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The Arup Journal

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London

Author
John Turzynski

Growth, change and renewal
As a world city, London has much to live up to in an ever-competitive and globalised planet. But it has an inherent energy, and this energy sparks imagination and creativity in its people. Over the centuries, the city's scientists, artists, writers, lawyers, bankers, doctors, engineers, architects and planners have found ways through technology, craft, and wit to recreate and redefine it.

London's essential nature has been threatened – by war, commerce, and clumsy "redevelopment" alike – but it has survived, and in doing so changed and evolved continually, sometimes in subtle ways, other times more radically. Often its history and maturity have made such reinvention difficult, but overall it has managed to adapt itself to meet the demands of the future while celebrating the past.

In more recent years, London's infrastructure has shown its age, struggling with 20th century neglect and 21st demand. But this is now changing, as the process of renewal continues. New technologies, creative thinking and smart design are being brought to bear on some truly visionary projects.

Whether below ground with rail and utilities infrastructure, above ground with buildings of every type, or the development of spatial policies and urban planning, the challenges need holistic and innovative thought and execution. Furthermore, the role of planning and design consultants has changed in recent decades, requiring the broadest understanding of legislation, of social and economic issues, of political agendas, while still delivering outstanding projects for this great capital city. London's community expects nothing less.

Arup and London

Arup has been based in, and worked for, London since its earliest days. More than 80 years ago, the firm's founder Ove Arup (1895-1988) and his then small but extremely able team applied their engineering skills to the creation of two iconic Modernist buildings still enjoyed and celebrated today: London Zoo's Penguin Pool in Regent's Park (Fig 2), and the Highpoint apartment blocks in Highgate, North London (Fig 3). Since then, the firm has been central to the delivery of many major works that have changed the face of London, from the South Bank and Barbican Arts Centres (Fig 4) to game-changing bank and trading projects for the financial centres at the City and Canary Wharf (Fig 5); from new passenger terminals for BAA (Fig 8) at Heathrow and Gatwick Airports to the stations, tunnels and other infrastructure that serve the High Speed 1 rail link to Europe.

Now, this special edition of *The Arup Journal* features some recent and current projects exemplary not only in terms of their design and construction, but also in how they respond to the changing needs of society, of individuals and of clients, not only in the capital itself but the UK as a whole.

Transportation

The King's Cross district of London has undergone radical change in the last 15 years. Its final piece of major infrastructure is King's Cross station (pp6-45), which crowns one of the biggest multi-modal transport interchanges in Europe. Linking to St Pancras International (Fig 6), the urban rail network Thameslink, and the London Underground system, King's Cross station opens London and the UK to huge numbers of travellers. Adjacent developments, including King's Cross Central, King's Place, the British Library (Fig 7) and the Francis Crick Institute, testify to the vision of what is needed in London.

The new station is the result of entirely modern technology applied to a Grade I listed 19th century historic building: new meeting old respectfully, honestly, and effectively. The process epitomises the impacts of regeneration, and underlines the special but all-too-common issues surrounding such projects. The underlying story also shows the importance of integrated design, working closely with the architect and other collaborators, and the essential relationships needed with the client, the contractors and all stakeholders.

King's Cross is just one – albeit hugely significant – cog in the great machine that is London's transport network. Beyond this one station, its other supporting infrastructure is under great pressure, and investment in improvements to the transport system continues through difficult economic times.

A major part of this investment is Crossrail, the major new east/west railway under Central London, construction for which has now commenced. Planned since the 1950s, this is one of the capital's most challenging projects, though most of it will be out of sight beneath the pavements and streets.

The planning and design associated with Crossrail's 26km of tunnels and six central stations has pulled together the best thinking in tunnelling technology, ground engineering and analysis, protection works to existing properties and major underground station design (pp98-111). The railway passes through and below some of the most valuable real estate in the world, highly complex networks of utility infrastructure, and busy streets and stations.

The engineering design that is needed to transform lines on a map into a safe and efficient railway uses highly sophisticated digital modelling and analysis, and relies on the skills and experience of civil, structural and geotechnical engineers. Their knowledge has been brought from other projects around the world, and has enhanced solutions to the particular demands of working below the city in many different types of soil, dealing with all sorts of surfaces structures, ensuring passenger comfort and safety, and linking into existing Underground and surface rail networks.

Building tall and building smart

The City of London is a densely populated area. The value of land is huge, and therefore optimising plot ratios is paramount; also, in recent years building height restrictions have been somewhat relaxed, and developers have taken advantage of this.

London now boasts several new very tall buildings, completed and at various stages of construction, and Arup has been instrumental in bringing these to fruition (pp66-97). The firm already had much experience in the design of such structures from around the globe, particularly East Asia, and brought its technical prowess to bear on London's new skyline.

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2. The Penguin Pool, London Zoo, Regent's Park: structural engineering design for original construction (1934-35), and restoration (1986-87).

3. Highpoint 1, Highgate, North London: structural engineering design (1934-35).

4. Barbican Arts Centre, City of London: structural and geotechnical engineering design for original construction (1967-77); project management for foyer improvement project (2002-06).

5. HSBC headquarters, Canary Wharf: multidisciplinary engineering design (1998-2002).

6. St Pancras International station: multidisciplinary engineering design (1999-2007)

7. British Library, Euston Road: Civil, structural and geotechnical engineering design for original building (1988-1997); multidisciplinary engineering design for British Library Centre for Conservation (illustrated) (2003-2007). St Pancras International station is on the right.

8. Terminal 5, Heathrow Airport, for BAA: Multidisciplinary engineering design (1996-2007).


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Our work on tall buildings is now firmly rooted in how they sit within the wider urban realm, by respecting the needs of people at street level adjacent to the building and in surrounding areas, as well as those high above the City. They are now part of the City of London's fabric, providing activities beyond those solely for the inhabitants – mixed use is now an increasing driver for success. Our contribution to the engineering design requires a wide understanding of the business case of clients, the requirements of City planners, and of course the needs of the ultimate users.

A deep knowledge of building techniques and technology is needed to construct successful tall buildings, and those in the centre of London are no exception. We have worked closely with contractors and their sub-contractors in sharing knowledge and experience to ensure that our designs are truly buildable within an environment of strict controls, severe space constraints,and demanding programmes. We now share digital information as a norm, and sit together with our contractor colleagues to develop the design into installation and construction drawings: very much collaboration at its best. Added to this has been the vital and integrated work across disciplines and across boundaries. Ultimately this relies on excellent relationships between all parties – something that we relish on all types of projects.

Our experience with optimisation has been brought to bear on our London buildings, and we now apply this beyond materials by looking at energy and resources, space usage, and the overall performance of building systems. Of course this has a huge impact on operating costs where the work of our building services engineers comes to the fore. And beyond this we are now designing with adaptability firmly in mind, as owners and developers look for designs that can be modified relatively simply for different environments, new technologies, and changing working practices. This is an additional challenge, but one that secures a longer-term future for these major landmarks in our capital city.

The One New Change development in the City of London (pp46-57) is notable for other reasons – particularly the need to protect and respect the historic fabric of the City and St Paul's Cathedral in particular. The inventiveness of the architect and the clever engineering required has resulted in creating space where none existed before, and satisfying the client, City planners, and of course the users. This prime example of innovative thinking turned the constraints of the City into an opportunity, and it succeeds while delivering a return to investors, part of the life-blood of continual renewal.

London has been a centre of learning for centuries, and proudly boasts world-renowned universities and educational institutes. Arup has worked on the design of educational buildings from its early years. Lambeth's Evelyn Grace Academy (pp58-65) follows a long line of new schools that the firm has engineered, but this Academy also sets a new standard in how a school responds to its community.

It has long been understood that a school's built environment has a huge impact on the teaching and learning that take place within it. By working closely with staff and pupils, the designers have created a special place where students are engaged and value their surroundings. This is a fine example of design and technology responding to the needs of people.

This sample of projects shows that engineers, planners and designers have not lost their edge in creating solutions to modern problems in a great world city: London. To adapt Sir Christopher Wren's epitaph in St Paul's:

"Lector, si monumentum requiris circumspice" *(Reader, if you seek his monument look around you)*

... or rather...
"Lector, si monumentum quaerunt circumspice" *(Reader, if you seek their monument look around you)*

Author
John Turzynski is a Director in the London office, and has led multidisciplinary teams on a wide range of building projects in the UK, mainland Europe, the USA, and beyond. He is currently Leader of the London and South East Sub-region, and a Member of the Arup Trustee Board.

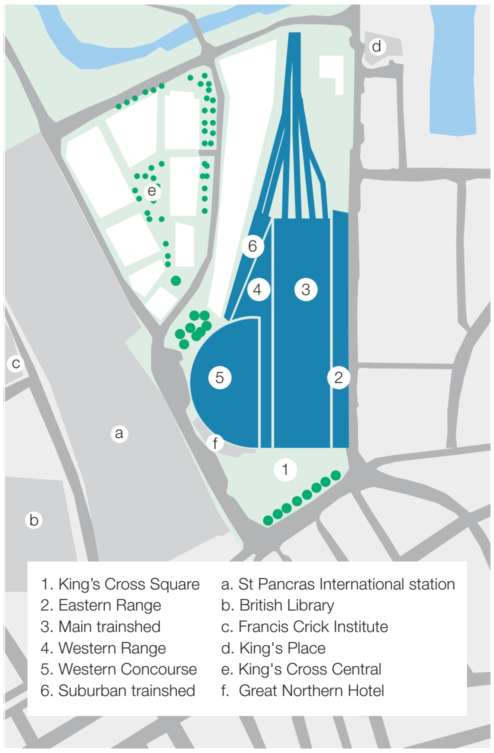
Image credits
1 *Thomas Graham*; 2 *Arup*; 3 *Dell & Wainwright*; 4 *Raf Makda*; 5 *Central Photography*; 6 *Hufton + Crow*; 7 *Peter Durant;* *8 David J Osborn*.

The King's Cross station redevelopment

Arup and King's Cross

Author
Mike Byrne

1.



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London's busiest transport hub
King's Cross is the busiest transport hub in London, and Arup has been extensively involved in the three major station projects that comprise it: St Pancras International[1, 2], which opened in 2007; the King's Cross and St Pancras Underground station that opened in 2009; and the redevelopment of King's Cross mainline station, which opened on 19 March, 2012.

The Arup story at King's Cross goes beyond the stations to include the regeneration of the whole area, but this *Arup Journal* feature focuses on the £547M redevelopment of the mainline station, and the work that has been done in collaboration with architect John McAslan + Partners (JMP) to create a project that will shape London's transport future for many years to come.

Arup's involvement goes back over 20 years to when the firm was first engaged to support various planning applications to increase the capacity of the existing station, which had remained substantially unchanged since the original building was completed in 1852.

Designed by Lewis Cubitt, it is a Grade I listed structure – indicating a building of exceptional historic interest. Nonetheless, the original station was unable to deal with the 40M passengers that now use it each year, and equally ill-equipped to meet the modern-day needs of Network Rail, which owns and operates most of Britain's rail infrastructure, and those of the individual train operating companies.

