) with Independent Power Producers (IPPs). This programme was mainly as a result of the government's ongoing Integrated Resource Plan (IRP), first promulgated in March 2011[2] to forecast the country's energy demand up to 2030 and determine the planned mix of generation technologies to meet it, as determined through a least-cost optimisation and public consultation process.

Importantly, the IRP allows for 18.7GW of renewables to be installed and integrated into the power system by 2030. Within the new mix, the DoE committed to procure energy from 8400MW of solar photovoltaics (PV), 8400MW of wind, and 1000MW from concentrated solar power (CSP) through the REIPPPP — effectively 21% of generating capacity from wind and solar by 2030.



2.

Prior to the IRP, SA's renewable energy policy was mostly driven by a target of 10 000GWh by 2013, and subsidies offered through the Renewable Energy Finance and Subsidy Office and the 2009 Renewable Energy Feed In Tariff programme[1]. This was not particularly successful, with few renewable energy projects being undertaken until a structured energy plan under the IRP was provided; the REIPPPP involves rounds of competitive bidding, with preferred bidders entering into a 20-year PPA with Eskom, and an implementation agreement with the DoE.

While solar PV and CSP both use the sun's energy to generate power, they are vastly different. PV modules convert radiation from the sun directly into electricity via semiconductors and the photovoltaic effect (the creation of voltage or electric current in a material on exposure to light). CSP on the other hand, uses mirrors to focus the sun's energy onto a concentrated point, similar to a magnifying glass, and uses the concentrated power of the sun to heat a working fluid, which in turn creates steam to turn a turbine.

The initial bid windows of the REIPPPP are set to procure some 3725MW of renewable energy capacity by 2016, with projects ranging from 5MW–140MW. Round 1 of REIPPPP commenced in August 2011, and the projects chosen in that round are now in operation. The latest bids were submitted in Round 4, in August 2014.

Enabling roles

As a consequence, all this has given Arup South Africa a wide range of opportunities to assist in developing renewable energy projects, and not just in the Republic itself (Fig 2) but elsewhere in Southern Africa, as renewable energy industries across this whole area of the continent have developed.

Many developers have sufficient in-house technical skills to take their projects to the stage where a bank will provide finance, but those without such skills rely on consultants such as Arup to help them select project sites, develop the designs to detailed concept level sufficient to tender, and bring on board an EPC (engineer/procure/construct) partner. Additionally, many large-scale infrastructure projects are developed using project finance, and can be seen as more risky than equity investors are comfortable with. To give project financiers comfort on the level of risk, Lenders' Technical Advisors (LTAs) are employed to do due diligence assessments.

Once a project has been selected by the government and awarded "preferred bidder status", the various contracts must be finalised. While the PPA itself has been standardised under the procurement process, the EPC, O&M (operation and maintenance) and financial contracts still have to be negotiated, and all require inputs from the engineering teams.

Once construction starts, three or more separate consulting engineering teams may be involved, including:

- the Owner's Engineer (OE), responsible for ensuring that the EPC contractor provides a facility that meets the EPC contract requirements;
- the LTA, whose primary role is to check that the project is proceeding according to programme and costs;
- the Independent Engineer (IE), whose duty of care is to both the buyer and the seller (the generation facility owner), and who has final say on the eventual generation capacity achieved by the developer; and
- a consultant who may be brought on board in an EPC management role when the project is procured on a split contract basis.

Arup South Africa's renewable energy team is now involved in OE, LTA and IE roles for a range of clients on solar PV and CSP, wind and hydro projects, ranging in capacity from 5MW–120MW.

Projects undertaken by the team totalling over 750MW capacity have reached preferred bidder status, and are now either working towards financial close, or construction and commissioning. If due diligence work is included, this total rises to more than 1800MW, equal for example to that of the Western Cape's Koeberg nuclear power station. As the OE, Arup has been involved in 130MW capacity of projects; as the IE in 450MW; and as the LTA, no less than 2130MW.

1. The 50MW Droogfontein solar PV array in the Northern Cape, where Arup is acting as Independent Engineer (see p35).

2. Some of the many South African renewable energy projects for which Arup is providing assistance.

Handling risk

Much of Arup's work involves handling and mitigating risk for the various parties involved. Risks occur at every stage of the project life cycle — from those associated with site selection to facility design, getting financing, construction, and then operating the facility.

The Owner's Engineer...

... monitors the performance of the EPC contractor, reviews the proposed designs, and checks that the works are in accordance with the contract. If the developer has an in-house technical team, it may perform this role, but if not it may be outsourced to consultancies like Arup; if the EPC contractor is competent, this role can be kept quite small. Ideally the OE is brought onto the project early, and helps draft the EPC contract to ensure that it has the tools needed to best facilitate the construction.

The Independent Engineer...

... has a duty of care to the Single Buyer's Office which, under the legislation governing the REIPPPP, is bound to purchase the electricity generated by each IPP. The IE independently certifies that the facility has been commissioned according to the relevant contracts, codes and consents, and also certifies that the equipment used to monitor the resource has been calibrated and installed in the correct location.

For much of the construction period the IE scope is quite light, limited to providing progress reports based on information provided to the IE and on-site visits. Once the project is complete, however, the IE has the highly important role of determining what the project's "achieved capacity" is. This is very important, as "achieved capacity" is the maximum the project can generate over its lifetime (20 years). If a project generates more power in any given hour as a result of exceeding the achieved capacity, then the project owner will not be reimbursed for the additional power.

The Lender's Technical Advisor...

... assesses the project, prior to finance being agreed and before detail design, to ensure that it is sufficiently robust for banks to lend the necessary finance and be sure of getting their returns. Once construction starts the LTA is required to ensure that any funds claimed are justified, given the project's progress, and to check monthly that its eventual cost will not exceed the funds available. The LTA has to assess any required project changes or variations and check that the costs are justified and affordable.

Once the project has been constructed, commissioned, and to a large extent de-risked, or even if it is only nearing completion, the financial investment industry starts to take note. A role then becomes available for engineering consultants to undertake due diligence assessments for potential equity investors. The focus of the due diligence now moves slightly, to assessing the quality of the construction and the interfaces remaining on the construction and O&M contracts.

Notable projects

Nobelsfontein Wind (operational)

This 73.8MW wind energy facility is currently being developed near the border between the Western and Northern Cape by a consortium of Gestamp Wind, SARGE and Shanduka. It comprises 41 Vestas V100 turbines, each of 1.8MW capacity, with hub heights of 90m and 50m blade lengths (Fig 3). Arup is the LTA to a consortium of South African lenders, and has provided technical advisory services up to financial close and during the 18-month construction stage. The project began commercial operation in July 2014, with Arup also appointed to monitor operations during the first years of operation.

Prior to financial close, Arup's responsibility as LTA was to identify and mitigate project risks from the lenders' perspective, relevant to permitting, capital and operational cost, construction programme, and operational performance. Working closely with the lenders' legal advisors, the firm helped the lenders understand, mitigate, and remove such risks by testing the appropriate financial model assumptions, and negotiating appropriate construction and O&M contract provisions with the owner (borrower) and respective contractors.

In contrast to current international precedent, the construction contracts for REIPPPP Round 1 projects were required by lenders to adopt a "fully-wrapped", turnkey EPC contract model. This requires the EPC contractor to deliver the complete scope of the works for a fixed price and programme, assuming liability for any excess cost and with damages payable for any time over-run. Furthermore, this model holds the EPC contractor liable for an operational performance guarantee, which has damages payable proportional to the total EPC price.

This type of contract was unfamiliar, and Arup provided significant input into the drafting in the interests of the lenders and owners. In particular, much effort was required to define the scope of work, technical performance specifications, design review conditions, testing criteria, performance requirements, and associated penalties. Notably, in view of the design complexity and increasing emerging operational issues associated with wind turbine foundations as turbines have increased in capacity, an international best practice performance and design review specification was defined by an expert Arup team in the UK for this aspect of the works, so as to reduce the associated risks.

During construction Arup worked with its wind energy partner for South Africa, ESB International, with responsibilities including monitoring progress and suitability of the works against programme and the EPC contract, assessing and certifying loan disbursement requests associated with construction progress, and evaluating project costs against the budget. Arup and ESB International's combined local and international experience, working with the owner and the OE, enabled various construction stage risks to be identified and mitigated.

Kalkbult, Linde and Dreunberg PV projects (undergoing commissioning)

The 75MW Kalkbult solar PV facility in the Northern Cape, developed by Scatec Solar, consists of over 300 000 PV modules and is estimated to produce 135GWh of electricity annually (Fig 4). Arup was involved as LTA from the pre-bid due diligence through construction and will continue to advise during operation. In September 2013 Kalkbult connected to the national grid and began to sell electricity — the first utility-scale PV facility to connect to the grid in South Africa.

3.

Arup is also currently providing LTA services to Scatec Solar for its subsequent projects, Linde (Northern Cape) and Dreunberg (Eastern Cape), both of which are under construction.

These use single axis tracking systems to maximise energy yield by regularly changing the angle of the modules to track the sun's position. Tracking comes at an additional upfront cost and introduces additional risks regarding operational requirements.

It is therefore critical that the systems are robust, suitable for the site terrain, and easily maintainable. Prior to financial close, Arup conducted factory visits to the preferred manufacturers to better understand the designs and their specific challenges.

Eskom PV portfolio (early planning stage, under construction and operation)

In 2012, Eskom decided to introduce solar PV facilities at its power stations, offices and substations around South Africa, and in July 2012, appointed Arup as the OE to provide technical input and general project management for the rollout of this portfolio, which has a combined installed capacity of 150MW. This included:

- the site selection for power stations, offices and substations
- conceptual and basic designs for the preferred sites
- development of technical specifications and contractor procurement documentation
- the technical evaluation and selection of contractors
- monitoring of construction and commissioning.

Eskom has comprehensive in-house knowledge of electricity generation and distribution, with associated codes and standards, but this is all tailored towards large-scale coal-fired power stations.

Through its OE role, Arup helped the client adapt its internal processes to accommodate procuring and installing smaller solar PV generation facilities, while still maintaining the quality for which Eskom strives in its electricity infrastructure.

Aside from Arup's overall input to the portfolio, Table 1 shows other individual projects on which the firm has worked.

4.

Table 1. Eskom PV portfolio

Project	Technology	Capacity (MW)	Status
Megawatt Park	Rooftop PV (Fig 5)	0.35	Operational
Rosherville	Ground-mounted PV (multiconfiguration)	0.4	Under construction
Grootvlei	Ground-mounted PV	15	Concept phase
Majuba	Ground-mounted PV	>30	Concept phase
Five transmission substations	Rooftop PV	0.2	Concept phase

5.

6.

Stortemelk hydro project (early construction phase)

This 4.2MW run-of-the-river hydro project is to be constructed at the existing Botterkloof Dam near Clarens in the Free State (Fig 7). The dam is directly downstream of the Lesotho Highlands Water Project outlet into the Ash River from where water is transferred to the Gauteng province.

Arup was appointed by NuPlanet Clean Energy (the project developer) and Rand Merchant Bank (the lender) as LTA in this project. It has an EPC management contract structure and a civil and installation contractor will be responsible for all construction works under supervision of the EPCM contractor. Financial close was achieved in mid-2014, with construction scheduled to be completed in 2016.

As part of its LTA assignment, Arup undertook a technical review of the project including the proposed equipment and projected yield analysis. The EPCM contract structure, though normal for such a project, presents a slightly increased scope of work for the LTA due to the increased and unique set of risks.

As such it requires more co-operation between the lender's technical, legal and insurance advisors to ensure that all risks that could not be addressed technically or through drafting of the contracts are sufficiently allowed for in the project insurance policies.

Risks identified during Arup's technical review were therefore discussed further with the relevant project stakeholders to identify risk mitigation measures where possible. In conjunction, Arup reviewed the construction contracts with the project's legal advisor to ensure that all foreseeable technical risks were addressed in the contract documentation.

Feasibility study for solar park

In August 2013 Arup was appointed to undertake a feasibility study for a 1GW solar facility that would make use of several different solar technologies, both PV- and CSP-based.

In particular, Arup's scope comprised an assessment of the technical, socioeconomic and financial feasibility of establishing this facility for both PV- and CSP-based technologies (Fig 8). This study included stakeholder engagement, consideration of appropriate procurement and governance models, and completion of a risk assessment to inform the next development stage.

7.

Considering the spatial constraints and specific objectives of the site, various scenarios were explored for different mix options of CSP and PV. Two were weighted toward CSP with energy storage, as one of the objectives of the facility is to supply mid-merit and peak power to the grid (in which the plant adjusts its output as demand fluctuates, so that power continues to be supplied reliably during periods of high demand).

In South Africa, this can generally only be achieved by solar technologies with energy storage, because peak demand usually occurs between 5pm and 9pm, once the sun has gone down.

Along with modelling these solar technologies, the study also included assessing the procurement and governance models that could be used for the solar facility, which were informed by the stakeholder engagement process outputs and assessment of relevant best industry practices. Additionally Arup undertook a potential rollout and execution plan, risk assessment, and cost and financial analysis.

The team's multidisciplinary approach to the study meant that the project's technical merit as well as the commercial and socioeconomic implications for the local economy could be efficiently assessed. The wide variety of factors included in the scope resulted in a unique set of risks, particularly in managing expectations and co-operation between the many parties involved. As a result of Arup's local South African presence, the team was able to add a detailed understanding of the local technical, commercial and legislative context to the project.

Droogfontein PV (commercial operation commenced April 2014)

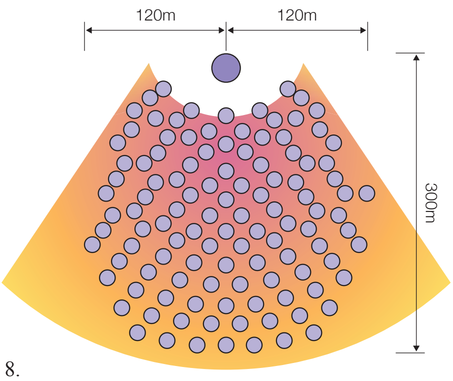
This 50MW fixed-tilt PV plant (Figs 1, 6) is located just north of Kimberly in the Northern Cape. Comprising 170 000 polycrystalline PV modules, 19 inverters and a 22kV/132kV step-up facility, the project is being developed by the SA branch of Mainstream Renewable Power Ltd, in conjunction with Globeleq, with Siemens South Africa as the main EPC contractor. Arup was appointed jointly by Eskom Holdings and Droogfontein Solar Power (the project company) for the IE role, as required in the PPA.

As part of the process, the Arup team works to get all party agreement on the methodology employed so as to reduce the risk of disputes arising from the final calculation of the facility's capacity.

Despite the limited scope and modest commissions, the Arup renewables team has chosen to pursue these projects as they provide important client exposure and project experience and hence are important in enabling the team to win future, more extensive, renewable energy commissions.

Conclusions

As several of the renewable energy projects with which Arup has been involved have come to completion, several key risks have been identified and lessons learned.
It became clear that reviews of contractors need to be done with great care, as several with proven experience in Europe and elsewhere had difficulties with delivering the level of quality required in South Africa. The same goes for international suppliers — the actual manufacturing is done locally and thus it is important that the same quality measures are put in place and priced for.



8.

Also, EPC contracts come with a cost premium but have not always provided the quality of project that lenders and borrowers have anticipated. In some cases, particularly on wind projects, EPCM contracts will provide developers with greater development transparency and hence control, and possibly cost savings.

Regarding specific technologies, as PV costs and project tariffs are both dropping, PV suppliers need to be carefully reviewed to ensure as far as possible that the quality of panels supplied meets the quality standards in the project financial assumptions.
Finally, as local standards of grid compliance are strictly enforced, this can cause delays in reaching commercial operation. As a result, careful monitoring of the programme and liaising with the utility (Eskom) is critical in meeting the schedule date of operation.

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2) www.energy.gov.za/files/irp_frame.html

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Vivienne Roberts is a project manager in Cape Town, and is currently co-ordinating Arup's OE service for a major PV project.

Richard Stanford is a mechanical engineer in Johannesburg, and has recently provided project management and technical support for Eskom's Megawatt Park rooftop PV installation.

Thinus Van As is a senior electrical engineer in Cape Town, and is the electrical lead on several PV projects.

Justin Wimbush is an Associate in Cape Town; he is the Arup South Africa Renewable Energy business leader.

Project credits
Nobelsfontein wind farm
Client: *Sarge Ltd*
Lender's Technical Advisor: *Arup*

Kalkbult, Linde and Dreunberg photovoltaics projects
Client: *Scatec Solar Pty Ltd*
Lender's Technical Advisor: *Arup*

Project controls expertise and mentoring for Eskom photovoltaic portfolio
Client: *Eskom Holdings Ltd*
Owner's Engineer: *Arup*

Stortemelk hydro project, Botterkloof
Client: *NuPlanet Clean Energy Ltd*
Lender's Technical Advisor: *Arup*

Feasibility study for solar park
Client: *Confidential*
Feasibility consultant: *Arup*

Droogfontein PV, Northern Cape
Clients: *Eskom Holdings* and *Droogfontein Solar Power*
Independent Engineer: *Arup*.

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Image credits
1, 6 *Droogfontein Solar Power*; 2, 8 *Arup/Nigel Whale*; 3 *Andrew Bowden*; 5 *Richard Stanford*; 4 *Justin Wimbush*; 7 *James Hampton.*

King Abdulaziz International Airport:

the structural design and fire engineering for Package 421

Location
Jeddah, Kingdom of Saudi Arabia

Authors
Matt Clark Joseph Collins Patricio Garcia Patrick McCafferty Cliff McMillan
David Scott Tabitha Tavolaro Jeff Tubbs Peter Tillson Chelsea Zdawczyk

1.

Introduction
King Abdulaziz International Airport (KAIA) in Jeddah, Saudi Arabia, opened in 1981. Famously, the 1981 airport included the tentlike Hajj Terminal, built specifically to accommodate the tremendous influx of pilgrims to the annual Hajj in Mecca.

Despite this, however, other facilities at KAIA became increasingly strained by the rapid growth in commercial and tourist passenger numbers consequent on Saudi Arabia's continued prosperity, and 2006 saw the start of a comprehensive redevelopment programme, including a new terminal. Arup's experience, innovation and skills contributed to solving the structural engineering design challenges of the new 670 000m^2 international passenger terminal building (PTB), designed to handle over 30M passengers per year.

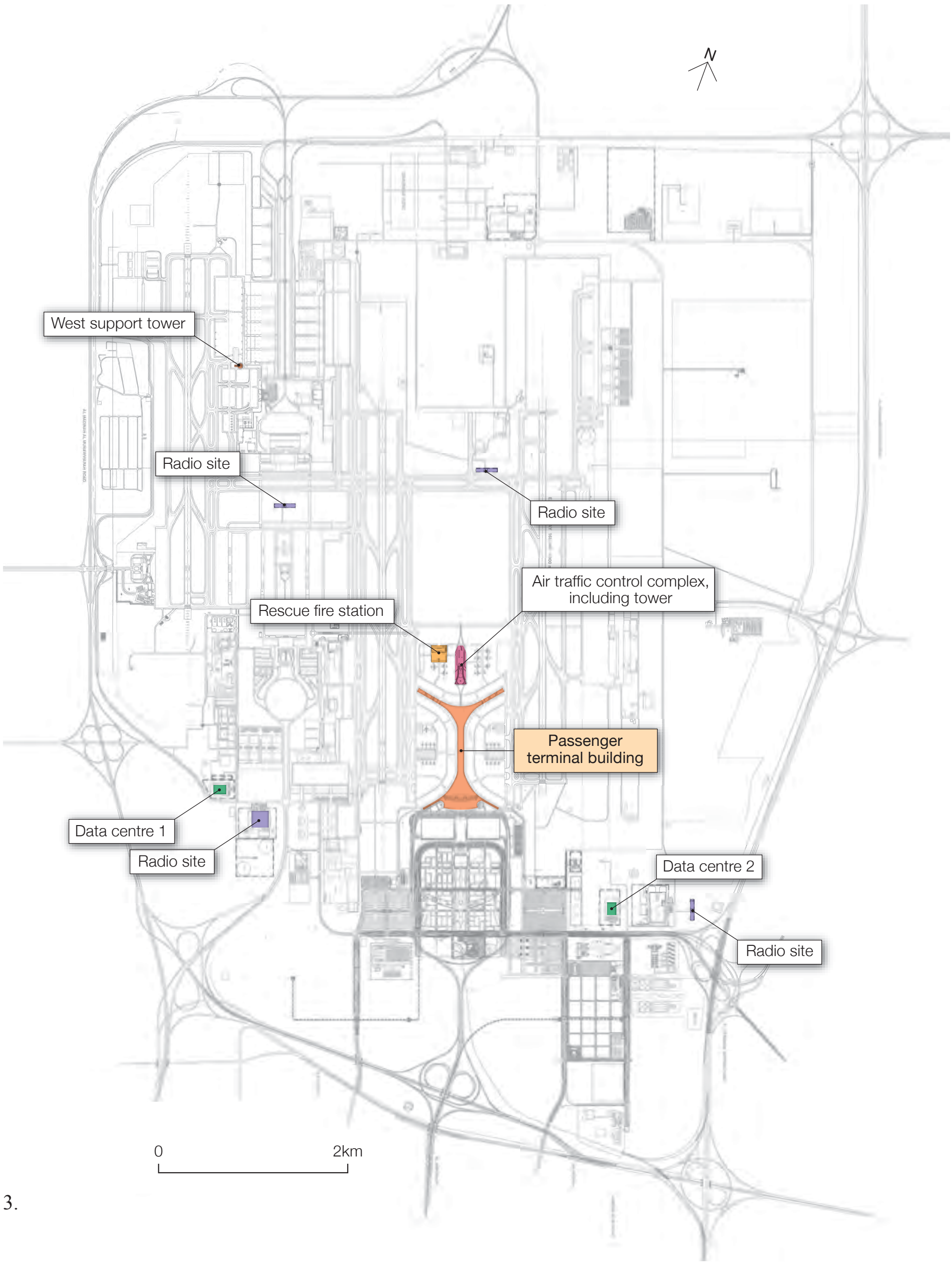
The 1.4km long facility (Fig 1) will house 46 Domestic and International departure gates, 94 boarding bridges, Processor Hall, International departures Hub, internal automated people mover (APM), the world's tallest air traffic control tower, and over 60km of baggage handling belts (Fig 2).

1. Original rendering of the project.

2. Rendering of baggage reclaim area at the Processor Hall (Zone A).

3. Site plan with the elements of Package 421.

2.



3.

Background

The owner, the General Authority of Civil Aviation of Saudi Arabia (GACA), originally let the project with a design team led by French airport designer Aéroports de Paris Ingénierie. At the end of the schematic design stage, however, GACA instituted a design–build bid and issued these schematic design drawings as tender documents for two new Packages, 421 and 422.

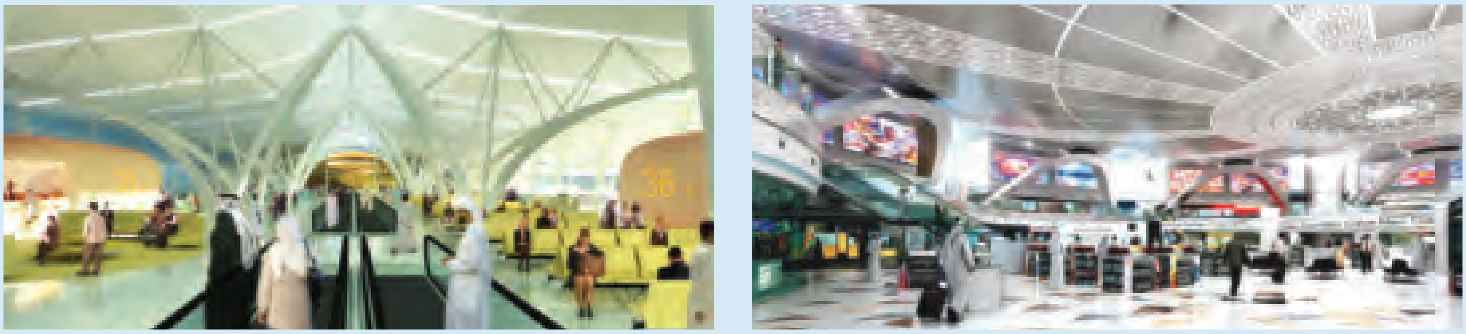
Package 421 comprised the main PTB and several ancillary buildings including the air traffic control tower, while package 422 consisted of the airside and landside civil components, plus several landside buildings including a mosque, transit centre, and elevated roadway (Fig 3).

The construction-winning company, Saudi Binladin Group (SBG), hired Arup to carry out the structural design for Package 421, as the project's structural engineer. For all the remaining design work on both Packages 421 and 422, Atkins was appointed as lead design consultant.

The design–build team was contracted to complete the project in 36 months, which required Arup to complete the structural design in 120 days from contract award on the understanding that the inherited schematic design was fully co-ordinated and sufficient basis from which to work. Final design for all other disciplines was to continue to the 300-day mark.

a) Exterior of Processor Hall (Zone A)

b) East and West Domestic Concourse Piers (Zones B+C)



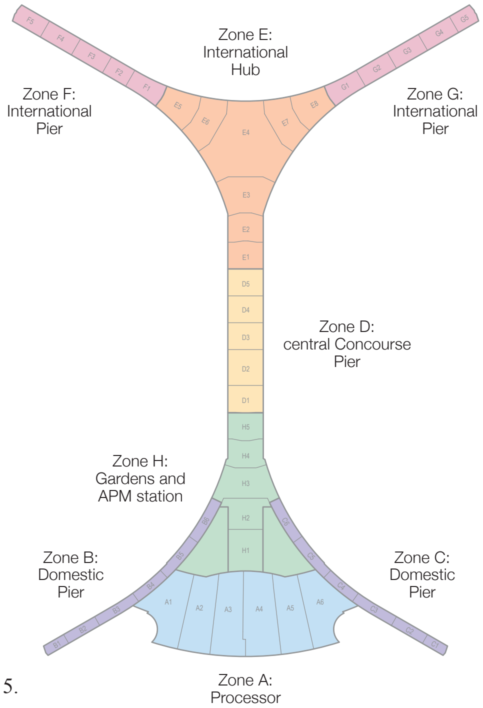
c) Central Concourse Pier (Zone D)

d) International Hub (Zone E)

e) East and West International Concourse Piers (Zones F+G)

f) APM station (Zone H).

4.



5.

Arup design management

Overall planning

To best handle the project, Arup divided the PTB itself into eight zones (Figs 4–5):

- Processor Hall (A)
- east and west Domestic Concourse Piers (B+C)
- central Concourse Pier (D)
- International Hub (E)
- east and west International Concourse Piers (F+G), and
- Garden and APM station (H).

In addition, there were several ancillary buildings including the air traffic control tower, west support tower, data centres and associated facilities and support structures, all of which were designated an additional zone.

The scale, diversity, and aggressive design schedule meant that no single Arup office could undertake all the work within the timeframe, so it was decided to divide the work between the New York/New Jersey, Boston, Chicago, San Francisco, Toronto, Madrid, Belgrade and Dubai offices (Fig 6).

The work was allocated in a rational breakdown that enabled each portion to be as self-contained as possible and wholly managed by individual design teams. The size, distinctness, and physical separation of the buildings and their segments allowed the scope to be clearly divided, with standard methods of production, project delivery, and document control instituted to ensure consistency.

The key to the success of this approach was:

a) a very clear work breakdown

b) dedicated leadership in the various offices by experienced engineers

c) clear protocols, design standards and approaches that were understood by all

d) a common BIM (building information management) platform

e) regular communication and weekly co-ordination calls.

Design team leaders in each office co-ordinated directly with their design lead counterparts in Atkins and the other consultants. Arup New York retained overall management and administration, but the individual teams were responsible for advancing the work, agreeing interim deadlines, and delivering their portion of the design.

Weekly design leader teleconferences ensured that design consistency was maintained across all offices, and provided a forum for raising issues to be brought to Atkins and SBG. The design leaders also joined separate weekly external teleconferences with Atkins to work through common co-ordination and scheduling items, allowing the engineering teams to focus on production.

Software decisions

Co-ordinating many teams across multiple time zones required significant planning to define working methods, common software platforms, design assumptions, and drawing standards; design notes developed during the first month established many of these parameters. After discussion of the merits of various software packages, the team concluded that lateral analysis of the concrete structures would be by *ETABS*, while the gravity analyses would use *SAFE* for the geometrically regular ancillary buildings and *RAM Concept* for the more complex PTB. Individual structural steel components were analysed with a combination of Oasys *GSA* and *LS-DYNA*, and the entire project was documented in 3-D using *Revit 2011*.

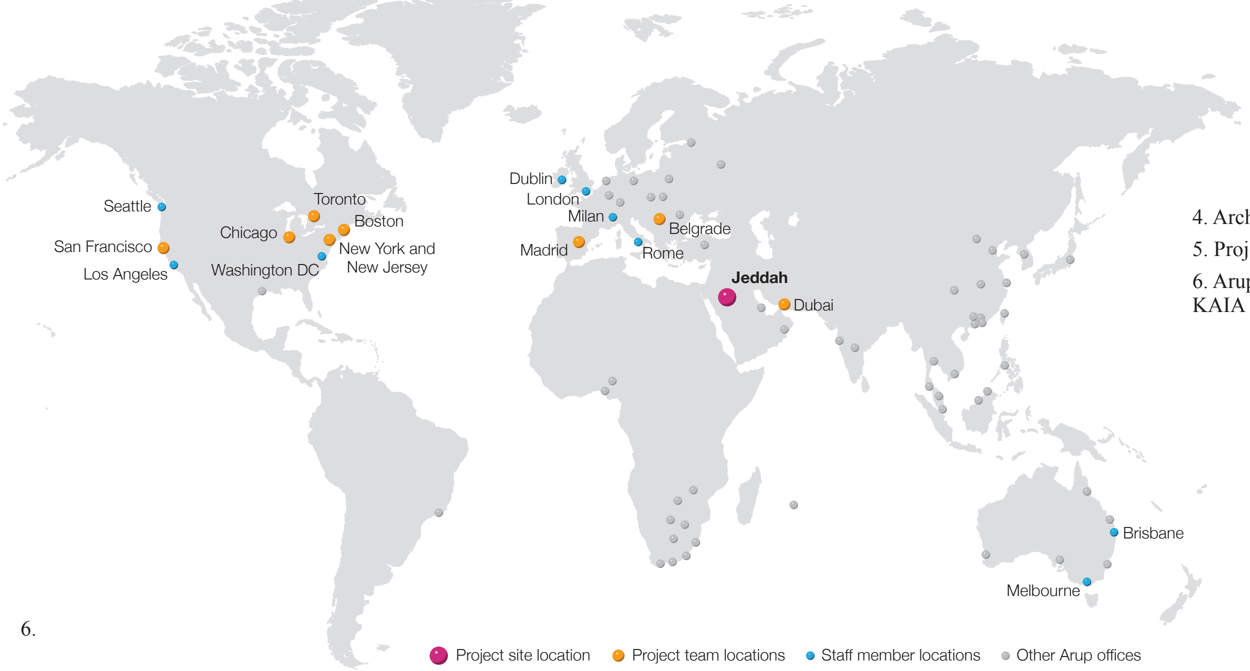
During the first two months of production, a sample submission was prepared for two 80m long PTB building segments. Including analysis models, calculation packages, and drawings to establish production standards across all teams, this sample submission was provided to SBG as representative of Arup's final deliverable.

The team recognised that obtaining timely approval from the Engineer/construction manager, Dar Al-Handasah (DAH), would be a key logistical hurdle, and therefore approached DAH halfway through the 120-day schedule with sample analysis and design calculations and drawing packages of representative segments of the PTB preliminary review.

The complete *Revit 2011* PTB model totalled 4.3GB and so, with vendor-recommended file sizes of <250MB, it had to be split up; as well as the division across the eight zones, the steel roofs were separated from the concrete podium by zone.

All 16 files were then linked for co-ordination and printing, and three dedicated *Revit* servers were located in New York, San Francisco, and Madrid to accommodate live synching across regions. This eliminated the need for copying files across offices, avoiding the risk of sharing or co-ordinating outdated versions of models among teams.

The 250MB file size limitation was feasible for all but the Processor Hall (zone A), where the concrete model was over 720MB and the corresponding roof model exceeded 825MB. As expected, these very large models proved challenging to manipulate during the latter stages of the construction documents phase, when dozens of modellers across the globe had to edit simultaneously.

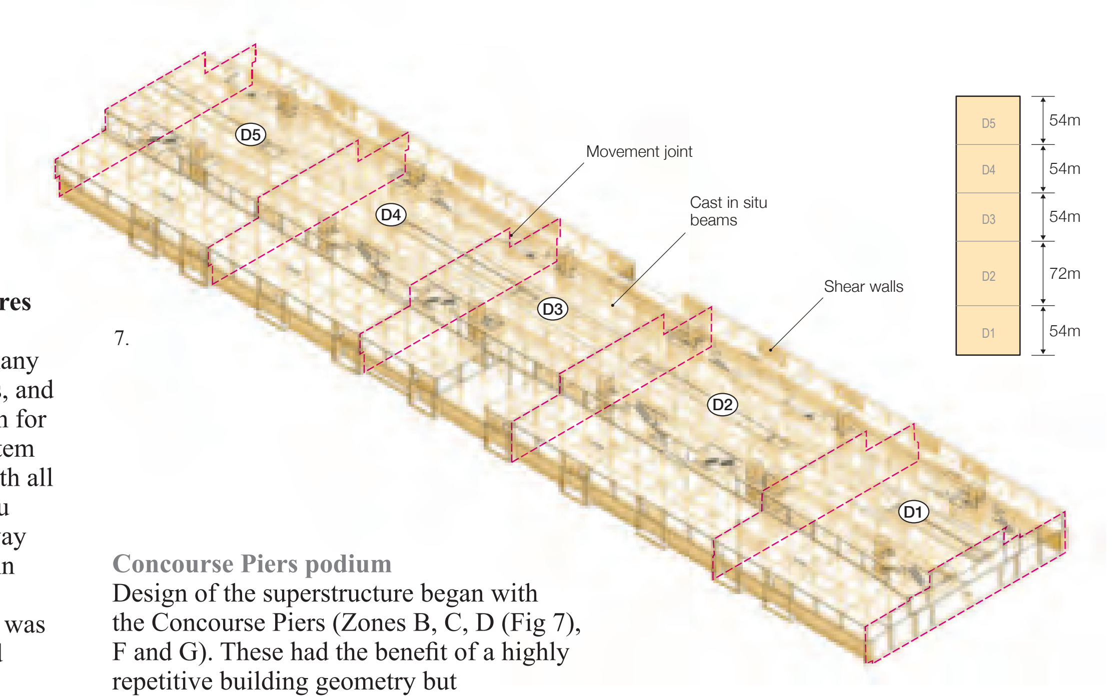


6.

4. Architectural renderings of zones.

5. Project zone demarcations.

6. Arup offices participating in the KAIA Package 421 structural design.



7.

Reinforced concrete podium structures

The design of the reinforced concrete (RC) podiums (Figs 7–9, 12) shared many similarities across the eight PTB zones, and Arup developed an integrated approach for all the teams to use. The structural system comprised RC shear walls laterally, with all but the Processor Hall using cast in situ beams on the column lines with two-way spanning slabs. Due to the large column spans in the Processor Hall (typically 13m x 18m), a one-way ribbed system was used instead, to control deflections and reduce concrete volume.

Because of the existing high water table and the possibility of future flood levels >2m above the highest water table, as determined by the geotechnical engineer, the PTB basement was designed as a jointless subgrade structure. With a 1.4km long subgrade and nearly 2km length of suspended ground level slab and mat slab, the basement was prone to significant thermal, creep, and shrinkage stresses.

Left unchecked, these could seriously jeopardise the facility's watertightness, and so the mat was cast with late pour strips at c60m spacing. These extended through the mat foundation below grade, up through the basement retaining walls, and through the ground level slab. The strips remained uncast until whichever was later: 90 days after placing the adjacent mat foundation and basement walls, or 45 days after placing the suspended ground level slabs.

With the nearby Red Sea's severe environmental conditions in mind, the concrete design strictly adhered to ACI (American Concrete Institute) guidelines[1] to ensure enhanced durability.

By controlling service level stresses in the reinforcing steel, combined with thermal and flexural considerations, and by providing a tanked waterproofing system continuously across the walls and underside of the mat foundation, Arup demonstrated that the basement would be well protected over the building's 100-year design life.

Concourse Piers podium

Design of the superstructure began with the Concourse Piers (Zones B, C, D (Fig 7), F and G). These had the benefit of a highly repetitive building geometry but correspondingly challenging unique wall layouts between the movement joints which, at 54m, 72m and 90m spacings, created a total of 27 independent segments within the Concourse Piers and 46 in all throughout the PTB.

Detailed multidisciplinary co-ordination during the project's first 60 days identified viable shear wall locations, appropriate for Jeddah's moderate seismicity, in each segment.

Column sizes and reinforcement percentages were likewise significantly reduced by introducing the stiff lateral system for the concrete structures. This minimised lateral and rotational movements, with the added benefit of smaller movement joints between building segments.

With the lateral system reconfigured, the gravity analyses were carried out using *RAM Concept* to evaluate the forces and long-term deflection behaviour of the floor framing and columns. Also, given the site's moderate seismicity, Arup could demonstrate through superimposing the lateral and gravity framing models that seismic load no longer governed the column or framing elements, enabling them to be of a yet more agile design.

The large temperature swings of Jeddah's coastal desert environment, from summer peaks of 45°C to winter minimums of 12°C, were another important factor.

The design criteria assumed a range of ±30°C for the roof and non-insulated spaces, ±20°C for insulated spaces not on grade, and ±15°C for foundations and basement walls in direct contact with the ground.

Simplified analyses showed the thermal effects to be up to three times as severe as any other lateral load case. This could severely impact the concrete shear wall design, so more advanced analysis was needed to show these demands to be overly conservative, and never actually experienced by the structure.

For example, rigid base conditions at the bottom of the shear walls were replaced with a fully modelled mat foundation to accurately represent its actual stiffness. Frictional soil stiffness was modelled as horizontal soil springs along the mat surface, with vertical soil springs introduced to more accurately represent the rotational restraint at the base of the core walls and linear shear walls.

Arup thus demonstrated the thermal demands to be equal to or less than those from the seismic system. This approach greatly increased the analysis effort, but demonstrated that in the cracked and partially restrained state, the structure satisfied code requirements.

International Hub podium

The International Hub (Zone E) podium design was similar (Fig 8). RC shear walls supply lateral resistance, and the floor framing is typically two-way flat slabs between beams on the column lines. Seven of its segments resembled those of the Concourse Piers, but the central eighth segment was more complex, due to its interaction with the central dish of the roof above. This imposed a lateral thrust onto the level 2 concrete slab from a series of sloped A-frame columns. The imposed forces resolve through the centre of the ring, counteracting those from the opposite A-frame.