Challenge and solution
The design challenge facing the Arup/JMP team was to create a modern, fit-for-purpose station befitting the role of King's Cross as London's premier transport hub, while retaining all the key parts of the existing structure. Also, together with the need to meet Network Rail's core project objectives, the scheme was pivotal to the regeneration of this whole area of London.

The design team's solution was to create a new 8000m^2 concourse alongside the existing station building, and so here the challenge was to develop an efficient and elegant structural solution for the new roof that would sit comfortably alongside the original station. The new Western Concourse has already been acknowledged as achieving this, evoking the grand station buildings of the past while catering for all the needs of modern-day travellers. The existing 1970s temporary concourse is being removed, restoring the front of the station to its former glory and creating the largest new public space in London in recent years.

Arup's involvement in King's Cross spans many years and many separate project elements, from the innovative structural design of the new concourse roof to all the core engineering and specialist skills required for a project of this nature.
The work has been done while keeping the existing station fully operational, and is testament to the hard work of the many people that have worked on the project over the years. The various articles in this feature form just a snapshot of what has been done to transform London's busiest station and restore it to pride-of-place as a major gateway to the capital.

References
(1) BENNETT, R *et al*. St Pancras Station and Kings Cross Railway Lands. *The Arup Journal, 39*(1), pp46-54, 1/2004 (Channel Tunnel Rail Link special issue).

(2) CHODOROWSKI, A *et al*. The Thameslink station at St Pancras, London. *The Arup Journal, 44*(3), pp36-43, 3/2009.

1. Staircase in the refurbished Eastern Range building.

2. Site plan.

3. The new Western Concourse.

3.

All change! Cubitt's Victorian marvel transformed by 21st century design

1. The 36m clock tower is the principal visual feature of the historic southern façade.

2. New use for the Parcels Office atrium space in the Western Range.

Author
John McAslan, Chairman, John McAslan + Partners

Background
The transformation of King's Cross railway station in London is one of the city's most significant infrastructure projects, involving a combination of modernisation, restoration and placemaking. JMP is lead architect and masterplanner for the project, completed in time for the 2012 London Olympics, in partnership with Arup as the principal multidisciplinary engineering designer. The Grade I listed station was designed and completed in 1852 by the Victorian masterbuilder Lewis Cubitt (1799-1883), and is regarded as one of the UK's great Victorian constructions[1].

The project's original client, Railtrack – the company that formerly owned Britain's rail infrastructure – established key requirements for this multi-phased commission, and these were developed forward by Network Rail, Railtrack's successor. From the outset, it was crucial that the station greatly expanded its capacity as an exemplary 21st century multi-modal transport hub, connecting to St Pancras, London Underground, Thameslink, and London's bus network.

Arup and JMP have led the design and implementation since 1998, when Railtrack projected that the annual number of station users would increase from 40M to 55M after 2012. JMP's core design team was led throughout by myself, first with Adam Brown as project director, then by Hiro Aso, and ultimately Simon Goode.

Early on, the design team established that King's Cross must not only deliver its core project objectives, but also remain an historic cultural asset that would support urban regeneration in a part of London infamous for its social and commercial deprivation. Furthermore, the team set exceptional environmental standards with a target of at least 10% of the station's energy use to be generated from renewable sources – which has been achieved with extensive photovoltaic arrays fixed to the crowns of the two trainshed vaults.

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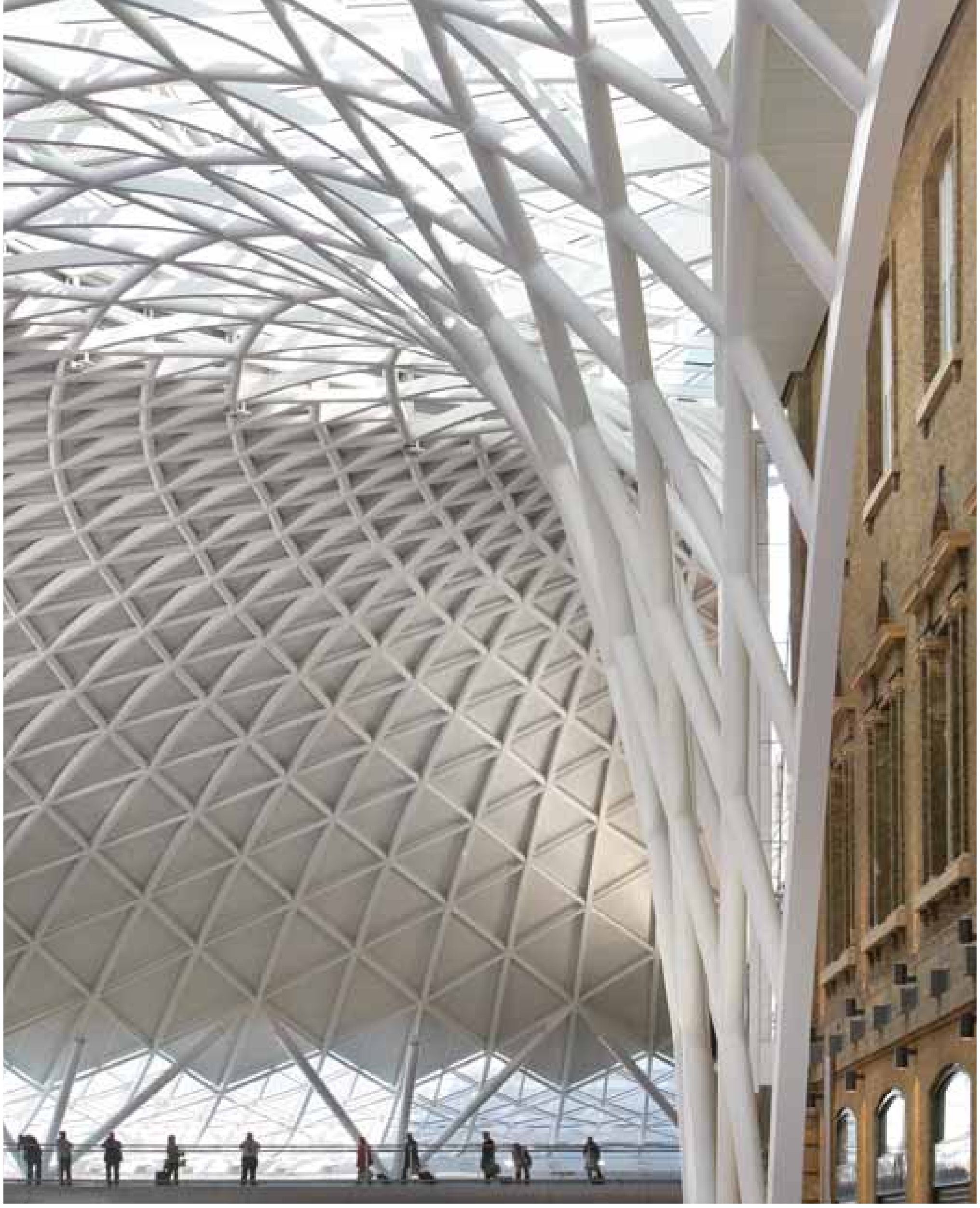
Context
The station stands at one of London's busiest three-route road junctions. Its long, flanking Eastern Range building marks the western edge of the massive Regent Quarter mixed-use regeneration scheme, while the £2bn King's Cross Central project is under way on 27ha of previously degraded railway land to the north of Cubitt's trainshed. Urban complexity has been matched by modal complexity: six Underground lines and their King's Cross-St Pancras concourse lie beneath part of the south-western segment of the station.

Project objectives
Several design and engineering objectives were established:

- the historically sensitive repair of the Grade I listed clear-vault trainshed, and its adjoining Eastern Range and Western Range (WR) buildings
- conversion of the Victorian sub-platform vaults to contain new servicing systems
- the creation of a new platform, which required a 200m excavation under the Eastern Range, the upgrade of all other platforms, and a new trainshed bridge and vertical circulation, servicing all platform and sub-platform services
- complex operational upgrades
- the formation of a new and substantially enlarged concourse to replace the significantly undersized temporary 2500m^2 structure from the 1970s that projected from the historic main southern façade. From the outset, the "unmasking" and restoration of this façade (Fig 1) was highly important to the Government's historic buildings watchdog, English Heritage, with whom JMP has enjoyed a long and successful collaboration.



3.

3. The Western Concourse roof structure splays upward into dramatic arches. One of the key design issues was to ensure that the structure did not damage the Western Range or its Victorian foundations.

4. Multi-volume reception area in the Eastern Range.

4.

The Western Range
The mixture of refurbishment and modernising alterations to the WR buildings was particularly complex as these were constructed at different times and for different purposes. This meant that the works had to accommodate a variety of original construction methods, differing storey heights, and interfaces with new structures.

Within the reworking of the WR, the solutions have incorporated architectural and engineering interventions, and invisible servicing, that have brought programmatic clarity and allowed the creation of wholly new volumes, such as the expansive gate-line at its southern end. The process has also opened up several delightful original Victorian spaces, such as the Booking Hall and the Parcels Office atrium (Fig 2), for transformation and re-use.

In particular, the modernisation of the Booking Hall and new gate-line required significant design innovation, notably the invisible strengthening of the historic iron girders spanning over the remodelled spaces. The Booking Hall balcony is supported by decorative iron brackets inter-spanned by solid sandstone slabs. A delicate and sympathetic structural solution has provided new balcony posts and strengthening to the stone slabs without impacting the craft aesthetic of the historic balcony.

The Eastern Range
While the WR transformation has been carried out with significant change to its historic fabric, works to the Eastern Range on York Way have been completed while retaining most of the building's structure. The result is a simple and repetitive architectural and structural rhythm across its multi-levels. The essential task here was to discreetly rework existing spaces while integrating new MEP services. The most visible intervention is the impressive new multi-volume reception area at the southern end of the 240m long building (Fig 4).

The Western Concourse
The project's single most significant design and engineering challenge was the creation of the new 8000m^2 concourse, designed to accommodate existing and future capacity from 2012 when a projected 17 peak-time train movements per hour would use its 12 mainline and suburban service platforms.

Arup and JMP investigated two principal options for the new concourse. The first, a massive new insertion within the southern half of Cubitt's trainshed, would have involved pushing the existing platforms some 120m northwards, which in turn would have widened the throat-tunnel under the Regents Canal at an unfeasible cost of £1bn.

The alternative strategy was to form the new concourse on the west side of the existing station, and that has resulted in its most compelling new feature in the form of the new 120m wide by 20m high Western Concourse. Superbly engineered by Arup, the semi-circular canopy radiuses outwards like a wave, recalling the parabolic structures designed by the Italian master, Pier Luigi Nervi, and Eero Saarinen's TWA Terminal in New York.

Arguably the most strikingly innovative moment in British transport architecture for at least two decades (and recalling the original impact of Stansted Airport and the Waterloo *Eurostar* terminal in the early 1990s), the new concourse became the most visible expression of positive change for King's Cross at its opening to the public on 19 March, 2012.

Constraints and opportunities

There was a range of critical architectural and engineering constraints to the Western Concourse design:

- the retention of the existing Grade I listed WR façades
- the enclosure formed by the curving, Grade II listed façade of the Great Northern Hotel some 60m to the west
- and the fact that London Underground had already commenced the construction of sub-surface concourses and ticket halls beneath the proposed new concourse.

The decision to design it in a semi-circular form allowed the pursuit of a highly innovative landmark form and structure. Notably, the design of its main structural supports "fits" the irregular subsurface structural grid at key points, and does not direct significant forces into the foundations of the WR or the Great Northern Hotel, or impinge on their historic façades.

The trajectory of the new canopy structure, forming the envelope of the concourse, originates within feet of the WR, and its potential effect on the historic structure of the Booking Hall entrance was of great concern to English Heritage. The roof is therefore structurally independent of the WR and supported by a mixture of pile caps and the perimeter walls of the Underground station below.

Perimeter tree-columns and a central funnel structure support the lightweight steel diagrid shell structure, creating a cavernous half-domed space with a dramatic double arch span alongside the façade of the existing historic buildings. The canopy's formal elegance optimised modularity and repetition in structural and envelope components, which in turn significantly reduced prefabrication costs and allowed rapid erection.

Internally, the Arup/JMP team has created a two-level concourse: a semi-circular ground-level threshold, and above it, under the sweeping perimeter of the canopy, a raised mezzanine balcony. This contains shops and cafes, with an elevated walkway passing through the WR to the new 65m long bridge structure that spans the historic trainshed and nine platforms, giving access to them via escalators and lifts.

The design of the platform bridge, which did not involve Arup, was a matter of acute interest to English Heritage, and took JMP some 18 months to resolve through the statutory approval process.

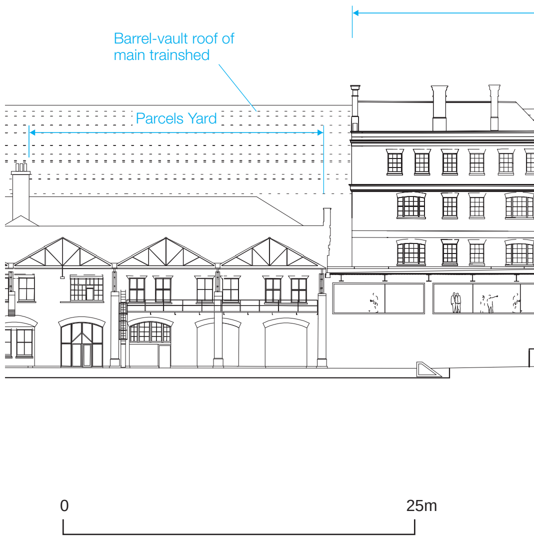
JMP also designed a complete new range of product design elements for the station that forms a clearly related family, such as signage and informational systems. As a team we were determined to avoid the piecemeal approach that so typically produces unnecessary visual clutter in stations, and believe we have succeeded in this endeavour through the design of this coordinated product range.

Summary

Ultimately then, the architectural and engineering reach of the King's Cross station project has brought together historically sensitive repair, modernising interventions, and instances of striking innovation that have depended on an exemplary collaborative process involving consultations with more than 20 stakeholders. It has also required significant co-ordination between multi-contractor teams over an extended multi-phased project period of 14 years. It is this process – and Network Rail's support of our vision – that has allowed our interventions to follow, in spirit, the bold architectural and engineering examples set by Lewis Cubitt over 160 years ago.

Reference

(1) http://www.victorianweb.org/art/architecture/london/55b.html



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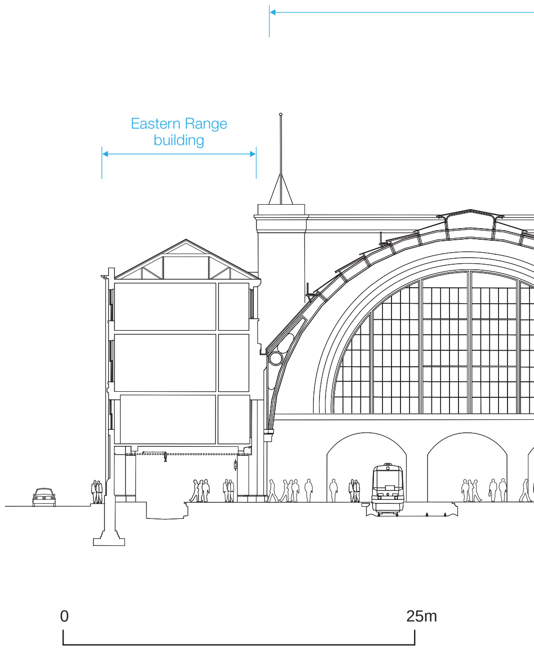

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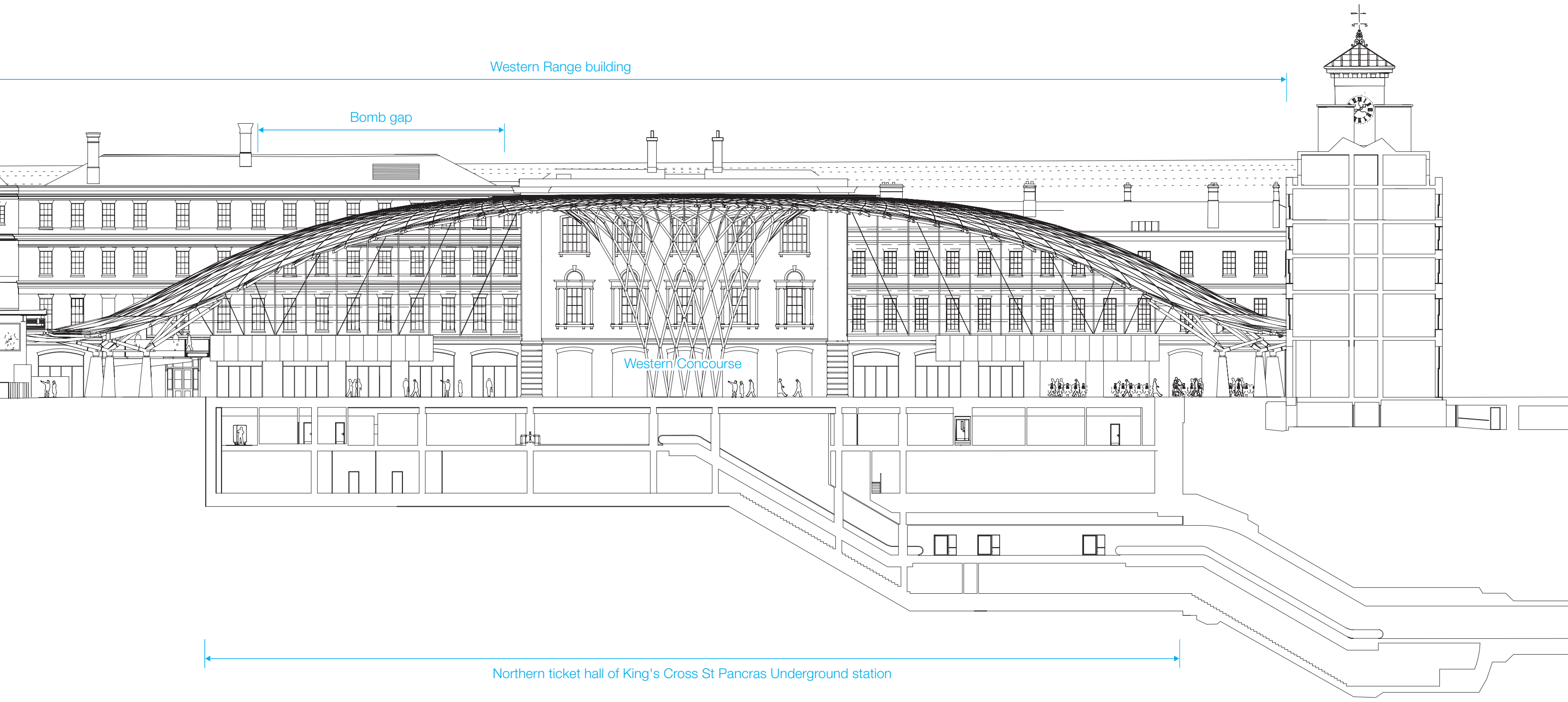
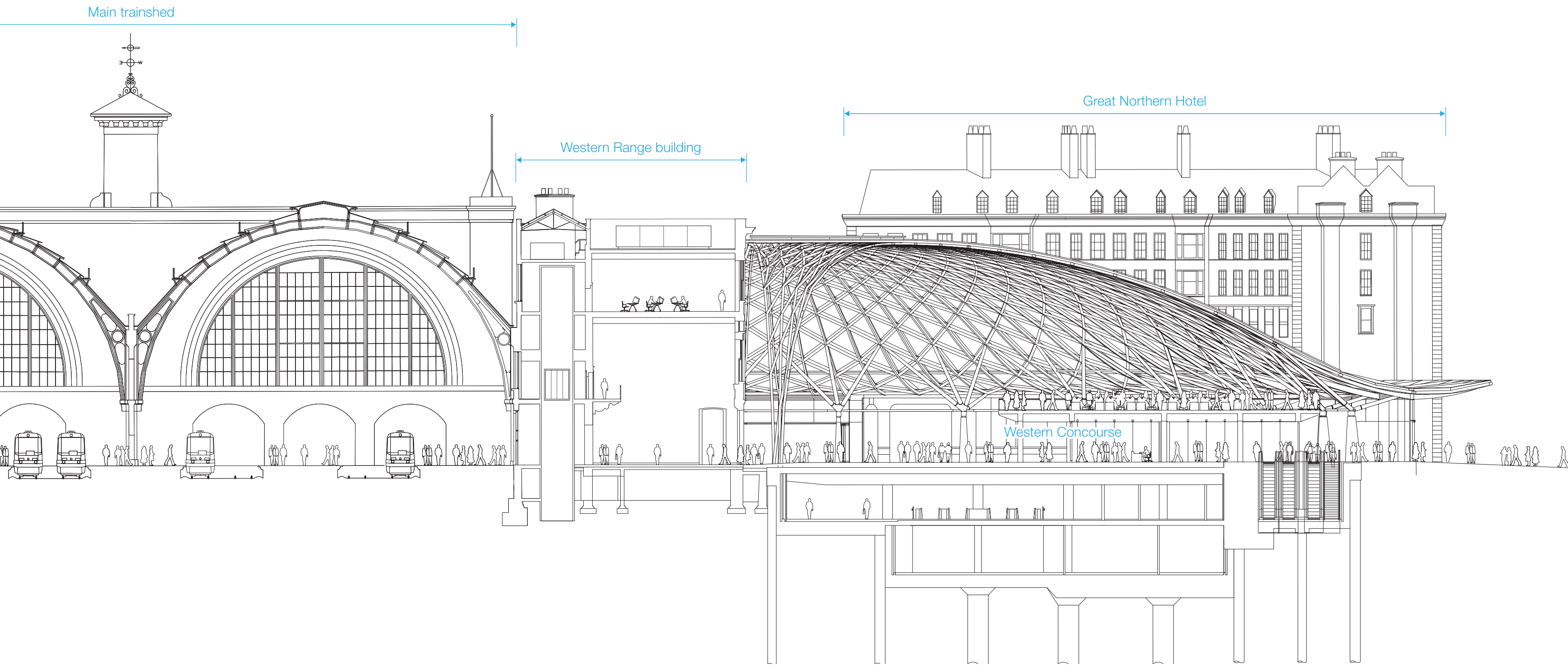
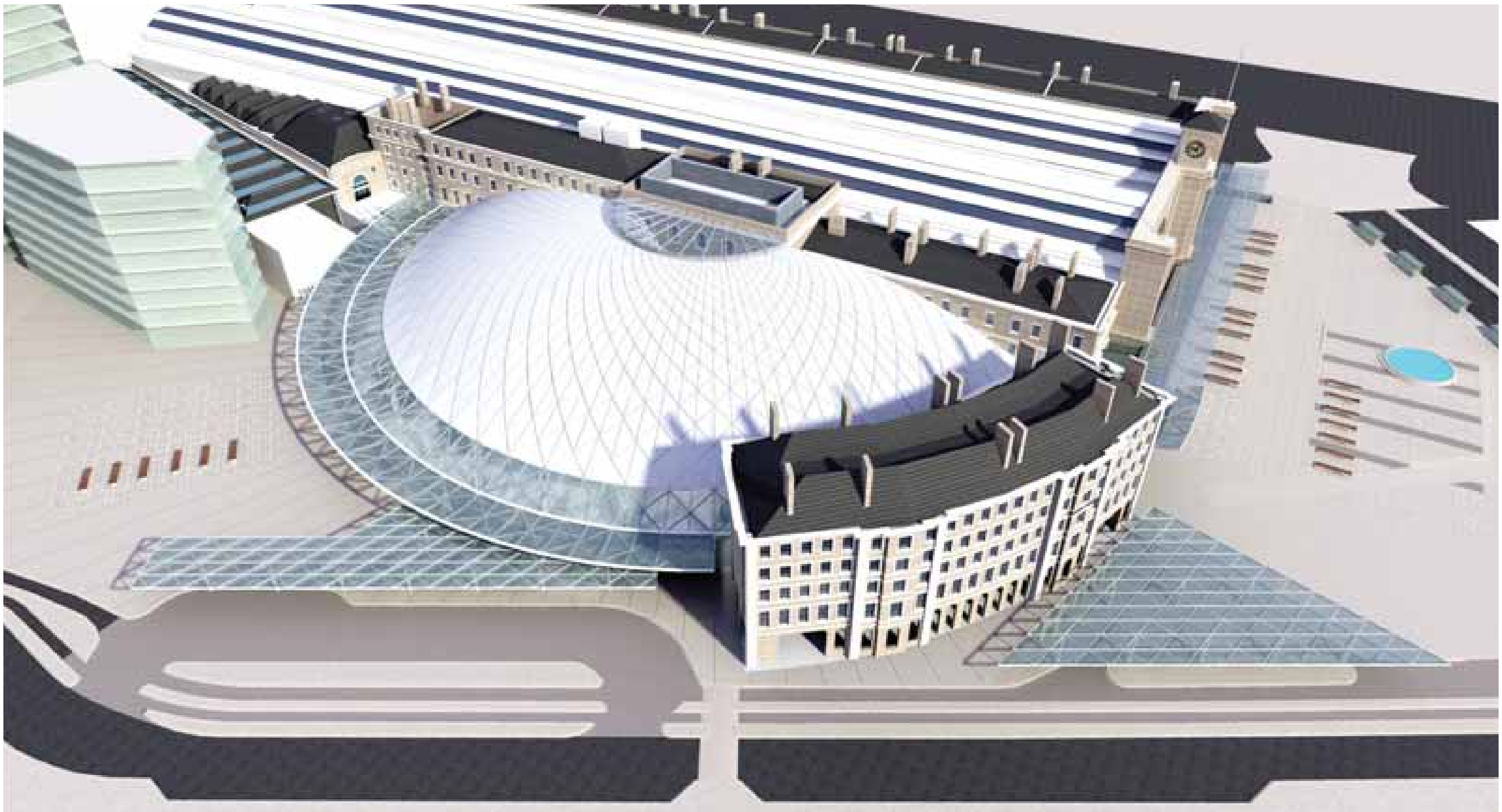