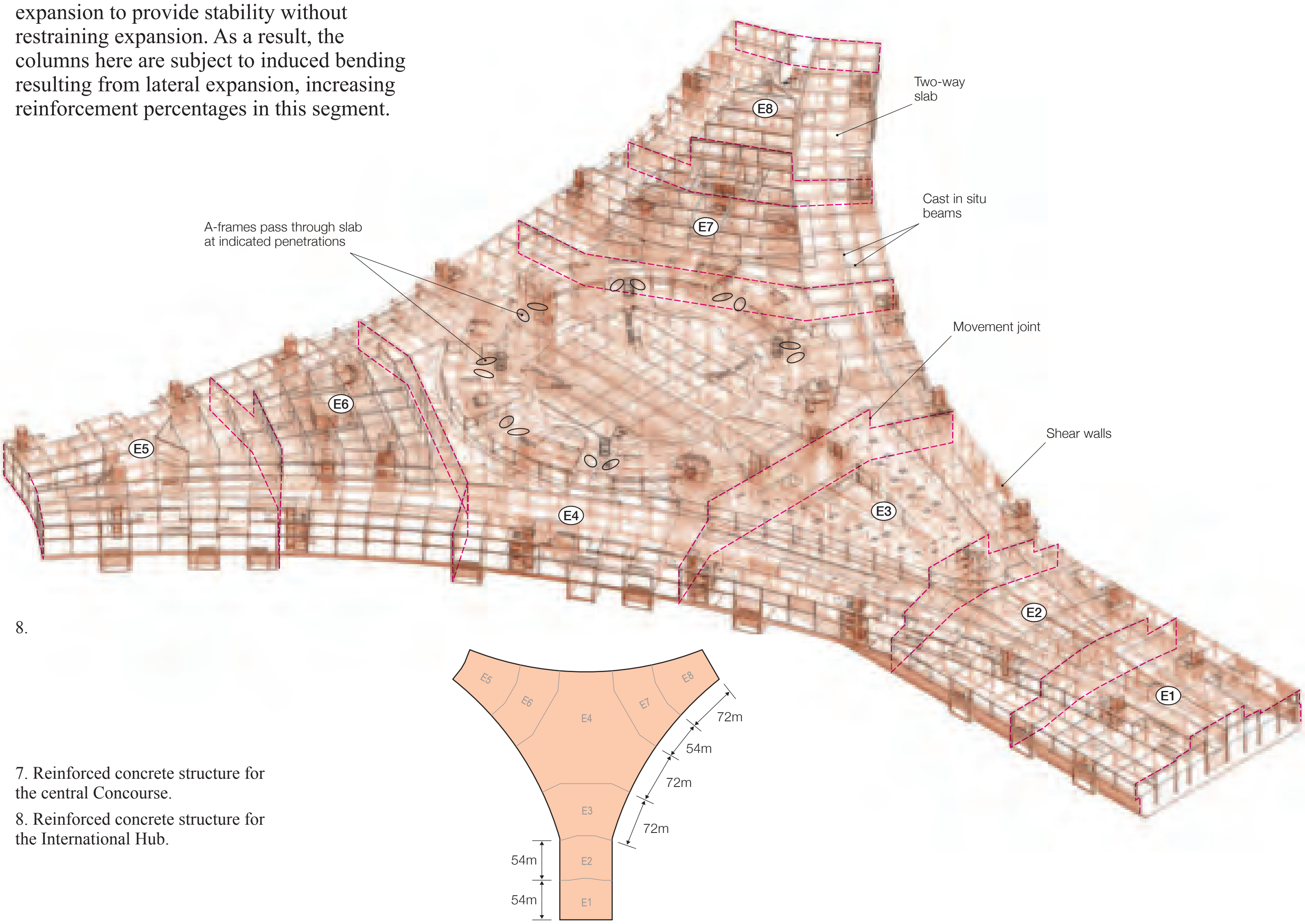
These opposing forces required at the Hub centre a jointless segment with a maximum width of 225m east–west. Primary cores were located central to the 125m ring of roof columns, with surrounding walls oriented transverse to the direction of thermal expansion to provide stability without restraining expansion. As a result, the columns here are subject to induced bending resulting from lateral expansion, increasing reinforcement percentages in this segment.

As well as the design challenges related to the landing of the A-frame roof columns, this central segment had to be redesigned to accommodate new retail, restaurant and plant areas not in the original concept. The area was especially critical for co-ordination as it is at the intersection of three grid systems: the central north–south spine Piers, the east and west International Piers (intersecting at 120˚ angles with the north–south) including curved transition grid lines, and the radial grid of the dining and shopping areas.

The transfer solutions at this intersection of grid systems thus needed to be redesigned and co-ordinated very rapidly, most of this happening while the foundations were being built and with the approval process well under way. The construction/design overlap needed considerable engineering judgment on contingencies for loading allowances.

South of the new dining and shopping areas is hotel space that also underwent much redesign. The original concept included a hotel, but the client wanted its usable area increased with an additional floor and a reshaped floor plan. In addition there were significant co-ordination challenges, since the hotel overlapped with the north end of the APM station on level 1, requiring some transfer areas to be considered.

Accommodating the APM as it crosses from north to south required several structural solutions. It circulates at level 1 in a single platform which widens in the APM station and then bifurcates into two separate platforms which become two independent tunnels as they slope down to reach the basement level and exit the building on the north side. Upon exiting the building, the APM tunnel continues north below grade to the APM maintenance facility and a connection to the future Phase 2 terminal.



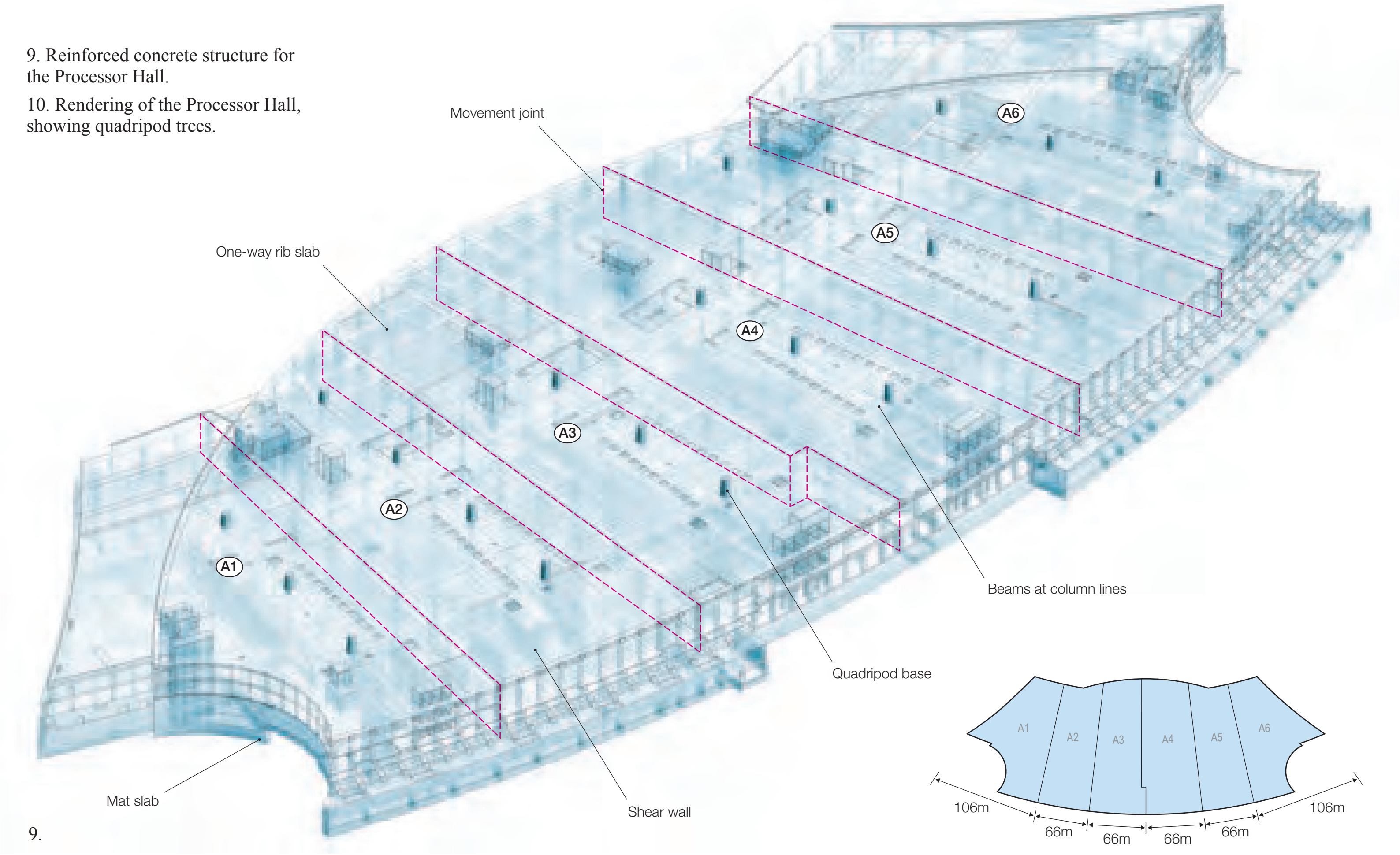
8.

7. Reinforced concrete structure for the central Concourse.

8. Reinforced concrete structure for the International Hub.

9. Reinforced concrete structure for the Processor Hall.

10. Rendering of the Processor Hall, showing quadripod trees.



9.

10.

Processor podium

The Processor (Zone A) podium design is a modified version of that for the Concourse Piers and International Hub, but its large column spacing justified a one-way ribbed system in lieu of the much heavier two-way flat slab system in the original Aeroports de Paris Ingénierie schematic design.

The ribbed scheme has much greater structural efficiency, and by running services between ribs, several co-ordination issues were resolved within the 5.1m floor-to-floor heights (Fig 9).

The system has 400mm wide x 0.8m deep ribs at 1.8m centres supported on 2.0m wide x 0.8m deep beams on the column lines. Initial analysis indicated 1.0m deep ribs as structurally efficient without undue long-term deflections; to achieve the required 0.8m depth, full top reinforcement had to be extended across the entire span of the ribs and half the top reinforcement across the centre span of the beams to control long-term deflection from creep and shrinkage.

The Processor's lateral system also required special consideration because of the size of the floor plates and the jointing of the roof, the stability of which relies on pairs of quadripod trees (Fig 10) to engage the flexural stiffness as a portal frame, so that each of the three roof segments spans east–west across podium movement joints.

The roof is thus subject to flexural stress as concrete podium segments move relative to each other; to minimise this, the concrete movements were kept to <25mm in any direction, creating an additional design demand on the lateral system.

In addition, the second suspended floor level is separated into north and south floor plates by a double-height atrium, so it was impossible to locate the shear walls centrally within the 60m x 120m floor plates. East–west and north–south core walls were instead required in both the north and south portions of the Processor segments, resulting in thermal forces on both the core walls and on the columns, as these walls flex against each other.

Because of the mass of the long-span Processor slabs, the seismic demands on these walls were proportionately higher than in the International Hub and Concourse Piers. Consequently, the Processor's seismic demands generally governed its lateral system design.

11.

Garden and APM station

The Garden and APM station (Zone H) is unique in the PTB, with structural forms differing from elsewhere (Figs 11–12). Here, a different solution at ground level was needed to accommodate the juxtaposition of the radial column grid from the curved Concourses above with the rectilinear column grid in the basement below; a thick transfer slab was used to handle the resulting two-way transfers.

To avoid transfers in the lateral system, its shear walls were concentrated away from the Concourses in the centre of the building segments. The southernmost is the largest unjointed segment in the entire PTB, some 290m x 110m, with the lateral system carefully positioned and oriented to avoid locked-in stresses due to thermal loads.

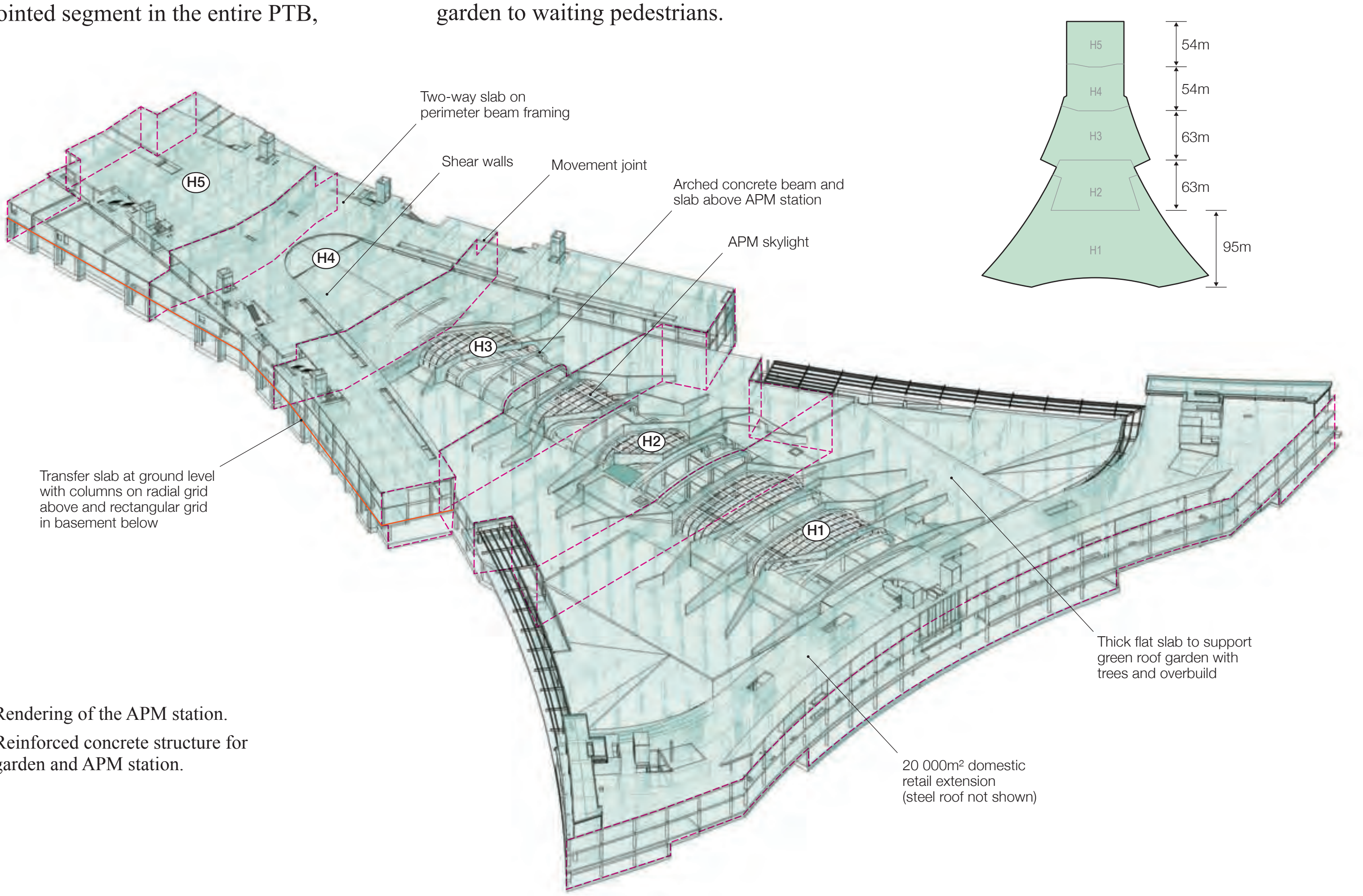
The garden and APM station feature the only portion of the roof that includes concrete. A green roof garden above level 1 supports heavy plantings and tall trees in addition to topping build-ups up to 4m above the slab.

The APM station is partly embedded in the garden with arched concrete beams and slabs creating the vaulted space for the tracks and station. The arched roof and walls are penetrated by irregular glazed skylights that introduce daylight and give views of the garden to waiting pedestrians.

As well as the complications of these unique systems, late in the design the client required an additional 20 000m² retail space to serve the Domestic Concourses. This required complete design from concept through construction documents in eight weeks, comprising flat slab floor framing and a lightweight steel roof surface with a warped form. The roof framing has straight long-span trusses of varying slopes and elevations, supported on and stabilised by cantilevered steel columns with moment continuity into the concrete structure below.

Careful management and intense architectural co-ordination delivered an adaptable foundation design four weeks into the process, with complete construction documents four weeks later issued for both approvals and construction on site.

12.



11. Rendering of the APM station.

12. Reinforced concrete structure for the garden and APM station.

The structural steel roofs

The International Hub and Processor roofs have a combined plan area of over 90 000m²; both are constructed as integrated systems of conventional steelwork and customised space frame systems, whereas the Concourse Pier roofs are framed with conventional structural steel beams, girders, and planer trusses (Fig 13).

Review of space frame systems

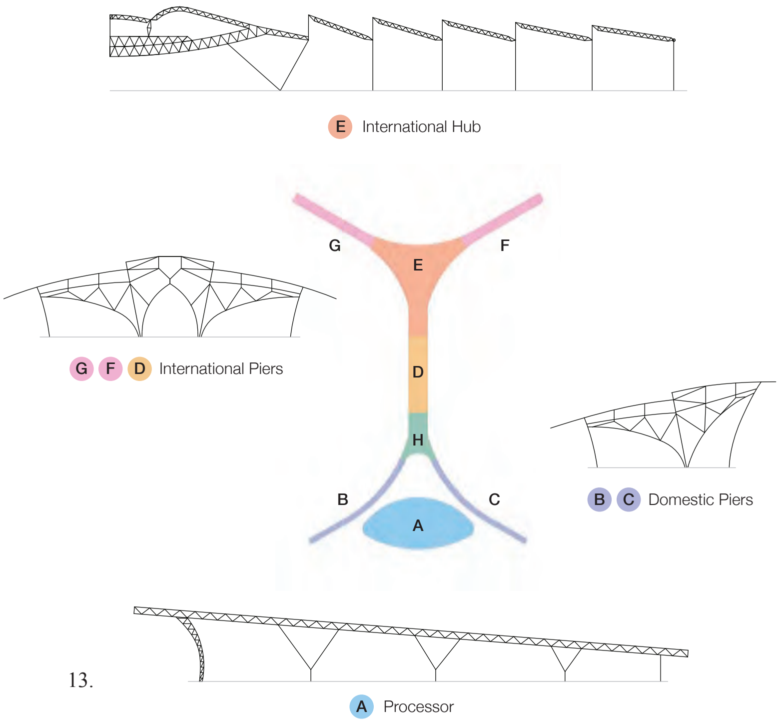
The structural "space frame" is perhaps due for resurgence as a contemporary engineering system. The term often conjures images of mass-produced, machine-age styling and aging, and relentlessly flat orthogonal roof typologies, but the impact of contemporary space frame design should be very different.

While still comprising the solid ball-and-tube system (Figs 14–15) developed in the 1930s, these systems now enjoy wider flexibility using 21st century computerised design techniques.

Modern manufacturing can integrate sophisticated analysis and design automation, so element length consistency is no longer essential, since all can now be automatically cut individually.

Angle variation is likewise not an issue as every node is CNC (computer numerical control) tapped, so the unyielding repetition which previously gave space frames their clunky and industrial reputation is no longer necessary and is often not efficient. The system is thereby freed to fill space in almost any fluid shape and can be easily sculpted for structural efficiency and/or aesthetic appeal.

Arup rapidly identified the intrinsic benefits of a space frame for the Processor roof, where the regularly spaced long spans from the interior "trees" benefited from the efficiencies of a two-way spanning system, in contrast to the one-way conventional welded truss system originally proposed. Arup therefore developed the analysis and design tools needed to automate the process of designing the roof as a space frame.



13.

14.

15.

13. Various roof profiles for the Processor, Hub, and Concourses.

14. The Processor space frame.

15. Space frame node.

Saudi Arabia has a long history of lightweight structures, and space frames shade many car parks, school playgrounds and shopping malls. For the International Hub, SBG had questioned the original design's conventional steel roof and suggested a space frame.

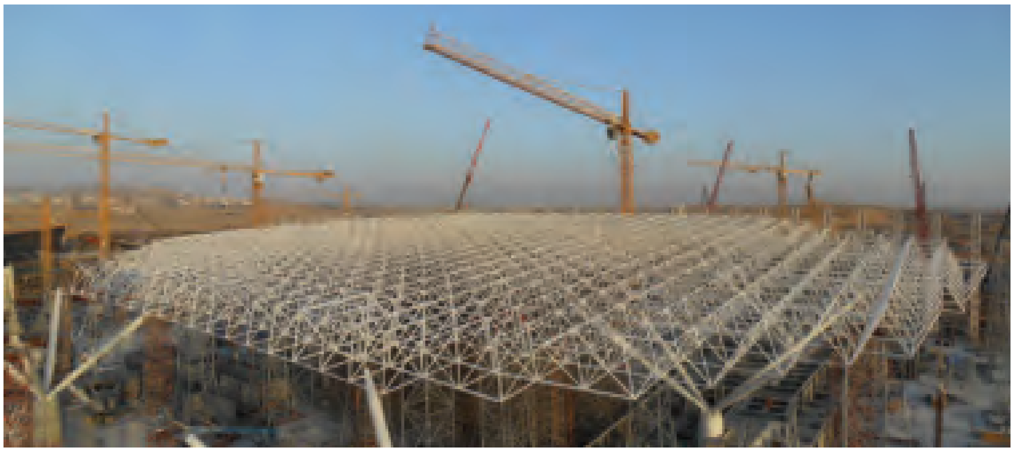
A local firm attempted to create a simplified model for cost comparison, and though this didn't fit the plan and could not achieve the required spans, it reinforced SBG's interest in such a system. The Arup team therefore adopted a space frame design for the Hub roof as well.

The challenges were to develop these systems without changing the shape or look of either roof; to draw the systems to construction document detail without the benefit of input from a specialist space frame subcontractor; and to do this all within the 120-day time limit.

Arup quickly demonstrated how such a system might look and how light it could be. By now the team was already four weeks into the 120-day schedule with the original design of both Processor and Hub roofs abandoned, and the clock was ticking.

Atkins, as lead design consultant, understood the importance of co-ordination for such huge roof systems in so short a time-span, and therefore worked with the Arup team to agree setting-out geometries, structural roof depths, and ceiling build-ups.

Atkins' co-operation enabled the team to define the most efficient internal geometries possible, given the constraints of the form that was originally required.



16.

The space frame design

Space frames are fairly simple to analyse as strut-and-tie axial force systems, and it is this extremely efficient force flow that makes them so light and economical. However, in working through the connections and interrogating the details, some interesting challenges unfolded.

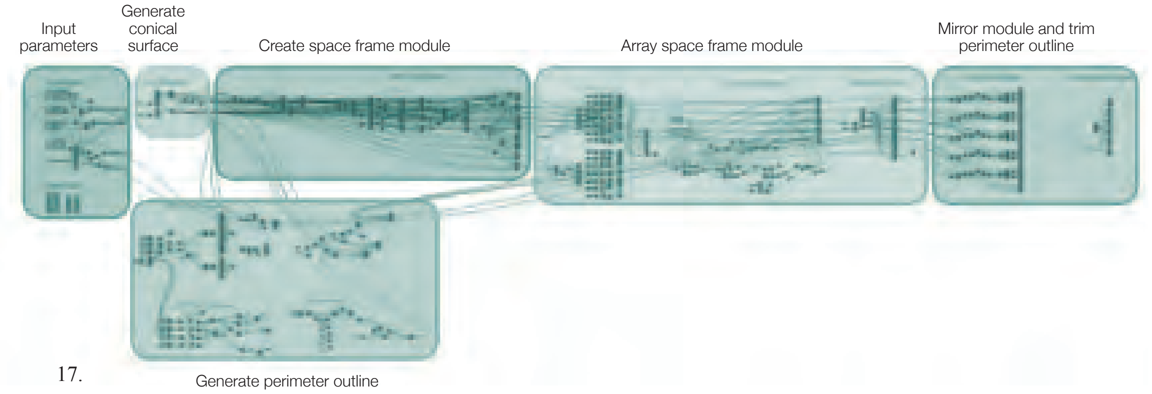
Questions of end fixity, local bending effects, indeterminacy, non-linear and buckling effects, fit-up tolerance, bolt prestress and load testing arose, making the challenges more interesting than they were initially thought.

Scaling up the system to the large spans of this project, and the extremely high optimisation level sought, meant that all such "secondary" issues became important and had to be investigated.

Also important was the fact that the roofs were hybrid systems, with conventional steelwork fully integrated and connected to the space frames; relative stiffness variations between the systems would thus significantly affect both. The construction contract would ultimately be split and so the engineering of both systems had to be fully compatible and highly detailed for this split to occur without the need for subsequent redesign by a subcontractor.

The basic building block of most space frames is a repeated geometric module, swept around the intended geometry while maintaining optimum element densities and system depth. Pattern density is critical: too dense, and members become small and under-used with too many nodes; too sparse, and long members in compression exceed the limits of optimum tube sizes. Make the roof too shallow and the forces cannot be managed; too deep, and member lengths become inefficient.

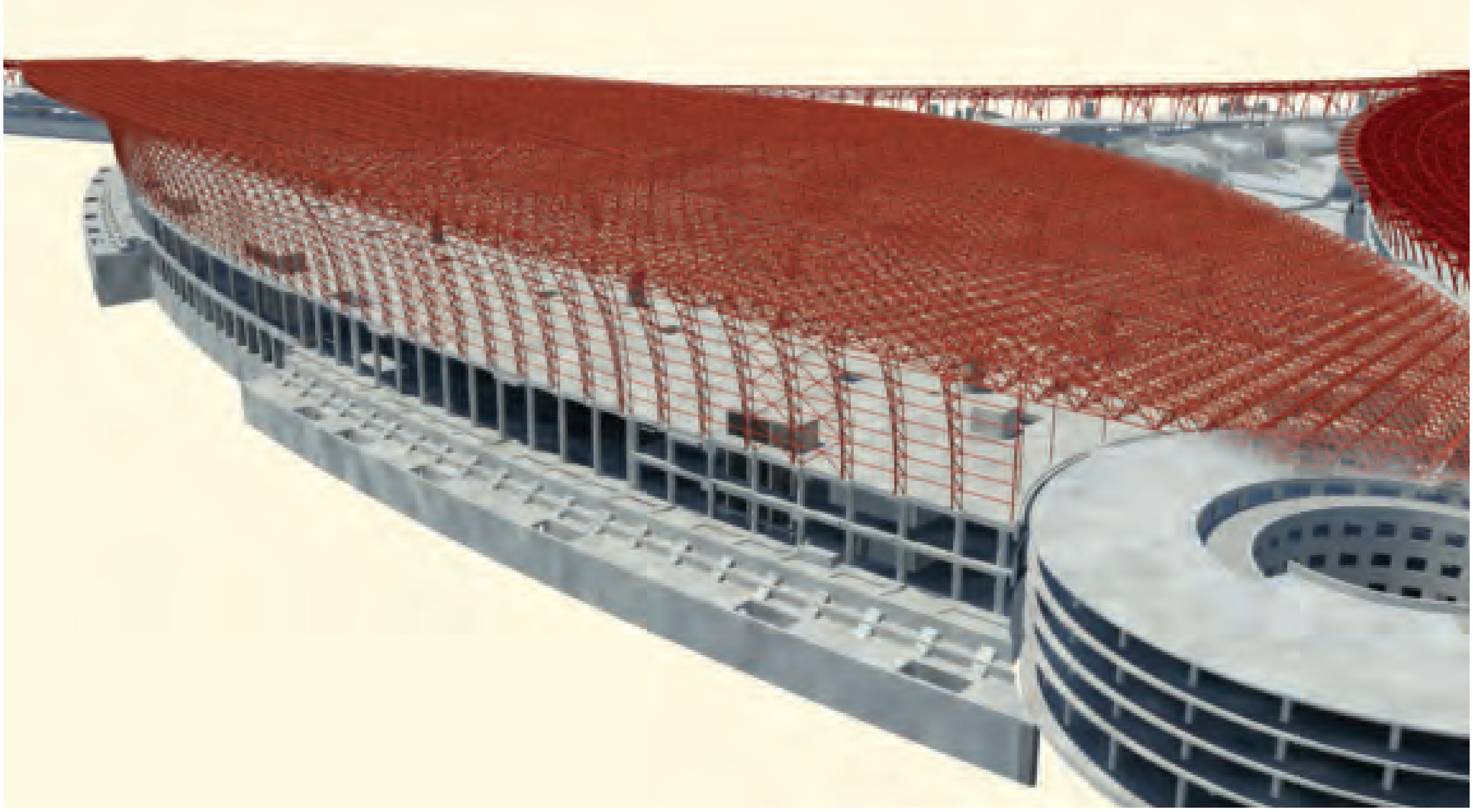
Arup developed geometry scripting tools using *Grasshopper* and manual *Rhino* methods to design the process of establishing base geometries for the best modular arrangement (Fig 17).



17.

16. The Processor roof under construction.

17. Processor roof geometry generator.



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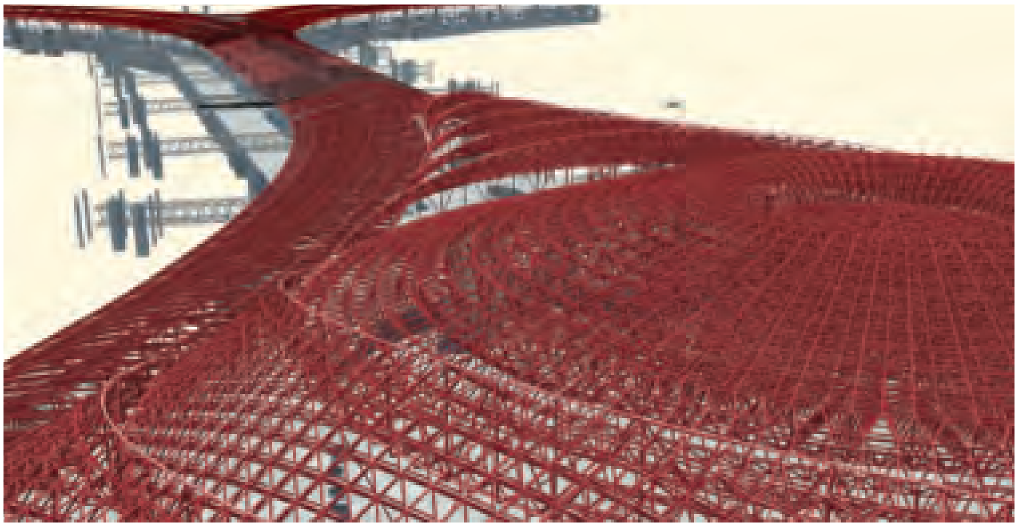


19.

18. 3-D rendering of Processor roof.

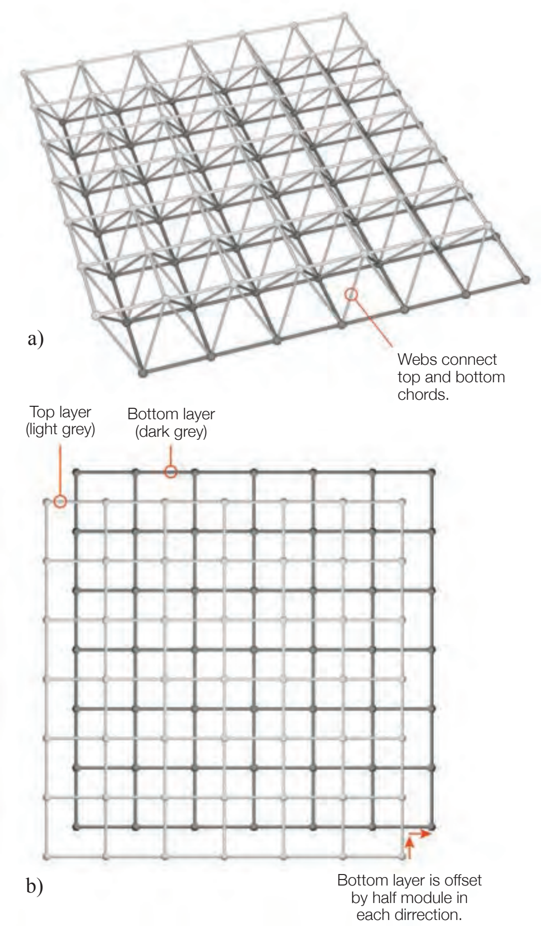
19. 3-D rendering of Hub roof.

The team established the Processor roof's overall form (Fig 18) as a projected slice from a single giant obtuse conical surface, but the unique forms needed for the Hub were somewhat more complex (Fig 19).

For the Hub roof, the element lengths, angles, and densities were continually adjusted after each analysis to enhance the number of elements, avoid over-sized tubes, and reduce connection node size, with particular care over the element count as the system approached the centre of the circle.

Both roofs employed a modified offset square arrangement (Fig 20); since both are circular structures, the typical module was in effect radial and circumferential.

The team created script routines to automate the iterative analysis and design procedure (Fig 21). Each design pass required no fewer than four iterations of element dimensioning and re-analysis, as both the loads and stiffness (and thus internal force distribution) changed significantly whenever even a small percentage of the elements changed size (Fig 22).



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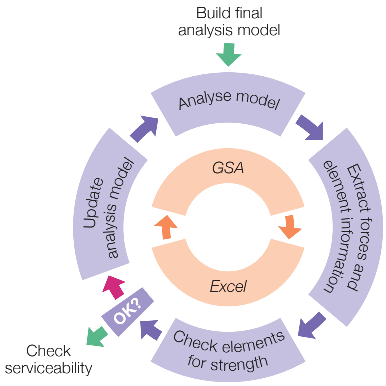

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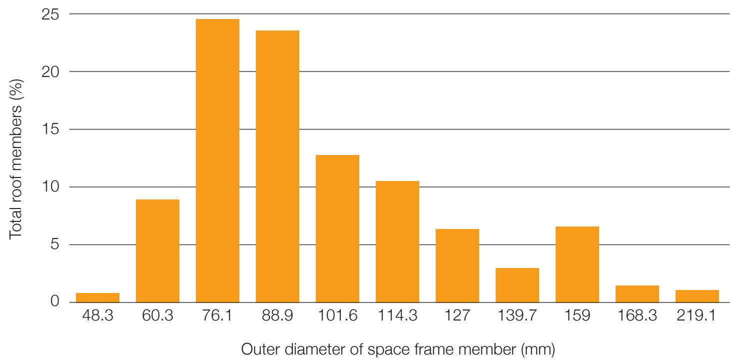


22.

20. Offset square diagrid pattern: a) axonometric; b) top view.

21. Space frame design optimisation flow.

22. Distribution of space frame member sizes in the Processor roof.

23. *LS-DYNA* analysis images of the stresses within the bolt under two expected loading conditions:
a) direct tension loading parallel to the axis of the bolt;
b) rotational loading, effectively putting the bolt into bending.

Details, details...

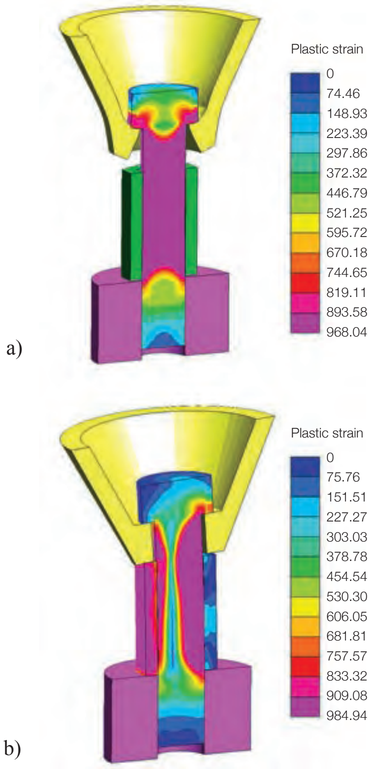
Space frame connections are conceptually simple but rather difficult and complex to predict in actuality. Most of Arup's previous experience designing them had followed the conventional design–bid–build contracting process, where the consultant's preliminary design is handed over to a specialist contractor for construction documentation. In such cases, the final connection details are generally proprietary and the engineering impact they have on member behaviour is not only difficult to quantify, but generally addressed by the contractor, not the consultant. With little prior knowledge of the nuances, and trying to avoid preconceptions of what space frame design entails, Arup independently investigated how they work.

The connection's rotational performance impacts both its own capacity and that of the slender thin-walled tubes it connects. Research in and understanding of this phenomenon is owned mainly by MERO-TSK International GmbH & Co[2], which has designed and tested physical systems and developed custom software over many years. Arup had no access to this information, and so had quickly to devise tests to improve its own knowledge base.

While the primary force-resisting mechanism of space frames is axial, all members in these PTB roofs were designed to withstand the flexural stresses from inclined member self-weight plus a single 115kg point load anywhere along the length (ie the weight of a worker standing on it during construction). The resulting shear at the interface between member and node imparts a rotation to the node that can only be resisted via the shear and flexural resistance of adjoining members. The system must therefore be able to transfer a minimum of shear and flexure at the member/node interface, but not so much as to unduly tax the members and the bolted connections in shear and bending.

After understanding and dimensioning a series of typical connections, Arup modelled this behaviour in *LS-DYNA* to better understand and quantify the relationship between fixity, stiffness, bending capacity, and axial capacity (Fig 23).

The software's non-linear solver modelled the opening of gaps in the connection interface as rotation occurred. Since each connection relies on a single high-strength



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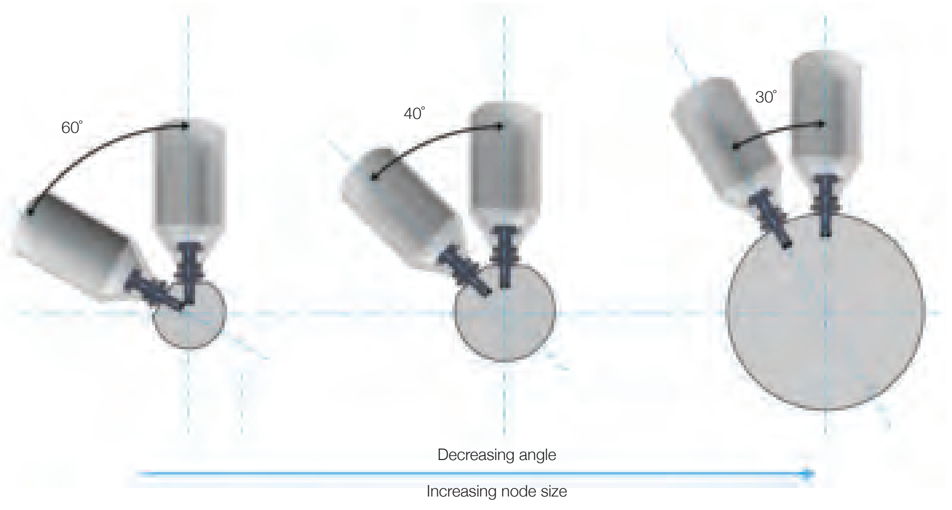

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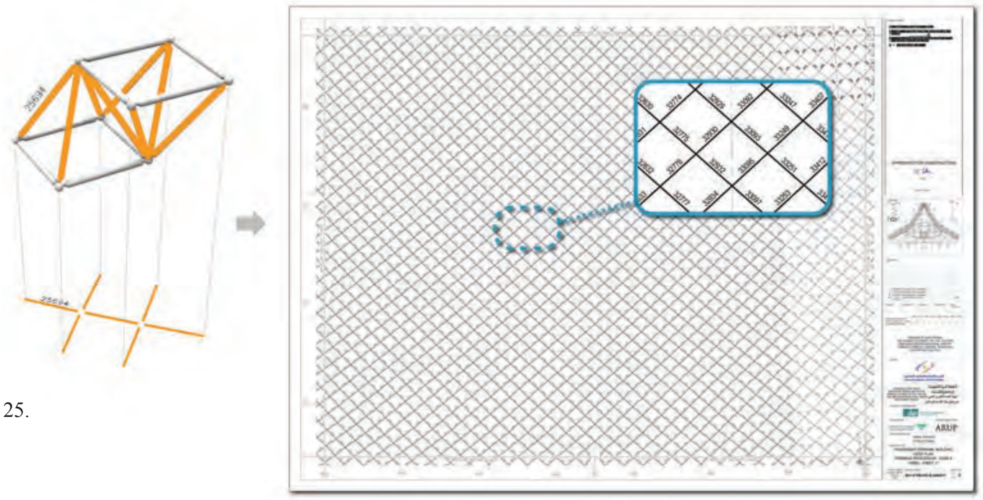


25.

24. Space frame node sizer.
25. Space frame drawing routine.

bolt, permanent bending forces from the slight shear and flexure at the interface could reduce the connection's tensile capacity under combined stresses within a bolt of limited ductility. Against this concern is the opportunity that rotational stiffness affords member compression capacity.

These detailed analyses allowed Arup to derive rational interaction capacity tables for families of connections. The design routine referenced this library of capacities at each iteration cycle so as to size every bolt in the system automatically.

Dimensioning space frame nodes is a data-intensive process. Dictated primarily by geometry (while respecting minimum thread lengths for different sized bolts), every connection was automatically and individually derived based on the relationship of adjacent element incident angles and diameters (Fig 24). The smallest node possible was then selected for each connection, and its weight (up to 30% of the entire system's self-weight) recorded and fed back to the analysis model for subsequent design iterations. The node weight may thus change the tube sizes in the next iteration, and so on. Continuous manual inspection of the interim results helps refine the geometry.

Space frame design delivery

The end result is a set of drawings showing every element in its plan position tagged with a unique index number (Fig 25).

An electronic database reports every node position and size, and every tube size, bolt, and cone and sleeve size, while an accompanying specification lists the required materials for the members and nodes and gives the outline of a testing regime to prove the system. Because each connection relies on a single bolt, every bolt is tested.
The conventional steelwork was also fully drawn and specified and did not change once a space frame contractor was engaged.

This package gave SBG exactly what it wanted. Arup delivered the entire design within the initial expedited schedule, although as noted previously the 120-day deadline was by then no longer a concern. Roots Steel International/Jinggong/MERO won the space frame construction subcontract, and Jinggong was selected to fabricate all the conventional steel parts. Arup maintained design responsibility for both systems.