5. North-south cross-section.
6. East-west cross-section.



1.

The Western Concourse roof

Authors
Mike King Alex Reddihough

2.

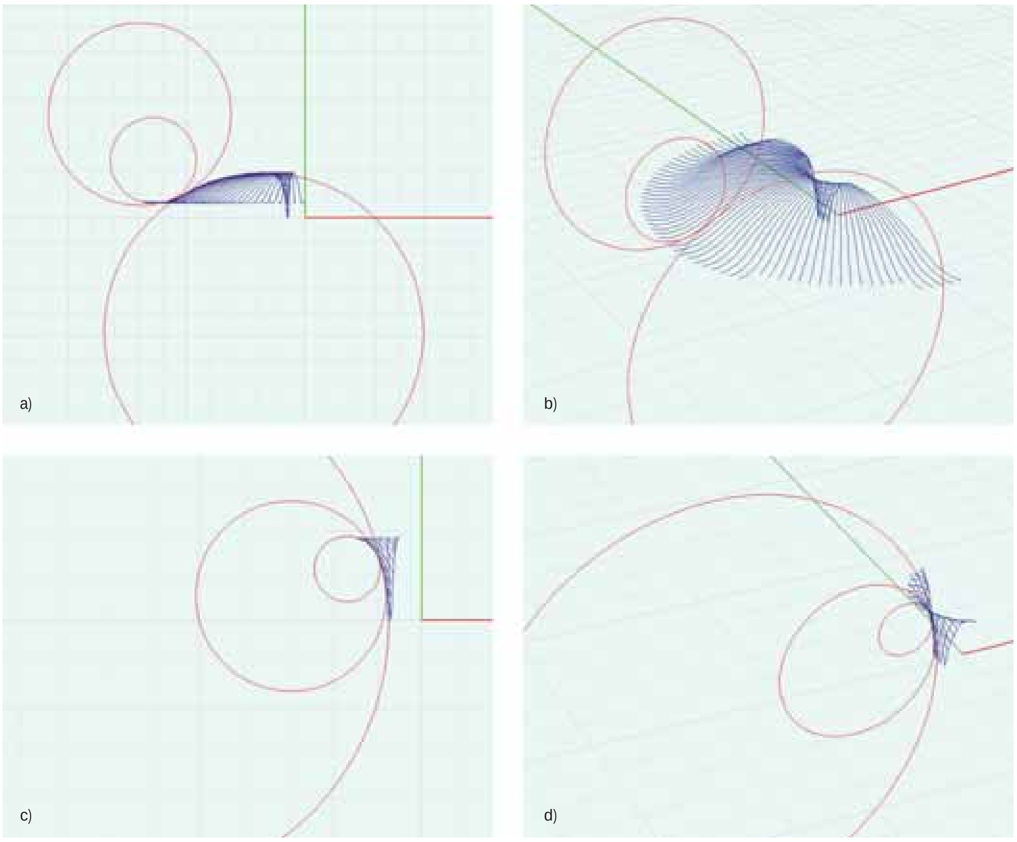
Drivers of the design
The roof design evolved through seamless collaboration between JMP and Arup, driven by the need to work within and respond to the following constraints and challenges:

- create a long-span structure that would bridge fully over the London Underground northern ticket hall “box”, already under construction at the time the Western Concourse roof was being designed
- develop an efficient and elegant structural scheme that did not apply any loads to the Grade I listed Western Range façade, and would also fit within the curved form of the Grade II listed Great Northern Hotel (Figs 1-2)
- create an architecturally welcoming space that was also visually and operationally unifying, forming a hub to serve both the suburban and mainline intercity platforms, which had always been disconnected. The semicircular plan thus created aids pedestrian flow between these two parts of the station as well as being a generous space for people waiting for their trains or arriving passengers.

Evolution of the design
The team worked together for many months, though the light, dynamic diagrid shell form came together relatively quickly. As well as the obvious architectural benefits of the semicircular plan geometry in terms of pedestrian and passenger flow, there were also great engineering advantages.

Key among these was that, as well as creating a thin shell structure, the doubly-curved S-shaped section (Fig 3) and semicircular plan form act to carry most of the roof load away from the WR façade and support it at the perimeter. Ideally, for structural efficiency, such a shell roof would form a complete circle, but the functional and geometrical constraints imposed by the presence of the existing buildings required it to be cut into a semicircle at the WR façade.

This meant that a flexurally stiff edge to the cut shell was required where it abuts the WR façade. This was achieved through deep vertical truss elements, also glazed to enclose the building envelope and enable views from the Western Concourse to the WR façade (Fig 4).



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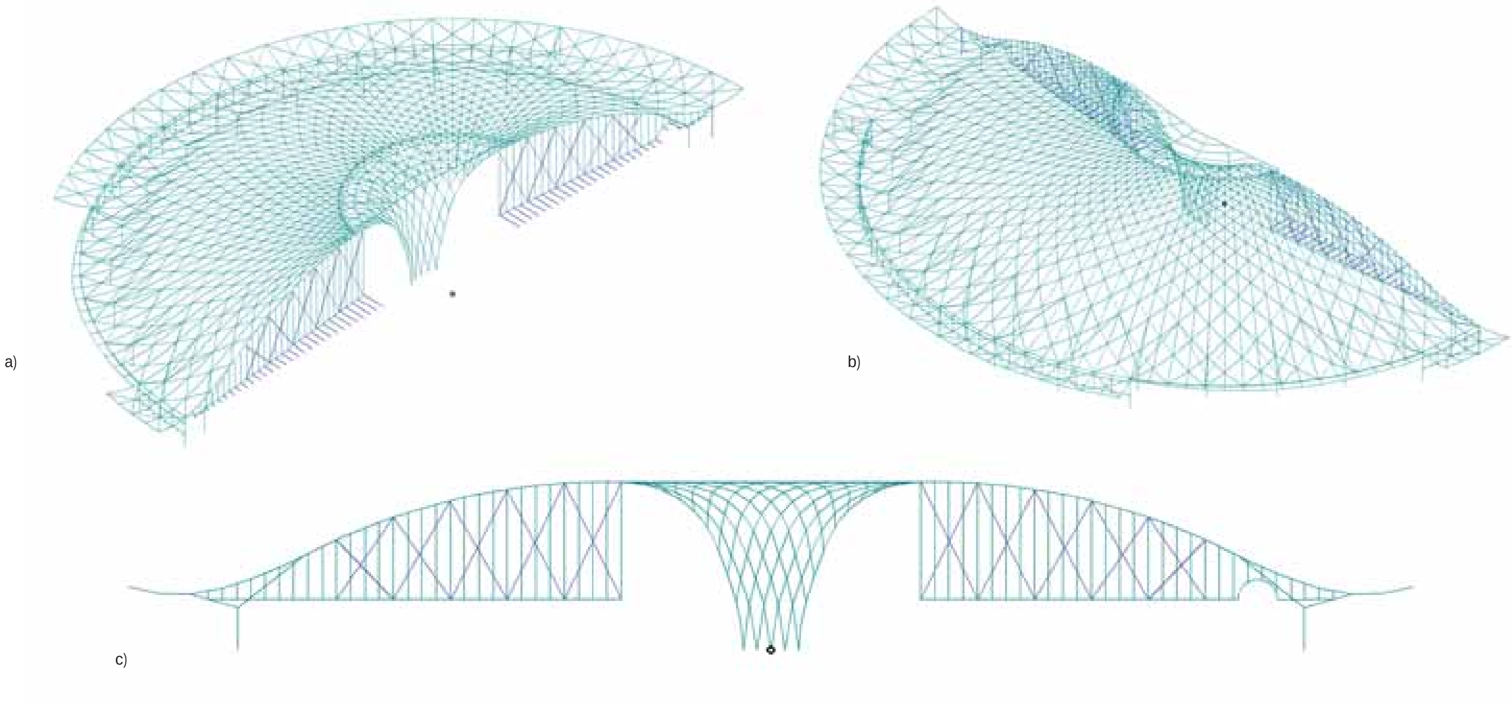

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1. Architect's design concept for Western Concourse roof.