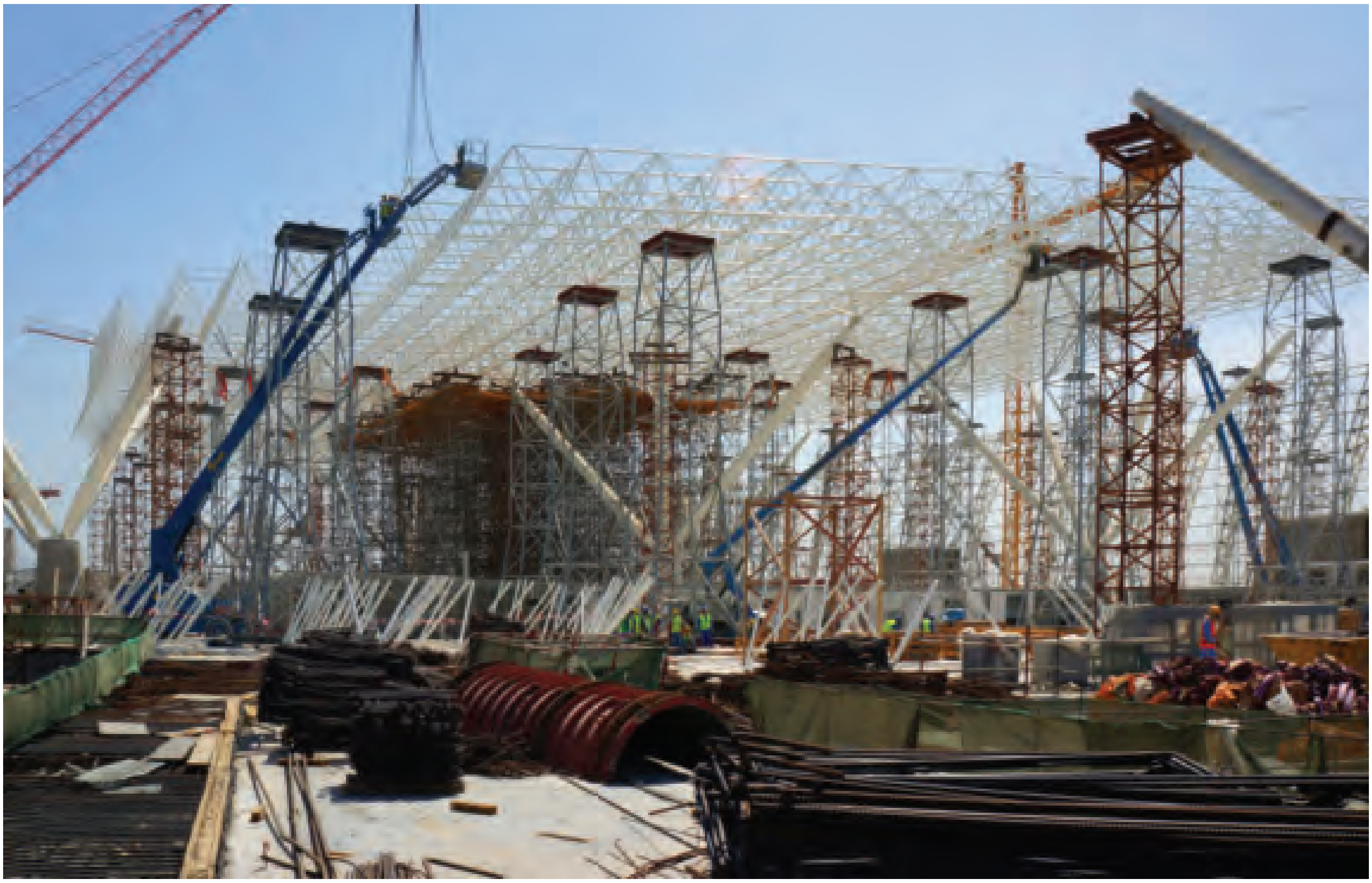
Space frame construction

This was the first project where MERO had not fully designed its own space frame system, and it is thanks to its engaging and open attitude to engineering and communication across contractual lines that the process was a success. From the outset, Arup and Roots Steel International/Jinggong/MERO defined a process of:
1) vetting Arup's connection and element designs; 2) matching them to MERO's standard catalogues; 3) creating cross-regional (but consistent) specifications, and 4) transferring and checking all data.

Roots Steel International/Jinggong/MERO found Arup's assumptions about connection fabrication and design to be remarkably close to its own data, with a few differences. Roots Steel International/Jinggong/MERO also proposed improvements to some of the team's connection details between space frame and conventional steelwork, particularly where the differences between an essentially zero-tolerance space frame system and a conventional welded structure become most challenging.

At the same time, changes directed by Atkins and SBG were incorporated right up to final release for fabrication. Many consistency checks on the data itself were likewise carried out during this process.

Interestingly, to provide an element length to within 0.1mm for a roof over 1km long, accuracy to the 8th significant figure is required. Some processing errors related to this accuracy were indeed uncovered, arising from the passage of data through *Rhino*, *Excel*, and *GSA*.



26.

27.

Conclusion

Arup's innovative design of the steel roof structure involved configuring the arrangement in collaboration with SBG and optimising the structure to achieve an outcome that was light, visually appealing and could be erected efficiently. The space frame in particular introduced unique features and led to a very elegant result.

26. Space frame construction.

27. Hub roof construction.

International Hub roof design

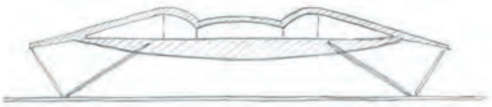
This “starfish” of unlikely proportions measures 300m tip-to-tip. Its central rotunda, which became known as the “lens”, is 120m across, with the starfish legs dubbed the “gills” due to their scalloped shape (Fig 28).

The roof is a single unjointed structure, built from a close integration of light filigree space frame components and contrasting large-diameter curved steel tubes. Both systems resist gravity and lateral loads, with the space frame restraining the long, large tubes and the tubes defining the free edges of the space frame. The tubes likewise provide traditional touch-points for the adjoining façades.

The starfish legs are supported vertically on slender columns, some of which ride on spherical bearings to allow the legs to expand and contract with temperature radially above multiple podium structures below.

Stability is provided by nine great arches arranged around the lens that lean in towards the centre. These reach directly into the space frame itself, with each leg touching 13 space frame elements through a single 350mm diameter spherical connection node. The resulting interaction between two systems of such different scale was complex and required very careful analysis to achieve successfully.

The top surface of the lens is a dome, while its inner surface takes the form of a broad, inverted dome or dish (Figs 29–30). For space frames to be efficient, they should replace secondary framing wherever possible, so Arup decided that the system should provide both surfaces of the upright and inverted domes. The considerable interior space created between these two domed surfaces houses back-of-house equipment and the electrical rooms.



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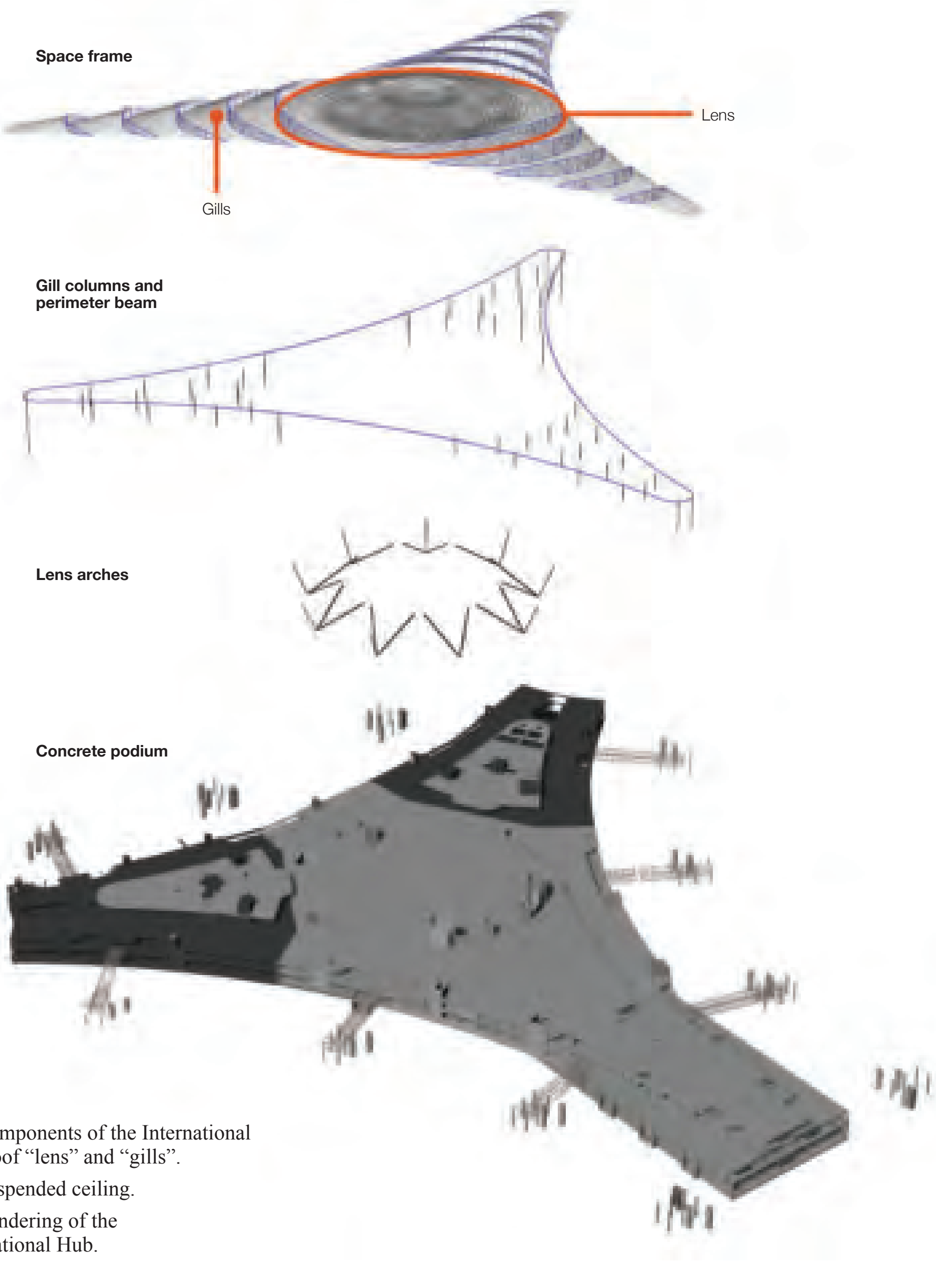


28.

28. Components of the International Hub roof “lens” and “gills”.

29. Suspended ceiling.

30. Rendering of the International Hub.

30.

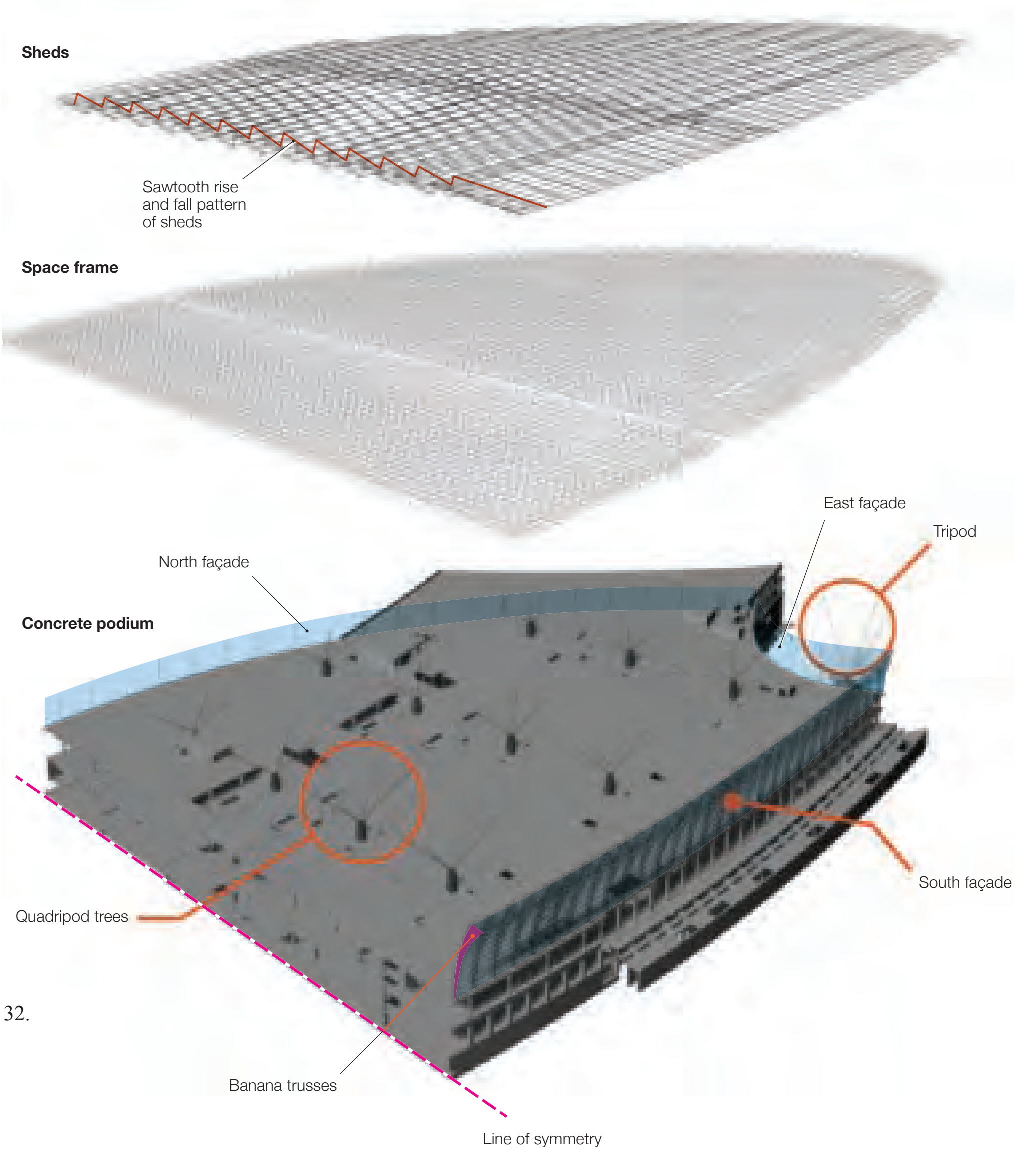
31.

Processor roof design

The Processor's 66 300m^2 space frame roof is supported by vertical columns along the north, east, and west façades; by curved "banana" trusses along the southern façade (Fig 31); and by the series of interior quadripod trees. Two external inverted steel tripods extend from grade to roof to prop the large eastern and western overhangs. A saw-toothed secondary structural steel "shed" assembly is supported directly on top of the roof space frame, giving the Processor its distinctive serrated exterior form (Fig 32).

The curved banana trusses rise and fall in elevation east–west along the southern perimeter, and this façade serves the dual purpose of supporting both the southern glazing system and the roof's southern edge. Discrete bays of the façade are cross-braced within the plane of the banana truss rear chords. This concentric arrangement provides a relatively rigid line of lateral restraint to both the façade and southern portion of the roof.

As previously noted, the portal frame behaviour of the three sets of interior tree pairs supporting the three roof segments engages the flexural stiffness of the roof so as to stabilise it laterally against forces from wind and seismic loads.

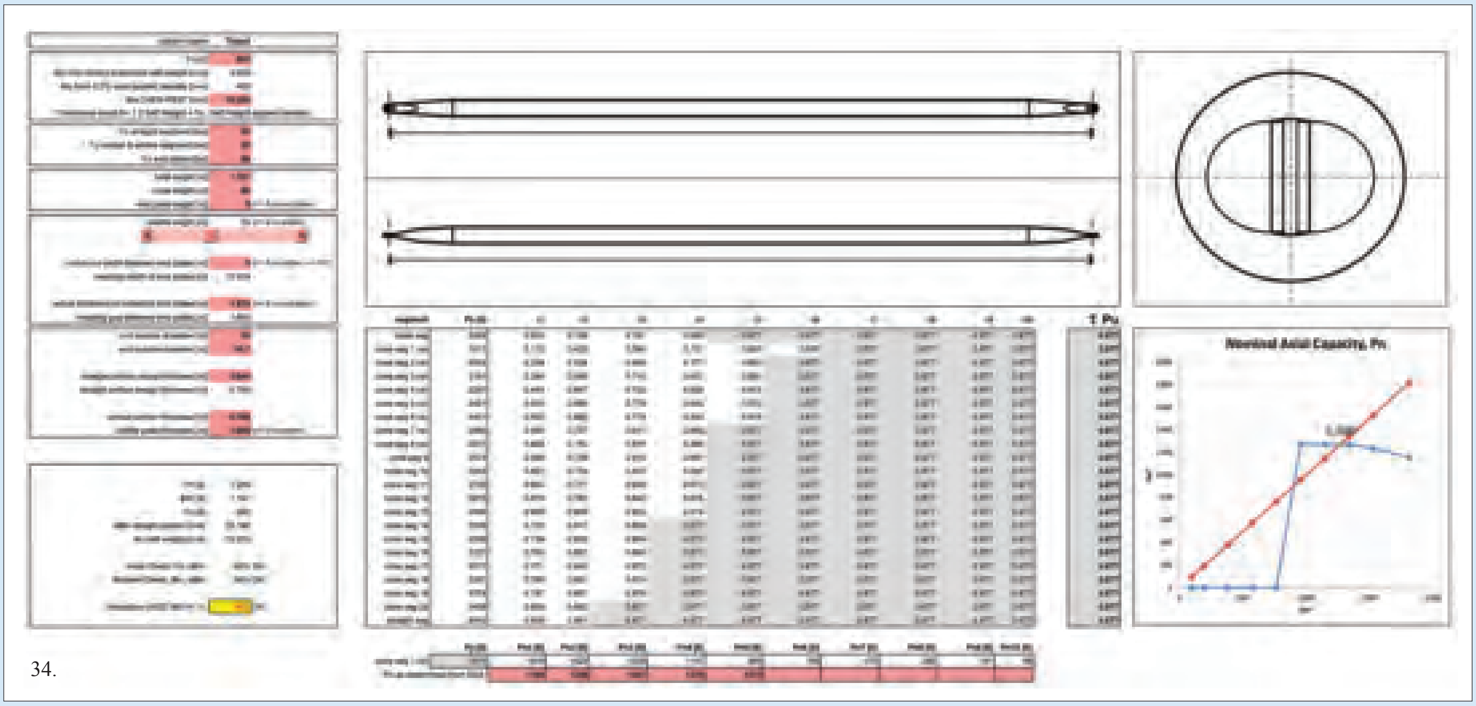


32.

31. Curved "banana" trusses along the southern side of the Processor.

32. Principal components of the Processor roof.

33.



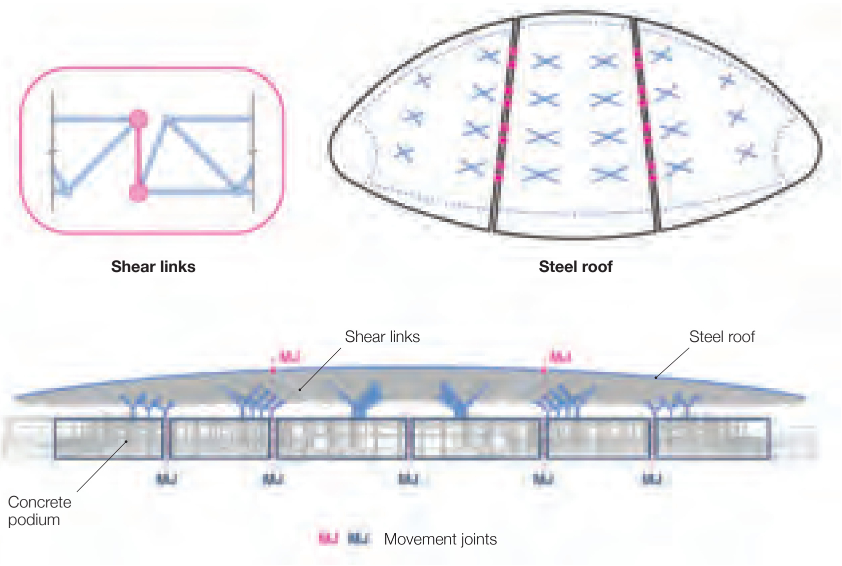
34.

Design of tapering steel branches and tripods

Each of the quadripod trees comprises a RC trunk and four flaring structural steel branches that have a central segment of constant circular cross-section and two conical end segments that are “whittled” towards their ends. The extreme west and east supports are inverted tripods, similarly comprising tapered steel supports converging to a concrete pedestal support.

The tapering branches were designed in accordance with the buckling requirements established by the AISC (American Institute of Steel Construction) provisions for stability analysis and design[3]. An interactive design spreadsheet (Fig 34) was written to parametrically define their geometry as a preprocessor for subsequent eigenvalue analyses. Once a tapered strut was defined, the program allowed for the automated iteration of assumed values of axial strength capacity, P_n, and corresponding modified section properties along its length as a function of this assumed level of internal force. This set of properties was then analysed in *GSA* to obtain the corresponding elastic buckling force, P_e. The entire process was iterated automatically until the assumed value of P_n equaled the resulting elastic buckling capacity, P_e, per the analysis.

Once this condition was satisfied, the corresponding value of P_n was reported as the unfactored axial compression capacity of the tapered column.



35.

The Processor's podium structure is divided into six segments by five north–south oriented movement joints, while the roof's three segments have two movement joints (Fig 35). Occasional pin-ended vertical steel struts within the depth of the roof along the joints serve as shear links between adjoining roof segments, preventing vertical slip along the joints while enabling the roof segments to translate laterally relative to each other.

This misalignment of the podium and roof movement joints necessitated much analysis of all permutations of relative podium and roof displacements, to quantify the internal force effects developing from differential movements between the two systems. While this analytical effort was considerable, it (and the marginal increase in roof steel tonnage arising from the extra internal forces induced by these relative movements) was outweighed by the benefits of removing the additional interior column props and additional roof joints in the original structural design.

The Processor space frame is 2.5m deep, with top and bottom layers of circular hollow sections arranged on a plan grid of about 3m x 3m. Circular hollow sections likewise connect the top and bottom layers of the space frame to complete the system.

36.

The saw-toothed shed steelwork is constructed from typical rolled steel beam sections and vertical circular hollow steel struts. The sheds are detailed to be independently stable within each discrete bay, to stop them binding with the space frame as the roof flexes.

Once all the space frame members were optimised for strength, some in localised roof zones were strategically up-sized to satisfy global wind drift limits and to accommodate localised diaphragm chord and collector strength requirements.

Concourse Pier roof design

The seven Concourse Piers cover more than 130 000m^2, with their roofs extending for a total of 3.2km. The steel elements supporting these roofs are an integral part of the architecture, and will be visible to passengers in the Concourses.

This required the structural members to have a consistent outside diameter acceptable to the architect. To achieve a structurally appropriate solution within these tight requirements, the Arup team therefore simplified the roof framing design.

Fewer, simpler, lighter

This vast expanse required an economical and repetitive structural system capable of simplifying the construction process.

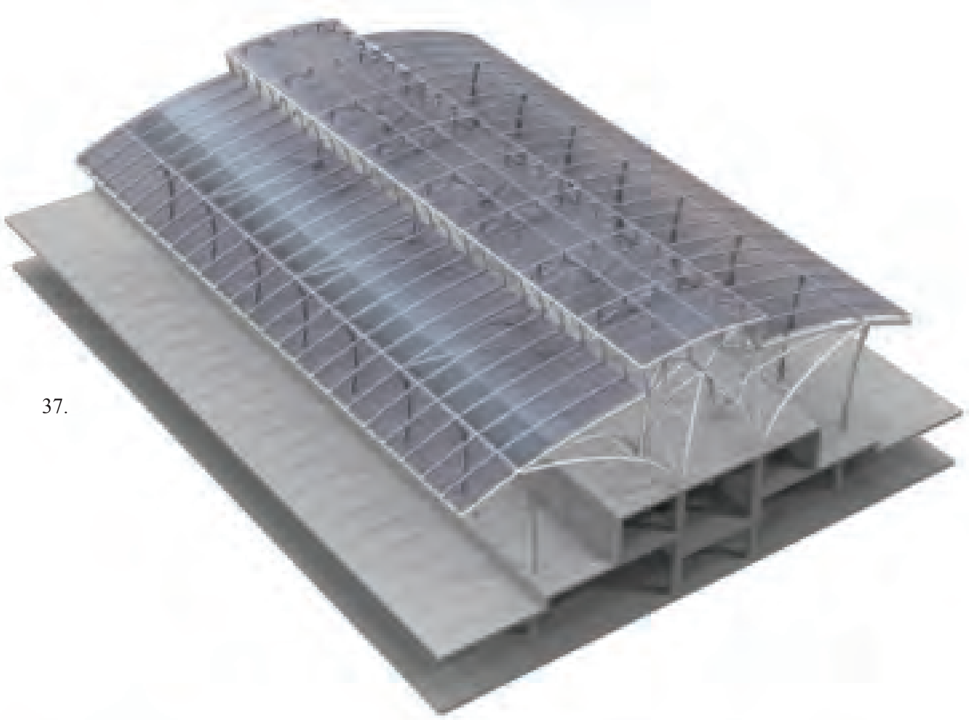
The typical Pier roof cross-section consists of two, sometimes three, curved surfaces, connected by a clerestory to allow air intake and exhaust, and the original structural design employed a bi-directional truss system with transverse primary trusses and longitudinal secondary trusses. These trusses contained many pieces, which would have complicated erection and impeded building service runs.

33. Tapered elements of quadripods being installed.

34. Tapered column design routine.

35. Processor roof and podium joint misalignment.

36. Quadripod installed.



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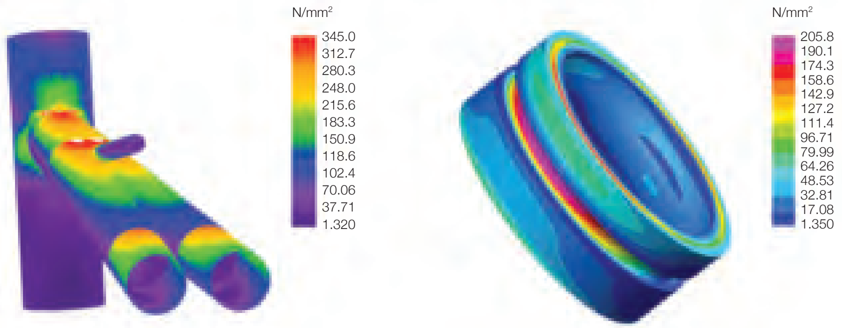


38.

37. Revised structural scheme for Concourse roof modules.

38. Finite element analysis images of crane connections.

Arup proposed a revised scheme that simplified the system considerably (Fig 37). Trusses were used within the natural depth created by the clerestory only, and made to span 18m between interior supports or "cranes", with all secondary members changed to rolled beam sections.

This system allowed the beams to be curved about their strong axis while other elements remained straight, and easy to erect with standard bolted connections.

Analysis of complex connections

The intended aesthetic for the roof resulted in numerous, complicated, and visible tube-to-tube connections, many of them at or just above eye level, necessitating a refined level of craftsmanship for what would otherwise have been straightforward and utilitarian details.

In total, the Concourse Piers have 183 supporting crane structures of varying geometry. They contain over 1300 tube-to-tube connections, not including the bespoke casting at the base, and all had to be individually cut and welded.

The architect insisted they be uniform in appearance and satisfy strict finishing requirements, so the connections were simplified as much as possible. Five basic types resulted, varying in both tube and internal plate thickness, but with the uniform exterior appearance required.

All five connection types were designed as welded assemblies, shop-fabricated to a high degree of accuracy and then transported to site and field-connected with simple circular welds at points of relatively low stress. Mock-ups were made for several locations along a typical crane, to verify that the structural robustness and aesthetic finish required could be achieved by the fabricator.

These mock-ups enabled Arup, the architect and the fabricator to resolve potential issues ahead of production, ensuring that the intended end result was achieved.

The structural behaviour of these assemblies was complicated and required detailed finite element analysis (Fig 38). The geometry was first modelled in *Rhino* and then meshed in *HyperMesh*. 2-D finite elements were used to model the configuration of each assembly, and inserted into the overall *GSA* analysis model of the crane.


39.

39. Casting Concourse roof elements.
40–41. Crane structures in position.


40.


41.

Member design optimisation

As with the space frame system design, the more conventional framing of the Pier roofs used an automated optimisation routine to maximise structural design efficiency.

Members were first grouped according to loading, unbraced length, and location within the structure, and one beam or tube size was selected for each group. Script routines in *Excel* extracted the loads for each member and load combination from the *GSA* model and exported these to a design spreadsheet, which then sized the elements in each group and exported these back into the *GSA* model.

The process was iterated until an optimised set of members was achieved.

As with any optimisation routine for conventional framing, a balance must be struck between the degree of individual optimisation versus standardisation of typical member sizes to accommodate practical construction.

To find this balance, Arup created a truncated library of acceptable member sizes for most of the framing, and then manually adjusted specific members where depth restrictions required shallower yet heavier sections.

This created an accurate representation of the boundary conditions of each connection and improved the analysis significantly.

GSA's linear elastic solver was unable to accommodate the non-linear material behaviour of the 2-D finite elements used to model the connections. However, the governing design codes assume that non-linear "plastic" section properties are used during ultimate seismic, wind, and gravity loading events.

The design of these connections would therefore have been severely compromised had material non-linearity not been considered. Arup responded by developing an analysis and design methodology that amplified the allowable stress for a given assembly, based on the axial load occurring in each member and the ratio of the elastic-to-plastic section properties.

This approach enabled the team to use *GSA*'s quick and easy modelling capabilities without compromising design efficiency. The simplified method was validated using equivalent model samples analysed in the much more computationally intensive non-linear analysis program *LS-DYNA* with very close agreement.

The team could therefore employ the simplified *Rhino–HyperMesh–GSA* workflow to design with confidence the many connection variations.

Each crane structure has at least two locations where three curving, tubular columns meet. In the original design, these came together at non-coincident workpoints, but due to architectural space constraints, were modified to converge to single coincident workpoints.

The original connection could have been easily fabricated from three separate pieces, cut, and then shop-welded, but as it proved impossible for the fabricator to maintain the required high level of architectural finish once the three pipes were made to converge, it was decided to cast these particular connections (Figs 39–41).

Casting meant that the architect could carve and sculpt detail with somewhat more freedom, creating shadow gaps and reveals at various locations along the piece.

These shadow gaps were up to 10mm deep, rivalling the thickness of the connected tubes in some locations. As Arup was concerned with the flow of forces here, *LS-DYNA* was used once more to analyse and design the connections using detailed 3-D solid, non-linear finite element models.

Ancillary buildings

Arup's work also included the structural design of 14 other ancillary buildings in the terminal complex. These were the main air traffic control tower, the west support tower, two data centres, the rescue and firefighting station, the crisis management centre, and several radio transmission buildings and maintenance facilities.

Although each presented unique challenges, the air traffic control tower was the most complex, requiring significant modifications to the original tender documents. This is the only one described here.

The air traffic control tower

The air traffic control complex comprises two main buildings: the air traffic control tower itself and its associated base building, and the surrounding two-storey technical block (Fig 42). Two concentric lines of movement joints isolate the tower, base building, and technical building from each other.

The tender documents specified a 130m tall air traffic control tower but GACA, keen for the tower to be the world's tallest, mandated that the roof height be extended to 136m from grade.

The tower is a 119m RC shaft supporting an 18m high, two-storey cab and "parasol" roof structure — the latter being incorporated purely to accommodate feature lighting. The tower is wrapped in an offset steel cladding system of varying depth, creating a tapered exterior profile. Crescent slices cut into the cladding are also illuminated by feature lighting.

The tower is founded on a 2.95m deep x 20m wide octagonal RC mat supported on 43 RC piles, each 1.2m in diameter. The central vertical RC shaft that serves as the tower's spine has a constant inside diameter of 10.55m, but its wall thickness steps four times up its height in segments that are 1.0m, 0.75m, 500mm, and 350mm thick.

Interior RC walls in the east–west direction are 250mm thick while the north–south walls are non-structural partitions.

The RC floor slabs are typically 200mm thick, except at the top of the shaft where this thickness has been increased to 500mm. The two levels of cab above the shaft are constructed in structural steel and composite floor framing.

The U-shaped, one- and two-storey technical block has an undulating and sloping steel-framed roof, so that the overall building height ranges from 5m–13m above grade. The technical block wraps around the one-storey base building, the roof of which forms an open-air terrace for the complex.

Both buildings have RC framing on shallow footings, while the sloping steel roof is framed with continuous radial girders connected by straight secondary beams that in turn support radial cold-formed steel purlins. These support the metal roof and define its architectural shape.

Engineering design challenges

The air traffic control tower being the world's tallest, its engineering design presented significant technical challenges.

Wind engineering

Arup's wind engineering experts assessed the tall, slender tower's dynamic behaviour, and concluded that it would be inappropriate to rely on code-specified wind loads because the tower's shape, with a height:width ratio of nearly 12:1, would result in significant cross-wind excitation. Clearly a wind tunnel test would be needed to model the structure's actual response.

To progress the design ahead of finalised wind pressure data, the Arup specialists derived an accurate approximation of these effects, enabling the design team to develop appropriate superstructure and foundation systems quickly and early.

This was critical to achieving the design schedule as the wind tunnel testing proved to be relatively difficult and time-consuming. (At issue was the appropriate Reynolds number to use — a parameter that correlates wind flow patterns around objects and must be carefully calibrated to represent accurately cross-wind excitation.)

By carefully adjusting the model's surface roughness, the wind tunnel testing agency eventually reproduced the expected full-scale behaviour. Close agreement was found between these final data and the approximate predicted values, so only minor adjustments to the detailed structural design were required once the results were available. This in turn enabled the team to produce the early foundation package needed to achieve SBG's aggressive construction schedule.

The wind tunnel investigation also confirmed that a tuned mass damper would be needed to augment the tower's inherent level of damping, to moderate the building's response to wind pressure and control induced accelerations.

A damper was not included in the tender documents, but the predicted accelerations greatly exceeded the occupancy comfort standards established in *ISO 10137*[4] unless tower damping was increased to a minimum of 4%. The design issue then became where to locate the device.

While the optimum location would be as high as possible, there was little space in the cab or shaft to accommodate it, but the team realised that the varying gap between the outer façade and internal concrete shaft formed an excellent space to suspend an annular inertial damper.

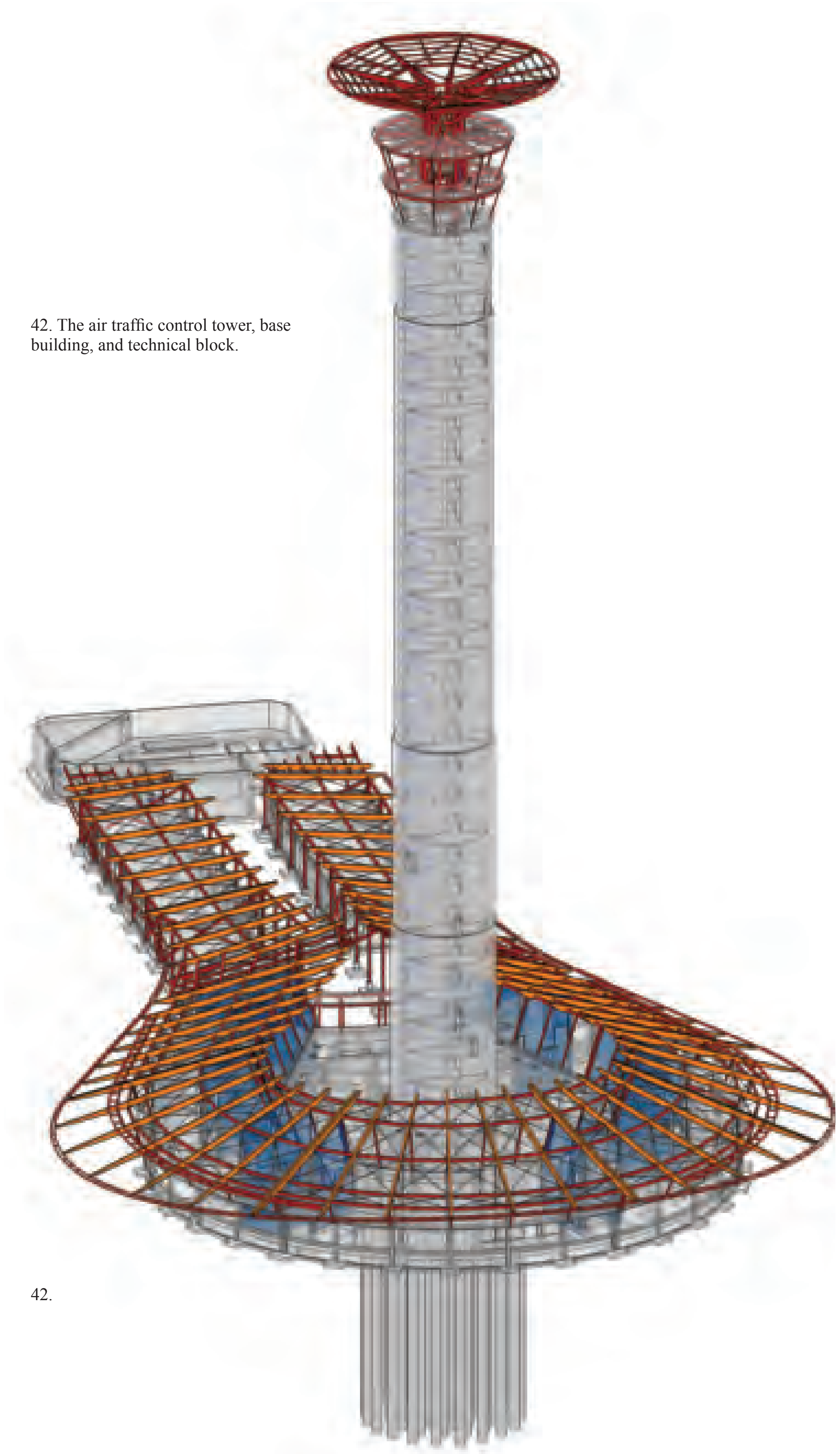
Arup developed the performance-based damper specification and GERB Vibration Control Systems was contracted to design and supply the 96-tonne device.

Foundation design

The original tender documents specified a large 2m thick mat foundation under both the tower and base building, supported on 89 piles varying from 15m length for the outer ring to 20m for the inner rings.

Arup determined that a smaller footprint would accommodate construction flexibility — an octagonal mat on just 43 piles, less than half the original quantity. While the axial force in individual piles increased, this could be accommodated by increasing the length to around 43m.

42. The air traffic control tower, base building, and technical block.



42.

Reducing the quantity of piles but increasing their length meant that the overall concrete volume remained much the same as the tender design. Similarly, while the new mat increased from 2m to 2.95m thick, the corresponding reduction in plan area meant little change to the original volume.
The benefit of the revised design lay in increased sequencing flexibility and reduced construction time.

By replacing much of the original wider mat foundation with simple slab-on-grade and shallow footings, the tower's construction schedule was freed from that of the surrounding buildings, enabling its time-intensive and much more complex foundations to proceed ahead of the surrounding buildings — and faster with fewer but deeper piles.

Tower shaping

Changes were made to improve constructability and efficiency of the tower superstructure. The original documents specified tapering concrete fin walls radially around the shaft, but these were replaced with a thickened outer shaft to accommodate simpler slip-form construction.

From levels 16–19 (the base of the cab), the original design called for a composite steel/concrete structure, but the complexity of introducing this was eliminated by extending the concrete shaft to level 19. The perimeter and core framing in the cab levels above were also revised to improve sightlines from the controller positions.

The tender design relied on large built-up frame columns around the perimeter for stability; these were replaced by a central lateral core structure, allowing the perimeter columns to become much lighter, gravity-only elements.

Performance-based fire engineering design

43.

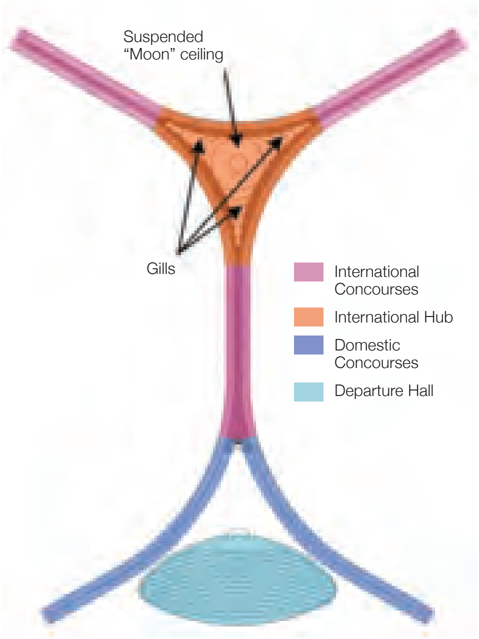
Code vs performance-based design

As already described, the design of the structural steel roof and roof framing was optimised, but prescriptive fire code requirements for the design did not align with this goal, as applying them would have added significant unnecessary cost. Indeed, for some of the smaller steel members, prescriptive methods were simply not available for applied intumescent fire protection materials. In addition, omitting fire protection on the steel shortened construction time and will reduce work needed for the roof's long-term maintenance. For these reasons, the design needed an alternative approach.

Typical prescriptive code requirements are developed to provide a wide range of safe and robust solutions, but given their wide range of applicability, they can over-design in some cases. By contrast, performance-based design allows for innovative approaches that address only expected hazards, giving the flexibility needed to meet demanding project goals but still enabling a robust fire protection strategy that meets the level of safety demanded by the codes.

With the PTB roof, performance-based methods allowed the design team to align the fire protection strategy, using these methods to assess and evaluate the inherent fire resistance of the members, and ultimately justify a largely unprotected roof based on performance rather than just the prescriptive rules in the code.

The analysis relies upon basic physics: should a fire occur, the fire and subsequent smoke and heated gases will rise to the ceiling in a plume, which will cool through entraining air as it rises. This smoke and heated gases will in turn heat the structural steel, and fire protection is applied to insulate the steel from the elevated temperatures.



44.

Performance-based design respects the fact that for sufficiently low exposures, the structural steel can retain the needed strength to support the building.

Proven techniques are available to calculate fire sizes, smoke flow, heat transfer to the steel and subsequent strength available, and to ultimately calculate the performance of unprotected steel during fires.

The scope of the analysis was focused on specific structural members that support or are integral to the roof in the Departure Hall (third level), International Hub (second level and mezzanines), Domestic Concourses (second level), and International Concourses (second level) (Fig 44).

Prescriptive code requirements

The US National Fire Protection Association (NFPA) Building Construction and Safety Code (*NFPA 5000*)[5] applied to this project. It permits roof steel to be unprotected when it is more than 6.1m above a floor below being used for assembly and other similar occupancies; protection is required for buildings with retail or storage occupancies.

As with most international airports, retail units and kiosks are important to KAIA's overall business model, and will be integrated throughout the PTB, so even though the roof structure is typically >6.1m above the floor, the code required the roof and structural members supporting it to have one-hour fire protection.

The performance-based approach

NFPA 5000 also provides for a comprehensive performance-based alternative to prescriptive requirements; the performance-based design must:

- define goals and objectives
- determine expected hazard scenarios
- develop a comprehensive fire strategy to address and mitigate expected hazards
- perform engineering assessments to demonstrate that the fire protection strategy effectively meets the goals and objectives, and
- adequately document the design.

Goals and objectives

Fire safety goals are given within *NFPA 5000* as:

1) "to provide an environment for the occupants inside or near a building that is reasonably safe from fire and similar emergencies," and

2) "to provide reasonable safety for fire fighters and emergency responders during search and rescue operations."[5]

These were further refined into performance criteria. For steel members heated by a fire in the building, the analysis referenced the American Society for Testing and Materials code *ASTM E119*[6], which indicates that failure occurs when the steel is heated to 538°C for columns and 593°C for beams and roof assemblies. This is based upon the loss of 60% of the steel strength in normal temperature conditions.

Hazard scenarios

Arup's fire team carried out a comprehensive review of expected and stated uses for the space so as to develop a set of fire scenarios. These included retail spaces, kiosks and other uses typical of large international airports. From these scenarios, estimated fire sizes were developed.

Fire strategy

The strategy for eliminating fire protection on the structural steel took account of the large volume spaces, sprinkler protection, and special protection to the high fire load areas. All the areas in question have high ceilings (>5.5m) and large volumes, which allow smoke and gases from a fire to spread and cool, resulting in relatively low temperatures near the roof steel.

In addition, the terminal is fully sprinkler-protected; also, much of the floor area will be for circulation only. This means the fire load will be generally localised to kiosks, check-in desks, furniture, etc, and the expected fire size is small. Enclosed retail and office spaces are protected through a combination of one-hour fire rating and sprinkler protection.

Analysis

The analysis followed a first-principles fire engineering assessment. Computational fluid dynamics (CFD) modelling (Figs 45–46) was used to calculate the fire development and smoke, and elevated gas temperatures close to the members.

Heat transfer methods were used to calculate the steel temperature increase in each member due to the fire.

As the steel members are heated from the fire and hot gases, some lose strength. This strength reduction due to heating was accounted for in the structural model; affected members were input into the structural model to determine the system's structural performance. This analysis was repeated for a range of fire locations so as to determine the severe case locations.

Two types of structural analysis were performed:

1) a simple and conservative linear elastic robustness check where heated elements are removed and stability is deemed to have been lost if other elements exceed 100% of their capacity

2) a more complex non-linear analysis where the steel elements are heated and allowed to expand to check that forces or local buckling as a result of thermal expansion does not cause instability.

Results

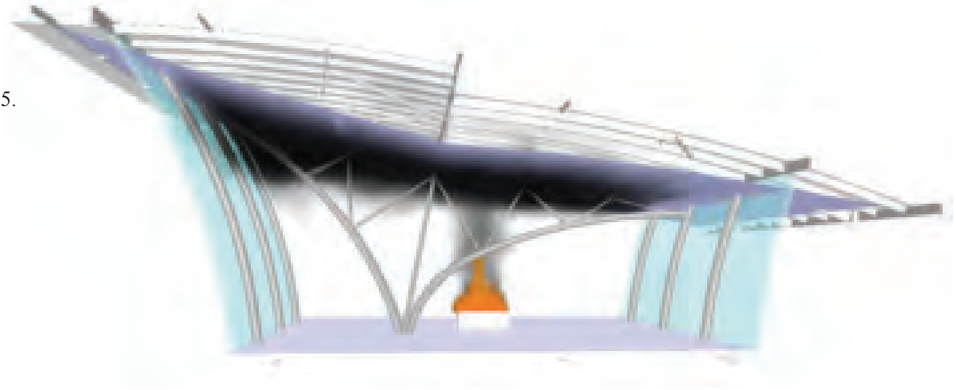
The results indicated that temperatures within structural members supporting gravity loads and exposed to expected fire sizes would generally be held below those established by *ASTM E119*[2]. One specific set of lateral load-supporting members did exceed the threshold, but the loss of these was acceptable as they could support their own weight and their loss had no effect on the structure's global stability.

A separate structural analysis of some of the roof members was conducted to verify that plastic behaviours of the heated members would not result in global failures. This analysis considered the impact of thermal expansion on the structure, and highlighted the robustness and redundancy in the various roof structures.

All these analyses relied on close collaboration between the fire engineering and structural teams, enabling Arup's overall team to quickly and efficiently pass critical data between different simulation platforms, and to share ideas and solutions.

The combination of information flow, efficient design iteration, and multidisciplinary design collaboration resulted in optimisation of the overall structural design — a process through which several members were slightly increased in size.

45.



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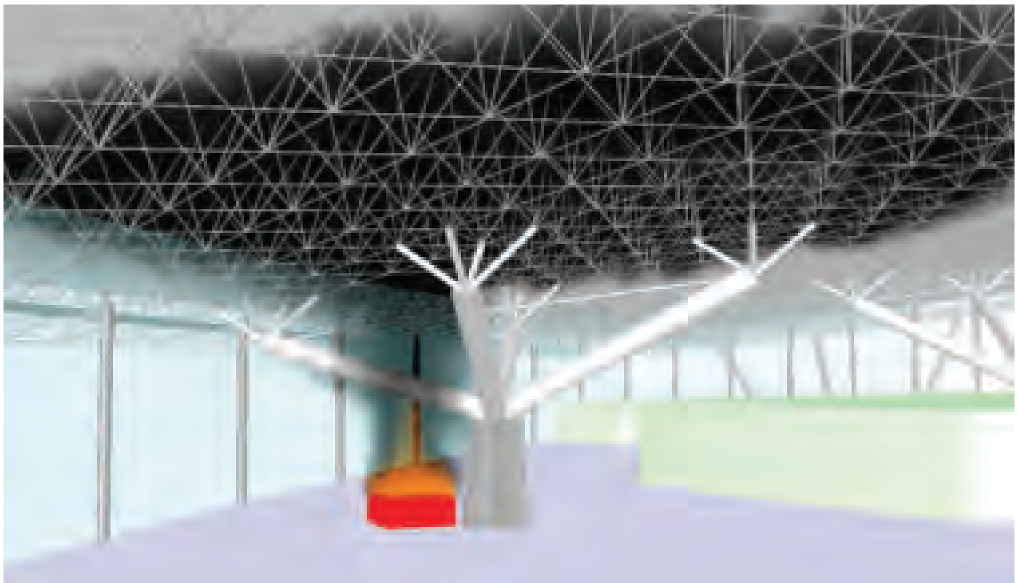


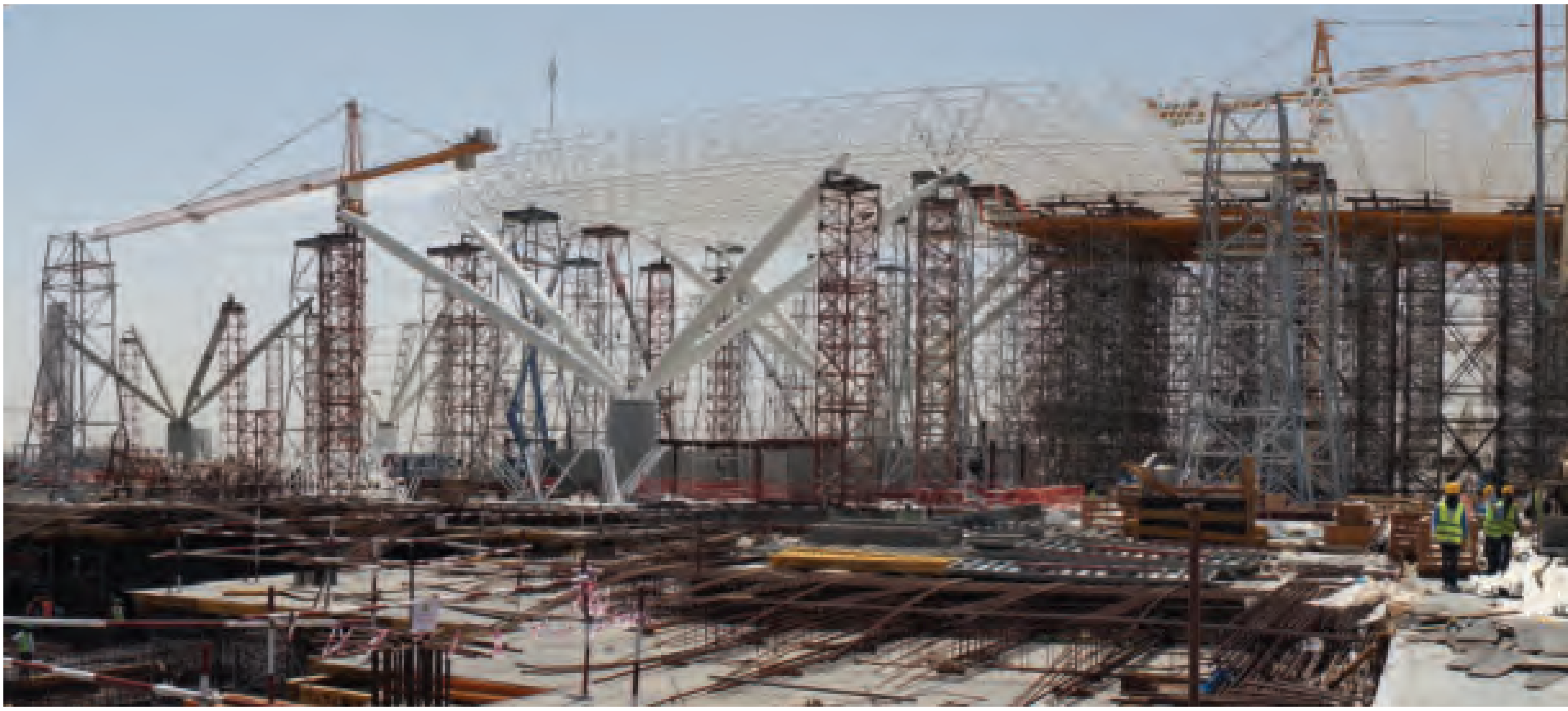
43. Rendering of Concourse.

44. KAIA terminal areas.

45. Domestic Concourse CFD model.

46. Departures Hall CFD model.

47 (overleaf). Peak construction in progress, April 2014.



47.

Conclusion

Engineering this huge terminal complex was a major opportunity for Arup, due to the short time available and the many design challenges. The team rose to those challenges to produce an efficient and distinguished structural design on time. Many Arupians — some no longer with the firm — in nine offices on three continents, contributed to that success. In addition to delivering the vast quantity of drawings reliably and on time, including obtaining approval of the calculations and drawings from the Engineer, this project demonstrated four special achievements:

Firstly, timing demanded that a fully developed design for the roof be produced in order to obtain competitive bids. These documents had to provide detailed design of the members and nodes, normally the specialist contractor's responsibility. Arup developed special software to process the design optimisation automatically.

Secondly, the fire engineering demonstrated that fire protection of the space frame members was not necessary below the 6.1m height, as would have been required per code. This was a decisive factor in making the space frame design feasible.

Thirdly, the design included long jointless reinforced concrete basement and floor structures constrained from movement by stiff wall elements. These had to be designed to tight crack width criteria and are subject to temperature and shrinkage stresses. The potential high water table with contaminants outside the wall made it necessary to minimise crack widths in the wall and floor.

Fourthly, Arup devised a rational breakdown of the work and its processes that enabled the design of each portion of the facility to be as self-contained as possible, and wholly managed by individual design teams. In this way the nine Arup offices involved could contribute to achieving the design goals and delivery on time. The size, distinctiveness and physical separation of the buildings and their segments allowed the scope to be clearly divided, with standard methods of production, project delivery, and document control to ensure consistency.

Key to the success of this approach were the clear work breakdown, quality leadership in the various offices, clear protocols and design standards, a common BIM platform, and regular communication.

Construction continues to proceed apace towards the opening of a project that will fulfil the client's aspirations for an international airport terminal that ranks with the best in the world.

Acknowledgements

"Arup's design efforts for Package 421 were instrumental in the successful delivery of the project." — SBG.

Special acknowledgements are made to David Scott, Nancy Hamilton, Ivan Jelic, John Flaherty, Karim Ezzeldin, and Hossein Mozaffarian for their leadership and interface with the the Saudi Binladin Group and with Dar Al-Handasah. Their co-ordination efforts were vital to the project's successful delivery.

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Project credits
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Space frame contractor: *Roots Steel International/ Jinggong/MERO* Wind tunnel testing agency: *RWDI*.

Image credits
1, 4a–c, 4e *Aéroports de Paris Ingénierie*, courtesy *Saudi Binladin Group*; 2, 4d, 4f, 10–11, 30, 43 *Areen Aviation*; 3, 6–9, 12, 17–20, 23–25, 28–29, 32, 34–35, 37–42, 45–46 *Arup*; 5, 13, 44 *Arup/Nigel Whale*; 14–16, 26–27, 31, 33, 36, 47 *Roots Steel International/ Jinggong/MERO*; 21–22 *Nigel Whale.*

Shenzhen Stock Exchange

Location
Shenzhen, People's Republic of China

Authors
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Goman Ho Junko Inomoto Florence Lam Andy Lee Patrick Leung
Rory McGowan Chas Pope Alba Xu

History and background

Shenzhen, located in southern China about 30km north of Hong Kong, has grown from a small fishing village to a city of over 10M people since being designated the first of the country's Special Economic Zones in 1979. In just 35 years it has become China's richest city, and home to many of the country's most successful high-tech companies as well as to significant foreign investment.

This made it an ideal location for China's second stock exchange after Shanghai. The Shenzhen Stock Exchange (SZSE) was founded on 1 December 1990 with the intention of being — as China's equivalent to the US NASDAQ — a venue for trading in high-tech and new high-growth securities. SZSE has grown to become the ninth largest stock exchange in Asia by market capitalisation, with over 1500 listed companies at a total share valuation of more than US$1.3tn in 2013.

Its first location was in Shenzhen's Luohu commercial district, close to the original Hong Kong border crossing, but within only 15 years the city had outgrown Luohu, and SZSE its headquarters. In February 2006, SZSE announced an international design competition for a new landmark building in a brand-new business zone in Futian district, 6.5km to the west (Fig 1).

The brief was for a 265 000m^2 building (180 000m^2 above ground) containing all stock exchange facilities as well as commercial offices for rental. Flexibility was needed for future expansion of SZSE's accommodation, and the building was also intended to be the first to achieve the highest, three-star, rating in China's new green building code[1].


1.

The design team

Arup was commissioned to provide engineering and consultancy input for structural, building services, façade, geotechnical, and fire engineering, vertical transportation, sustainability, building intelligence and lighting. The firm led the design from concept to the end of the design development phase, including structural approvals, working with engineers from Shenzhen General Institute of Architectural Design & Research (SADI), which acted as the Local Design Institute (LDI). Following a joint competition effort from London and Beijing, the project was led from the Beijing office, with support from Hong Kong.

OMA started the project from its Rotterdam office, and construction was overseen by its Hong Kong office as well as a site office in Shenzhen, working day-to-day with the client and contractors throughout to ensure that the design intent was maintained through to delivery: a key factor in ensuring a high quality architectural outcome. OMA brought in other specialists during the project including Inside/Outside (landscape and interiors) and 2x4 (signage).


2.

3.

4.

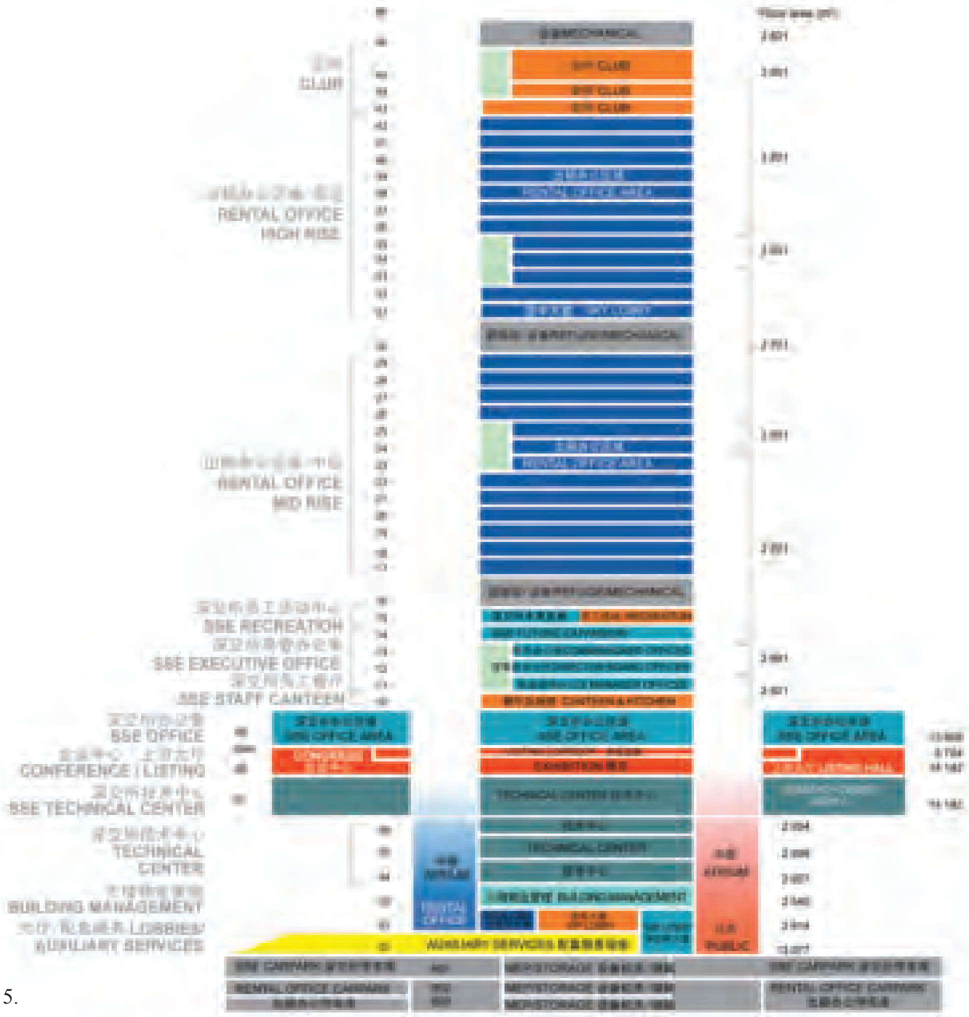
Architectural concept

The winning scheme (Fig 2), developed by Rem Koolhaas's practice OMA in close collaboration with Arup, places the stock exchange functions in a dramatic three-storey podium floating above ground, "lifted by the same speculative euphoria that drives the market" (Figs 3–4). This podium cantilevers on all sides from the building's other main element, the 246m tall tower.

By building the podium with its under-surface 36m above ground level, a covered urban plaza is created, large enough to accommodate public gatherings and performances. In addition, the podium roof becomes an elevated landscaped garden for the building's employees and visitors. The upper levels of the 46-storey tower have the leasable office space plus offices for SZSE staff, with the top floors containing an executive clubhouse (Fig 5).

Two 17m wide atria on either side of the tower provide separate entrances for the different users, and are surrounded by an outer braced tube structure that provides further support for the elevated podium. A textured, translucent all-glass façade causes the building to sparkle and change appearance according to the lighting conditions.

Three levels of basement accommodate car parking and plantrooms, while a single-storey plinth over part of the site contains retail areas. Technical floors are at various levels throughout the building height.



5.

1. Shenzhen Stock Exchange in the context of its city surroundings.

2. Rendering of competition scheme.

3–4. The architectural concept of "lifting" the base of the building. By constructing the podium, which houses the main stock exchange function, several storeys up the tower, a generous public plaza is created at ground floor level.

5. Architect's elevation, showing the disposition of the building's internal spaces.

Structural concepts

Shenzhen is in a region prone to severe typhoons and subject to moderate seismicity. Both factors influenced the tower design, but the main focus was to achieve a robust, rational and economic solution for the cantilevering podium, whose floor plates measure 163m x 99m in plan and extend up to 37m from their supports (Fig 6).

At the competition phase the team decided that the podium and tower should be combined as one structure, with the tower and atrium perimeter columns providing vertical and lateral support for the cantilevering structure. The podium itself would be framed by a robust 3-D array of steel transfer trusses over its full 24m height. The form of the primary structure was thus rationalised as a "triple tube" system plus the cantilevered podium frame (Fig 7).

Initial analysis showed the podium and its supports accounting for up to 60% of the structural steel in the building, despite representing only 25% of the superstructure floor area. Arup therefore did extensive optimisation to identify the most efficient and rational arrangement for the structure and its supports, and studied and advised on possible construction techniques to demonstrate how the structure, with steel elements up to 4m^2 in cross-section, could be built. Ultimately, some 39 000 tonnes of steel was used, all erected within 18 months.

Tower structure

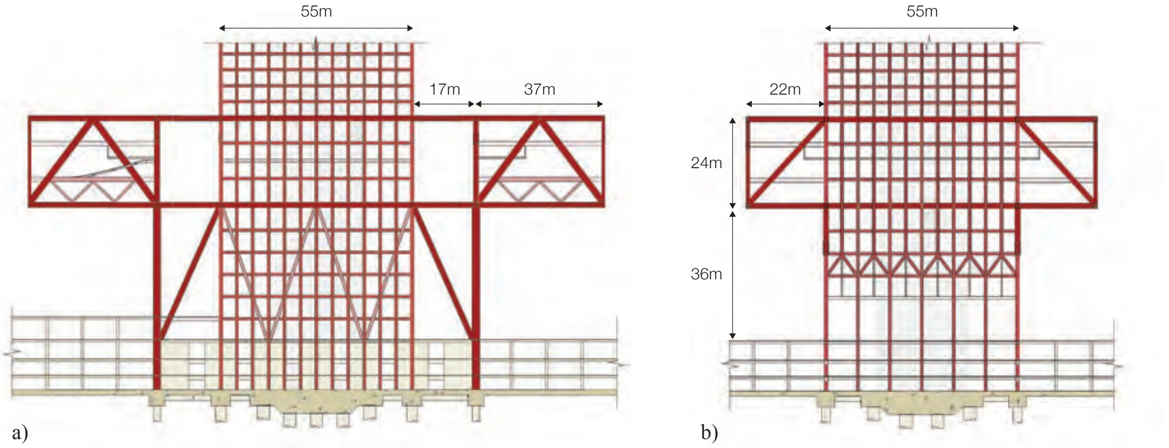
The tower's lateral stability system consists of its reinforced concrete core, perimeter moment frame of closely spaced composite (steel + reinforced concrete) columns, and deep steel beams. The composite sections give increased ductility and help control the steel weight of the building.

The moment frame is continuous through the podium levels down to the foundations. Alternate columns on the east and west faces are transferred above the atrium floors via belt trusses between levels 4–5 (Fig 6b), to give wider column spacing at the entrance lobby level. In addition, some columns transition into steel-only sections (or concrete-filled boxes) for compatibility of connection with the steel podium trusses that run concurrently with the tower perimeter frame on the north and south sides.

The tower floor slabs act as diaphragms connecting the core to the perimeter frames. The combined system carries the vertical and lateral forces into the foundations, which are hand-dug caissons up to 3.5m in diameter founded on the rock layer 15m~25m below the raft slab. Each caisson can carry a load of up to 99MN.

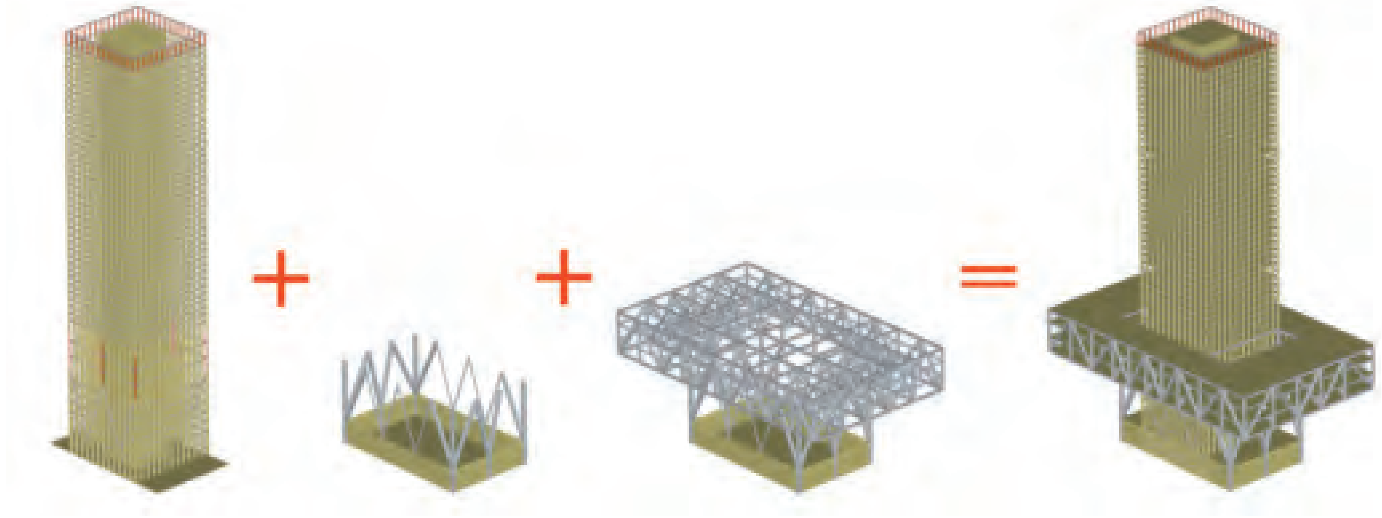
6. Podium key dimensions:
a) East–west section;
b) North–south section.

7. Structural concept.



6. a)

b)



7.

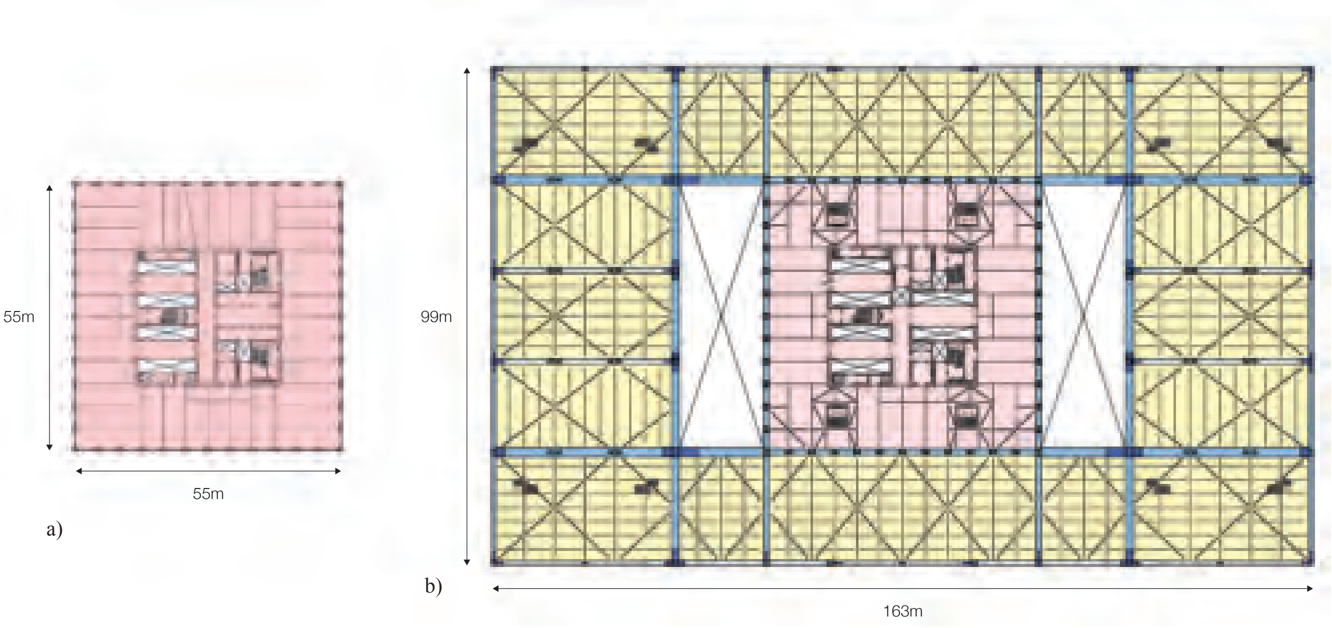
Tower core ("inner tube") + composite perimeter frame ("intermediate tube")

Trussed "outer tube" around atrium

Steelwork 3-D mega-truss cantilevered podium

Components coupled together

8.



9.

The tower floors are 55m x 55m on plan, and framed using lightweight steel beams spanning up to 13m and working compositely with 150mm concrete slabs on permanent steel formwork (Fig 8). The ceiling services zone is integrated with the steel beams. The three-storey basement is framed in reinforced concrete.

Podium structure

The cantilevering podium contains three floors, a mezzanine and an accessible landscaped roof. The floors are framed by 2m deep steel floor trusses and secondary beams working compositely with concrete slabs up to 180mm thick on permanent formwork. This framing spans up to 22m between the 24m high primary trusses, enabling the very large column-free spaces required by the brief, in particular for the main listing halls and auditoria (Fig 9).

8. a) Tower structural floor plan, and b) Podium structural floor plan, showing primary trusses (blue) and diagonal in-plane bracing.

9. Podium framing showing services ducts running through floor trusses.

10.

The team selected the primary truss layout (Fig 11) after comparing several options, taking into account structure weight, robustness and architectural planning. Since the stiff network of trusses and braced columns would tend to attract lateral loads from the tower core and columns (similar to an outrigger system), it was also necessary to adjust the initial design to simplify the load path for seismic forces. The top and bottom floors try to act as the flanges of the cantilever, and thus attract significant in-plane forces, so horizontal steel braces were introduced to channel these forces into the primary trusses.

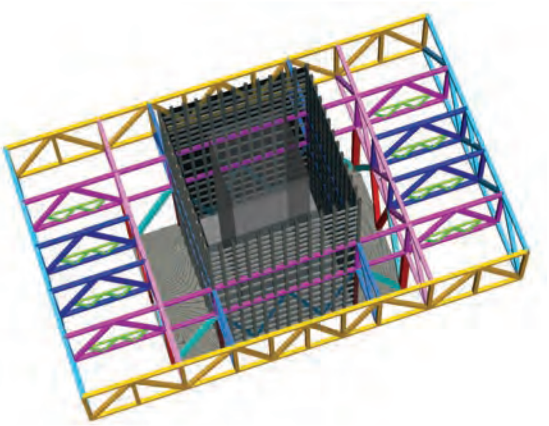
The podium gravity loads are primarily carried by four vertical and four inclined columns, all on the outer faces of the entrance atria (Fig 6a). The sheer size of these meant that their arrangement had a major impact on the building's architecture, so many variants were studied before a solution acceptable to client, architect and engineer could be identified.

The podium corner columns are designed as 2m x 2m concrete-filled steel boxes, and each carries some 156MN in the ultimate condition. Given their critical importance, additional studies were made, including blast performance and finite-element connection analysis (Fig 12). The latter was essential for understanding the load paths through the joint, and to ensure that the connections would be stronger than the connecting elements (ie so that any failure stemmed from ductile yielding of the elements themselves, not brittle failure of the welds).

The lateral loads applied to the podium are primarily resisted by 1.7m x 1.7m steel diagonal braces in each face of the two atria. In the basement, this bracing is transferred into a series of concrete shear walls, with encased steel columns to carry the concentrated vertical loads.

Analysis

The raised podium makes the building seismically irregular, so its design lay outside the scope of the prescriptive Chinese codes of practice. Arup's analysis demonstrated that gravity and wind load cases would govern most aspects of the design, but nevertheless the structure had to be reviewed and approved by a panel of government-appointed Chinese structural experts who would scrutinise the structural system, its seismic resistance, and damage control mechanisms.



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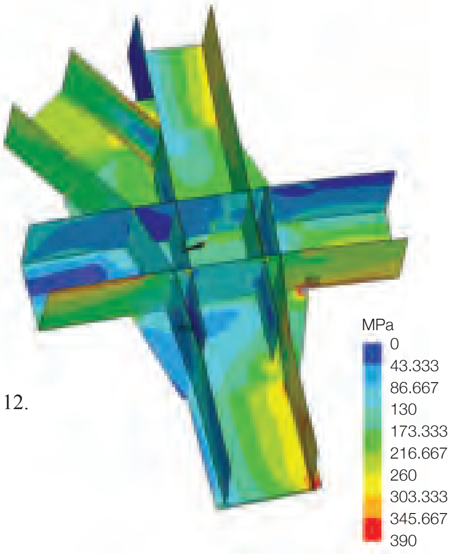


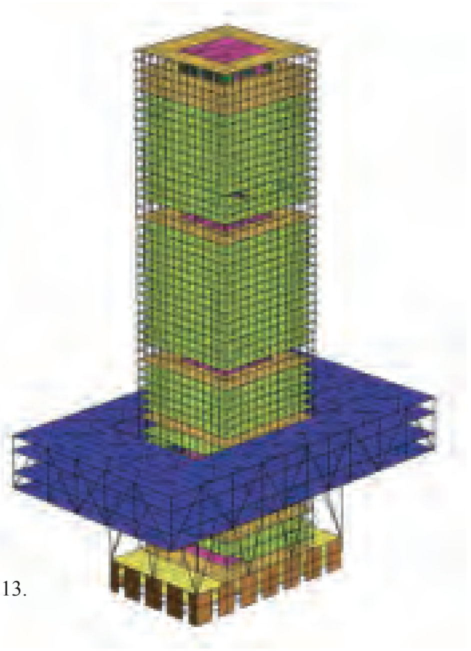
12.

10. South elevation.

11. Podium truss layout.

12. Connection analysis.

13. Non-linear structural analysis model.



13.

Arup proposed a performance-based design approach so as to achieve set requirements at different levels of seismic event (ie no "structural damage" during a 50-year return level 1 earthquake, "repairable" under a one-in-475-year level 2 event, and "no collapse" in a rare one-in-1600-year level 3 event). The team carried out explicit and quantitative design checks using appropriate linear and non-linear seismic analysis to verify the performance for all three design earthquake levels.

The elastic analysis and design were done with two different software packages as required by the Chinese design codes — in this case *ETABS* and *MIDAS*. These were used to analyse the performance under gravity and wind loads, as well as level 1 seismic loading using code and site-specific response spectra.

The analysis was verified by the results of multiple linear time history analyses. Key elements were also checked elastically, with assumptions of factored properties to simulate the structural damage under level 2 and level 3 events to ensure that the necessary performance targets were met.

The elastic analysis demonstrated that the tower perimeter frame would attract sufficient lateral shear force for the tower to act as a tube-in-tube structure: effective sharing of this lateral force between core and frame is a key requirement of the Chinese "dual system" seismic design philosophy.

To check the structural performance during a severe earthquake, a non-linear time history analysis was carried out in Oasys *LS-DYNA* (Fig 13). This simulation subjected the structure to a ground motion excitation history, and considered both material and geometric non-linearity. It enabled the team to confirm that the no-collapse condition would be satisfied, and that structural elements would remain elastic or deform in a controlled plastic manner.

The post-buckling strength of key podium elements was also checked, to ensure these would retain enough residual capacity to hold up the structure after resisting a severe earthquake. Certain key elements had to achieve enhanced performance levels (for example, no yielding/buckling of podium primary trusses and supports under a level 3 earthquake).

Wind tunnel tests at Shantou University confirmed that any movement would satisfy human comfort requirements, in particular vertical acceleration of the podium. The response of the overall podium structure to human-induced vibration was also checked, in addition to standard dynamic checks of each floor.

Arup's ability to apply recent experience of designing similar buildings in China (including Beijing's CCTV Headquarters[2]) to the SZSE analysis process was a major factor in the team securing expert panel approval within just four months.

Construction

SZSE's unusual structural form led to some specific construction issues. From early in the design Arup studied possible methods to identify safe, practical and economic ways to erect the raised podium. These included piecemeal cantilever erection of the primary trusses using crawler cranes, as well as conventional propping and falsework.

It became evident that the choice of construction method could impact the design of the permanent structure, so the team specified a range of measures to mitigate this; for example late-cast strips in the podium floor slabs, concreted after most of the cantilevers' weight was applied so as to avoid them attracting significant in-plane gravity forces. The tower also had to be constructed to a specified minimum height before de-propping the podium, to ensure a sufficient permanent counterweight against tensile reactions in certain columns caused by the cantilevering trusses.

The groundbreaking ceremony took place on 22 November 2007, with excavation and foundation construction following during 2008, before the main contractor (China Construction 3rd Bureau) took over in January 2009. The contractor ultimately chose to construct the podium on temporary props (Fig 14), erecting the steelwork and permanent formwork prior to de-propping, after which concreting the slabs began. Just 18mm of vertical movement was measured at the cantilever tip during de-propping — very close to Arup's analytical estimates.

Steel erection was completed in June 2010, only 18 months after the main contractor started work, with the building handed over to the client in October 2013.


14.

15.

14. SZSE under construction showing podium props.

15. SZSE under construction with podium props removed.

16. East elevation of completed building, showing the podium roof garden.


16.

Building services

Sustainability

Sustainable design is rapidly gaining ground in China, but the concept of green building is still relatively new: the first Chinese standard[1] for green building design was only introduced a few months before the SZSE design began in 2007. Arup's team worked closely with all disciplines to communicate the requirements for achieving the three-star rating required by the client, and to manage the implementation of a holistic sustainability strategy.

The headline sustainability features include very high levels of resource efficiency, eg saving 40% more water and 20% more energy than required by conventional design codes, and a self-shading façade design. The façade depth passively shades the building (and eliminates glare) during most of the day the year round, so very little internal shading is needed (Figs 17–18).

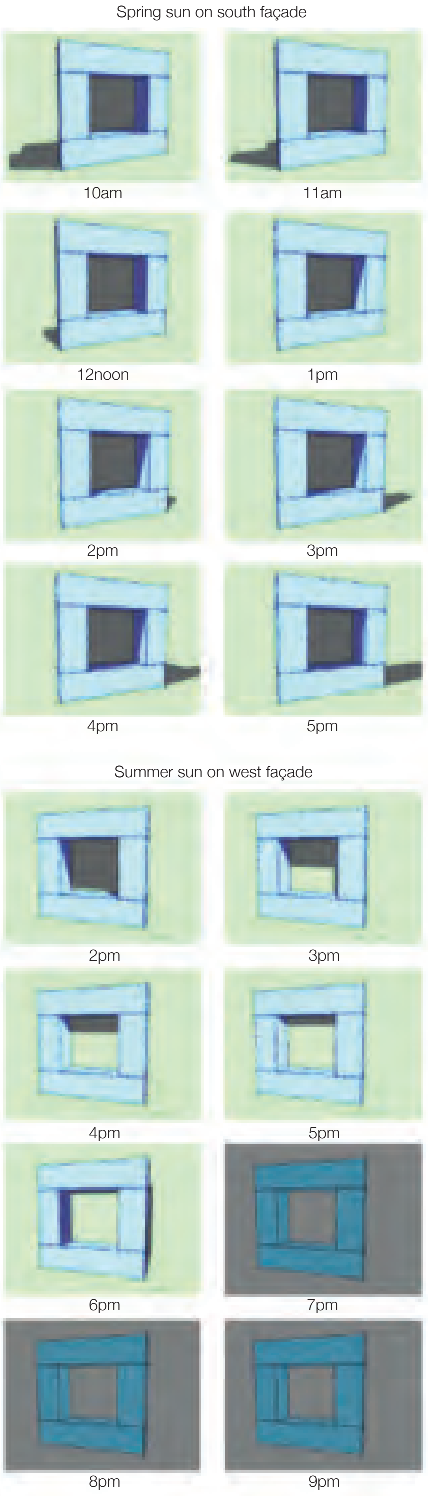
In addition, operable vents in the tower windows enable natural ventilation of offices during the cooler months. A computational fluid dynamics (CFD) model was developed to analyse the effectiveness of the proposed vent concept and ensure occupant comfort (Fig 19).