2. The original taxi rank and parcels yard alongside the Western Range buildings became the site of the Western Concourse. The Great Northern Hotel can be seen to the right.

3. How the diagrid shell geometry is created by three tangential circles rotated about a vertical axis (a, b); how the funnel geometry is created by three tangential circles rotated about a vertical axis (c, d).

4. Analysis model:
(a) isometric of concourse roof, showing cut edge and funnel;
(b) isometric showing opposite aspect of concourse roof;
(c) cut edge of the semicircular shell.

The funnel

The central support to these trusses, and to the semicircular skylight above, is arguably the most dramatic structural and architectural element of the roof structure. The "funnel" was developed in response to the challenge to create an efficient structural support at the centre of the roof as well as a strong architectural focal point.

It is easy to see it becoming a symbol of King's Cross Station, and is such a natural meeting point that anyone meeting someone at the station will almost certainly use the words *"…I'll meet you under the funnel at King's Cross"* (Figs 5-6).

Its structure is a natural extension of the diagrid shell form, curving from the horizontal diagrid at the edge of the roof skylight to near-vertical at the support at ground level. As the funnel structure is doubly-curved, it has strong resistance to out-of-plane buckling, enabling the use of relatively slender tubular steel sections.

The client required the steel tonnage to be benchmarked against other long-span roof structures so as to be satisfied that, as well as this being an iconic structure, the team was also delivering an efficient structural system.

Geometry and structural elements

The entire roof diagrid geometry and funnel form were developed and finalised through "sculpting" in Arup's 3-D structural analysis software, *GSA*. Conceptually, the roof structure is divisible into radial rib elements (primarily bending forces) and a diagrid (largely in-plane shell forces) (Fig 7). The former are fabricated as boxes to produce a more efficient section for bending and to visually distinguish them from the diagrid tubes, which are conversely optimised for axial loads.

The fabricated box rib radial sections are typically 150mm wide, varying from 250mm-450mm in depth in line with the changing bending moments. The diagrid tubes are standard circular hollow sections, varying between 139mm and 219mm in diameter.

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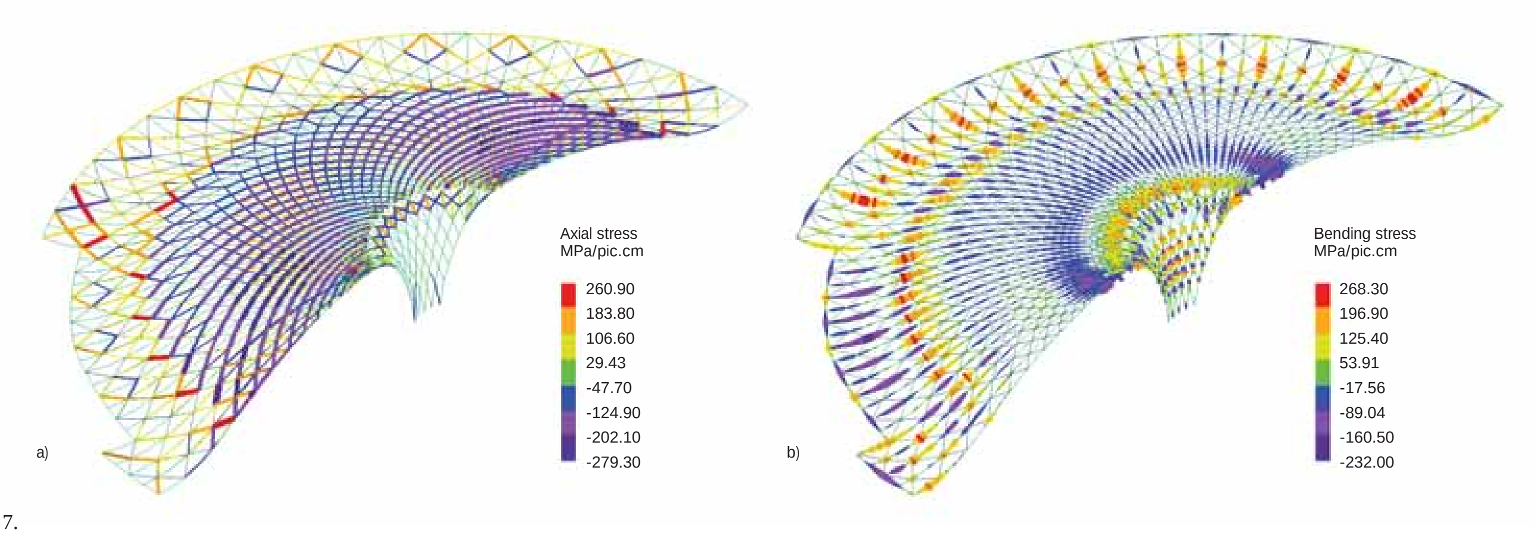

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The "tree trunk" columns at the bottom of the funnel need to resist large net lateral thrusts from the branch struts supporting the roof, thus enabling shell action in the roof diagrid. These forces are up to 600 tonnes at the top of the columns in the radial direction, and produce considerable bending moments in the column itself and large overturning loads at the baseplate. The restraint forces in the minor axis (circumferential direction) are more modest – "only" 90 tonnes in the horizontal direction.

The carefully-shaped tapered ovoid section makes these columns look deceptively slender for the forces carried. At the base, a typical tree column is 1.4m on the longer axis and 0.6m wide, skilfully fabricated from large CHS sections connected by curved plate. The baseplates measure 1.8m x1.0m.

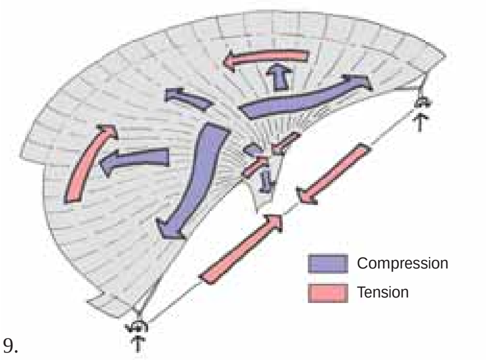
8.

5. The funnel form.

6. The overall diameter of the roof is 138m: the north-south span of the roof is the longest at any railway station in Europe.

7. The diagrid shell axial forces (a) and bending forces (b).

8. Funnel element being fabricated.



9.

The branches are pin-ended at the connection to the diagrid shell to allow the roof to articulate, and avoid bending forces being transferred from the diagrid radial members into the branches themselves.

All but two of the tree columns are identical. Two “super-tree” columns with only two forward-facing branches, carrying significantly larger forces than the typical case, stand 114.7m apart on opposite sides of the funnel, and provide the edge restraint to the shell adjacent to the existing WR building. The super-tree columns are larger – 1.9m x 0.65m maximum dimension, with a 3.35m long baseplate – and each is 54.6m from the closest point on the funnel.

Some of the trees are carried directly on dedicated concrete bored pile foundations, while others are supported on the basement concrete box structure of the London Underground Northern Ticket Hall. These foundations were all built as part of the London Underground works, also designed by Arup[1].

The long span, wider across the WR building façade than any other railway station in Europe, presented several structural challenges. A key part of the analysis involved checking for global and local buckling of the elements under the very high loads. This was also carried out using GSA, in combination with a custom-built automated spreadsheet which analysed every element of the roof under around 100 separate load combinations.

Connections

The connections between the tree column branches and trunk have to transfer significant forces from several directions down to the foundations, and are among the largest and most visible parts of the concourse roof structure.

10.

It was decided that a solid cast “node” (Figs 10-11), sculpted to smoothly transition the geometry between branches and trunk, was the best solution, though it is not something often found on such a scale in a modern building. A 3-D finite element model of each node was analysed to optimise the plate thickness and geometry within the constraints of the casting process.

The detailed design of the roof required close collaboration with the architect, as all the structure is fully exposed. No bolts are visible from the underside, as all connections are hidden within the structural members themselves.

The constantly changing geometry of the roof required careful grouping of connection types to give some uniformity to the connection design while still achieving an efficient and lightweight roof. The overall result is a very clean structure, with no interruptions to the curving geometry of the diagrid (Fig 12).