As well as being a notable amenity for staff and visitors, the landscaped roof of the cantilevering podium is the major source of rainwater collection, reducing run-off into sewers. While the structure must be locally reinforced to support the earth loading, this exemplifies how the design considered the building's total sustainability, rather than optimising a single discipline alone.

Resilience

Since the financial consequences of a shutdown of the exchange would be severe, resilience was the other major driver for the building services design. All systems for the major technical rooms had to be designed for continuity of operation, so the design included back-up systems, independent supplies and spare capacity.

The critical spaces include the technical centre — the operation and management space that supports the daily operation of the securities market, and the digital heart of the stock exchange. It has the highest safety and security requirements, and occupies the three floors in the tower immediately beneath the podium (Fig 20).



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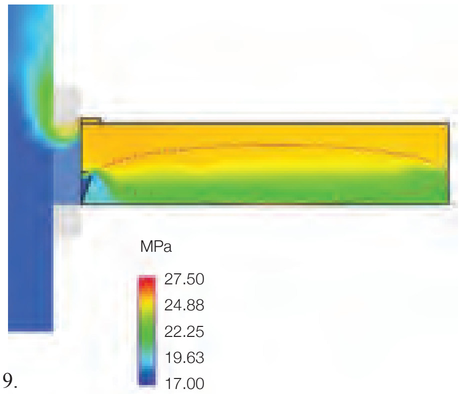

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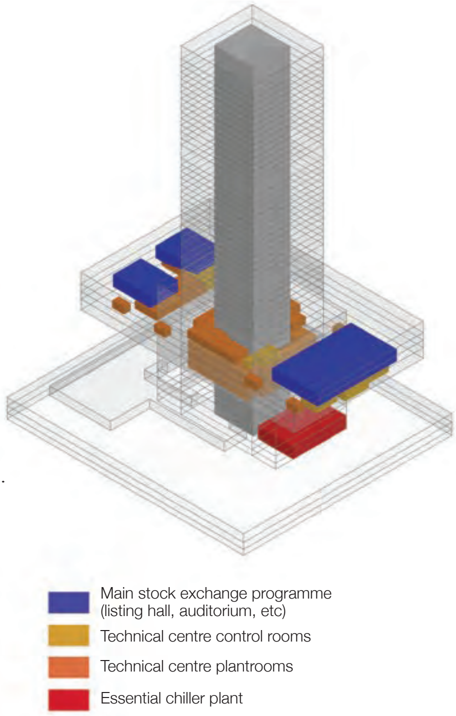


20.

17. Self-shading from façade system.

18. South and west façades showing deep window recesses.

19. Natural ventilation analysis.

20. Location of key technical rooms.

21.

21. Cooling towers (beyond trees) incorporated into landscaping.

22. Air-conditioning water schematic: The chilled water risers are supplied at 5°C from the main chillers and returned at 12°C. Plate heat exchangers are provided at mechanical floors to limit the maximum pressure in the pipework.

23. Typical office VAV system.

Air-conditioning systems

Shenzhen lies just south of the Tropic of Cancer, with a warm, monsoon-influenced, humid subtropical climate due to the Siberian Anticyclone. Winters are mild and relatively dry, and frost is very rare. The monsoon reaches its peak intensity in summer when the city experiences very humid and hot conditions with temperatures of almost 40°C.

SZSE is cooled by a central air-conditioning plant, consisting of two distinct systems:

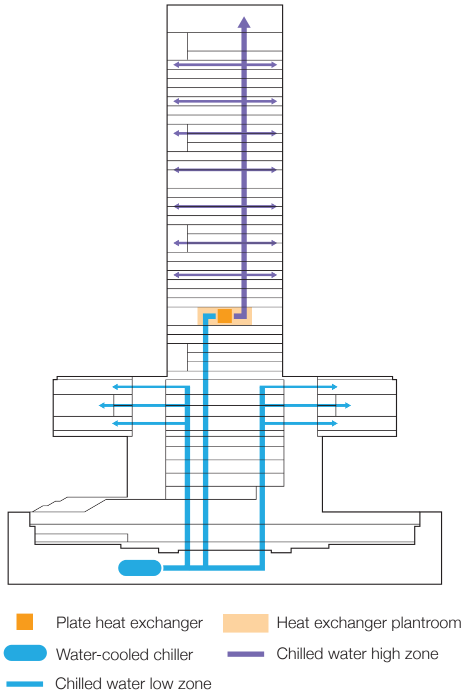
- the main chiller plant, with four water-cooled glycol chillers and associated ice storage plant, serving the rental and SZSE offices, executive club and commercial areas; the plant uses low-tariff electricity at night (just ¼ of the daytime peak tariff) to produce and store the cooling energy in ice tanks; this is released during the daytime to reduce high tariff electricity use and demand on the chillers, giving savings in both chiller plant capacity and operation cost
- the essential chiller plant with three water-cooled water chillers serving critical areas including the technical centre, trading hall and data centre; these chillers, associated cooling towers, and pump sets are connected to diesel generators to ensure continuous operation should the mains power fail; the main chiller plant can also act as a standby system for these critical areas if necessary.

Heat rejection is by cooling towers in the basement, connecting to the outdoors via ventilation shafts integrated with the landscaped northern area of the site (Fig 21).

A ceiling-supply variable air volume (VAV) system was chosen as the air-side system to the typical office floors:

- It has a high degree of flexibility for serving perimeter zones, cellular offices and large internal zones from the same supply air ductwork.
- It provides an environment responsive to different heating and cooling loads in any particular area, with each VAV box controlled by its own in-room thermostat and modulated as needed to maintain the necessary environmental requirements, as well as enabling the system to self-balance (ie avoid temperature gradients, etc, across a room).
- It requires minimal maintenance in the tenant space.
- It makes free cooling possible, ie use of outside fresh air during spring, autumn and winter to eliminate the emitted heat from lighting and computers (thus reducing demand on electric chillers) and improve internal comfort; changeover of summer/winter operation mode is controlled by the building management system (BMS).

A decentralised air-handling system is used, with two VAV air-handling units (AHUs) within the core on each typical office floor (Fig 23). Enthalpy wheels on the service floors provide heat recovery and dehumidification from the cooled/dry exhaust air to the hot/humid incoming fresh air, and deliver fresh air to the AHUs. Additional fans enable free cooling when allowed by the external temperatures (Fig 24 overleaf).



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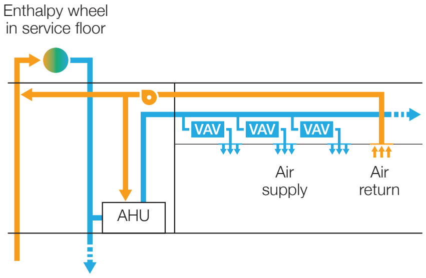

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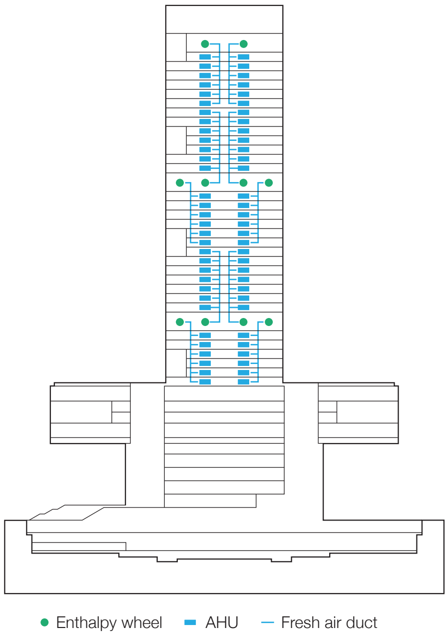


24.

Other energy efficiency systems

- The AHUs are equipped with pre-filter, high-efficiency bag filter, and bio-oxygen generator to improve the indoor air quality — crucial in Shenzhen due to the city's relatively poor outdoor air quality.
- Kitchen exhaust is treated prior to atmospheric discharge, using grease removal equipment including electrostatic precipitators and water scrubbers.
- Podium air-conditioning exhaust is discharged to the level 7 soffit, providing a cooling effect to the envelope and thus reducing fabric heat gain.
- The fresh air ratio is increased to promote the use of free cooling in the mild season and to reduce chiller plant energy usage.
- Carbon dioxide (CO_2) sensors are installed in office AHUs to control the indoor CO_2 level to an acceptable level. At times of low occupancy, the fresh air rate can be reduced to save cooling energy.

24. Tower air supply schematic.

25. Air-conditioning and smoke extract from the podium, located in the roof garden.

25.

A computer room air-conditioning (CRAC) system was adopted for the technical centre's data centre and UPS (uninterrupted power supply) room, which requires an uninterrupted cooling supply and has stringent humidity control requirements. The CRAC units are located in a services corridor by the data centre, with bunded floors to separate the data centre from the corridor in case of water leaks. Supply air is blown from the CRAC units into the equipment room via the raised floor void and floor air grilles, and return air extracted via openings in partition walls.

To ensure reliability of the data centre cooling system, a redundant "N+2" system is used, with two additional CRAC units provided as standby. Should an accident occur and up to two CRAC units malfunction, the others can still provide full cooling capacity and keep the crucial data centre operating normally. "N+1" CRAC units are similarly provided to other technical rooms inside the technical centre.

Comprehensive utilisation of water resources

SZSE was one of the first Chinese projects to embrace the concept of "comprehensive utilisation of water resources". Though the schematic design began in 2007, "comprehensive utilisation" is still an advanced design concept today.

Recycled rainwater is used for irrigation, cooling tower make-up water supply, and other uses that require high water quality, while greywater is used for toilet flushing (Figs 26–27). Apart from being a primary contributor to the three-star green building status, the water recycling systems also provide significant economic benefit.

Due to air pollution and ground dust, the rainwater initially collected is not considered clean. The first 3mm of rainfall (around 6% of the estimated total rainwater quantity) is discarded and a further 12% stored for the roof garden and landscaping, so that 82% of the total rainwater can be recycled — some 47 600m^3 per year (Fig 28).

A cost-benefit analysis comparing the cost of treating and using rainwater against using municipal water confirmed that, over time, recycling would be beneficial.

Meanwhile, all wastewater is collected and treated by a membrane bio-reactor unit, the key equipment in greywater treatment for minimising smell and pollutants (Fig 29). The 100 000m^3 of greywater provided by this system is estimated to save some US$50 000/year.

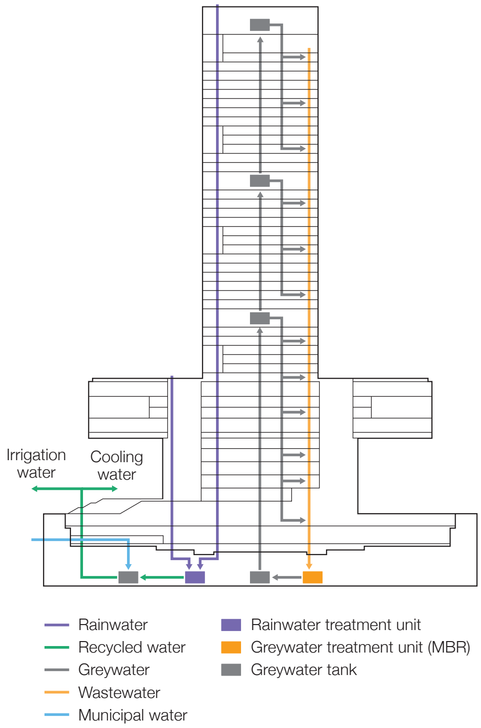
Improved living standards have focused increasingly on drinking water safety, so for these supplies the design includes a specialist treatment process (Fig 30). To prevent secondary pollution in the pipelines, the system is designed for increased flow velocity, and shallow pipe angles are reduced to stop water stagnation.

Solar hot water system

Due to the subtropical climate and the heat gains from lighting and office equipment, there is rarely a demand for much heating in Shenzhen. Space heating was thus not considered for typical office floors, though it is provided for additional comfort in the executive offices and club at the top of the tower.

Since the climate also supplies a high level of solar energy to the building, solar hot water heating and air source heat pumps can be used as heat sources in addition to conventional gas-fired water heaters. The inclusion of this renewable energy source contributes to the three-star green building award.

Solar water heating serves the club's guest rooms, as well as the service staff shower rooms. The air source heat pump provides spare heating capacity. It is predicted that 452 000MJ will be produced by the solar energy system, saving 16% of the building's heat energy requirements. This is in excess of the 10% energy saving required by China's green building standard[1].



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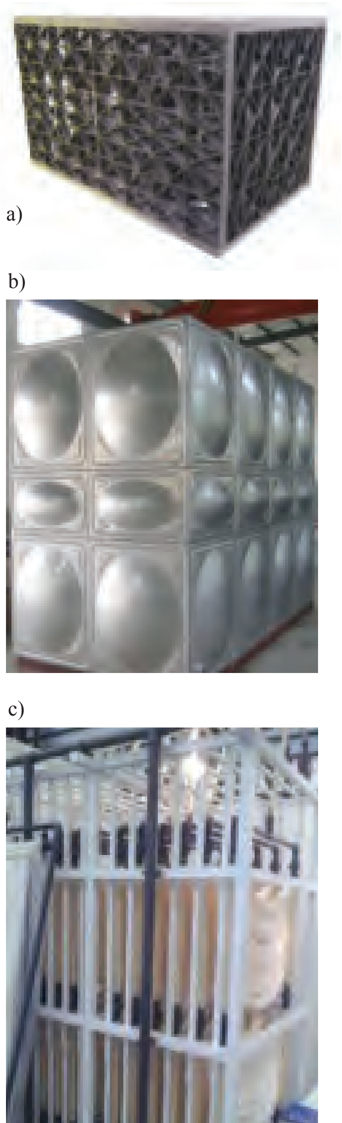
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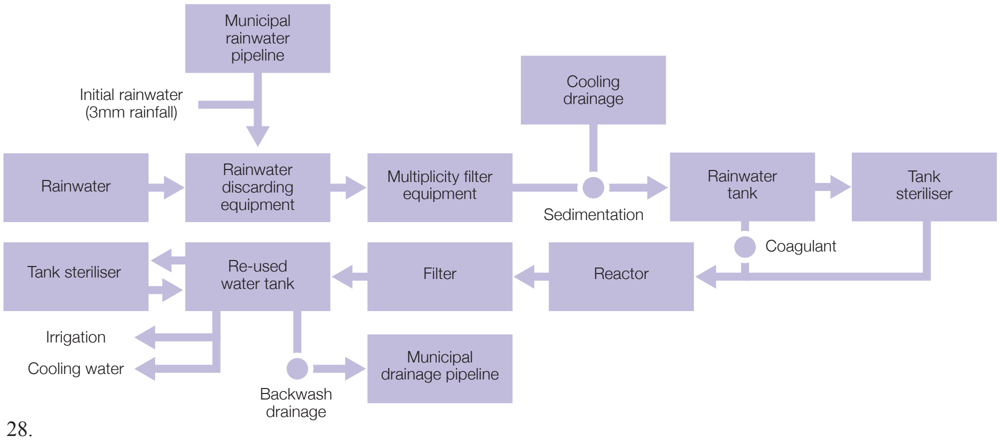

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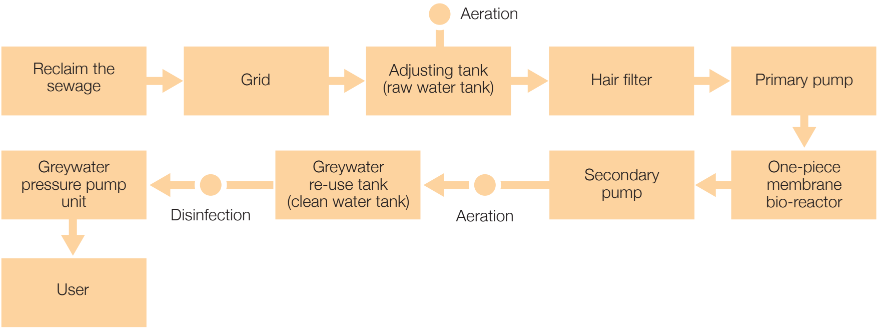

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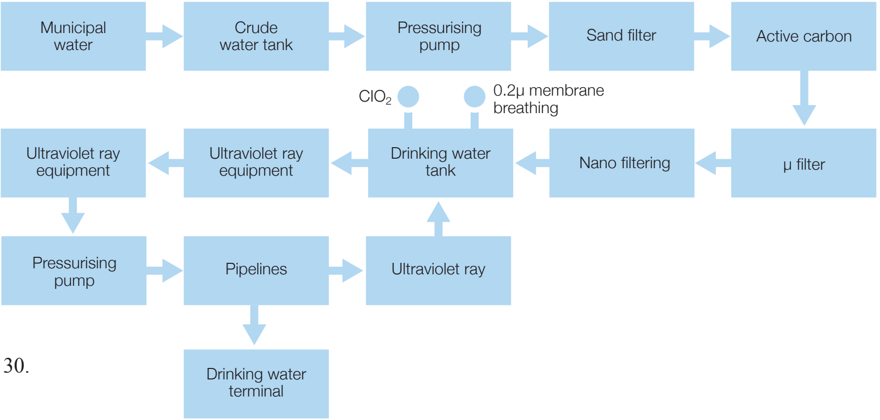


30.

26. Water systems.

27. a) Rainwater treatment unit
b) Greywater tank, and
c) Greywater treatment unit
(membrane bio-reactor).

28. Rainwater treatment process.

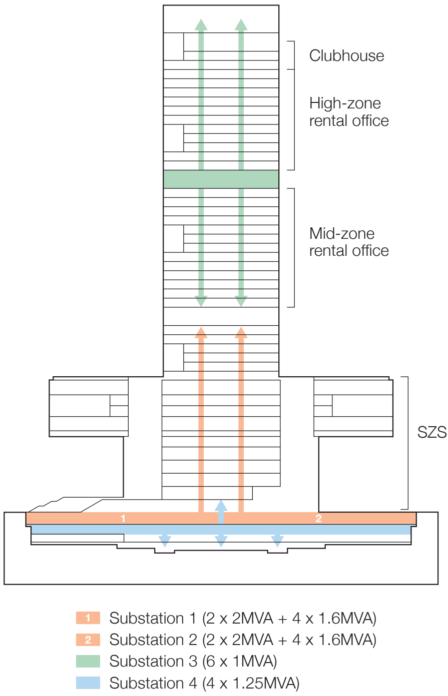
29. Greywater treatment process.

30. Drinking water treatment.

31 (overleaf). Podium roof garden.

31.

32.



33.

32. Listing hall.

33. Location of 10kV/400V substations.

34. SZSE lift diagram.

35. The west atrium.

Electrical power supplies, service strategy, and 10kV infrastructure

The trading areas, including spaces for future tenants involved in financial stock trading, require a highly reliable and resilient yet flexible electrical power supply system. This is achieved by applying a high-security, energy-efficient and reliable supply with close remote monitoring from the BMS.

An electrical network management system (ENMS) linked to the BMS effectively controls and manages the normal and emergency functions of the 10kV and 380V infrastructure. It allows peak demands to be identified, automatic load shedding and reconnection, the ability to choose maintenance periods based on historical operation and consumption; and cost monitoring, which enables tenant billing.

The district power network provides six 10kV supply feeders from three independent up-stream HV networks and substations to serve the estimated maximum electrical demand of 31 400kVA. Three feeders provide the base building power, with three more dedicated to the power supply for the technical centre.

The two main 10kV switchrooms are at B1 level, and a total of 22 transformers serve the building (Fig 33), each normally working at 70%–80% maximum loading but restricted to <50% for those serving the technical centre. The transformers are in linked pairs and normally supply separate circuits, but electrical interlocking enables power sources to be switched seamlessly in the event of one device malfunctioning.

There are two groups of emergency diesel generators, one rated at 4 x 2000kVA (again using an “N +1” system) for the technical centre, the other at 2 x 1600 kVA to supply fire, critical and tenant loading for the base building. The generators can start up and support the emergency equipment within 15 seconds of a power supply failure.

The brief required the system reliability for the technical centre to reach the international standard of 99.9995%, so an independent dual-source 10kV feed with 100% backup is fed to the technical centre. In addition to the emergency diesel generators which have eight hours’ capacity, two separate UPS systems ensure complete backup capacity.

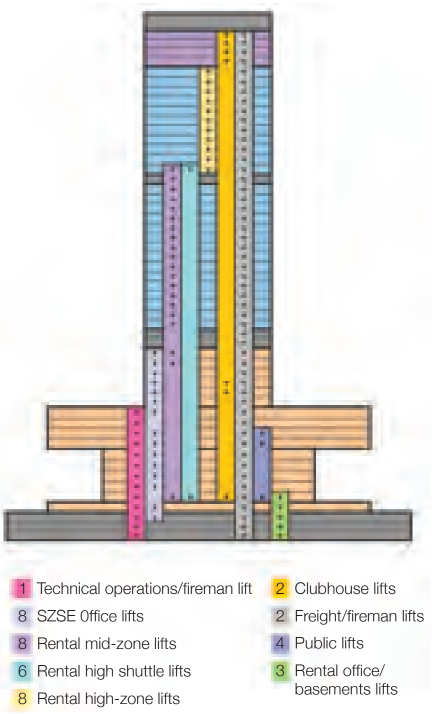
Vertical transportation

The brief stipulated that the lifts for the multiple different categories of users should be strictly separated, both for security reasons and ease of circulation. To achieve this, the lift groups were arranged into seven banks as follows:

- SZSE offices (including reserved floors for future expansion)
- rental offices (high/mid-zone)
- clubhouse
- technical operations (combined with the fireman lifts)
- freight deliveries (combined with the fireman lifts)
- underground car park
- public access to the stock exchange floors.

For the rental office lifts a “sky lobby” system was chosen, so as to minimise space-take in the core at the congested low levels. High-zone occupants take high-speed shuttles to a sky lobby at the bottom of the high zone of the rental offices, and then transfer to local high-zone lifts. The mid-zone offices are served directly from the base lobby. The sky lobby provides amenity facilities for all rental tenants. This system enables the mid- and high-zone lift shafts to be stacked, improving floor efficiency and enlarging leasable area. A total of 40 lifts serve the whole building (Fig 34).

34.



Building intelligence

The many different systems in modern commercial buildings — lighting, HVAC, security controls, electricity, etc — must be integrated so as to gather and present data intelligently.

However, such systems often use different platforms, so there is a risk of being difficult to manage and maintain. Given the complexity and technical needs of the SZSE building, the client specified an intelligent system that would be advanced, secure, reliable, flexible, convenient and efficient, as appropriate for a leading example of 21st century financial architecture.

Arup's concept design made use of state-of-the art information and building technologies, and the resulting BMS is designed to allow free mobility of the stock information, and provide effective and convenient management for the building. It has three major integrated components:

IT infrastructure
This provides a sharing platform for all intelligent systems with the building, enabling a proper interconnection and smooth information transmission between SZSE and the external information/communication network.

The system has live sharing of all information types — voice, data, image, multimedia, etc — allowing users to check or use any data at any time. The common platform also enables intelligent control of all equipment inside the building, helping to conserve energy and minimise labour costs.

Security management
As a high-profile financial building, SZSE has a high security requirement, so smooth and reliable surveillance monitoring is essential. Security systems including CCTV, access control, intrusion detection, etc, offer real-time situational information for security operations.

This integrated platform enables the standardised enforcement of security policies and procedures throughout the property.

Intelligent facility and building management
This integrates various building systems, including property management, car park management, and building automation. The integrated platform provides a unified real-time situation overview using an intelligent dashboard, giving operators and managers a clear overall picture of everything happening around the property.

35.

Fire safety

Arup's performance-based approach to fire safety was essential for justifying many of OMA's innovative design features, in particular the large raised podium and atria. If designed strictly in accordance with prescriptive fire codes, large spaces require compartmentation while escape distances are limited, resulting in major compromises to the architectural design intent. At SZSE, the key fire safety challenges were solved as follows, in all cases justified by fire engineering analysis and submitted for approval by an expert panel and the Fire Services Department.

Fire compartmentation

The main stock exchange spaces in the podium, including the listing hall and conference rooms, far exceed the code limitations on fire compartment size.
To avoid having to introduce fire curtains, the Arup team justified the safety level of an enlarged compartment through qualitative and quantitative analysis to assess the available and required safe times for all occupant egress.

Smoke control

Smoke spread analysis was carried out to develop suitable smoke control systems for the large atria and major spaces, to ensure sufficient time for evacuation and design the smoke exhaust systems.

Evacuation

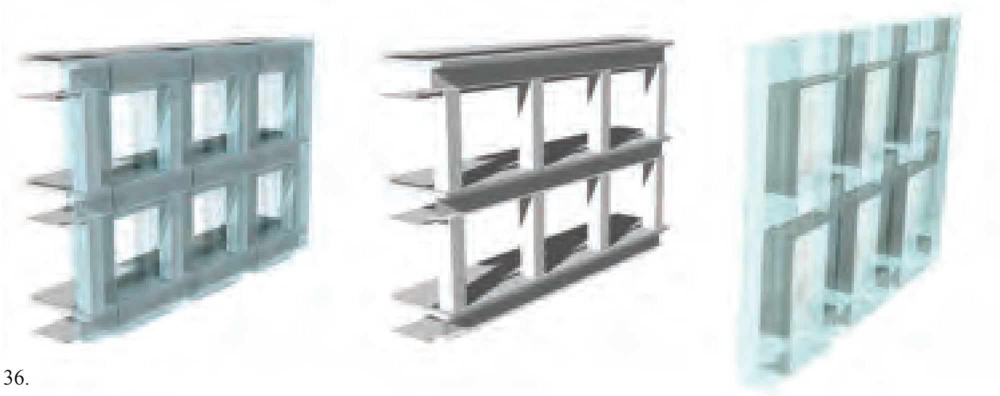
The distance from the corner of the raised podium to the corner of the tower is some 60m, an escape distance well beyond the code limit. The team thus proposed an innovative upward evacuation from the podium floors to the landscaped roof.

Fire protection systems

The 36m high entrance atria required special considerations for the design of the fire alarm and automatic extinguishing systems. In particular, typical sprinklers would be ineffective, so long-distance "throw" sprinklers were used instead.

Fire resistance of the steel structure

A performance-based structural fire protection design was adopted for the podium trusses. Based on a series of design fires, the steel element performance was analysed so as to develop a reasonable and cost-effective structural fire protection strategy to meet the requirements of both architectural finish and fire safety.



36.

37.

Façade

The architectural concept for the façade was to clad the structure in glass, creating a "fluid translucency" that would reveal the construction while simultaneously rendering it mysterious and beautiful (Fig 36). This became a conceptual system of textured, patterned glass panels without frames and with open joints, supported on minimal fixings from the structural beams and columns, and surrounding large clear windows with low-level openings for ventilation. Arup's involvement began as OMA started to develop this innovative concept into a detailed design.

The façade system design was lengthily scrutinised at various project stages by a panel of experts comprising academic professors, design professionals, and materials specialists from the local façade industry to assess the suitability, performance and cost-effectiveness of the team's proposals.

Their main focus was the application of pattern glass to the elevations; there was no global precedent for the use of such glass as external cladding for a high-rise, so no local or international design codes could be referenced. With the help of local glass manufacturers, the team therefore embarked on a research study aimed at developing a set of production standards and rules for the design and construction of pattern glass; this was finally accepted by the panel of experts.

Textured glass, made by passing between specially engraved rollers, is commonly used for interiors and applications requiring privacy such as bathroom windows, but there was no Chinese code for such glass when toughened or heat-strengthened — treatments that would be necessary for this type of application. The team therefore used evidence of heat-treating and laminating textured glass on other projects around the world to gain expert panel approval.

Finding ways to fix the heat-treated, laminated, patterned glass panels was also a key area of feasibility. The architect preferred to have a clean system without expressing any mechanical fixings, so structural silicone sealant was proposed instead of conventional bolted fittings: Arup was able to demonstrate that the panels could be attached without bolts and remain secure even if badly damaged. The patterned glass panels were pre-glazed onto sub-frames to form cassettes, which were hoisted up the building and mechanically clipped onto the backing frames that had been pre-installed on the structure. This was a much faster process than the original bolted approach.

The framing and ventilating options for the windows were also developed, including exploring the feasibility of bringing ventilation air in through the joints in the glass rainscreen cladding. Eventually, a low-level opening vent was found to be the most practical and effective.

Several options for the translucent glass cladding were developed to a prototype stage by competing façade contractors, and full-scale mock-ups were constructed for evaluation. This allowed assessment of the visual effects of alternative fixing systems, and mitigation of the risk of air flowing through open joints and staining the back of the glass. In addition, the structural strength and robustness of competing options was tested to ensure that the glass would not be brittle (ie risk of shattering) if damaged in service.

After the team assessed the prototypes, the chosen system developed by the façade contractor supports the laminated patterned glass on all edges and retains it with structural silicone glazing and a mechanical backup. The size of the perimeter framing and the sealed joints between panels proved relatively unobtrusive, ensuring that the appearance remains consistent as the building ages. The air and vapour barrier remained on the window wall system behind the column/beam cladding.

The finished building constantly changes in appearance due to the textured glass surface, the translucency of the panels, and the play of diffuse light on the structure behind (Figs 37–40). The ground-breaking use of pattern glass on this project is likely to be cited as a reference by others in future.

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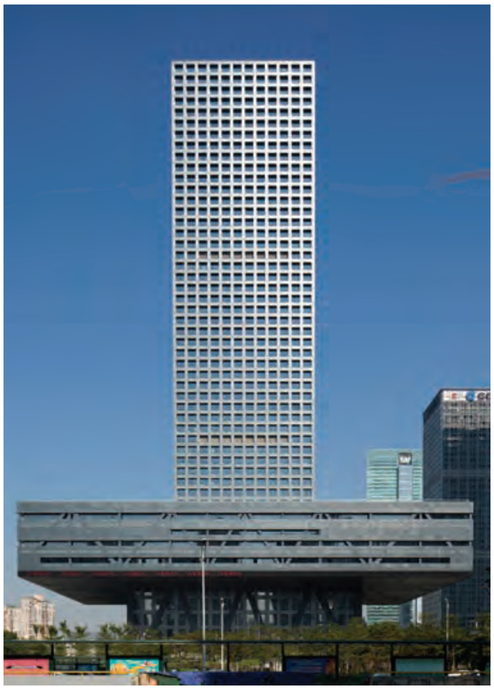


40.

36. Initial façade concept: cladding the structure in glass.

37–40. Play of light and reflections on the tower façade.

41. Tower lighting integrated within façade system.

42. SZSE at night.

Lighting

Façade lighting design principles

The vision for the building's lighting was to project SZSE's identity through an elegantly illuminated façade with an imposing structure behind. The basic architectural massing comprises the tower as a vertical element and the podium as a horizontal element, and the exterior lighting reinforces these two distinct forms by subtly illuminating the grid openings of the vertical tower and creating a gentle glow of bands on the horizontal podium, with the main structure expressed in silhouette. The lighting scheme, complementing the world-class architectural design, has the potential to set a new benchmark for the rest of the city.

Arup provided architectural lighting design services for the façade, landscaping, and all the public spaces including the atria, lobbies, listing hall, exhibition centre, executive offices, conference rooms, sky gardens, lounges and restaurants. All the integrated lighting elements on the façade were carefully designed to minimise light pollution and any potential glare for occupants of surrounding buildings, as required by the Chinese green buildings standard[1].

The tower

The façade lighting scheme for the tower aimed to create a distinct luminous figurehead in contrast to its neighbourhood, and without competing in brightness or colours. Cool white (4000K) LEDs with elliptical beam distribution (10˚ x 60˚) are installed within each window bay to trace out the imposing structural grid, defining its identity and presence at night without needing the office interior lighting switched on after hours (Figs 41–42). Sightlines were studied for the tower lighting with respect to glare concerns inside the building. Each luminaire, in a small slot at the base of each window bay, has an adjustable lens that focuses the light away from occupants.

DMX[3] controllers are installed to provide floor-by-floor zonal controls, giving further energy savings by dimming the luminous tower grid after midnight.

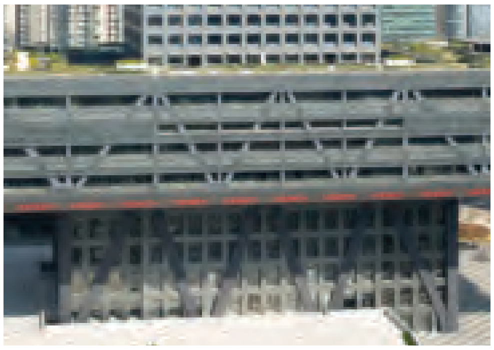
41.

42.

43. Red banding on the podium for daytime announcements.

44–45. Podium lighting analysis.

46. Podium soffit lighting.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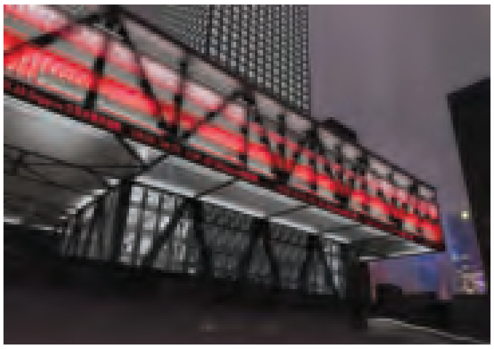
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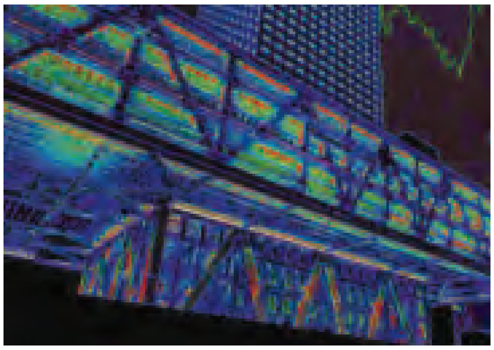
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The podium

Given that the raised podium is the heart of the building, light as used as a communicator, glowing and "broadcasting" the virtual activities of the city's financial market with a change of colour from a day-to-day white to special bands of red programmed for specific listing ceremonies or events (Fig 43).

Horizontal "light beam" elements (fluorescent lamps of 4000K cool white), periodically interrupted behind the diagonal structural trusses, are installed to back-light the patterned glazed façade from within the podium. Bands of red fluorescent lights are installed at the balcony level and behind the openings of the rain screen façade to create a dynamic layer for special events.

Detailed computer studies (Figs 44–45) and an on-site mock-up were created to determine the optimum specification of the translucent frit patterns for the glazed façades. 50% translucent frits were selected to maximise the light diffusion in creating a glow against the night sky while maintaining some transparency in the podium façades.

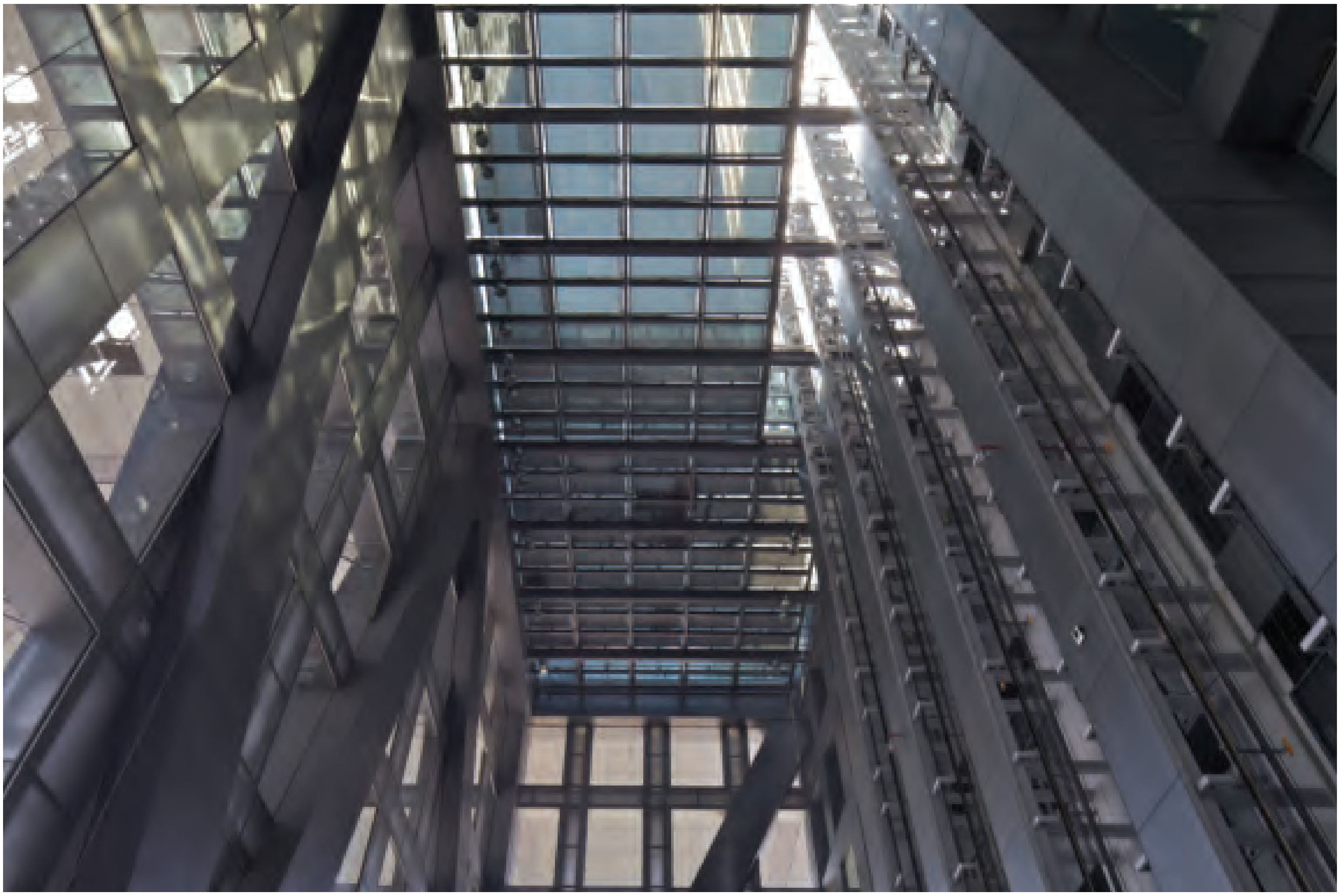
The glass soffit of the podium is backlit in a similar way to its façades to give it a sense of lightness, as though it has been lifted by the illumination over the entrance plaza underneath (Fig 46). Each luminaire is equipped with dimmable DSI ballast to facilitate various scenes to be programmed and switched.

Plaza and landscape lighting

The plaza is intended to be a night-time "canvas" for light while providing a welcoming public realm for pedestrians. The ceremonial plaza provides exclusive access for VIP, SZSE executives and club visitors, with column lights strategically located to reinforce the route up to the ceremonial lobby, creating a strong procession and sense of arrival.

The park along the north side of the building provides an immersive experience of nature in this highly urban neighbourhood. The lighting complements the architecture of the park to create a magical luminous landscape at night, welcoming the public to visit and enjoy this nocturnal outdoor space.

On the podium roof garden, a mosaic pattern unfolds, defining spaces and functions with different planting types and paving tiles. The lighting has to cater for various functions but also coherently reinforce the landscape features. Floor-recessed LED marker lights delineate the pattern, providing visual interest while limiting glare to people in the tower above. Additional lighting highlights the plants and pathways as well as integrating them with the pergola structures.



47.

Interior lighting design principles

A strong lighting concept running through the whole building is the illumination to the core walls. This is achieved with a continuous slot light, making the core appear to penetrate through the heart of building.

In general, interior lighting design intends to echo the use of various spaces, whether entrance lobbies to produce a grand and inviting lit environment, podium lighting to feature the ceremonial spaces, or the top executive floors to create an exclusive and entertaining lighting. Where possible, luminaires are integrated with other services and interior design to minimise the visual clutter on the ceiling.

Atria

The two atria below the podium boast high ceilings with abundant daylight admitting through skylights and the glazed façade (Fig 47). After dark, general lighting is provided by luminaires mounted to the roof structure, enhancing the dynamic spatial appearance and highlighting the textured glass of the atrium walls. The atrium adopts a cool white lighting that ties with the tower façade lighting and shows the structures in silhouette for the external appearance.