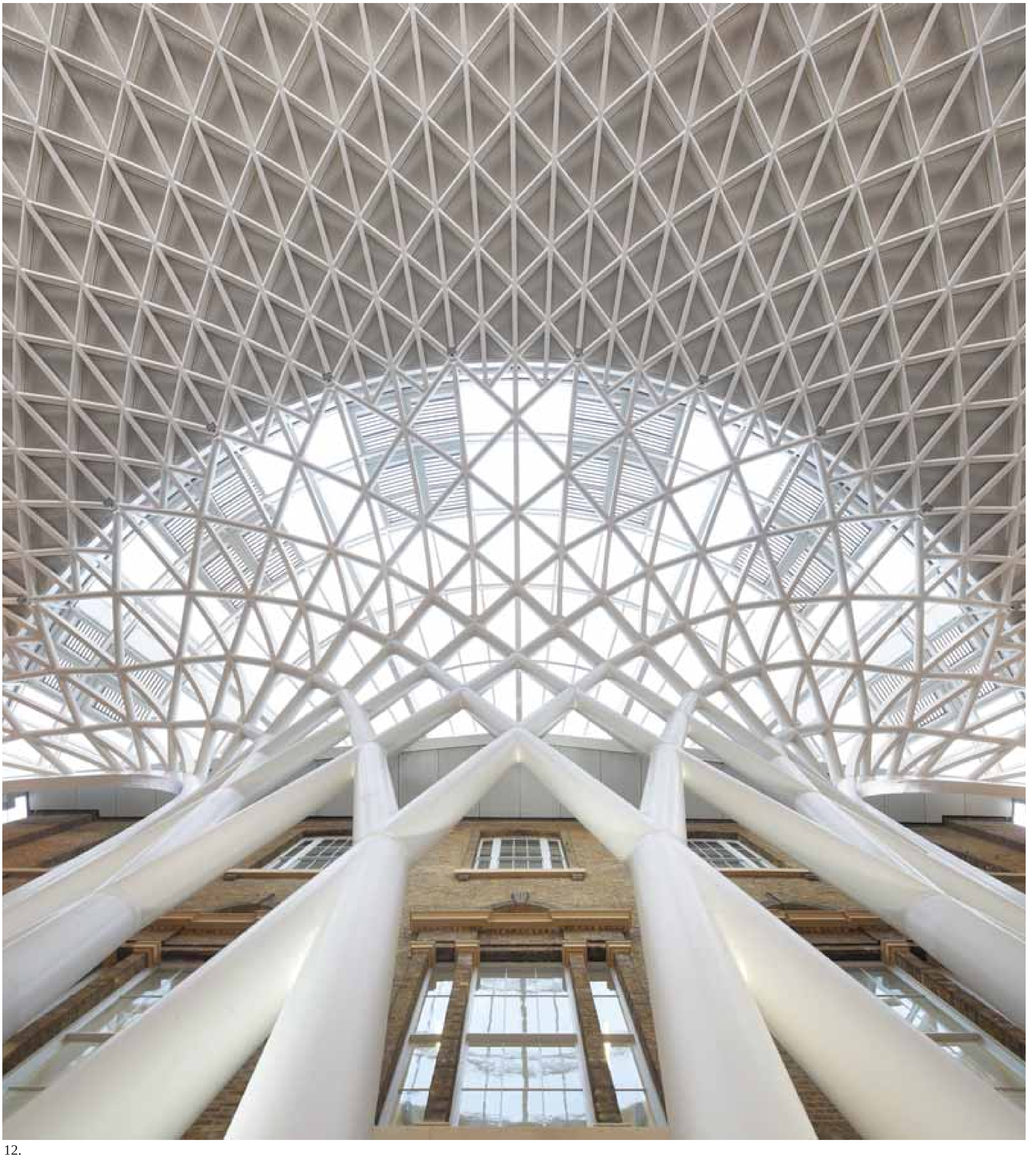
11.

9. Global force diagram.

10. Perimeter “tree” columns, 12m apart and 52.1m from the centre of the funnel.

11. Solid cast node, showing lifting eyes.

12. All connections are hidden within the structure.



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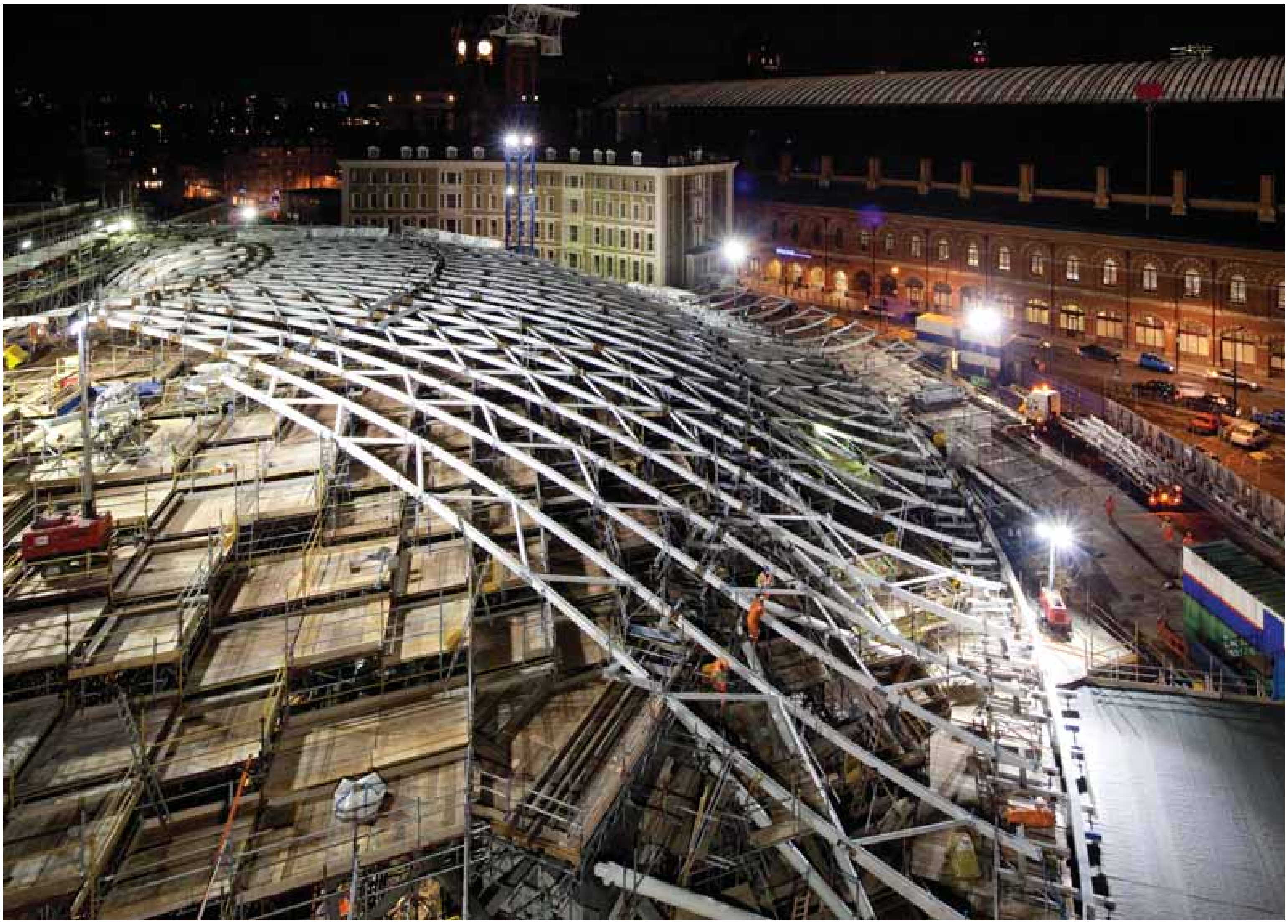


13.

14.

15.

16.

Construction

The construction of the roof on such an extremely constrained site while maintaining station operations required careful planning and sequencing. A huge scaffold was erected, onto which the prefabricated "ladders" of the roof structure were dropped in and connected in situ. Once the shell was complete, the scaffold was gradually removed to let the roof settle under its own weight; the recorded deflections all within the limits predicted by the analysis model.

Reference

(1) EVANS, P *et al*. Super subterranean hub: updating King's Cross St Pancras. *ICE Proceedings: Civil Engineering*, *164*(CE2), pp73-80, May 2011.

13. Prefabricated roof structure being placed on scaffolding.

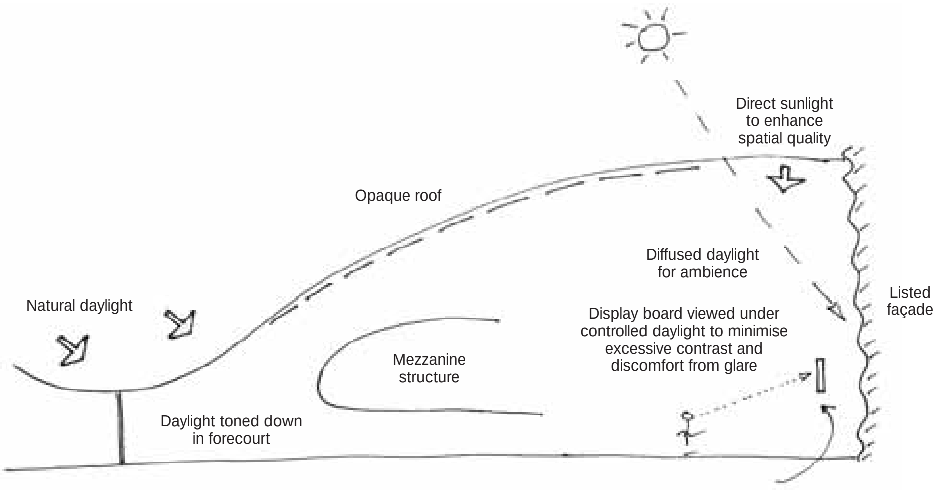
14. The complete roof structure in place.

15. Placing roof cladding elements.

16. The completed Western Concourse just prior to opening.

Lighting the roof

Authors
Simon King Florence Lam



1.

Use of natural light

Daylight plays a significant role in creating a light and airy atmosphere in the Western Concourse, giving the passengers a sense of both the time of day and of connection to the city.

The design of the roof glazing aimed at a holistic approach in balancing comfort, energy and cost, with the glazed panels strategically positioned near the heritage façade of the Western Range building so as to visually enhance their presence with daylight, but also ensure that glare impact on the customer information display panels is minimised (Figs 1-2).

Lighting design

The roof is a major visual element within the concourse and needed to be illuminated sympathetically. The essence of Arup's concept was to uplight the diagrid, using highly efficient and colour-stable, ceramic-based, metal halide projectors to ensure that it is lit homogeneously (Fig 3).

Most of the uplighters are mounted in areas where lamp replacement and maintenance can be done easily and safely during the working day without disrupting the station's operation; for instance, the main functional lighting is mounted on a maintenance platform above the roof of the food court (Fig 3). Making the station's services accessible was paramount from the outset, so as to ensure that an aesthetically pleasing building was maintenance-friendly as well, but without divulging its secrets to the admiring eye of the public.

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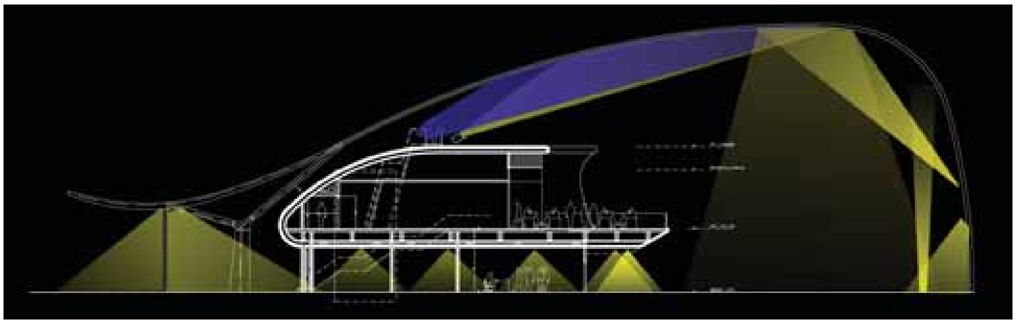

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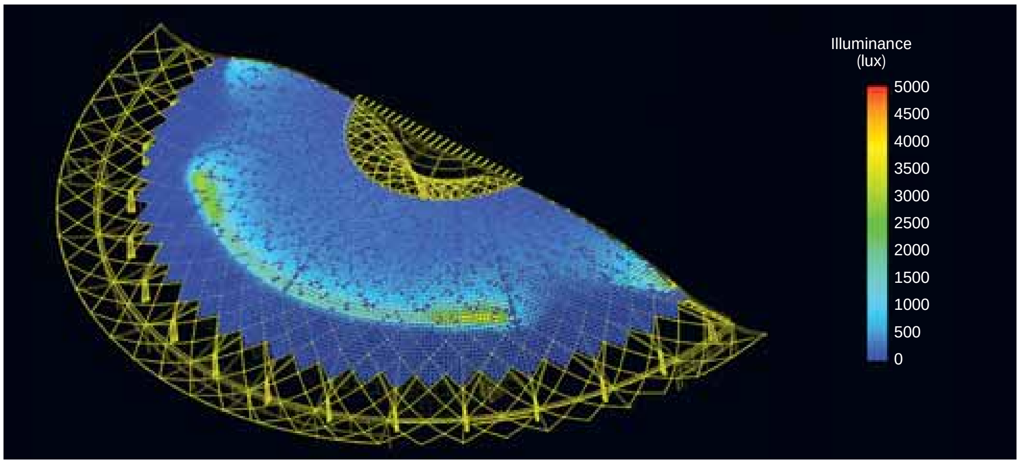


4.