Listing hall

The listing hall is the double-height ceremonial space where new companies are listed onto the stock exchange.
The space embraces vast areas of backlit glass ceiling, while the central stage receives additional accent lighting from track-mounted spotlights recessed within ceiling slots (Fig 48).

Sky Club

At the top level 46, perforated metal sheeting is used for the ceiling of the executive club, creating a key feature with the patterning resembling clouds. The various sizes of ceiling opening are covered with diffused covers and are backlit with cool white lighting. Additional downlights are provided to supplement the functional lighting as well as to accentuate the interior furniture.

Lighting control system

This consists of multiple DSI (digital serial interface), DMX and relay controllers linked to an Ethernet network to form a building-wide solution managed by a central controller. The system enables the user to control and configure the façade lighting as required, and also allows for optimised energy usage and the provision for future expansion if needed.

48.

49.

47. Main atrium.
48. Listing hall.
49. Main auditorium lighting.

50.

Conclusion

Completed in October 2013, Shenzhen's new stock exchange represents a fusion of Chinese and international design technology and truly fits the Shenzhen regional government's requirement for "a first-class landmark by first-class design and first-class construction".

SZSE has already become a landmark in the city, and its unusual floating podium feature has earned it the local nickname "the miniskirt", while the plaza area is set to become a major urban feature. The project will surely become one of the instantly recognisable symbols of Shenzhen's development, as well as an impetus to new forms of architecture and urbanism.

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3) http://en.wikipedia.org/wiki/DMX512

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Alba Xu is an Associate Director in the Beijing office. She was the lead electrical engineer.

Project credits

Client: *Shenzhen Stock Exchange* Architect: *OMA Stedebouw BV* Associate Architect and Local Design Institute (LDI): *Shenzhen General Institute of Architectural Design & Research* SMEP, façade, geotechnical, fire, vertical transportation, sustainability, building intelligence and lighting design consultant: *Arup — Sacha Abizadeh, Francesco Anselmo, WH Au, Jessica Cao, Liang Cao, Chris Carroll, John Chafer, Edwin Chan, Fanny Chan, Henry Chan, Kitman Chan, Johnson Chen, Mark Chen, Raymond Cheng, Vincent Cheng, Robin Ching, Mark Choi, Kenneth Chong, Katie Davies, Graham Dodd, Xiaonian Duan, Yong Guan, Da-Gang Guo, Jun-Ping Guo, Yue Hao, Goman Ho, Gerald Hobday, Nancy Huang, Junko Inomoto, Dogan Kozan, Michael Kwok, Oliver Kwong, Florence Lam, François Lancelot, Allison Law, Joey Law, Andy Lee, Ray Lee, Patrick Leung, Eddycol Li, Fu-Gui Li, Jing-Yu Li, Miao Li, Wan-Ying Li, Di Liu, Michael Liu, Peng Liu, Penny Liu, Jacky Lo, Hui-Yuan Long, Mingchun Luo, Yong-Qiao Luo, Chen-Jie Ma, Frankie Ma, Lily Ma, Phoebe Ma, Melissa Mak, Wendy Mak, Rory McGowan, Maggie Meng, Jason Ng, Julian Olley, Tiffany Or, Si-Ki Po, Chas Pope, Yuan Qi, Yi Ren, Wei-Guang Ruan, Feng Rui, Cindy Shan, Kimi Shen, Li Shen, Hai-Ying Shi, Lewis Shiu, Siegrid Siderius, Kenneth Sin, King Sin, David Song, Timothy Sze, Matthew Tang, Wai-Shing Tang, Alex To, Michael Tomordy, Felix Tong, Isaac Tsang, Matthew Tsang, Sam Tsoi, Imke Van Milm, Steve Walker, Ge-Bing Wang, Jian-Chao Wang, Lu-Peng Wang, Qi Wang, Yan-Dong Wang, Yi-Hua Wang, Yue Wang, Kevin Womack, Chris Wong, Edwin Wong, Ingrid Wong, Paul Wong, Sabrina Wong, William Wong, Tie-Jun Xiao, Freddie Xie, Alba Xu, Christine Xu, Irene Xu, Dong Yan, Sui-Hang Yan, Raymond Yau, Rumin Yin, Kai-Sing Yung, Jacky Zhang, James Zhang, Jerry Zhang, Li-Ping Zhang, Lipy Zhang, Juliet Zhong, Yu-Bai Zhong, Ji-Wei Zhou, Ling Zhou, Xue-Li Zhu, Yue-Hui Zhu* Main contractor: *China Construction 3rd Bureau* Landscape architect and interior designer: *Inside/Outside* Signage designer: *2x4*.

Image credits

1, 4, 15–16, 35, 42, 46–47 *Courtesy OMA, photo Philippe Ruault*; 2–3, 5, 14, 21, 36, 41 *courtesy OMA*; 6–8, 11–13, 17, 19, 44–45, 49–50 *Arup*; 9, 20, 25 *Chas Pope*; 10, 18, 31, 38–40, 43, 51 *Marcel Lam*; 22–24, 26, 28–30, 33–34 *Arup/Nigel Whale*; 27 *Internet sources;* 32, 37, 48 *Philippe Ruault.*

51.

The Reid Building, Glasgow School of Art

Location
Glasgow, Scotland, UK

Authors
Greg Hardie Gavin Kerr Lee Kirby
Dan Lister Andrew McDowell
Derek Roberts Andy Sheppard

1.

Historical background
Designing a new structure to directly face the acclaimed Mackintosh Building at the Glasgow School of Art was a daunting architectural and engineering challenge.

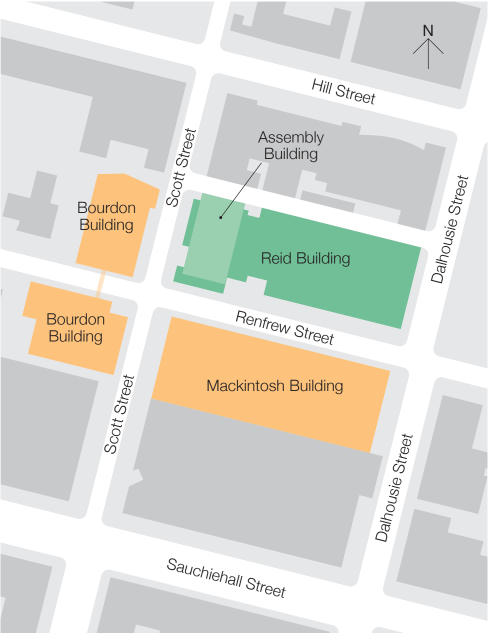
Founded in 1845, the School occupied various premises in the city until rapid expansion after 1885 under its dynamic headmaster Francis Newbury (1855-1946) necessitated a new permanent building. In 1896 the practice Honeyman and Keppie won the architectural competition with a scheme by one of its designers, Charles Rennie Mackintosh (1868-1928), himself an alumnus of the School. Newbury advocated Mackintosh's design, and construction began in 1897. The first phase was completed two years later, but for funding reasons an eight-year hiatus ensued, during which Mackintosh refined and developed his concept for the remainder. Finally completed in 1909 with the construction of the west wing, this building proved to be one of the few major projects that Mackintosh was able to realise fully, and his posthumous reputation as a key pioneer of modern architecture led to it being generally recognised as a masterpiece. "The Mack" became one of Scotland's most cherished architectural icons, and is listed Grade A ("buildings of national or international importance…").

In the decades following the opening of the Mack, on the south side of Renfrew Street in Glasgow's hilly Garnethill area (Figs 1–3), the School's estate continued to expand, with the acquisition and construction of a range of properties not only on the north side of the street (including the Foulis Building and seven-storey Newbery Tower, completed in 1970 — both now demolished), but also elsewhere in the area.

2.

'It is not easy to build opposite a masterpiece. At what point do you defer to the existing, at what point do you depart from it? How do you harmonise with a historical building while realising a work of today? How do you respond to the larger context including the urban grain, the topography, the climate and the changing qualities of light? How do you maintain an identity of your own while respecting the unique character and spirit of a revered work?'

William J Curtis, architectural critic, laying down the gauntlet to the team in *Architects' Journal*[1].



3.

The fire

The national and international feeling for the Mackintosh Building is best reflected by the response to the disastrous fire in its west wing, which happened in May 2014, only a month after the opening of the new building that is the subject of this paper. The fire destroyed, among other parts, the iconic Library. Following an international appeal, and support from a series of international artists and celebrities, and from the general public, a programme of restoration is now under way.

1. The Mack seen from the steep incline of Scott Street (circa 1978).

2. The north-facing Renfrew Street façade of the Mack, during site works for the Reid Building on the north side of the street.

3. Location plan.

Background to the new project

Despite the School's steady growth, a long-term estate strategy completed in December 2007 determined that the Mack was still, a century after its opening, the only fully fit-for-purpose building in the estate. The other accommodation was found to be ineffective, inflexible, unable to accommodate long-term planned growth, and the single greatest risk to long-term academic and financial sustainability.

After an extensive appraisal of options, the School developed a vision and plan for a redeveloped campus, with the Mack at its heart and a new "exceptional architectural companion that will act as a touchstone for the development of the future estate". The School needed a practical yet visionary building to deliver a modern and forward-looking facility at the centre of its campus, and through open competition selected Steven Holl Architects, supported by Arup as multidisciplinary engineer and JM Architects Ltd as associate architect.

The brief

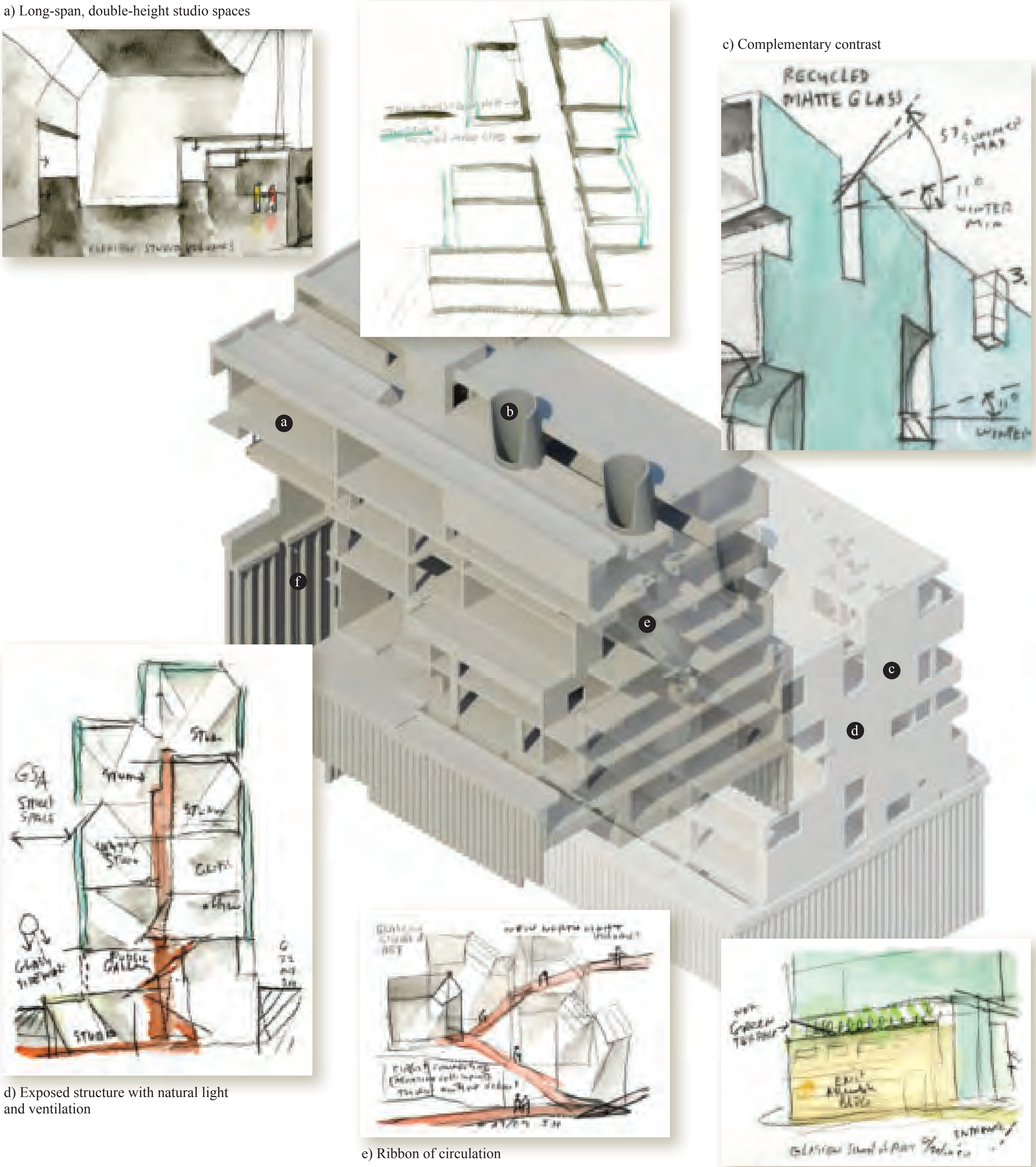
Excellent new teaching and studio facilities in a high quality environment were required, to inspire creative education and research in the visual disciplines of the 21st century and, to fulfil the School's redevelopment strategy, uniting departments previously widely dispersed across the city in an efficient and sustainable location. The brief specified:

- a building of suitable international architectural quality to be built opposite the Mackintosh Building
- 11 650m² of accommodation on a tight site with restricted planning heights, but retaining the large studio space proportions required for a world-class arts facility, with robust and adaptable studio, workshop, and project spaces to support various creative environments
- a building surrounded by live facilities, including a primary school and live arts school, both contained in movement-sensitive listed buildings
- a facility rated BREEAM "Excellent"[2], with additional stringent energy and carbon targets including small power/plug loads
- natural daylight and ventilation delivered into a deep-plan building
- the required level of architectural quality and complexity within the £2400/m² cost plan
- operational cost-effectiveness and affordability across the estate's life-cycle, including more efficient use of space across centrally managed lecture, seminar and project accommodation through the provision of shared facilities.

Thus the School needed the new building to address the significant challenges of its site and urban context, and to be of exceptional and lasting design quality. Primarily it had to provide inspiring, stimulating and comfortable environments for the people who work, study, visit, meet and play in it:

"It must excite. It must also offer a sense of place, a sense of identity and belonging, and be a fitting complement to the neighbouring Mackintosh Building. Purpose, function, social needs and comfort are paramount." — Competition Brief.

4.



a) Long-span, double-height studio spaces

b) Driven voids of light

c) Complementary contrast

d) Exposed structure with natural light and ventilation

e) Ribbon of circulation

f) Building over the Assembly Building

Architectural concept

The Reid Building (named after Seona Reid, a former director of the School) opened in April 2014. Its design remained strikingly faithful to the competition-winning scheme, with the architecture relating to the Mackintosh opposite through "complementary contrast" — the Mack's light internal structure but heavy façade reflected in the new building's solid geometrical structure and light rainscreen glass façade (Fig 4).

The architecture primarily focuses on the interior, designed from the inside outwards to deliver the facilities required by the School, yet is also carefully considered from the outside in, taking full cognisance of the precedent across the road.

The Mack's large proportions are directly referenced across as a recess in the façade, with the new-build studios overhanging on extensive 7m cantilevers to create an inverted feature terrace. Externally the façade is a plain sheet, interrupted only by the large-scale geometric steps and overhangs, forming a "soft" unadorned elevation to avoid conflict with the Mack's intricate façade.

Internally the design aim was for the building to be sculptural and playful, as an art school should be, combining exposed concrete geometry and natural light to form a permeable series of interconnected spaces.

The in situ concrete frame design was integral to this holistic approach, providing a complex of ever-changing walls and floor plates to enable the varied and sculptural architecture to be realised. A 15m grid of wall lines sets the building's rhythm, providing inspiringly open studios with large north-lit apertures.

In the centre are three 5m diameter concrete tubes, inclined 12° to Renfrew Street, which reference in architectural terms the three two-storey Library windows on the west façade of the Mack (Fig 6).

The Reid Building's perforated "driven light voids" are the core of the circulation route, integral parts of the structural frame that also draw daylight into the atrium and act as natural ventilation chimneys.

Keeping the Assembly Building

The original brief called for demolition of all the School buildings on the site facing the Mack, including the 1930s Assembly Building, with the Students Union housed in it to be incorporated within the new building. Steven Holl proposed to retain this one listed building, maintaining its individual character as separate student space and enabling the new building to incorporate within its footprint some of the area's visible heritage. The School enabled the Student's Union to brief and direct the scope of this refurbishment and remodelling, to provide an improved series of venues within the building.

However, to achieve a cohesive massing, and fit the required accommodation onto the site, three additional floors were needed to clear-span 16m over the Assembly Building, and cantilever 12m out to provide a structure-free corner. To meet the overall accommodation requirements within the confined site, a two-storey basement under the new-build area was also necessary, with constraints exacerbated by the adjacent movement-sensitive listed buildings.


5.

4. Elements of the design concept.

5. The north-west corner of the listed Assembly Building, incorporated with the Reid Building footprint.

6. Library windows on the Scott Street elevation of the Mack — the architectural inspiration for the Reid Building's "driven light voids".

Complex circulation spaces, articulated as a ribbon of precast stairs and in situ ramps, wind up through these tubes and the adjacent studios, promoting connection between departments.

Delivering the building within the £2400/m^2 cost plan required careful engineering. Adopting an exposed frame to define the internal volumes and architectural quality was a key strategy; investing in the structure enabled expensive follow-on trades to be minimised.

The varied textured and smooth concrete finishes provide interesting, practical and durable surfaces, able to resist the rough-and-tumble a working studio environment exerts on the building fabric.

These challenges required the engineering design and site teams to deliver a holistic solution, using technical expertise and a pragmatic approach to balance the various driving criteria.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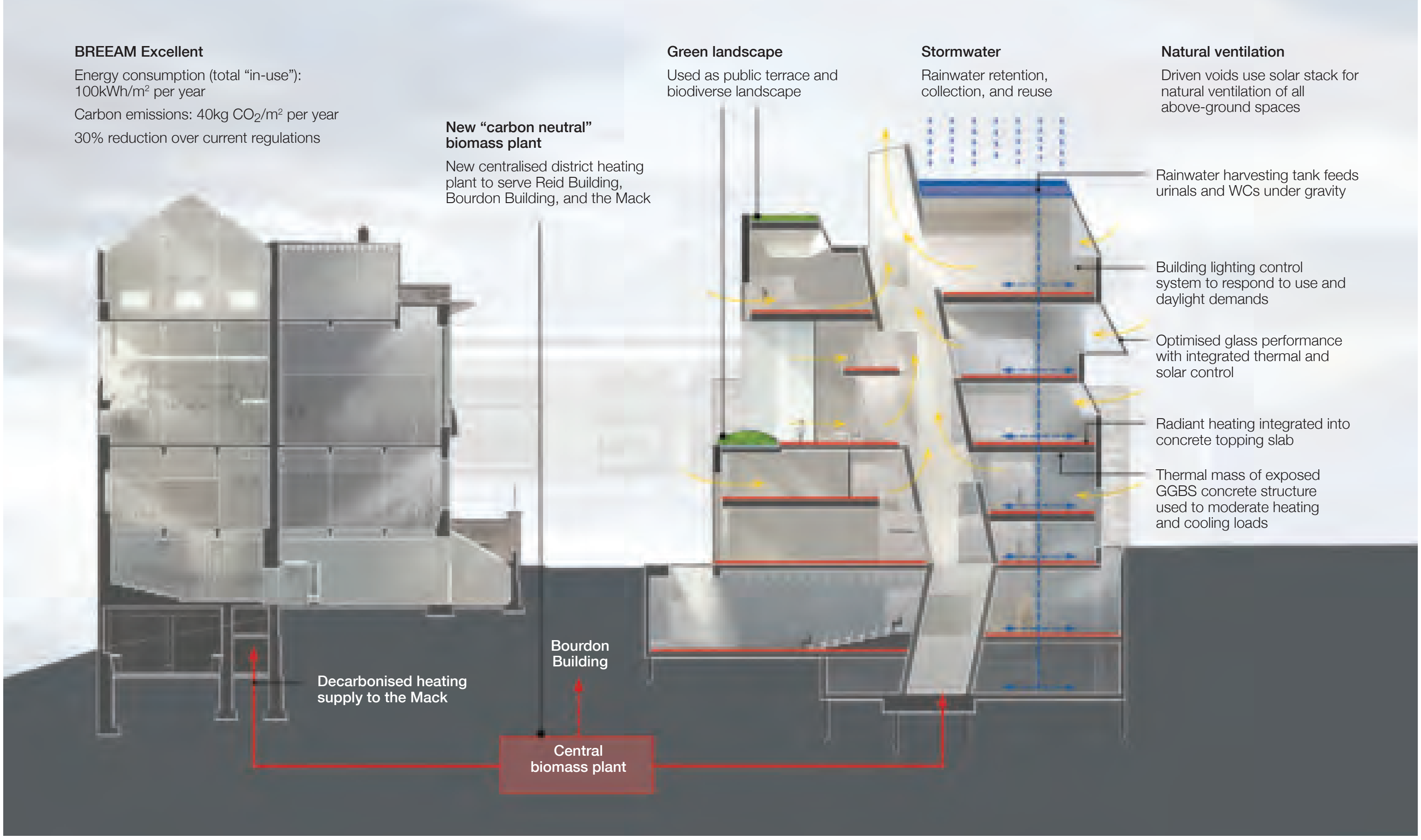


8.

Meeting the sustainability challenge

The School set a sustainability brief at the outset, which led to the two principal requirements already noted: the energy and carbon targets (100kWh/m²/annum and 40kgCO$_2$/m²/annum including small power/plug loads), and the BREEAM "Excellent" rating[2]. This was required by the Scottish Funding Council and formed a solid basis on which to include the most effective environmental sustainability features (Fig 8).

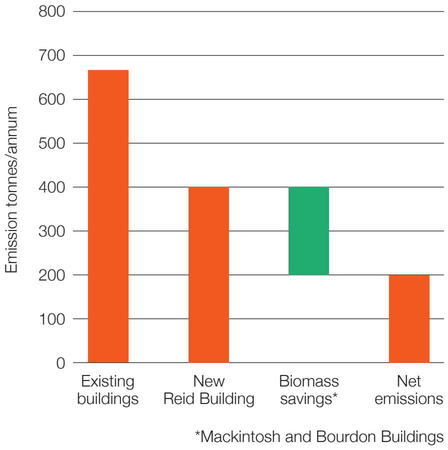
Focusing attention on total energy usage, rather than just that covered by regulations, reflected the School's desire for real-world sustainability improvements beyond mere compliance. Comparably, the BREEAM strategy was developed to give practical operational benefits, not just collecting credits to meet a rating.

Arup led further debate and several feasibility studies into the most effective way of delivering real energy and carbon improvement, given the budget constraints.

The conclusion was that by investing some of the project budget plus some of the School's forward maintenance budget, upgrading the School's existing district heating network would enable significant carbon savings not just to the new building but also the Mack and the adjacent Bourdon Building (completed in 1979 as the home of the Glasgow School of Architecture). The old gas-fired boilers were replaced with a new 500kW biomass boiler system, supported by efficient new gas-fired modules.

This lateral thinking approach maximised sustainability return on the investment, with campus-wide benefits beyond the project's initial remit, including decarbonising the Mack's heating system, where the fabric could not be "improved" for aesthetic and conservation reasons.

The biomass boiler thus lowers the emissions of the Mack and Bourdon buildings by 197 tonnes/annum, a significant reduction when combined with the fact that the new building has emissions 40% lower than those it replaced (Fig 9).



9.

7. The Reid Building's Renfrew Street façade, with the south-west corner of the Assembly Building protruding from below the cantilevering new-build structure.

8. Key sustainability design features.

9. In-use carbon savings.

Key environmental features contributed to the building's sustainability credentials and BREEAM "Excellent" score:

- rainwater collected at the highest roof level for toilet flushing throughout the building without additional pumping, a gravity-fed passive approach enabled by the tiered roof structure integral to the design strategy
- a "blue roof" designed to attenuate surface water at roof level to alleviate discharge rates to the sewer system
- using the concrete structure as the finished form to define the internal architecture (Fig 10), minimising the number of follow-on trades and greatly reducing waste and embodied energy
- specifying 50% GGBS (ground-granulated blast-furnace slag) to reduce the embodied carbon of the concrete structure by almost 40%
- bolted connections and hard stamping of steelwork to facilitate easy identification on eventual deconstruction
- highly species-rich planting on the terrace and green roof, providing significantly greater biodiversity benefit than a simple sedum option.

Embodied carbon assessment

Evaluating embodied CO_2 allows a comparison to be drawn between the impacts of the structure compared to the operation of the building over its design life. To help define the balance of in-use carbon and embodied carbon, Arup developed an assessment tool and benchmarked the scheme against various other constructions.

Responding to the School's sustainability KPIs (key performance indicators), the team assessed the embodied carbon produced in demolishing and constructing the new building and compared it to the CO_2 produced in operating the new and existing buildings. (This contributed to development of an Arup tool derived from an internally funded research project, known as the project embodied carbon calculator (PECC).)

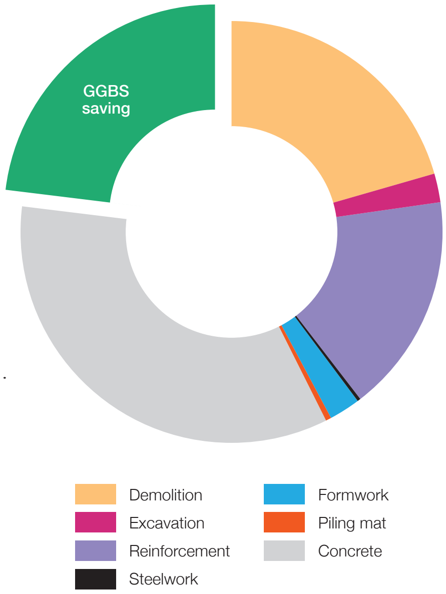
The embodied carbon of the demolished buildings was determined to be 1900 tonnes. Combining this with the embodied carbon of the new building, 5600 tonnes, gives a total renewal embodied carbon "cost" of 7500 tonnes (reduced by over 2000 tonnes from using GGBS: Fig 11).

10. Construction progress on circulation route.

11. Carbon assessment of the new-build structure.

12. Natural and electric light together illuminate studio spaces at dusk.

10.



11.

The embodied energy in the building is therefore equivalent to 17 years' operational emissions, reflecting, in part, how low they are. Perhaps more pertinent is the statistic that it will take just 11 years for the savings in operational emissions to "pay back" the carbon invested in the construction. When considered against the new building's 60-year design life, there will clearly be a much reduced environmental impact than if the development had not occurred.

Lighting

Overview

Light, and how it plays with architectural form, is integral to Steven Holl's work and sits at the heart of the Reid Building's architectural design. The Arup lighting team worked closely with the architect to deliver Holl's vision for considered lighting to complement the architectural form, while at the same time fulfilling the technical requirements and providing appropriate lighting levels for the various studio, office and workshop spaces.

The team supported the architectural daylight strategy while developing a unique electric lighting scheme to enhance the sculpted concrete form. The predominantly north-facing studios have large inclined glazing to maximise access to the desired high-quality diffuse north light, creating an inspiring work environment and removing daytime reliance on electric lighting.

The electric lighting design was developed to complement, not compete with, the architecture — a sleek, simple aesthetic consistent with the Holl style while being as unobtrusive as possible. The team investigated options for the studio and general spaces and developed the lighting strategy for the "ribbon of circulation", before finally focusing on specific unique spaces, such as the "Windows on the Mack", the lecture theatre, the exhibition space, and various lighting details integrated into the architecture.

As well as being sensitive to the building's setting, the challenge was to deliver the lighting scheme to a stringent budget, in terms of both energy and capital cost. Arup worked closely with manufacturers to develop details and understand the manufacturing process, with the aim of delivering the architectural vision within the strict cost budget typical of a higher-education building.

12.

Lighting the studios

The unique form of the building, coupled with the varied and generous proportions of the studio spaces, presented similarly unique challenges to the development of the lighting design. In response to these challenges, Arup again worked with the architect and a lighting manufacturer to develop a new product range that delivered the exacting visual aesthetic in terms of fitting proportions, appearance in the space and quality of finish, as well as meeting the requirements for light distribution technical performance.

Through this process, Arup helped to develop a product family unique to this project, but which could be commercially available in the future.

The primary lighting technique employed throughout the Reid Building is a bespoke, tubular, extruded aluminium profile modular system, 89mm in diameter, capable of operating as a single 1.5m unit or as a continuous run of up to 12m, with a seamless functional downlight component and a separate LED uplight to illuminate the soffit, and available with a wide down distribution or wall wash in suspended or wall-mounted options (Fig 12).

At the time of design, high output LEDs of sufficient quality were still in development. LED options were indeed investigated, but the range of mounting heights and the proportions of the studios formed too great a challenge. The most practical and cost-viable option combined energy-saving T5 fluorescent lamps for functional direct lighting, though delivering the required light output from a small form brought other challenges, such as integrating controls and emergency lighting components, as well as maintaining internal thermal conditions.

Several features were integrated into the fittings to maximise system efficiency:

- use of single high output T5 lamps, allowing for an efficient reflector design and increased light output ratio, while also allowing lamp overlap to deliver a more uniform lit appearance
- separation of direct and indirect components to further increase the efficiency of the downlight reflector
- provision of an LED uplight component designed to be very low heat and power consumption, but with appropriate output and technical and aesthetic quality to achieve the required performance
- application of T5 high-output eco-lamp (73W instead of 80W) to further reduce consumption
- high-performance satin diffuser to increase efficacy while reducing shadowing cast between lamps
- integration of discrete machined openings within the luminaire housing to allow air movement and maintain optimum operating temperatures
- integration of miniature photocells to dim luminaires in response to natural light levels
- selection and installation of fluorescent and LED control gear to maximise thermal efficiency
- self-contained emergency module battery packs incorporated into thermally separate extension sections to maintain operating conditions.

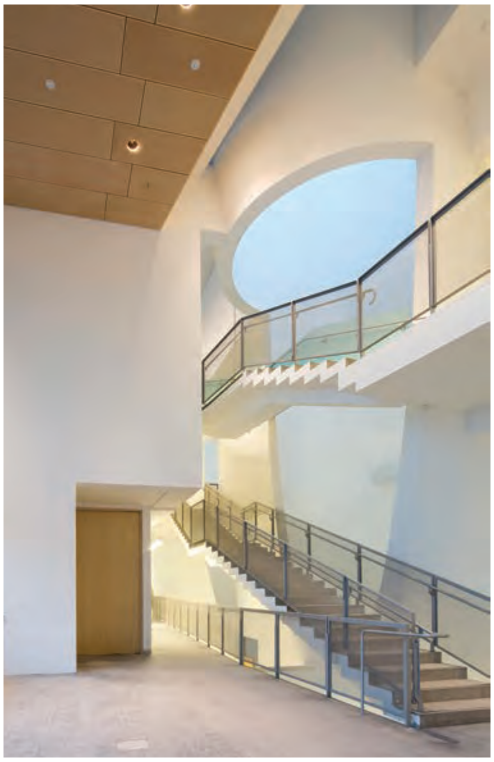
Over 1300m of the linear system — the main workhorse of the lighting scheme — is installed throughout the building, but while it forms the primary light source for many academic and office spaces, some areas house particularly detailed tasks that require a different lighting approach.

13.

13. Combiined background and task lighting in studio.

14. “Ribbon of circulation” cutting through one of the light voids.

15. Looking up into one of the driven voids.



14.

These include the silversmithing and jewellery-making, needing bench-mounted task lights (Fig 13), and the fashion and textile screen printing workshop, where the linear system is suspended lower above the long screen printing benches. Again, in the digital workshop and the centre for advanced textiles, high colour rendering lamps meet the technical requirements of the tasks undertaken within.

The installations in the teaching spaces, studios and seminar rooms deliver an energy density of 13.5W/m^2, 18% below the notional target rate at the time of design. While this may appear high relative to current best practice, it directly reflects the unusually large volumes of the spaces. The operational load is much lower, due to the automatic lighting controls throughout the teaching spaces, and the daylight-linked dimming and absence detection.

The studio and general lighting also formed the external lighting strategy — to use the various transparencies of the cladding system, the general space lighting, and movement of occupants to animate the façade at night and reveal the activity within.

The lighting challenge was to achieve a constant visual aesthetic, both from within the studios themselves and when viewed from the outside, ensuring that the right amount of light could be delivered within different height and proportioned spaces with the same visual configuration.

Ribbon of circulation

The so-called “ribbon of circulation” — the winding ramps and stairs that transect the driven voids, connecting one floor to the next — had its own technical challenges for the lighting design team: how to maintain the clean architectural form and provide a lit effect to complement the vision, while delivering a practical and appropriate lighting solution easily maintainable by the School. Once more the team worked closely with the architect, exchanging 3-D models to communicate proposed options, and developing a language of lighting solutions that both achieve the desired aesthetic and provide a safe environment.

The voids punch light down into the heart of the building (Fig 14); their scalloped openings visually connect the lower floor levels with the outside world, and showcase the variability of natural lighting in colour, temperature and hue against the warm static source of the electric lighting. At night, the concept works in reverse, pushing soft ambient light up into the voids from LEDs located in them (Fig 15).

Daylight support

Maximising the provision and quality of natural light is always a key priority for an art school, and the Reid Building was no different. The design of the tall, deep studios and its inclined driven voids aimed to deliver natural light right down into the heart of the building. Arup provided technical advice and support to the architect, to understand the technical daylighting performance of these varied spaces and achieve compliance with BREEAM daylight requirements.

The attention to detail regarding the availability of natural light did not stop at the outer envelope. The design team needed to consider how the massing and materiality of the Reid Building would influence the surrounding buildings. Glare and reflection studies were carried out to assess the impact of the building massing and determine the effect of the new glass façade on its neighbours, particularly the renowned quality of the north light in the studios in the Mack.

"... a design strategy that has been driven forward with a mixture of poetics and ruthless pragmatics: qualities that are singularly appropriate in this context, and developed with an artistry and skill."

Professor David Porter, Head of the Mackintosh Building School of Architecture.

Assembly Building

A key feature of Holl's competition design was to retain the existing Assembly Building and incorporate it into the new structure, reflecting the site's urban history. The stone face of the listed building contrasts with the new smooth glass façade, and this contrast is mirrored in the interior, where the design, here led by JM Architects, maintains the raw, exposed, almost industrial feel.

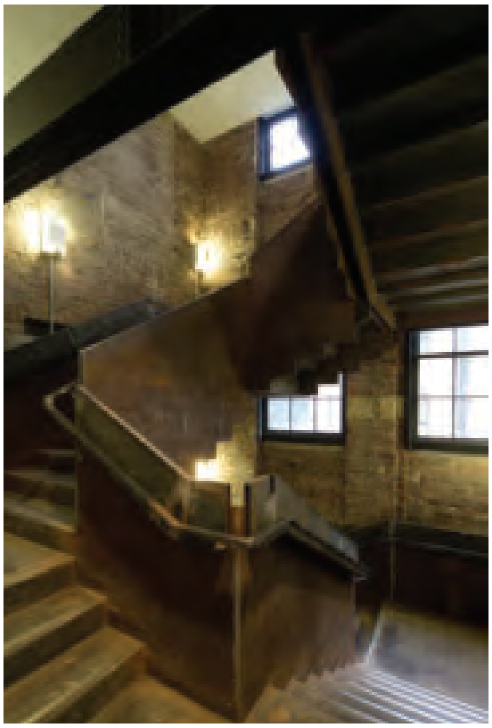
The original building was stripped back to its bones, exposing brickwork, stone and steel (Fig 16), and the team developed the lighting design here to complement the rough and raw interior with bespoke fittings that reinforce the building aesthetic and differentiate it from its modern neighbour. The Assembly Building is primarily the Students' Union, providing a wealth of flexible facilities and hosting events from exhibitions to live bands. The lighting design for each space responds to its form and function while keeping a holistic focus on the overall refurbishment.

The venue and Vic Bar spaces reinforce the raw aesthetic thought and use reclaimed industrial lanterns and bespoke wall and pendant luminaires inspired by traditional building-site lighting. These industrial elements continue throughout the front-of-house and circulation spaces. Even the cleaner, sleeker galleries pay homage to the core design of the building through the use of industrially-inspired track lighting, in contrast to the sleeker, more discreet luminaires used in the Reid Building.

The light scheme has maximum flexibility at its core: "layered light" is fundamental to creating the desired atmosphere and ambience in each space to reflect its use at any time. A building-wide lighting control system allows each space to be tailored to any user requirement, be it as exhibition space, café, or night concert venue.

Luminaire detailing and integration

The Reid and Assembly Buildings between them required seven different bespoke luminaires to be developed. Arup, architect and supplier agreed the desired aesthetic for each application, investigating options for positioning screws and fixings, and adjusting the light source position to conceal it from direct view where possible. Be it integrating light sources into concealed architectural details or developing a completely bespoke original wall sconce, the same level of care and attention was taken throughout.



16.

17.

16. New lighting in the stripped-back Assembly Building, complementing the new "raw steel" feature stair introduced as part of the refurbishment.

17. Profile of driven light void, showing "elbow" reverse at the ground level.

Structure

The structure forms the scheme's backbone. The technical challenges of the large overhangs, of the complex geometries and the deep basement all came together in the solution, with the concrete frame forming a central element in the practical requirements of this high-quality environment as well as the architectural vision.

The three driven voids

The voids act monolithically with the major wall lines of the structure; each of the three is uniquely defined and cut so as to deliver the extensive overhangs to the south façade. These overhangs, combined with the voids' inclination, promote a significant southward gravity slew, inclining the building towards the Mack. Deflections are limited by vierendeel frame action of the perforated concrete wall elements, combined with the bending of the driven voids.

For greater structural and cost efficiency, an "elbow" was introduced into the voids at ground level (Fig 17), turning the cylindrical structures back on themselves to help counter the slew with some centring of the load at foundation level. At the lower basement level the tubes double as storey-deep sprinkler tanks.

BIM model geometry in Arup's finite element software gave in-depth analysis of the void/wall lines, each with a unique pattern of cutouts and overhangs, to efficiently deliver the design of these major elements. Modelling to match these patterns to strut-and-tie force distributions also enabled a thorough understanding of the structure's behaviour, despite its elements' free-form nature.

Each driven void structure was created by bespoke steel shuttering, re-used up through the height of the building. To create the unique "sharp cuts" of the voids' openings, timber formers were CNC-cut (computer numerical control) and fabricated to fit precisely within the steel shutters.
The contractor fabricated the formers directly from the design team's digital model, thus streamlining the process and securing precise finishes.

Mock-ups and trial pours optimised the process. Self-compacting concrete was used where avoiding active compaction gave the best results, with the tremie pipe submerged within the pour to avoid honeycombing.

18. Studio glimpsed from inside one of the voids.

19. New structure cantilevering over the Assembly Building.

20. Exposed concrete in the studio spaces.

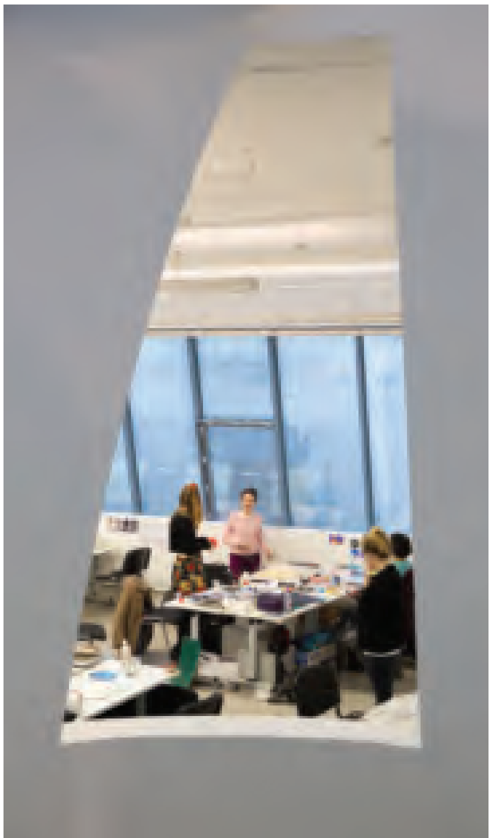
Ribbon of circulation

Within the atrium space, the winding circulation route that threads its way through the building is formed from monolithic extensions of the floor plates. Precasting these units was the only practical solution, but this approach had challenges. The 10m–12m stair units implied both large handling weights and high formwork costs for creating each unique unit conventionally.

To resolve this, the treads were separated from the spine beam, so that each set could be made in a standard mould, reducing casting variations to the spine beam only and optimising cranage requirements. The tread elements were then bonded to the spine beam on site, using a specially developed epoxy mortar to give structural connectivity and the required monolithic look.

The finished units span, cantilever and hang from the central structure in an Escher-like route that winds up through the School, affording glimpses between departments and promoting interactions (Fig 18).