5.

1. Daylighting concept.

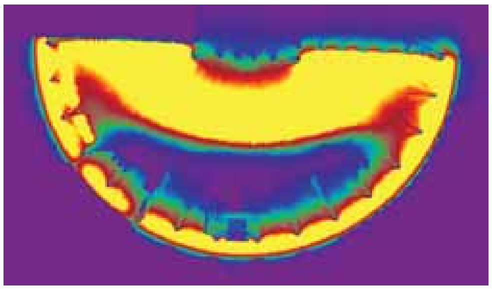
2. Sympathetic and homogeneous uplighting allows the customer information display panels to be easily read.

3. Section through the concourse, showing lighting principles.

4. Amount and distribution of light across the ceiling produced by the electrical lighting.

5. Definition of diagrid roof, and effect at floor level of lighting.

6. Amount and distribution of light across the concourse floor from the electrical lighting.



6.

In the initial concept stages of the lighting design, it was apparent that the level of intensity with which the uplighters would project onto the diagrid was a cause for concern (Fig 4). However, the positive effects from illuminating the depth and complexity of this striking structure far outweighed concern over any intensity issues, which were limited by careful aiming and positioning of the uplighters. It would have been a travesty to conceal it from the eyes of the travelling public during the hours of darkness (Fig 5).

The efficiency of the luminaires was also a top priority, as the design involved uplighting the roof high above a vast public space that requires an average maintained illumination of 200 lux at floor level to ensure a safe and pleasing environment for the station users (Fig 6).

The luminaires are connected using interleaved circuitry, which provides greater resilience in the event of circuit failure. The lighting control system maximises efficiency as it benefits from the use of daylight-linked controls, and also provides a further service benefit from the alternate switching of luminaires so as to maximise lamp replacement interval.

7. LED DMX projector.
8. The central block wall washing.
9. Funnel uplighting.

7.

Colour lighting scheme

A colour lighting scheme was suggested at the masterplanning stage, and this was maintained throughout the various design stages. The colour blue was chosen to provide a complementary contrast to the natural beauty of the WR's sand-coloured brickwork, and the final stages of the design took the aspiration a stage further by providing a full colour spectrum range using equipment by DMX-controlled LED projectors.

These projectors were selected with RGBB colours: red, green, blue and blue (Fig 7). This would enable the diagrid roof to be washed with any colour while maintaining the daily emphasis on blue, and allow the station to alter the roof's colour for special events, such as using green for St Patrick's Day. This would be supported by a sophisticated control system enabling the feature lighting to be controlled in conjunction with the daylight.

8.

The WR building is washed with sympathetic LED lighting in the hours of darkness, enhancing the beauty of the heritage backdrop, and creating a contrast to the 21st century engineering of the concourse (Figs 8-9).

By contrast, the main funnel steelwork is illuminated with in-ground cool white uplights from the granite floor to emphasise the flowing structure, mimicking sweeping curves that are more akin to the natural world than is usually the case with steelwork (Fig 9).

9.

Planning for pedestrians

Authors
Andrew Jenkins Chris Rooney

Overview
The planning and design of successful public transport interchanges and railway termini requires an imaginative approach that addresses a whole range of issues, from operational planning through to the construction and implementation of the final design. Pedestrian planning is an integral part of this process.

Throughout its more than a decade-long involvement with Network Rail and John McAslan + Partners on the King's Cross project, Arup has advised on the station planning, with the innovative use of dynamic passenger modelling techniques (*Pedroute*, *Steps*, and *Legion*) to simulate crowd movements to and from the trains.
These models have been used to test the infrastructure design – both for final usage and construction phasing – and to understand passenger space requirements in terms of facilities such as ticket offices, shops, information, and access routes to platforms and trains.

These models and their interpretation have allowed a continual review of the station design and the interfaces with London Underground, St Pancras International, and public realm areas, with the aim of delivering a world-class station environment fit for the demands that will be placed on it in the future.

2.

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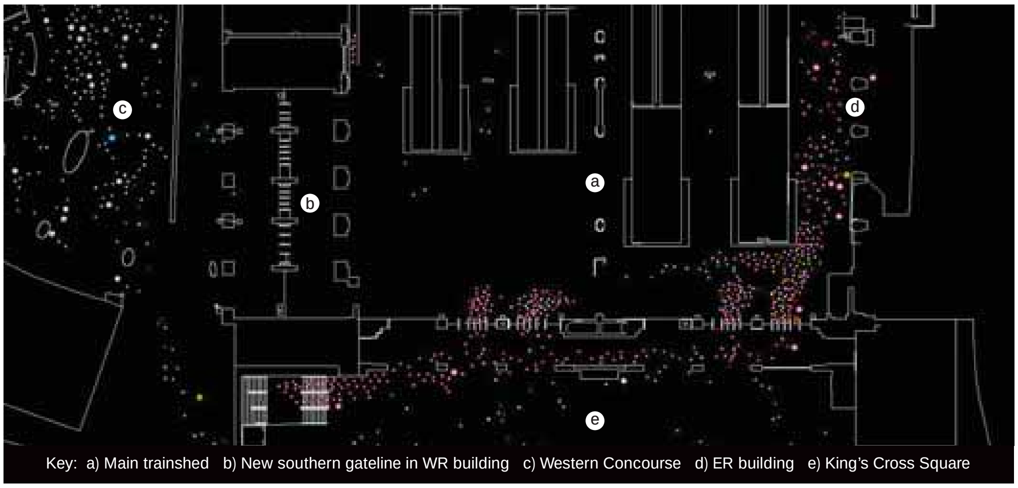
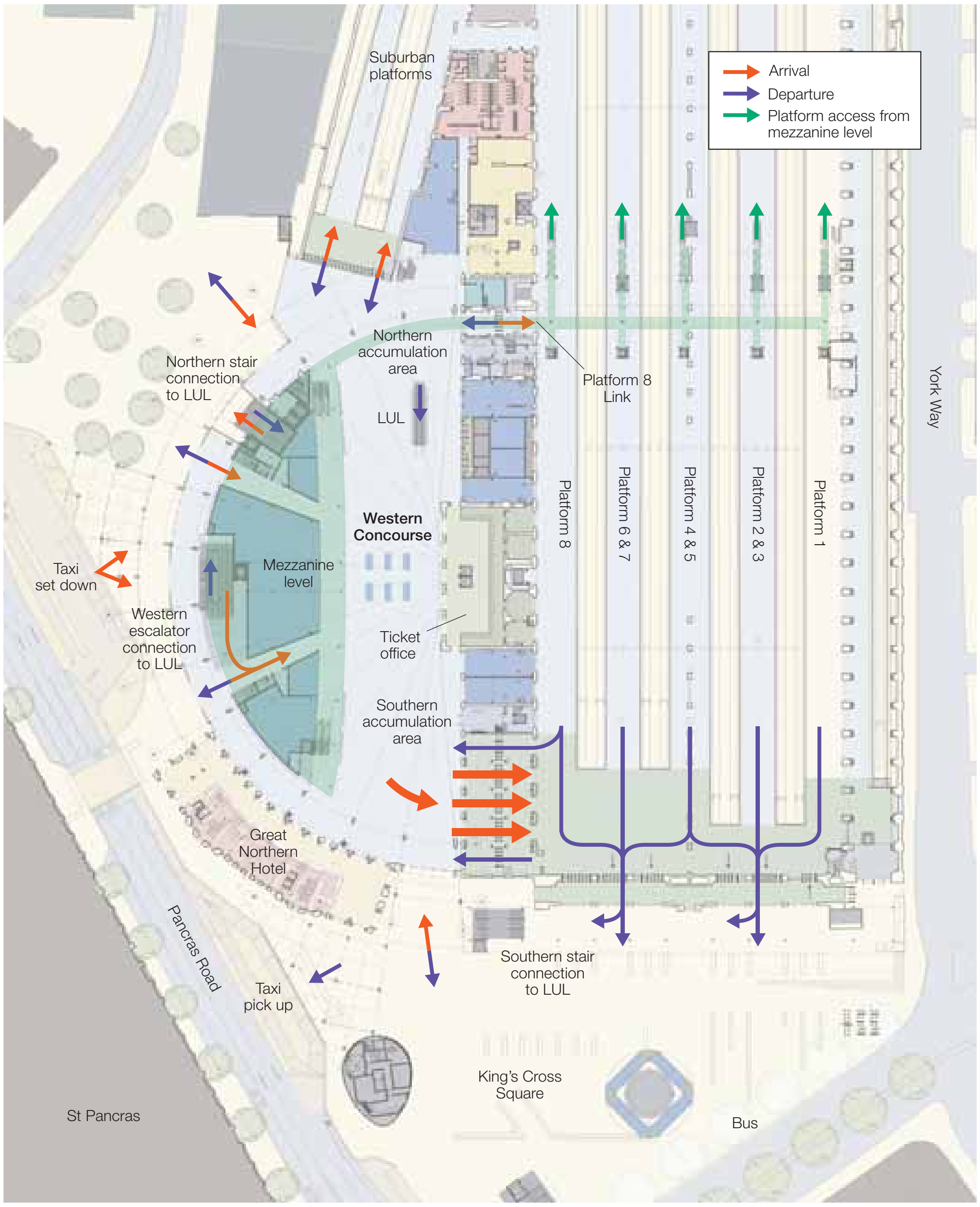


3.

1. Station prior to refurbishment.
2. Passengers arriving on platform 1.
3. *Legion* model of individual passengers arriving on Platform 1 and exiting the station through the new Southern Façade gateline.



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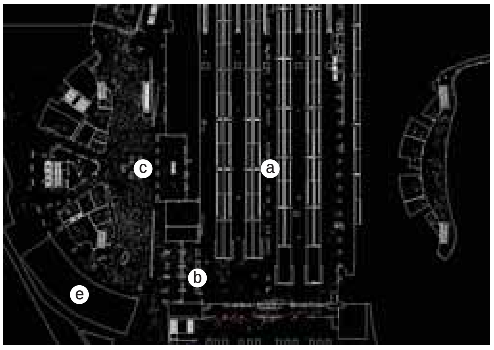


5.