18.



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20.

Studio spaces

Emulating the famous studio spaces in the Mack, Steven Holl designed large north-lit studios in the new building, with 15m clear spans formed in 300mm–350mm thick reinforced concrete flat slab construction acting continuously with the main wall lines. The use of upstanding concrete beams to define the rear walls of the studios improved the structural behaviour of these slabs.

To facilitate retention of the existing Assembly Building, three floors of the new studio spaces were cantilevered 12m out to provide the structure-free corner already noted, using the main wall lines to form the cantilever (Fig 19).

The ever-changing spatial layout and its relationship with the central ribbon of circulation meant there was no repetition of beam or slab profile throughout the building. This required much bespoke design input and careful planning on site.

Exposed concrete finishes

A dense, rough-cut 50mm stack-bonded board finish gives a coarse texture to the exposed wall and beam shutters, contrasting with the smooth plywood finish of the exposed soffits and steel shuttered central void structures.

To keep the desired clean aesthetic, much of the servicing was cast into the structure, requiring advance co-ordination to determine what would be required.

This finish was created at a series of workshops at the yard of the main contractor, Sir Robert McAlpine, which developed a series of full-scale mockups to establish and iterate the finish itself, the shutter tie details, and the construction processes to deliver consistent quality on site.

The material's actual texture is clearly visible (Fig 20), as the exposed concrete walls are simply painted white. This follows from custom in the Mack, where over the academic year the students can exercise their artistic freedom and cover the studio walls in paint and doodles. The School then whitewashes the studios prior to the next academic year, refreshing the "artist's canvas" that the structure provides.

The concrete surface is thus a robust and practical solution — as well having a pleasing architectural texture.

21. Temporary mega-props as part of the deep basement excavation.

22. The voids extend through the building's full height.

23. Large-format actuated operable windows connected to the BMS.

Assembly Building

To avoid extensive temporary backpropping through the Assembly Building, a steel deck, hung from a major transfer beam at fourth floor level and spanning between the primary structural concrete walls on each side of the Assembly Building, was included as part of the permanent structure. This was designed to carry the wet concrete weight of the floors above when first poured.

This deck provides lateral restraint to the walls of the 1930 building, which required internal façade retention while the existing roof was removed and internal floor modifications made, but it does not apply additional loading to the existing building. This element forms both the Assembly Building's new roof and the Reid Building's floor, beneath which a further new-build gallery space is suspended within the volume of the Assembly Building.

Basement

Delivering the required additional space without visually overshadowing the Mack necessitated considerable excavation. The lowest two storeys of the building are set 12.5m into the hillside, immediately adjacent to the listed St Aloysius School, and also extend out under the footway towards the Mack opposite.

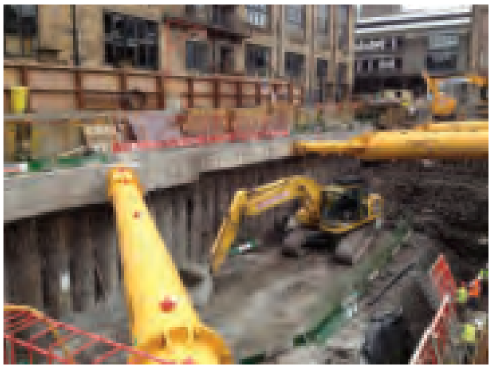
Construction of the basement was additionally constrained by many buried obstructions and existing services, including a movement-sensitive 900mm diameter Victorian cast iron water main.

A sequenced finite element analysis modelling the soil–structure interaction was used to assess the potential ground movements associated with excavation so as to avoid damage to this buried infrastructure and the historic urban fabric.

The building is founded on a drumlin (hill) with 26m depth of glacial clay, which is susceptible to heaving. Water levels were also surprisingly high across the site, with ground water peaking abut 2m below ground, so potential movements under the 1.75m thick folded raft foundation needed careful consideration.

The building was designed to balance the uplift condition at its full height, but this required dewatering during construction, and detailed analysis to find a bearing solution that gave significant savings over a piled raft. The balance of likely heave and settlement, which individually would have been up to 60mm, was carefully analysed to determine the window of acceptable combined behaviour within which the building has performed.

The team used inclinometers in the piles to monitor their movement as the basement was excavated. Continuously monitored stress gauges on the 1.2m diameter temporary props (Fig 21), plus an array of prisms and inclinometers fixed to the adjacent buildings, gave a good correlation between the theory and practice on site.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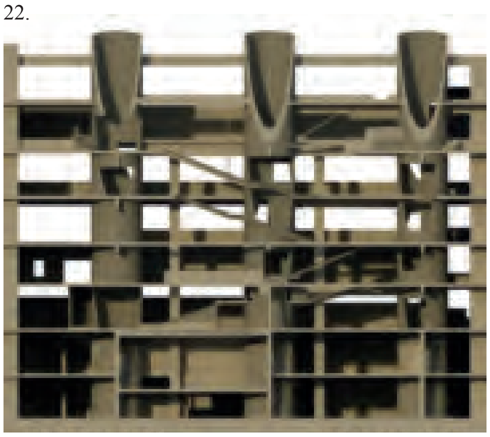



23.

Building services

Heating, ventilating and air-conditioning

The driven void concept, originally conceived architecturally in terms of light and structure, was developed by Arup as a way for the dense, deep-plan studios to breathe — the voids and the narrow atrium that create the ribbon of circulation also forming a route for air to circulate around the building (Fig 22).

By the conventional stack effect principle, the voids would act as chimneys drawing fresh air through the studios from locally-controlled opening windows at the perimeter to huge BMS-controlled windows at the top (Fig 23). The hilltop location's almost constant windiness, however, means that the air rarely follows such a path, rather exchanging between the elevations and often entering through the driven void windows, and so a range of different operational conditions was assessed.

The whole of the building above the ground floor is naturally ventilated, occasionally assisted by specialised process extract fans for specialist spaces or equipment.
Below ground a series of air-handling units (AHUs) service the specific requirements of the lecture theatre (Fig 24) (variable occupancy and fresh air rate), workshops (variable process extract requirements), and exhibition space (using a displacement vent system).

The School's accommodation brief was a challenge with the building height constraint, and the second basement level was built to accommodate plant, equipment, workshop and storage. The generous architectural spaces for studios and circulation required the services distribution to be accommodated in what was left over. Most services are thus on show, creating an "industrial" feel in some areas (Fig 25). Close co-ordination of routing was prioritised around the ribbon of circulation, the entrance, and other key public spaces, with services being set out in detail by the architect.

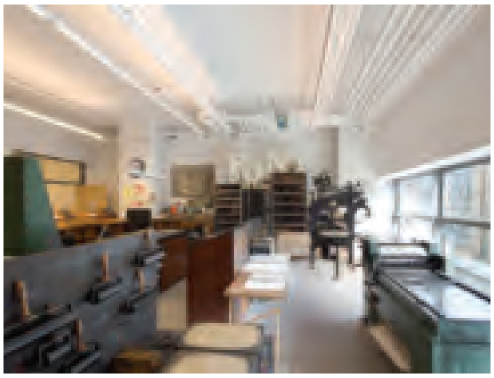
Adopting underfloor heating reduced the quantity of exposed services. Heating pipe loops were cast into the finishing screed, a zone also used for electrical and ICT (information and communications technology) distribution, and floorboxes.

24. Lecture theatre.

25. Exposed services in the print studio.

26. Recessed observation/reflection space in the silversmith and jewellery studio, with views to the south and west.


24.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26.

A remarkably small air-cooled chiller is installed on the roof, serving AHU coils and fan-coil units in selected workshops and ICT-rich areas. To reduce capital cost and energy consumption, the chiller system incorporates significant diversity, as most of the building would not need cooling at the same time as the Students Union venues were at their full capacity.

Electrical

Meeting the aesthetic aspirations, in particular for the circulation, corridors and studios, was a major challenge to the electrical design. Typically, electrical services are located in corridors, but in the Reid Building, the ribbon of circulation, together with the driven voids, forms the main architectural feature.

Since this "circuit" is fundamental to the architect's vision, the aesthetics of the space is paramount. The exposed soffit and concrete walls meant that the design team had to find innovative ways to conceal services without a suspended ceiling or raised floor.

The solution was to have minimal ceiling trunking in the studios to feed equipment at high level, with the main electrical distribution hidden in the floor in an underscreed system. Standard off-the-shelf underscreed trunking products had neither the dimensions nor the cable capacity required, so bespoke trunking and floorboxes were developed.

Workshops with the manufacturers and with the School ensured that the solution was feasible and met the brief. Similarly, conduits from the underscreed to final outlet locations were cast into the structure to preserve the aesthetics.

27.

Fire alarm system/Lift

To further reduce the need for cabling and containment, a wireless fire alarm system was used throughout, with the added benefit that such a system easily adapts to design changes during construction. With rooms being added and omitted, a wireless system allows for modifications to detector locations and numbers with minimal consequence to cabling, containment and co-ordination with other services and structure.

The main passenger lift was bespoke designed, and at some 3m x 3m and 5-tonne rated, sized to allow the transportation of large artwork and displays. This was a substantial improvement, as students previously had to manually lift or hoist large items up and down the staircase in the former building.

Energy

The set energy target included small power/plug load consumption. During the briefing stage, Arup gathered details on all the equipment to be transferred to the new building from the existing premises, and obtained an approximate assessment of new equipment likely to be purchased. The electricity drawn from each was multiplied by an estimated daily usage factor, and hence annual energy consumption estimated.

The remainder of the 100kWh/m^2/year target was then the goal for the HVAC and lighting schemes. This target proved very useful to preserve energy-saving features, such as façade and roof insulation, mixed mode systems, lighting control systems, etc, from "value engineering" and aesthetic preferences.

A dedicated metering and monitoring system has been installed for the School and Arup to easily monitor and analyse the many electricity, heat, gas and water meters. This is separate from the BMS and has proven to be no more expensive than providing the facility through the BMS.

Acoustics

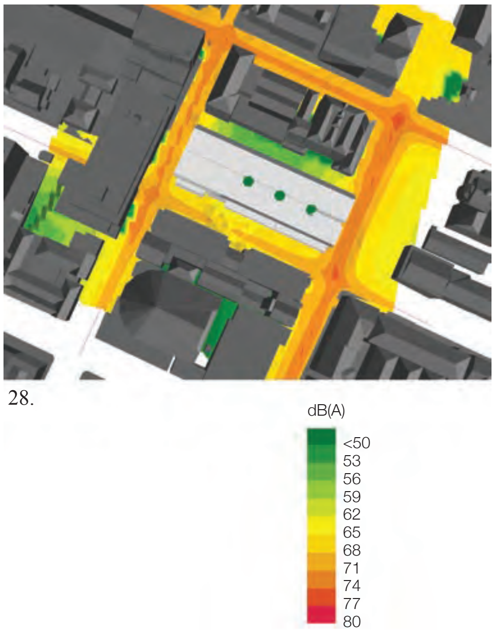
The open nature of the design, flowing uninterrupted over the five superstructure floors, presented some challenges. Arup worked closely with the School to define appropriate acoustic standards while maintaining a vibrant art school acoustic permeating around the building.

The new building was designed to be naturally ventilated despite the proximity of major roads, and to test the feasibility of this strategy an environmental noise survey was undertaken, with the results used to calibrate a 3-D noise model of the new building and surrounding roads and buildings.

To set the internal noise criteria, noise measurements were taken in spaces in the existing buildings where the School was happy with ambient noise levels. These spaces were used as the new building's benchmark, and the results (Fig 28) showed that the predicted noise levels would allow the use of openable windows. The benchmarking study also assessed the existing facilities, and investigated acoustic issues in them of which the School was aware. This included acoustic tests in the atrium in the Foulis Building (completed in 1963 and demolished to make way for the Reid Building), and also measuring the reverberation time within the studios in the Mackintosh Building.

A 3-D acoustic model (Fig 29) was then developed to create auralisations of the ribbon of circulation and adjoining spaces. To present the auralisations to the School, Arup used its *Soundlab* facility built within an acoustically insulated room. This allows clients, architects, engineers and musicians to hear how different spaces perform acoustically and how architectural form shapes sound quality.

It has been used to optimise the design of everything from train stations, sports stadia and airport terminals, to concert halls, museums and office buildings. The School director and some department heads listened to the *SoundLab* auralisations and used this to determine the design criteria benchmarks — striking the balance between creative acoustic vibrancy and local acoustic needs.



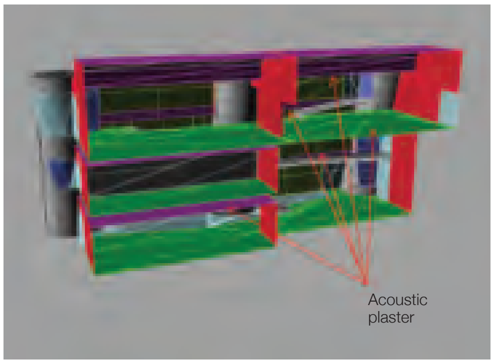
28.

27. Typical northlit studio.

28. Soundmapping the Reid Building's immediate surroundings.

29. Acoustic model.

30. North façade glass rainscreen.



29.

30.

Façade

The façade has two principle types, a glass rainscreen to the opaque areas (Fig 30) and steel-framed curtain walling to the vision areas. Here again, achieving the architect's vision involved numerous challenges to be resolved by Arup's façades and materials teams, the first being that the glass had to be fixed without any visible means of support.

A key design driver for structural glass assemblies is to consider breakage performance — ie if a pane breaks it will not endanger building users or the public. This consideration led to the development of laminated glass panels for the rainscreen.

Due to its high strength, fully toughened glass was adopted as the structural inner pane of the assembly, but as when toughened glass breaks it shatters into small fragments with no residual strength, it was laminated to heat-strengthened panes to provide structural redundancy in the event of breakage.

As the project progressed, the visual appearance of the glass assembly was established through experiments with the density of the acid etching to the outer surface and the translucency of the interlayer that bonds the two panes together. Once the interlayer design was confirmed, full-size breakage testing established the panels' breakage performance.

With this successfully completed, full-scale production of the rainscreen panels proceeded. They hang on the building by a bracket arrangement that allowed for tolerance adjustment during installation to achieve the setting-out required by the architectural design.

The steel-framed curtain walling comprises a steel profile folded to a T-shape to minimise sight-lines, with an aluminium glazing profile fixed to it. As this was a bespoke arrangement, an off-site weather test was undertaken to demonstrate the airtightness, watertightness, and structural performance of the system prior to full-scale fabrication and installation.

The architect was keen to avoid the "black picture frame" effect around panes of glass common to flush curtain walling systems, so development and testing with the glass subcontractor was undertaken to achieve a grey colour to the factory-formed double-glazed unit edge seals and site-applied sealant.

The interaction of the grey sealant with the high-performance solar control coating and argon filling to the units also had to be carefully considered. On the north elevation, the studio glazing is "cranked", whereby it extends horizontally from the building before inclining backwards to gain north light. The horizontal sections are at a level that they can be accessed by building users, so to ensure their safety these sections were designed as a glass floor with the associated structural and impact performance.

Overall the façade makes a significant contribution to delivering the high environmental performance of the Reid Building by incorporating these features, such as high insulation performance and natural ventilation.

"You walk into this building and you are overcome by a sense of awe…"

Robbie Coltrane, actor and alumnus, officially opening the Reid Building.

32.

31. Central circulation space on the ground floor.

32. Main entrance, with integral glass installation designed by GSA alumnus and Turner Prize winner Martin Boyce, with support from the design team.

Conclusion

The brief spelled out that the principal measure of the project's success would be *"its ability to support creativity, learning and social interaction across the full range of the School's programme. It must not create sterile environments where people's creativity is stifled and intimidated by its surroundings; nor where users are afraid to make mistakes."*

Already the Reid Building's interconnecting spaces and studios are being appropriated for wider uses. Concert performances are held in the voids, viewed from all levels of the building; impromptu art exhibitions are springing up, and areas being adopted as temporary creative working spaces. And the central space defined by the structural elements that shape the building — never part of the original brief — has now become the heart of the School.

The School wanted a building that not only complements its sustainability and redevelopment programme, but also inspires future generations and can stand the test of time next to its famous neighbour. The structure is the architecture, a sculptural form of perforated inclined tubes and planes intersected by an Escher-like stair. As you go through the space, you see through and between the studios; this "creative abrasion" allows the different parts of the School to work together and feed off one another in a more coherent learning environment.

The structural design was a linchpin in this holistic approach, and extensive co-ordination of design and construction was required from all parties – assisted by the digital modelling interfaces used by the engineers, architect and contractor.

This BREEAM "Excellent" building uses 20% less carbon than the building regulations required and in addition has decarbonised the wider campus' heating, including that of the listed Mackintosh, by adoption of a biomass district heating network as part of the scheme.

Delivering the building within the strict £2400/m^2 cost plan required careful engineering incorporating a holistic approach, technical skill and a pragmatic approach to balancing the various driving criteria. Successfully delivering such ambitious spaces within a challenging budget while surpassing exacting criteria for sustainability is a testament to the approach adopted, the team's close collaboration, and the driving aspirations of the client.

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1) CURTIS, WJR. Facing up to Mackintosh. *Architects' Journal*, November 5, 2010.

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Awards

- Institution of Structural Engineers 2014 Structural Awards: Winner, Arts or Entertainment Structures
- LUX Awards 2014: Education & Healthcare Project of the Year
- *Architects' Journal* AJ100 Building of the Year, 2014
- Glasgow Institute of Architects Supreme Award 2014
- Concrete Society Awards 2014: Building (Education) Category – Certificate of Excellence.

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Dan Lister is a senior designer in the Sheffield office and led the lighting design.

Andrew McDowell is an Associate Director in the Sheffield office and Project Director for the Reid Building. He also led the building services engineering design.

Derek Roberts is an Associate in the Sheffield office. He was Project Manager and led the structural engineering design.

Andy Sheppard is a senior consultant in the Sheffield office and led the sustainability design.

Project credits

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Project manager: *Turner & Townsend LLC*
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Main contractor: *Sir Robert McAlpine Ltd.*

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Tunnelling under an icon:

the Sydney Opera House Vehicle Access and Pedestrian Safety project

Location
Sydney, New South Wales, Australia

Authors
Mark Adams Seth Pollak Nik Sokol

Introduction
The Sydney Opera House is one of the world's most iconic structures, and Arup has been involved with it since acting as structural engineer for the original design and construction. Now, the firm is continuing to work with and for the Opera House on the AU$152M Vehicle Access and Pedestrian Safety (VAPS) project, design of which started in 2009.


1.

From its opening in 1973, the traffic arrangements for servicing the building required that delivery vehicles share with visitors the open Forecourt and Broadwalk areas (Fig 1). With the visitor numbers growing to 8.3M a year and 1000 vehicle arrivals and departures every week, it became abundantly clear that the original shared delivery access routes could no longer cope with this combined volume.

Funded by the NSW Government, the VAPS project will separate pedestrians and delivery vehicles safely and efficiently, while maintaining, during its construction, continuous operation of the six performance spaces and seven restaurants within the complex. It is also the first phase of a renewal programme over the next decade, planning for which is ongoing by the Sydney Opera House Trust.

Overview
The VAPS project is the largest undertaken at the building since it opened. Managed by the SOH Building Development and Maintenance team, it resolves the conflict between vehicles and visitors by diverting

Arup and Sydney Opera House

Arup's continuous involvement with the Opera House since its inception has given the firm a unique knowledge and understanding of the building, notably the potential for structural interaction between the precast concrete "shell" roofs and the complex substructure. In summary, its work there has comprised the following:

1959–1973: consulting engineer for all three stages of the original design and construction[1, 2]

1973–1998: ongoing involvement in inspections, reporting, and maintenance, particularly concerning tile lids and tiling, glazing, precast cladding, durability issues, and Broadwalk structures; also structural interventions including southern escalator installation, undercroft design and construction, and some internal structural modifications

1999–2005: Opera Theatre renewal — concept design: structural, acoustic, geotechnical, façade and fire engineering, and 3-D CAD modelling; areas included the underground loading dock, new scenery dock, lowered stage, lowered and augmented auditorium seating, new access arrangements, and new ceiling system, as well as structural analysis of the existing roof to check its resilience in the face of small predicted movements to support pedestals arising from proposed substructure works (the Opera Theatre was renamed the Joan Sutherland Theatre in 2012)

2006–2009: Western Foyers Upgrade Project (WFUP): structural, audiovisual, geotechnical, fire and façade engineering, and risk and security consulting for aspects including Bennelong lift installation, northern extension of undercroft basement, replacement of structural walls by new internal column arcade, new ceiling structure, new toilets, and remodelled northern entry

2006–2008: WFUP Playhouse and Studio Theatre upgrades: structural and fire engineering

2006–2009: WFUP escalator installation to southern foyers: structural and fire engineering

2009–2010: Western Venues Masterplan (Western Venues Theatre Systems Redevelopment Project): structural and fire engineering, and theatre planning, audiovisual, and acoustics consulting, including loading and structural analysis for Concert Hall ceiling system, and functionality upgrades to the three L+12 western venues

2009–2015: Vehicle Access and Pedestrian Safety Project (VAPS).

the freight traffic via a cut-and-cover access ramp and mined tunnel underneath the Forecourt into a newly excavated sub-level loading dock, with access tunnels and shafts linking to the existing Opera House basement and ground-level facilities.

Arup's multidisciplinary engineering design includes structural, tunnel, geotechnical, civil and fire engineering, and theatre, traffic and security consulting. The firm also provided resident engineers to address the Opera House's structural, geotechnical and tunnel engineering needs during the construction. Scott Carver is the architect of the VAPS project, in conjunction with Utzon Architects.

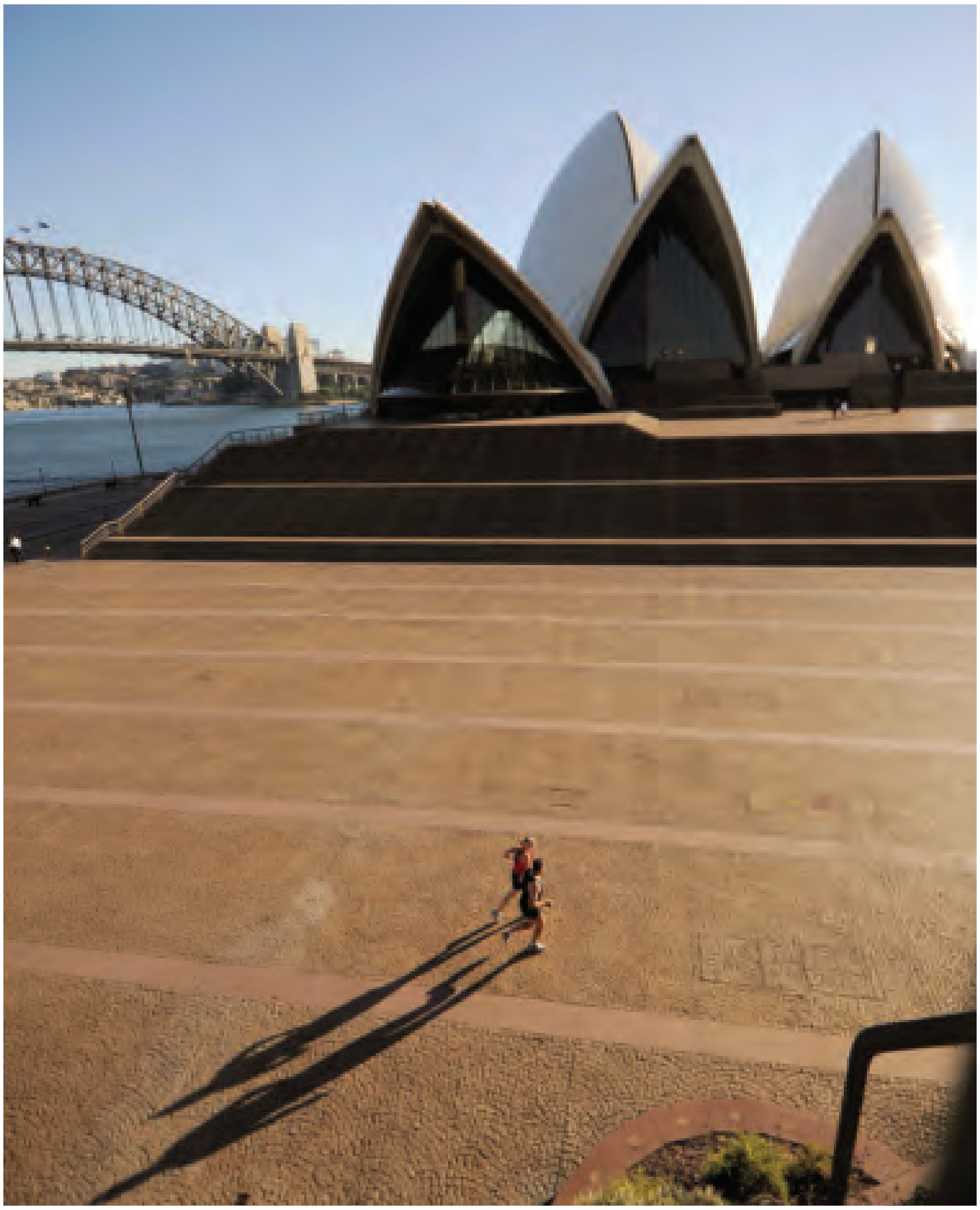
This account of the tunnel design and construction pays particular attention to the risks of excavating under a UNESCO World Heritage Listed site, with primary engineering challenges that included low rock cover, high surcharge loads, a high horizontal stress regime, and a skewed, heavily loaded, 17m span flat roof intersection between the main access tunnel and loading dock. Particular attention is also paid to excavation methods, ground support design, and comparisons between design assumptions and observations made during the ground and structural instrumentation programme.

Project elements, and overview of site progress

The major VAPS facilities include:

- the 50m long, 11m span access tunnel, both cut-and-cover and mined, beneath the forecourt area and continuing under the 100m wide Monumental Steps, the most prominent pedestrian access to the Opera House (Fig 2)
- the 15m deep, 45m x 45m underground loading dock and truck turning bay (TTB) excavated beneath the renovated vehicle concourse, and constructed using top-down construction techniques
- an egress passage from the loading dock to the cut-and-cover portion of the forecourt tunnel, constructed as a mined tunnel
- access corridors to the Concert Hall and Joan Sutherland Theatre at the northern end of the loading dock, using top-down and mined tunnelling techniques respectively
- a cross-passage between these two tunnels, constructed using mined tunnelling techniques
- new lift shafts and stairwells interfacing with the existing operational areas of the Opera House basement and ground level, constructed using traditional excavation
- on the surface, raising the level and replacing the existing granite cobbles with a smoother and more consistent type.

Construction and closure of parts of the forecourt commenced in February 2011, and the tunnelling and excavation work was completed in 2014 without interruption to pedestrian access or the performance schedule, averaging more than 40 events per week.



2.

1. The Broadwalk and Forecourt in 2001.

2. The Forecourt and Monumental Steps in 2010.

3.

The underground work proceeded throughout, almost entirely behind or beneath the scenes. All planned performances and tours continued and for the busy shops, cafes and restaurants along the Broadwalk areas it was business as usual. The forecourt was partially reopened in September 2013, and rotating occupation of work areas will continue until the project is completed in 2015.

Initial ground support design

The design of the initial ground support for the project was founded on principles developed and applied over the past 30 years in the local Sydney sandstone (Hawkesbury Sandstone), beginning with the Opera House underground parking station[3] adjacent to the VAPS project.

In the vicinity of the Opera House, the Hawkesbury Sandstone is generally horizontally bedded and massive. The main discontinuities within the rock mass include widely spaced vertical joints, laterally extensive shale bands and occasional erosional planes, the latter two of which can cause delamination of rock slabs from the tunnel roof during excavation.

Using the voussoir beam rock mechanics model (an analogy between the behaviour of a voussoir in construction and that of naturally occurring rock), calculations were verified by 2-D and 3-D discrete element analyses, and the timing of the support installation was closely tied to the excavation sequence so as to limit ground movements under the structures. A rigorous instrumentation and monitoring programme measured sidewall deflection and tunnel convergence, both of which were compared to the design assumptions.

Design methodology

The temporary support design of the mined tunnels included analytical beam-arch and numerical (discrete element) methods. Based on the structural uniformity and specific behaviour mechanisms observed in the Hawkesbury Sandstone, an empirical rock mass classification design approach like the widely-implemented Q-system[4] or Rock Mass Rating[5] was not considered appropriate to arrive at a safe and reliable temporary support design*. The methods adopted account for site-specific joint orientations and properties as derived from both the ground investigation and nearby rock exposures, ensuring against over-simplification of the rock mass, as can happen with empirical methods.

Failure mechanisms considered and designed against in the analyses included:

- reinforced rock beam failure through lateral stress-induced bedding shear displacement
- vertical slip of the reinforced rock beam under surcharge and self-weight loading along joints at the abutments
- compressive crushing of the rock at the top of the beam midspan under deflection
- build-up of localised water pressure in bedding joints due to laminate seam or aquitard (low permeability bed that inhibits groundwater flow)
- beam delamination at midspan due to vertical tension from self-weight and surcharge loads
- support installation delay leading to excessive beam deflection, block rotations, and ultimate instability
- rock reinforcement bond failure
- debonding of thin shotcrete membrane, causing flexural failure, or punching shear due to a detached block between bolts
- instability of vertical walls, both at tunnel face and temporary drift walls.

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*Rock mass classification systems such as Q and RMR are methods by which rock engineers quantify properties of the rock mass, to estimate how it will respond to tunnel excavation and what kinds of support measures will be required. The parameters and how they are considered in the analysis are based on the experience of their developers from a database of numerous projects. Rock mass classification is an empirical approach to quantifying rock mass evaluation, which would otherwise be qualitative and subjective. For many projects, it gives engineers a common language and helps them, however roughly, to characterise the rock mass, select tunnel stabilisation methods, and determine rock loads. In addition to achieving rock mass stability, the ground support design for VAPS was principally governed by limiting ground movements under structures, hence the empirical design approach was considered inadequate.

3. The Forecourt, June 2014.

Voussoir beam analysis

The voussoir beam or linear arch analogue has been used for Hawkesbury Sandstone in nearly every tunnel project since the Opera House underground parking station. The method applied to the VAPS tunnel ground support design is that proposed by Diederichs and Kaiser[6] and modified[7] for simplicity.

In this "hybrid" voussoir beam analysis, once the shape and stress distribution of the linear arch thrust line has been established, the component of stress along and normal to the bedding plane is calculated by considering the slope of the parabolic arch as a function of distance along the beam. The shear and normal stress are then compared to the shear strength of the bedding plane, and then a pattern of rock bolts is designed to carry the excess stress.

2-D numerical analysis

The analytical results were confirmed, and site-specific geology and loading conditions incorporated, through numerical modelling using the Universal Distinct Element Code (*UDEC* v.4.01, Itasca[8]). Joint set orientations were determined through examining borehole optical televiewer data using Raax Australia's Borehole Image Processing System (BIPS)[9].

Justification of the adopted joint pattern was established through a block size analysis (after Palmström[10]) using the dip angle and depth of the recorded fractures in the raw borehole televiewer data. The data were cross-referenced with core logs and photos to exclude cross-bedding accidentally logged as fractures by the televiewer. The block size distribution in *UDEC* was plotted after a normal distribution profile, and the estimated block size from the Palmström[10] analysis was verified as falling within the standard deviation of this profile. Once satisfied, the model was considered "calibrated" to the actual block size. In addition to the orientation and size of the rock blocks, the strength parameters of the contacts between the blocks has a marked influence on model behaviour (Table 1).

Table 1. Discontinuity shear strength parameters

Type	*φ*	*Dilation*	*Normal stiffness (MPa/m)*	*Shear stiffness (MPa/m)*
Bedding (clean)	34°	3°	4000	400
Bedding (1mm–5mm clay infill)	29°	3°	1500	150
Erosional plane	20°	0°	200	20
Sub-vertical joint (clean)	34°	0°	4000	400
Sub-vertical joint (1mm–5mm clay infill)	32°	0°	1500	150

Table 2. Forecourt mined tunnel key results comparison.

Analysis type	*Mid-span deflection (mm)*	*Horizontal abutment (kPa/m)*	*Minimum thrust arch (kPa/m)*
Voussoir beam	1	599	336
UDEC	10	800	400

A significant characteristic of Sydney's geology is the high ratio of horizontal versus vertical stress locked into the rock mass. This is known to cause relaxation during tunnelling, which can manifest as shearing along bedding planes and opening discontinuities (dilation). Along with increased ground movements and loss of shear strength, this dilation may result in increased groundwater inflow.

Site-specific stress measurements were obtained using hydrofracture techniques. Additionally, various in situ stress results have been published with a range of stress magnitudes for the Hawkesbury Sandstone in Sydney. For conservatism, two cases of horizontal stress were examined for the VAPS study: a lower bound stress profile critical to tunnel stability (minimising confinement of the voussoir beam abutments), and an upper bound profile that maximised shearing along bedding planes (ground movements). The site-specific stress measurements formed the basis for the higher bound stress, which was verified by regional finite element modelling.

Results

The results (Table 2) show that the mid-span deflection of the rock beam is greater in *UDEC* than in the analytical model. This is likely due to the effects of an erosional plane above the tunnel crown incorporated in the *UDEC* model.

The temporary support designed for the tunnel comprised 5m long rock bolts at 1.25m centres and pre-tensioned to 75kN. A 100mm thick steel fibre shotcrete layer was specified to retain any ravelling pieces in between the bolt pattern. As a conservative measure, the benefit of shotcrete was not included in design calculations or models.

Designing under the Monumental Steps

A 16.25m long section of the forecourt tunnel runs obliquely under the strip footing for the Monumental Steps. As with all structures here, the movement tolerances allowed were very small, around 5mm. The strip footing for the Monumental Steps applies a high surcharge load, up to 700kN/m; this had to be considered in the tunnel design and presented a particular challenge for its long, flat, roof span.

Stability analyses in *UDEC* indicated that the load propagated directly through the rock, with load-spreading limited by interlayer friction of bedding planes.

Analysis using the standard rock support system revealed a narrow pressure distribution bulb, high loads on the tunnel roof, and unacceptably large ground displacements and settlement under the stairs — all compounded by the skewed angle between the tunnel and the steps (around 45°). The 2-D case of subjecting the full skew span to the surcharge load applied across the top of the model was not geometrically accurate, so it was decided to model the entire forecourt tunnel in 3-D.

Table 3. Summary of layer attributes for temporary lining design case under monumental steps.

Layer no	*Thickness (mm)*	*Shotcrete type*	*Reinforcement*
1	100	S1*	Fibre
2	100	S1	Fibre + mesh + Φ40mm L-bar
3	100	S2	Lattice girder
4	100	S2	Lattice girder
5	100	S2	Φ40mm straight bars
6	100	S1	Fibre

*S1 = steel fibre reinforced S2 = plain shotcrete

Table 4. Results of sensitivity analysis of in situ stress profiles for forecourt mined tunnel.

Model	*Stress profile*	*Surface settlement (under MS)*	*Surface settlement (under forecourt)*	*Sv (mm)*	*Sh (mm)*
UDEC	Pells12	N/A	5.5	8	10
	VAPS hydrofracture	N/A	5	8	12
3DEC	Pells12	5	12	10	13
	VAPS hydrofracture	5	12	12	16

Sv = in-tunnel vertical convergence

Itasca's *3DEC*[11] software was chosen to develop the discrete element model (Fig 4) because it:

- accounted for the geological structure of Hawkesbury Sandstone
- provided suitable comparison with the 2-D *UDEC* models also used in the design
- prevented a new set of geotechnical continuum parameters being defined that would characterise an anisotropic rock mass as an isotropic one
- provided a more conservative load spread from rock mass bedding than a continuum model.

The design intent was to provide a stiff and robust support and construction sequence that minimised movements to the overlying stairs, only 6.9m above the crown (cover/span ratio of 0.58). A full-face excavation, with short 1m–1.5m advances, was considered preferable over sequential methods involving complex reinforcement and shotcrete overlaps.

The passive support consists of a 600mm thick shotcrete lining, reinforced with lattice girders, welded wire mesh, and additional steel reinforcing bars at critical locations.

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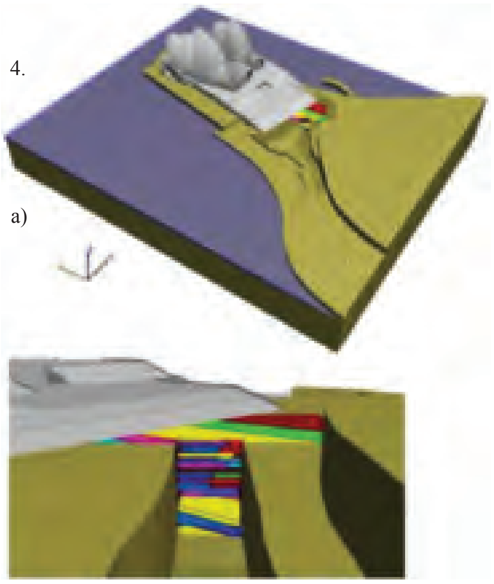
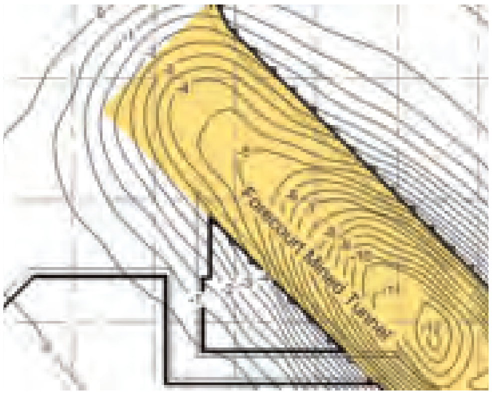


4. (a) Global overview of *3DEC* model; (b) rock mass model for the Forecourt tunnel.



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5. Settlement contours based on 2-D and 3-D analyses; 5mm settlement was predicted under the Monumental Steps, compared to 12mm away from them, where less stiff support was used close to the tunnel portal.

Tensioned rock bolts between lattice girders were designed to promote beam action within the horizontally bedded rock, and also to prevent shear displacement of the rock during the future loading dock excavation. For each 1.25m advance (13 in all), the maximum axial force and maximum/minimum bending moments were extracted from the lining beam elements, so at each stage every previous 1.25m wide beam element was rechecked for a change in stress. Reinforcement was then designed to meet the critical demand.

In this unique design, 40mm diameter reinforcing bars at 200mm spacing were installed as "L-bars" in the lining extrados at the roof corners, and as straight bars between lattice girders near the lining intrados. This provided positive moment reinforcement in the correct locations of the lining, and allowed for complete encapsulation by the shotcrete. The final design rock bolt spacing of 1.44m x 1.25m (longitudinal/transverse) was set to fit with the required lattice girder spacing of 720mm on centre (Table 3).

3DEC model results

With the inclusion of the temporary support, the maximum top of rock displacement under the stairs was calculated as 5mm (Fig 5). In general, the *3DEC* model produced similar in-tunnel convergence displacements compared to the 2-D model, but surface settlements were greater for the 3-D model, probably because of the major principal stress running parallel to the tunnel axis, which is largely ignored in the 2-D plane strain model. In addition, the *3DEC* model incorporated the forecourt tunnel portal, a boundary condition that introduced more relaxation than the 2-D case.

Two separate in situ stress cases were evaluated in the 2-D and 3-D models: Pells' recommendations[12], and one that considered the high in-stress results obtained from hydrofracture tests in VAPS boreholes (Table 4).

6. Excavation of cut-and-cover section of the Forecourt access tunnel, June 2012.

7. Site progress, March 2013.

8. Site progress, April 2013.

9. View into the Forecourt tunnel during full-face roadheader excavation, September 2012.

6.

7.

8.

9.

Construction progress

Access ramp (cut-and-cover)

Construction of the ~50m long tunnel access ramp began in March 2012 and involved the removal of ~8000m^3 of rock. The ramp was initially excavated adjacent to an existing rock wall by hydraulic hammers (Figs 6–8) to a depth of ~8m, at which point the contractor covered the area with an acoustic shed to allow a double shift excavation programme. A 300kW roadheader completed the ramp excavation to its final depth of ~14m below ground surface at the tunnel portal.

Forecourt tunnel (mined)

Before commencing tunnel excavation, the contractor requested to use a double-corrosion protected, lighter gauge rock bolt (DCP310) in lieu of the designed rock bolt (RB550), to facilitate compatibility between the rock bolt type and drill rig available to the project. Reanalysis using *3DEC* verified that the proposed DCP310 rock bolt was adequate, provided a decreased spacing of 0.75m x 1.0m (longitudinal/transverse) was adopted.

Roadheader excavation of the ~40m section of mined tunnel began in August 2012. After staggered advances through the first 3m of the portal area, the remainder of the tunnel was excavated full face with 1.5m advance lengths (Fig 9). For the standard ground support, shotcrete was applied after mining and allowed to reach a minimum compressive strength of 1MPa to comply with personnel re-entry requirements. Tensioned rock bolts were installed to complete the initial ground support prior to advancing the next round.

As already discussed, the temporary liner for the section of the forecourt tunnel under the Monumental Steps was notably more robust, and was designed to be installed in three distinct passes, with the full 600mm thickness achieved no further than 3.75m from the face (Fig 10). Through this heavily reinforced section, the contractor worked with Arup to optimise the excavation and support sequence.

Advance lengths of 1.5m were maintained to allow a more efficient cycle, reducing plant movement and interchange of activities such as shotcreting and steel installation. The 40mm diameter bars were prefabricated into panels and lifted into place. Edge boards were used for accurate profile control and to ensure that the lattice girders and steel reinforcement were installed to the design position in the concrete profile.

Tunnel convergence and surface settlement over the tunnel were closely monitored and observed to be below the design predictions, allowing the excavation to proceed with confidence that structural movements would remain within allowed tolerances.

Loading dock and truck turning bay

Prior to the top-down excavation for the loading dock and TTB, a new roof structure was constructed beneath the Monumental Steps across the footprint of the loading dock. The steps are supported by a series of tied arches formed by concrete beams buried immediately beneath the existing pavement, while the new roof structure consists of a post-tensioned beam grillage supporting the new concourse slab.

The primary beams for the new roof were supported on foundations bearing directly on rock outside the excavation footprint. The new slab was cast (Figs 11–13) and the roof structure load transferred from the temporary columns to permanent walls within the loading dock.

Access for mining underneath the new roof structure was gained on the east side of the Monumental Steps (Fig 14). The top bench of the loading dock and TTB were excavated by a 125kW roadheader (Fig 15), beginning


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10. Typical temporary support installation sequence for the section of Forecourt tunnel under the Monumental Steps.

11–12. Construction of new loading dock roof structure under the Monumental Steps, May–June 2012.

13. Concrete pour for new roof structure complete.

14.

14. Surface excavation for the truck turning bay and access for mining under the new loading dock roof slab from the east side of the Monumental Steps, July 2012.

15. Excavation by roadheader beneath the new roof structure of the loading dock, September 2012.

16. After excavation by roadheader, a remotely controlled robotic hammer removed blinding and formwork to create a safe area for personnel re-entry.

15.

16.

from the surface exposure of the TTB and advancing under the new vehicle concourse slab. After each ~5m advance, to avoid working under unstable materials, a remotely-controlled robotic hydraulic hammer scaled blinding concrete, formwork and residual rock from the base of the slab (Fig 16). This sequence was repeated until the top bench reached the rear of the loading dock, where it interfaces with the access tunnels.

The cross-beams for the new roof slab were not designed to span the entire loading dock excavation, so piles were bored through the temporary bench excavation invert and new columns formed to temporarily support the cross-beams. Similarly, the existing tie beams supporting the Monumental Steps could not span the whole excavation, so direct hangers or cradles for their support were installed from the new roof grillage, maintaining isolation between existing and new to allow independent movement.

Initially, the rock in the southern part of the loading dock was left unexcavated, forming a 7m thick wall in front of the forecourt tunnel breakthrough location while the tunnel's final lining on the other side was cast. This rock plug was left in place to provide continuity of the rock beam and out-of-plane confinement and minimise ground movements under the Monumental Steps. Arup and the contractor reviewed the rock conditions and observed ground movements, and the rock plug was allowed to be reduced to 4m (Fig 17).

17.

17. Interim level bench excavation of the loading dock, with 4m thick rock plug on the left side, and a further 6m depth remaining to be excavated, December 2012.

18. View looking northeast through the egress passage towards the loading dock: the 90° turn originally planned was replaced with a curve to allow for roadheader mining.

19. View looking north towards rear of loading dock after bulk excavation had been completed.

20. Underpinning posts and sand jacks that will temporarily support the post-tensioned floor slab, February 2013.

18.

19.

With the forecourt tunnel final lining completed and at design strength, the remainder of the loading dock top bench was excavated. The 125kW roadheader then excavated the egress passage directly over the forecourt tunnel (Fig 18).

The 300kW roadheader proceeded to mine the Joan Sutherland Theatre corridor and the bottom bench of the loading dock and TTB, including excavation of the remainder of the rock plug and the breakthrough from the loading dock into the mined tunnel, completing the removal of ~18 000m^3 of sandstone from this area (Fig 19).

The Joan Sutherland Theatre corridor

This ~10m wide, 15m deep, 40m long corridor extends from the loading dock to a new lift for scenes and large goods (lift 21). Excavation by hydraulic hammer began at lift 21 from within the Opera House and proceeded southwards. Underpinning beams supporting existing ground-level rooms in the building were installed progressively with the excavation.

The bench of the corridor was advanced from the loading dock using the 300kW roadheader, which dug back towards lift 21 underneath a newly-constructed stairwell and post-tensioned floor slab supported by sand jacks (Fig 20). When the permanent walls in the Joan Sutherland Theatre corridor were completed, the sand jacks were released to transfer the load of the stairwell and floor slab to the permanent structure.

20.

Cross-cut and Concert Hall tunnels

After completing excavation of the Joan Sutherland Theatre corridor, a cross-cut tunnel (proposed by the contractor) was advanced to the west with the 125kW roadheader, to provide access for excavating the Concert Hall tunnel, which was subsequently advanced to the south and north. These tunnels, like the egress tunnel above the forecourt tunnel, have rectangular profiles and were supported with a standard pattern of rock bolts and shotcrete.

Instrumentation and monitoring

A robust instrumentation and monitoring program was specified so as to:

- verify geotechnical design assumptions
- monitor ground movements and effects on adjacent and overlying structures
- confirm temporary support and advance lengths suitable for actual ground conditions
- allow adjustments to temporary support or construction sequences/methods/advance lengths based on a comparison of predicted against actual behaviour
- measure tunnel convergence and open cut sidewall deflection and stability
- provide early warning of instability and allow corrective action to be taken
- allow the contractor to quantify construction impact in relation to any third party damage claims, and verify that it is as predicted and acceptable.

Instrumentation and monitoring on the VAPS project included six in-place (automated) inclinometers and two in-place borehole extensometers, 200+ monitoring points on the surface and the building, monitoring points for excavation and tunnel deformation, noise and vibration monitoring, geological mapping, and crack monitoring. The instrumentation subcontractor developed and maintained a monitoring website, with data from the inclinometers and extensometers updated every 15 minutes. All other instrumentation was manually read with survey reports uploaded daily.

Coloured trigger levels were assigned to each instrumentation point, with green representing 80%, amber 100%, and red 125% of calculated design values. There was a significant range of design values for various structures, however — typical values ranged from 0mm–12mm. In the case where no structural movement was predicted, an amber trigger level of 3mm was assigned to the point.

Geological mapping and additional support

Throughout the excavation period and after each tunnel advance, geological mapping gathered information on key parameters needed to validate the design or select rock support.

Spot bolting was required on the existing rock wall adjacent to the access ramp. The newly excavated vertical sidewalls of the ramp and loading dock occasionally revealed potential rock wedges/blocks formed by subvertical joint intersection with bedding. Unstable blocks were either scaled and removed, or supported with spot bolts. The sidewalls were generally self-supporting, as observed in similar sandstone cuts around the Sydney area.

Around the loading dock, many footings sit adjacent to excavation edges. Prior to placing footings, the rock was assessed to verify its bearing capacity, typically 3MPa or 5MPa. In some instances, rock bolts were installed under footings to prevent potentially kinematic rock wedges being mobilised or planar failure, and in one case, to reinforce and anchor a temporary prop footing vulnerable to accidental impact.

Management action team/permit to tunnel

The management action team — Arup, the contractor (John Holland), and the instrumentation subcontractor — examined the instrumentation results daily, identifying notable trends and responding to any alarm trigger breaches in accordance with the contract documents. After assessing risks and reviewing instrumentation, ground behaviour and relevant geological/structural observations, a permit to tunnel was issued.

A valid permit is required daily for compliance with the New South Wales code of practice[13] and includes detailed information on the work area, construction sequence, constraints, ground support type, requirements for personnel re-entry and a summary of instrumentation observations.

Extensometer observations

The two borehole extensometers were installed to observe ground movements over the middle of the forecourt tunnel crown. Less was found than anticipated, principally because (1) as already discussed, the contractor opted to install rock bolts at half the spacing specified in the design, thus stiffening the rock beam; and (2) in the forecourt tunnel, specifically under the Monumental Steps, shotcrete achieved higher strengths than assumed in the design.

Inclinometer observations

Excavation of the north wall of the TTB and the east wall of the loading dock created the longest sandstone wall on the whole project, and this was where the most lateral ground movement was anticipated. The wall runs generally perpendicular to the NE–SW principal horizontal stress direction.
One inclinometer was installed just beyond this wall to monitor the ground relaxation during mining, and showed a clear response, logging 10mm deflection towards the excavation, matching the predicted ground movement of this wall (Fig 21).

The lack of significant movements recorded since completion of the loading dock and TTB excavations to full depth confirmed that rock excavation and immediate stress redistribution were responsible for the observed deflection.

Tunnel deformation monitoring points (TDMPs)

Three-point arrays (sidewall, crown, sidewall) of TDMPs were installed progressively behind the advancing tunnel faces, but showed no significant convergence in any of the four tunnels monitored.
Most sandstone relaxation and associated ground movement is believed to occur almost instantaneously after excavation and so, despite being installed as soon as practicable after advancing the tunnel face, the TDMPs likely did not capture most of the tunnel convergence.

Excavation deformation monitoring points (EDMPs)

Arrays of EDMPs were installed progressively with the loading dock and Joan Sutherland Theatre corridor excavations, but as with the TDMPs, much of the rock relaxation had probably occurred by the time is was safe to install them. However, around the loading dock excavation, most EDMPs showed minor movement into the excavation.

EDMPs and in-place inclinometers generally indicated similar movement directions with varying magnitudes of deflection within the predicted value threshold, indicating a highly anisotropic in-situ stress state.

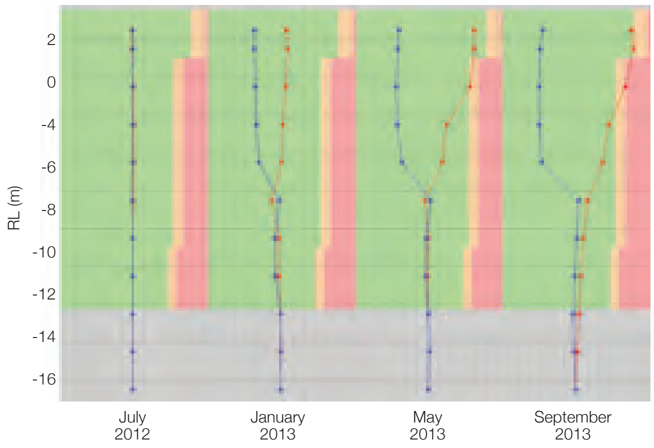
Structural monitoring

Over 200 survey targets were installed outside and inside the Opera House within VAPS project's zone of influence. The vast majority on the interior never recorded an alarm reading. For the few that did breach a trigger alarm value, the data were shown to be from survey error, or very minor structural movement.

Those exterior target arrays installed specifically to the underside of the Monumental Steps almost continuously indicated movements, particularly in settlement/heave, that breached the specified trigger levels for both positive and negative changes. The data collected showed clear correlation of structural movements and air temperature (Fig 22), though a few monitoring points on the Monumental Steps indicated movements which could not be thus attributed. These were considered to be caused by excavation, and typically involved small lateral movements of <5mm, which were acceptable and within the expected range.

Conclusion

The Sydney Opera House is a unique environment in which to design and construct an underground project.
The complexity and sensitivity of the existing structure, the excavation shape, and the geotechnical conditions drove the development of robust ground support designs, innovative construction sequences, and a comprehensive instrumentation programme. The designer, contractor and client worked closely together to optimise the support and sequencing, and as a result there has been no disruption to the performance schedule. The VAPS project will be handed over for operational use in 2015.

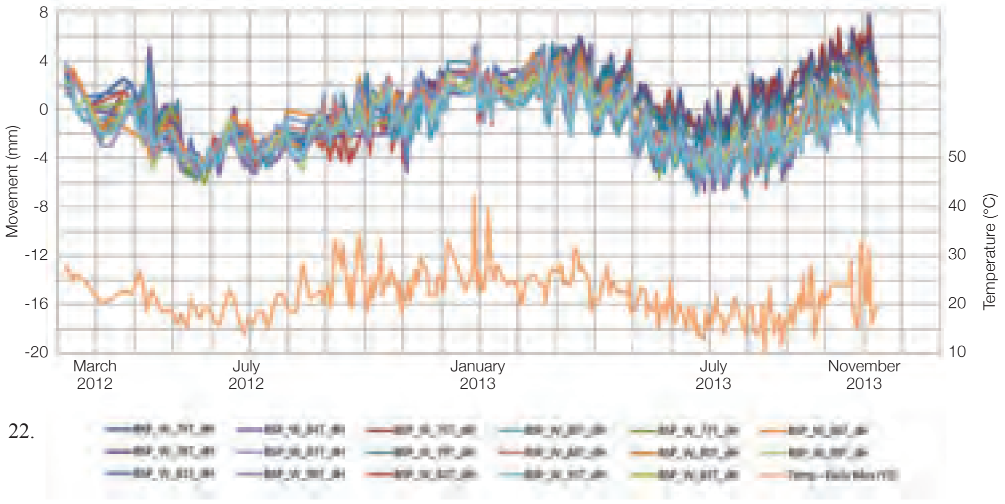


21.

21. Cumulative displacement profiles of inclinometer IN-5 from before (July 2012) during (January and May 2013) and after (September 2013) excavation. Note close correlation of design (amber shading) and observed (red line with dots) values. Grid cell width is 2mm. Grid cell height is 2m.

22. Plot of change in vertical height of survey targets on the underside of the monumental stairs (upper lines) and air temperature (lower line) over 18 months. Note the correlation between thermal fluctuations and structural response of the stairs.

23. Progress at the loading dock, June 2014.



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Project credits
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1 *Peter Ross*; 2 *Jack Atley*; 4–5 *Arup*; 6–10, 13–20 *Nik Sokol*; 11–12 *Mike Cook*; 21–22 *Lynton Surveys*; 3, 23 *Jeremy Piper*.

Our inheritance, the next step?

Philip Dowson

Sir Philip Dowson — founder-partner, with Ove Arup and Derek Sugden, of Arup Associates in 1963 — died on August 22, 2014, at the age of 90. His lifelong concern with the built environment, and with architecture's ability and need to shape, enhance and enrich it, is expressed as well as anywhere in this paper, first published in The Arup Journal*, June 1976, and reprinted here as a tribute to him. It was originally given as a talk to a joint meeting of the Building Services Engineering Society*[1]*, the Joint Building Group*[2]*, and the Junior Liaison Organization*[3]*, at the Institution of Civil Engineers on 30 October 1975.*

I was asked to give this talk with particular reference to Architectural Heritage Year[4] because our practice has been concerned for some time with the rehabilitation of old buildings for new uses and, as it was also put to me, we have been concerned with designing new buildings to fit into the fabric of old historic sites. The title of my talk — "Our inheritance, the next step" — is, of course, an enormous subject, but a talk has to have a title. It gives me, however, the opportunity to dwell and observe on some aspects which have been preoccupations of ours. I make no apology that I should look at these through the eyes of an architect — not an historian or theoretician — and I shall talk unrepentantly from what may appear a rather architectural point of view, if simply to avoid the kind of discussion which can so rapidly become the shape of an inverted pyramid — not an unreasonable shape for an architectural discussion, one might add, for those who may think we are prone to seeing things upside-down.

I believe Architectural Heritage Year marks a watershed in a number of ways:

1) The public is at last waking up and protesting at what is happening to our environment.

2) Our resources are being examined in a new light and in new ways.

3) For many the Modern Movement has turned sour.

4) The designers are losing their nerve and tending to revert to a reactionary position of safety.

5) There is a recognition of the need to conserve and re-use much of our building stock which we have been too ready to destroy without reason.

6) The failure of much comprehensive redevelopment — in Jane Jacobs'[5] words, "Cataclysmic Change" — and the recognition of the need for blood transfusions rather than transplants.
It is easy to raze an area of a city and rebuild it in a matter of years, but what of the social infrastructure that is lost? That will take generations to heal.

7) To quote Theo Crosby[6] — *"There is an appalled realisation that we have unwittingly lost irreplaceable treasures, discarded irrecoverable aesthetic and social pleasures for the benefit of an ephemeral technology."*

There is indeed a crisis in architecture.

Two years ago, at the JLO Conference in York, I made the point that public criticism, in step with mounting concern over conservation, and a healthy dislike for much that has been happening to our cities, towns and our countryside, will be increasingly directed towards the environmental professions who are, in their view, largely responsible. We *can* argue that society gets the cities and architecture it deserves; that economic considerations pre-empt to a large extent the results that all of us deplore; that organisations are too often indifferent to architecture, or at any rate disinclined to accept it until it has first been disinfected by financial propriety.

Nevertheless, in the meantime, the centres of great cities have been disembowelled. Redevelopment has too often become synonymous with destruction. The scale of buildings has become so large as to be out of reach of ordinary mortals, and the inhabitants have become alienated and the places unloved. This, I believe, remains true.

So the environmental professions have a formidable problem of bridge-building to undertake between the public and themselves.

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[1] Founded in 1972 (with an inaugural lecture by Ove Arup), this short-lived body evolved from the UK Institution of Civil Engineers' Building Services Group and was also sponsored by other UK engineering institutions. In 1976 the then Institution of Heating and Ventilating Engineers (not a sponsor of the BSES), merged with the Illuminating Engineering Society to form the Chartered Institution of Building Services (now the Chartered Institution of Building Services Engineers). This made the BSES effectively defunct, and it was subsequently dissolved.

[2] The Joint Building Group was formed in 1963 under the auspices of the Institutions of Civil, Electrical, Heating and Ventilating, Mechanical, and Structural Engineers, the Royal Institute of British Architects, the Royal Institution of Chartered Surveyors, and the Institute of Building, *"to improve efficiency within the building and construction industry by promoting interprofessional discussion on common problems"*. A proposal championed by Ove Arup for the JBG, the BSES, and the Junior Liaison Organization to amalgamate into a "society for the built environment" never materialised.

[3] An inter-disciplinary group, active in the 1960s and 1970s, for young building industry professionals.

[4] The declaration of 1975 as European Architectural Heritage Year was an initiative of the Council of Europe, and led to the formation of ICOMOS (International Council of Monuments and Sites) and in Britain of SAVE Britain's Heritage, both of which remain active to the present.

[5] Jane Jacobs (1916–2006): American-Canadian journalist, author, and activist known for her influence on urban studies. Her best-known book was *The Death and Life of Great American Cities* (1961).

[6] Theo Crosby (1925–1994): British architect, editor, writer and sculptor, and founding Partner of Pentagram.

1.

We are viewed at present like a pack of hounds that have lost the scent or, to change my metaphor, the architect as the conductor is seen to be working from one score while the orchestra is too often playing from another. There is the deep, and not unreasonable, suspicion that any specialists, if left to themselves, are inclined to seek solutions drawn too largely from within their own specialisms. This is a question of ends and means. Because of the very excitement of the limited professional or technical chase, it is easy to overlook the purpose of the hunt. The means are so fascinating that we become seduced by them. It is a moot point to what extent we are willingly misled by the siren songs of technology, or hijacked against our better judgement by its imperatives. Both are evident.

So it is not perhaps surprising that, through lack of confidence or understanding, or both, administrations and bureaucracies fall back on proliferating rules and regulations. Of course, regulations are necessary, but I believe the best games are usually played with fewest rules. As Peter Martin[7] also said at York in another context — *"We have to beware that the present righteous indignation of the public does not result in a rash of legislation which is only half thought out, academic, and unlikely to achieve the stated objectives.*
The professions have to be much more *on their guard than they have been in the past, otherwise their imprisonment will become more* rigorous *within a system which they* ought *to take part in leading."*

Design, however, needs good designers, as well as an active public interest, and this purpose will not be served if the designers are submitted to such great pressures that they either lose their nerve altogether or have it gradually eroded. This risk is very real. As designers, we *have* to be excited by the prospect of what can be achieved and, for this to be the case, we *have* to be secure in the knowledge that what we are trying to achieve is relevant to the public, or our client's, interest. As designers we need encouragement, just like anybody else if we are to succeed, and that needs understanding on the part of our patrons as well, who, if this is to be the case, must in turn be secure in the knowledge that we are working competently and professionally in their *real* interests, although they may feel, from time to time, that they are taking their life into their hands and are bound on something of a mystery tour.

Watershed

We are then, I believe, at a watershed.

Architecture at the moment is subject to a large number of movements which reflects its dilemma. It is an art, a craft and a science, but on the whole the art has recently been at odds with the science and the craft has been disappearing. As an architect, I am worried that I am continually being asked to solve increasingly impossible problems, with a danger that better techniques will merely make it possible to support and extend the life of otherwise obsolete ideas, rather than to find an application for new and perhaps more appropriate ones.

Whether we have failed the Modern Movement, or whether it has failed us, is perhaps another discussion. But the re-assessment and soul-searching that is going on at present must not be a retreat but an attempt to focus more keenly. It is inevitable, I suppose, that we have had to go through the various phases we have experienced in the last 50 years.
In observing, for example, on the Modern Movement's elimination of all decoration and embellishment from buildings, in pursuit of social aims within an industrialised society, it is interesting to note how rapidly these social aims, and the process of elimination, generated a strong aesthetic compulsion of its own. This went closely in step with the painters and sculptors of the time, and it soon achieved a very distinctive style. This style, however, in company with what the Movement fundamentally represented, was debased and exploited after the last war, and has become associated in the public's mind with "Modern Architecture" and with the reconstructed devastation — what else can it be called? — of large areas of our great cities.
The public is protesting, the money is running out, and so the sacking has to stop.

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[7] Peter L Martin, CBE, author of the classic *Faber & Kells Heating & Air Conditioning of Buildings* for several editions, Chairman of the Heating and Ventilating Research Association 1967–68, President of the Institution of Heating and Ventilating Engineers 1971–72, and Chairman of the Association of Consulting Engineers 1983-84.

Our inheritance

Consider Venice, not only for what it represents but also because it is so relatively little changed. A city always of tourists and merchants, it has been so carefully and methodically recorded by Canaletto, who was the nearest thing to an 18th century photographer that we have. We can check how accurate he was, and therefore have confidence in the accuracy of his paintings of London, which I shall come to presently.

No questioning then the integrated skill of the architects, civil engineers, craftsmen, artists, or very particularly, the level of enlightened patronage. There were no planning authorities as such then, just a social acceptance that if you built you tried, for whatever reasons, to add to the beauty of the city. (If not, you could run foul of the authorities and be found buried head down with your feet sticking out of the pavement of St Mark's Square!). Craftsmen rarely *waste* their materials, and those who worked in this city, and built it over the centuries, seemed to have been as *mindful* for its site and its spaces, as the craftsman is for his materials.

In this respect it is also important to recognise that the simple human gesture of reassurance — to touch — to feel — to handle, to which any pilgrim church bears witness, is basic. Whatever other architectural aspirations there may be, the need for reassurance at this elementary level should surely be self-evident; that is, if a secure relationship is to exist and alienation is to be avoided. Indeed, whatever else Venice may be, and represent, it is also a supremely tactile place. You can actually *handle* Venice anywhere as you walk, as you could have done with London in Canaletto's day.

London was called by 18th century travellers "the jewel of Europe". This was not designed by a swarm of architects — but, by and large, by builders working within a tradition. Cities represent the physical embodiment of the attitudes and values of their societies, of which they are the clothing. Most of these buildings, constituting the fabric of the city, were the result of traditional crafts, aided by pattern books and effected, of course, by the swing of fashion, which in turn stemmed from the great patrons, and the few architects who were employed by them (and I am always being told that they have usually been a cussed lot). As Sir Christopher Wren himself remarked — *"Architects are as great pedants, as critics and heralds"*[8].


2.

I would like to dwell for a moment on this vernacular aspect, as the greatest part of our inheritance is traditional vernacular architecture, architecture without architects, which has evolved almost like a species, with time to embody and reflect the countless pressures of social pattern, climate, economics, transport, materials, techniques, and so on, as well as the fashion and style which invested these great traditions in the past. Traditions where the appropriate and the preferred survive, a kind of Darwinian theory of building design evolution.

It is worth reflecting on the richness that these traditions derived from apparently such simple means, and the manifest delight in natural materials which they exhibit.
Also, recognise the discerning eye and thinking hand of the craftsman, and the language of construction, which testified to such a humane approach, and at times such a highly sophisticated architectural result.
It is an achievement which, to a remarkable degree, combines a coincidence of thought, feeling, understanding and method. Leonardo da Vinci remarked, *"When the spirit does not work with the hand, there is no art"*[9].

What so many of these vernacular traditions had, and what we seem to have lost, is the art of designing in an intimate way, or for that matter in a monumental one, which still embodies the kind of scale which is interesting to the eye and, particularly, acceptable to the touch, so that in approaching these buildings we naturally use them. We lack a satisfactory grammar of detailing derived from the way we make our buildings, which is implicit in the result, or a decorative tradition which can reinforce and emphasise that which is basic to a design. Decoration, please, which elucidates and does not obscure the design idea. We badly need the delight and interest of intelligent and imaginative detail in our modern buildings. It is also increasingly difficult to achieve, the designers having to work more and more via remote control, within an industrialised context.

However, when one examines any vernacular design, it is immediately apparent that the interdependence of the various designers and craftsmen working within the tradition was taken for granted, and their individual contribution was appreciated and understood by each other. Indeed, it *must* have been so to have achieved the results which they did.

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[8] From a letter to the authorities of Trinity College, Cambridge, on the plans Wren had submitted for the new library, as quoted in *Memoirs of the Life and Works of Sir Christopher Wren* by James Elmes (London, Priestley and Weale, 1823).

[9] Source not found.

2. Canaletto, *The Thames from Somerset House Terrace towards the City*: "the nearest thing to an 18th century photographer that we have."

3. Wills Factory at Bristol, UK: "A 'future' which is past"? *Architectural Review*, October 1975.

Europe is rich in a marvellous inheritance of buildings and places, a veritable treasure-house of many cultures; the result of both very self-conscious societies, as well as others whose designs are derived from very unselfconscious attitudes, vernacular in tradition. Both have, of course, been of considerable influence on each other.
But these places must be treasured. The built environment had qualities then reflecting values that are so manifestly lacking in those that on the whole we build today. Of course, the façades of these glorious towns hid much ill, but they also bestowed great benefits. Those who lived in and built these places clearly had great pride in them, and I submit that this does not happen by accident but only by loving care.

Turning more to today, William Morris, whom I always look back to in some ways as one of the founding fathers of the Modern Movement, remarked, *"Never have anything in your house which you do not know to be useful or believe to be beautiful"*[10] — the functional and the aesthetic.
Nevertheless, we must remember that the movement was a visionary one, and its leaders were deeply committed to its social aims. (Its aims were in many ways revolutionary, and its architecture indeed perhaps too often a polemic). Yet I believe that in it there were certain inherent assumptions which, for all its visionary momentum, have failed to move its audience and, at worse, alienate it. Amongst these was a romantic view of technology, where there was too little correspondence between word and deed. Functionalism was preached, but aesthetics too often practised.

Dreams

Of course, it is easy to be wise after the event, but we have to distinguish between dreams and aspirations. The Modern Movement can be much criticised for constructing dreams, whilst the public aspired to something different, something in their terms more recognisable, rather more simple, less esoteric, more ordinary, but good and welcoming, something to which perhaps they may have to reach up to — for artists must always stretch us — but which they could nevertheless grasp and relate themselves to more readily. In being able to feel more in sympathy with what was being built they could feel more secure, and therefore more able to make it their own.
The heroic period of the Modern Movement — the period of the '30s — failed generally to provide this quality. There are, of course, splendid exceptions.

This brings me to a quotation from *Architectural Review* in its leading article in its October 1975 issue on the new Wills Factory at Bristol[11] (Fig 3) — *"Certainly it is a building which sums up the experience of the middle two quarters of the 20th century... It is equally possible to say that it is not 'architecture' at all, that it cannot 'touch the heart'; and that it symbolises a way of life, of work and of organisation, which we are anxious to get away from… A work of architecture is also a work of prophecy, of advertisement. In so far as this job is classifiable as architecture, it is heralding and extolling a 'future' which is past — an event which has come and gone and has proved disappointing."*

I believe this sums up very much the position as it is at present — the architectural position that we have arrived at today — so where do we turn?

In observing on some personal convictions I first want to touch on the subjects of conservation and compatibility, with some examples and then, before ending, take a rather more technical glance at a particular development.

3.

The next step

Conservation

In touching first on the whole vexed question of conservation, I would like to say that firstly in conserving we are learning, and I would predict that this movement — it has already become one — will, and may already, be having a surprising influence on architectural thought and development.
It is rare indeed to find an issue on which "student youth", "amenity societies", and the "establishment" should share so much in common — even a bit dangerous perhaps — and the fear now amongst some, is that the bandwagon could already be out of control. A fear that the ideas themselves will be run over and become victims of their own success. That what could be a sobering and thoughtful movement towards a more humane and more sensitively scaled approach to planning and architecture, will become frozen into a dogma of preservation or, worse still perhaps, embalmment, reproduction or historicism.

I, personally, do not share this view.
I welcome the moment and its challenge.
It gives an additional impulse and guide to design. It *adds* to proper limitations, which is never a bad thing, and aids the search for better answers to more real problems.
The need to conserve our natural resources, particularly energy, is alone already having a profound effect on the design of buildings.

Conservation, as we are now beginning to realise, is a necessity — we cannot afford to go on destroying our building stock in such a profligate manner — and this is a very political question. However, unless we, in the environmental professions, take a very active role in this field, and give a lead.
It would be perfectly reasonable for the public to reflect that they got along very well without separate professions, as we understand them, for a very long time, and who is to say that our predecessors' values, and quality of judgement in the field of the built environment, on the evidence of past results — which they are now trying to protect — are not more than a measure of our own?

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[10] From "The Beauty of Life," a lecture before the Birmingham Society of Arts and School of Design (19 February 1880), later published in *Hopes and Fears for Art: Five Lectures Delivered in Birmingham, London, and Nottingham, 1878–1881* (1882).

[11] Designed by Chicago architects Skidmore, Owings & Merrill with UK architects York Rosenberg Mardell for the tobacco manufacturer WD & HO Wills, with a structure in *Cor-Ten* "weathering" steel, then architecturally fashionable. The factory opened in 1974, closed in 1990, and has since been refurbished and repurposed as the Lakeshore housing development.

Compatibility

Next the question of compatibility — between ideas — of scale between old and new — between materials and so on. "Compatible" may be an unfashionable word, smacking of moderation, compromise, of a lack of conviction or of invention. Indeed, at a time of so many conflicts of interest, it can be argued that the idea implied would at best be meaningless, and at worst merely obstructive. However, I personally believe it to be very important in any design approach. It has to do with the appropriateness of a balanced solution. As an example of these two aspects — ie conservation and compatibility — I am turning now to something a little more specific and technical both in a conservation sense as applied to energy, and to the design of an office building as a subject.

Just as to start with, a new material will often inherit the forms of an older one, until it is better understood, and a new grammar applicable to the new material is developed, so the form and anatomy and planning of office buildings, with controlled environments, is taking time to be better reflected and absorbed within their designs. And on this score, I hope that the design of the very large modern office building, as at present understood, is reaching towards the end of its course.

The classic example is the wide utopian interior, in which the occupants have contributed no part but their presence, in a precise and pre-ordained arrangement. The endless, perfectly lit, air-conditioned nightmares — the spacelessness — the clinical perfection of detail aimed at solving technical problems, rather than enriching the place of work, and so the human experience, are too well known to need illustrating.

The danger is the anonymity that goes hand in hand with adaptability in some of these interiors; when the accepted priority for adaptability does not recognise the need for individual identity or expression, it becomes a kind of tyranny. I remember walking round an esteemed German example of open office planning (cutting my way through the undergrowth of indoor plants) and coming across a large notice which simply read "We hate *bürolandschaft*".

4.

5.

The design of the new Regional Headquarters Building for the CEGB (Figs 4–7)[12] had all this very much in mind and tried, with them and a representative of the Tavistock Institute, to plan a place of work which will be a community for 1200 people, and which will take account in its plan, of:

1) the social and administrative structure of the organisation — studied by the CEGB and the Tavistock Institute

2) the importance of "identity" to the individual in the physical structure; a structured scale and space to which he can relate at his place of work

3) the needs of conservation, particularly energy

4) the compatibility of the design as a whole within a beautiful and sensitive site.

This next is going to be a slight digression and very difficult to try and express — but I will try!

We have, by the organisation of the spaces, tried to reflect the social and administrative structure, and exploited the way that spaces can establish a relationship between the small and the large-scale and between the man-made and the natural surroundings.

Nevertheless, however the spaces are organised, they have to be constructed. If the buildings are made, or put together, out of units of an appropriate size and in such a way that the construction method itself plays a part in establishing the characteristic of these spaces, then a more articulate architecture can result and establish a stronger sense of place and location: more descriptive, more understandable.

By emphasising clearly what is being done, by how it is being done, we can help to illuminate architectural ideas, and so lend weight to the purpose, identity and mood of the buildings themselves. I have also always felt that the richness and unity that can at once be derived from the diverse use of repetitive elements, and the strands that can be woven within strict disciplines, can help to identify the part with the whole, and so help to create a sense of belonging. This is not the expression of structure for its own sake, so much as accepting the consequence of how it is made which will be implicit in the result. This is an important distinction.

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[12] The Central Electricity Generating Board was the principal authority for Britain's nationalised electricity industry from 1957 until its privatisation in the 1990s. In the early 1970s Arup Associates designed the new headquarters for the CEGB's South-West Region as a pioneering "green building" — Philip Dowson described it in detail in another early *Arup Journal article*[1]. The building was recently refurbished as the new UK headquarters for Computershare Investor Services PLC.

6.

7.

8.

To return to the case of CEGB. By working towards limiting conditions in the conservation of energy, we had to relate the detail to the whole very directly. For example, by cooling the perforated main slab at night to control the temperature of the interiors during the day, severe restraints were imposed, at one end of the scale, on the planning and sections for the air distribution system to work and, at the other, on the detail of the desk design, because "task lighting" is necessary in the circumstances to keep heat loads down. The interdependent nature of an integrated system in this case is very apparent.

It is attractive to speculate on the consequences of working towards limiting conditions in this way. The notion of "limits" could perhaps give a new slant to "Less is More", and keep us more closely in touch with recognisable answers to real problems.

I would like to finish with two examples of buildings which do not easily fall into any architectural pigeon-hole or category, one small-scale, and one large, and both by the same architect, Jørn Utzon, and both of which for me inspire hope.

First, a housing scheme at Elsinore[13].

Each house here has its own private court-garden, but closely linked to the communal gardens — now grown up with trees. A simple, straightforward L-shaped house is the basis which, sensitively and variously grouped together, creates a real and compact human environment. It is certainly a very distinguished development, but more than that, it is a place in which one could readily imagine living, and can imagine the possibility for free and happy children growing up within homes that have an individual identity within a larger embracing one.

4–7. The South West Regional Headquarters for the CEGB — building within a landscape, "a structured scale and space to which [the individual] can relate at his place of work", and embodying energy conservation principles.

8. Housing at Elsinore by Jørn Utzon — "... sensitively and variously grouped together [...] a real and compact human environment".

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[13] In 1953 Utzon won a Swedish architectural competition for a scheme of small L-shaped courtyard houses; it was not built, but the mayor of Elsinore, Denmark, liked the concept and provided land for Utzon to build, between 1956–58, his 60 Kingo Houses (named after the developer) on an integrated site. Now known as *Romerhusene* (Roman houses), the development remains a very desirable residential location in Denmark.


9.

The second example is the Sydney Opera House.

Every generation (as every individual) has a need to discover itself, if it is to have a *recognisable* identity, and so the self-confidence to act in its own interest.
It must put a mirror up to itself and have its symbols, for self-recognition, for self-respect and to inspire effort. On this point, I should like to dwell for a few moments on the Sydney Opera House itself.

In human terms alone it has been an extraordinary endeavour and achievement, and in the high service of what I believe to be largely an imaginative and symbolic idea. Of course, it provides for many other things as well, and has to fulfil many other purposes. But for all its functional aspects and its technical brilliance, it is finally and most importantly a symbol and a work of art. It is having an influence not only in Sydney, but in Australia as a whole, and at a number of levels which are very profound indeed; and which perhaps people are only just beginning to be aware of.

They are discovering in its presence things which are important to them, and that have to do with values, It has changed their view, just a little bit only, maybe, but it has enriched it.

I believe it is a great building. A kind of marvellous Trafalgar Square on water, full of life and activity; which, anchored in the harbour at the very focus point of the city, commands a presence without entirely dominating it which is unmatched in any other city that I know of. Taxi drivers will also tell you that it is very beautiful, and I believe they are right. There must always be a place for the splendid architectural gesture of this kind, provided, of course, that it is splendid, but these will always be very few and hazardous. They are perhaps an impudence to the gods, whose retribution will almost certainly be visited sooner or later on those involved — on those who would aspire to fly so high!

I, personally, just marvel at how this wonderful architectural rogue elephant managed to find, or blunder, or stampede its way through today's tightly woven mesh of anti-patronage. The very word "patronage" is almost a provocation, and yet enlightened patronage we must have, if we are to have fine architecture at all. Patrons who, in making great demands, must also be prepared to take great risks.

In concluding, I would make two pleas — one to do with means and the other with ends. On the first, I must assume I am preaching here to the converted. Certainly a closer understanding and integration between the professions is essential, particularly in government and local government, where some of the most archaic and rigid professional divisions still exist, originating from the traditional departments with their own separate career structures. This segregation, I believe, can too readily result in a destructive and artificial division of what are closely associated activities, and which must greatly contribute to the discord in so many developments that afflict our cities, towns, and much of our countryside — monuments to isolated thinking.
As Casson[14] has remarked, *"If architecture is frozen music, then this is frozen noise"*.

Second, we have seen heralded since the war a number of architectural movements — the New Empiricists, the New Brutalists, the Metabolists, and so on.

I would *plead* for a return to a *new architecture of humanism* — that is what we are here for — all of us who are involved in the design of our surroundings; to create circumstances in which the various designers will be in a better position to deal with our very complex situations, whether he is a traffic engineer, whose problem can be as much social as technical, or an HVAC engineer, whose concern must be controlled environments sensitive to human responses. We must continually remind ourselves that the purpose must be to try to develop

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[14] Sir Hugh Casson, CH (1910–1999): British architect, interior designer, artist, writer and broadcaster on 20th-century design.

9. Sydney Opera House — "a kind of marvellous Trafalgar Square on water".

10. Philip Dowson with Ove Arup in the early 1960s.

11. With former Arup Chairman Sir Jack Zunz at the inauguration of the new sculpted head of Ove Arup at Kingsgate Footbridge, Durham, in September 2011.

methods that can compete with the pressures of scale and technology, and to revalue them in *human* terms. We have to try and produce an architecture that is human and not brutalising and, whilst obviously embodying as fully as possible the "technical", will not continue to do so at such great social expense.

We have an obligation, a Hippocratic Oath if you like, to be sensitive in using our resources for human purposes, and not to attack our environment but to conserve it, to be used and to be enjoyed. And to this end, we have to co-ordinate our activities in today's climate of technical proliferation, if we are to secure the realisation and the survival of humane ideas.

People, on the whole, ask us for rather simple things, and they ask for them in simple language. They want their houses to be homely. They ask, with increasing anger now, why architects don't build "beautiful buildings" — these words we avoid at our peril. They are a cry for very human and ordinary things; for places to live in, or work in, that people can respond to and enjoy, and this means that they must be understandable in ordinary human terms. That is not to patronise, but to respect.

I would like to close with a quotation from Walter Gropius, who was one of the real fathers of the Modern Movement, and this was said many, many years ago:
"We must recover a comprehensive vision of the wholeness of the environment in which we live. In our mechanised society we should passionately emphasise that we are still a world of men, and that man in his natural environment must be the focus of all planning." [15]

The next step is not a new step, perhaps, at all, but an old one that we have yet better to understand.


10.


11.

Reference
1) DOWSON, P. Offices. *The Arup Journal*, *12*(4), pp2–23, December 1977.

Acknowledgment
Grateful thanks to *Andrea Beddard* in Arup's London Library for background research on the now-defunct organisations and groups mentioned.

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"The issues are as fresh as they were nearly 40 years ago... the ideas are strong and challenging."

Sir Jack Zunz

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[15] The Walter Gropius Archive, Routledge, 1990–1991.

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Marking 30 years of Arup's presence in China, Shenzhen's new Stock Exchange is a distinctive addition to the city's skyline (photo: *Philippe Ruault, courtesy OMA*).