6.

7.

8.

Key
a) Main trainshed
b) New southern gateline in WR building
c) Western Concourse
d) King's Cross Square
e) Great Northern Hotel.

4. Study of passenger flows.

5. *Legion* model of individual passengers waiting in the Western Concourse prior to moving through to the platforms to board the trains during the evening peak period.

6. Passengers waiting in the Western Concourse prior to boarding trains. The yellows and oranges show the areas where most people are waiting at this time; although accumulation is high, passengers are able to move freely to and from the trains and retail areas.

7. Southern accumulation area on the Western Concourse.

8. Passenger densities across King's Cross Square; areas of congregation or congestion are indicated by the yellows and oranges. It is free from any congestion or accumulation of people except at bus stops on the south side and the exit gates from the main station on the north side.

Design objectives
The Western Concourse is a huge improvement in passenger facilities at King's Cross, with more space for passengers to wait before boarding trains, and a combined waiting area for both intercity and suburban passengers.
The former concourse at the south end of the station was used mainly by inter-city passengers, while those departing from the suburban shed (platforms 9-11) had only a confined space immediately south of the platforms, with limited facilities.

Passengers now arrive at the concourse via new escalators from the new London Underground Northern Ticket Hall, from buses, taxis and the surrounding streets, and wait in a spacious, light area in advance of being called through to trains (Fig 7).

Information is displayed on two large screens, and all ticket selling and information facilities are on the ground floor which also provides enhanced retail, supplemented by other shops on the mezzanine level. The main train shed (platforms 0-8) is accessed directly from the ground-level concourse via the historic Western Range building, and from the mezzanine level via a new footbridge and escalator connections.

Challenges
The operational and passenger demographic at King's Cross provided particular challenges to the station design and operations teams. This is one of London's primary public transport hubs, providing interchange between mainline UK and international rail services, buses, taxis, and London Underground. King's Cross St Pancras Underground station is served by the Victoria, Piccadilly, Northern, Circle, and Hammersmith and City lines.

The level of interchange between all transport services places huge pressure on the infrastructure. In parallel with the redevelopment and enhancement of the mainline station, London Underground undertook its own significant enhancements with the new Western and Northern Ticket Halls, which opened respectively in 2006 and 2009.

In addition, new commercial, educational, residential and retail developments to the north will add significantly to the numbers of people using the station. In total, King's Cross station will accommodate up to 40M passengers per year after all these developments and train service enhancements are complete.

Many of central London's railway stations and interchanges are used predominantly by commuters during the standard morning and evening peak periods, but this is not necessarily the case at King's Cross.

Although commuter flows are very high and trains arrive full in the morning and depart full in the evening, the station is also used by a wide variety of occasional users not necessarily familiar with it. Older and younger people, family groups and tourists all use the station for destinations such as Cambridge in East Anglia and other cities in the North of England and Scotland. They are often encumbered by large bags, travelling with children, and do not progress through the station with the same certainty or speed as the typical London commuter.

Arup took all this into account when planning the layout and amount of space for accumulation areas, walkways, ticket gates, stairs and escalators.

Assessment of pedestrian movements and interchange
Arup worked with Network Rail and the train operators to develop a functional specification for the redeveloped station, using *Legion* pedestrian simulation models to test the final design and also the main construction phases. All the stakeholders considered the various ideas and the team tested the model and design through many iterations to arrive at a station that provides both capacity and convenience for passengers. Arup's work ensured that Network Rail gained planning consent for the new Western Concourse and for the enhancements to the existing station.

The models reflected future train timetables, train configurations, and passenger demand. Just as importantly, they also took in the various passenger behavioural profiles seen at a complex interchange such as King's Cross. The team modelled commuters walking quickly and directly, tourists who do neither, and others with large bags and other encumbrances. Passenger surveys were undertaken to get accurate data on passenger flows, the profile of movements over time, and the proportion of passengers who had no bags, small bags, large bags, bicycles, or were using wheelchairs.

These data sets were input to the models and used to test known capacity constraints such as ticket gates. The train operators also provided statistics on the number of passengers using ticket gates who have their tickets rejected and have to seek assistance from gate attendants.

Behavioural characteristics like these can significantly affect the efficiency of passenger flow, and it was critical to the good design of the station, and to gaining the agreement of all the stakeholders, that the modelling was seen to be as realistic as possible.

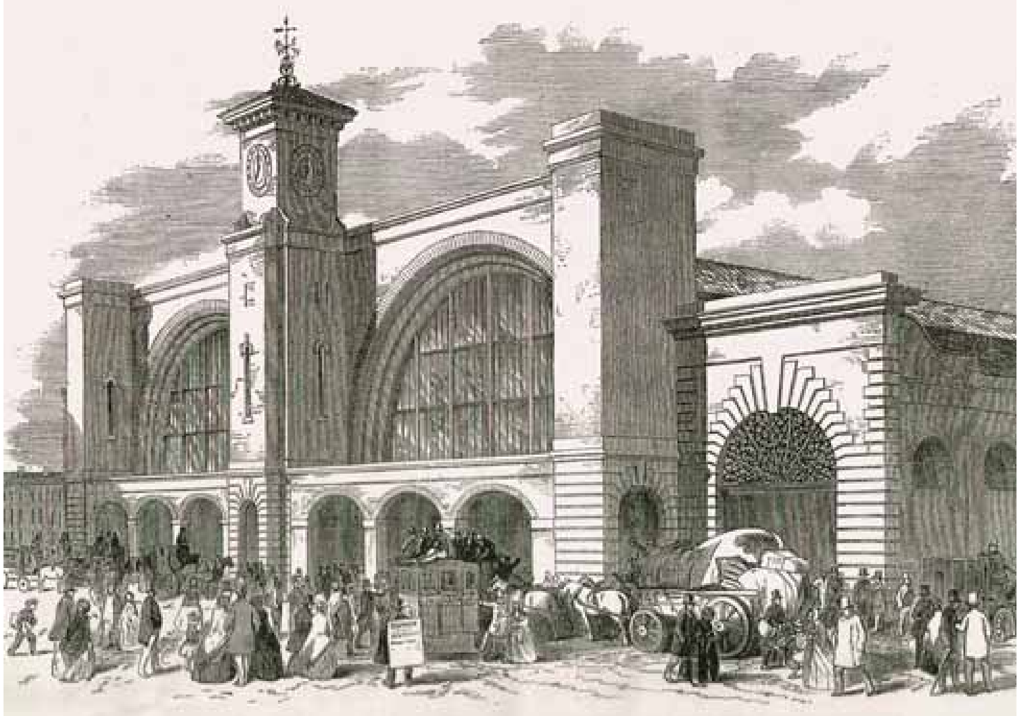
Arup determined the design requirements with Network Rail and JMP, and developed an operational plan for managing passenger flows during the extensive construction and upgrade works where significant parts of the station were closed off to passengers or where temporary walkways and accumulation space were required.

King's Cross Square
Assessing passenger movements and circulation was not limited to the station itself. Arup worked with Network Rail and architect Stanton Williams on the design of King's Cross Square to the south of the station, in the area where the previous concourse was (Fig 8). It had to be planned to accommodate movements into and out of the station and to and from buses and the Underground, as well as people walking through towards Euston Road and York Way, all within an attractive open space where people can meet and enjoy the views of the newly restored King's Cross and St. Pancras stations (see also pp41-42).

Summary
In summary, the team's goal was to make King's Cross station and its environs an intuitive place to use. Arup considered passenger movement at every stage of the project and treated the station and its surroundings as a single system to help ensure that the station visitor experience is pleasant, easy and seamless.

The Western Range

Authors
Nicholas Bailes Graham Redman
Sarah Tattersall Ken Wiseman



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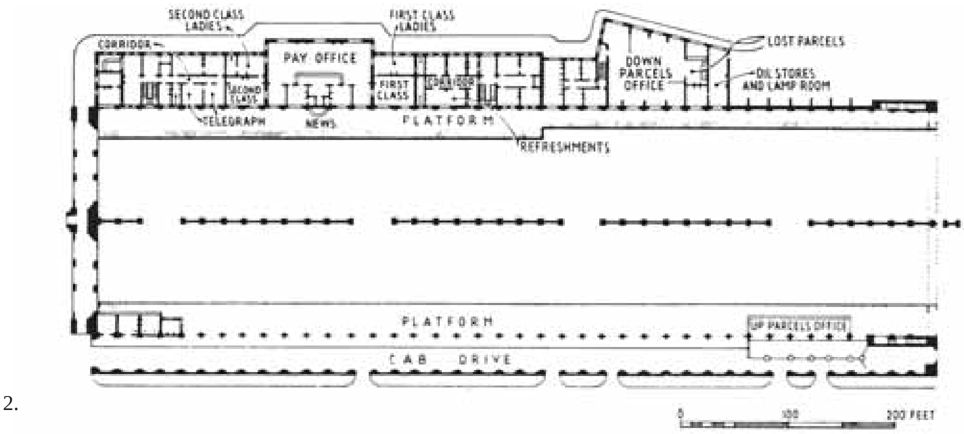


2.

Introduction

Passengers in the 1850s taking a train from the impressive new King's Cross station made their way via gardens on the west side to the Pay Office (booking hall) in the centre of the Western Range buildings (Fig 2). Having bought their tickets, they exited to the departure-side (west) platform or perhaps, if they had time and means, waited in the first or second-class lounge – or fortified themselves with a "swift half" in the Great Northern Hotel.

This was a busy location. Contemporary prints show a great deal of activity around the station, with the yard in front full of comings and goings: the well-heeled being dropped off from hackney carriages in front of the Pay Office, and carts trundling in and out of the Down Parcels Office just to the north (Fig 1).

But by the beginning of the 21st century, the WR was far from new and grand, or the focus of passenger arrivals at the station. The ground floor of the Pay Office had been partitioned off for various uses, and just to the north of it a great "bomb gap" from the 1941 Blitz (Fig 3) had never been rebuilt, leaving the north end of the building cut off from the south.

Some offices were still in use, but it was a long climb to the fourth floor unless one risked a ride in the slow and astonishingly cramped, asbestos-clad 1970s-era lift that had by then been installed in the middle of the grand Victorian stairwell.

Parts of the upper floors were disused, and above the trap-door over the left-luggage counter was a mysterious area almost everyone had forgotten about. Since the 1970s, inter-city passengers had waited in the cramped, low-ceilinged Southern Concourse, known unaffectionately as "the green shed". Lewis Cubitt's straightforward design, with its clear passenger movement lines, had essentially vanished.

Aims of the works

The redevelopment offered Network Rail and JMP the opportunity to rethink the entire station (Fig 4). The WR buildings would now be its centre geographically and functionally, containing facilities for passengers (ticketing, shops, a pub and the first-class lounge), station operations (staff and management offices, and the station control room) and train servicing (the on-board services logistics operation housed in the basement).

The implications included structural changes – from minor repairs to major reconfiguration – their aims, broadly summarised, being to:

- create links between the new Western Concourse and the platforms in the main trainshed to the east
- rebuild the bomb gap to form once again a single unit rather than two islands

3.

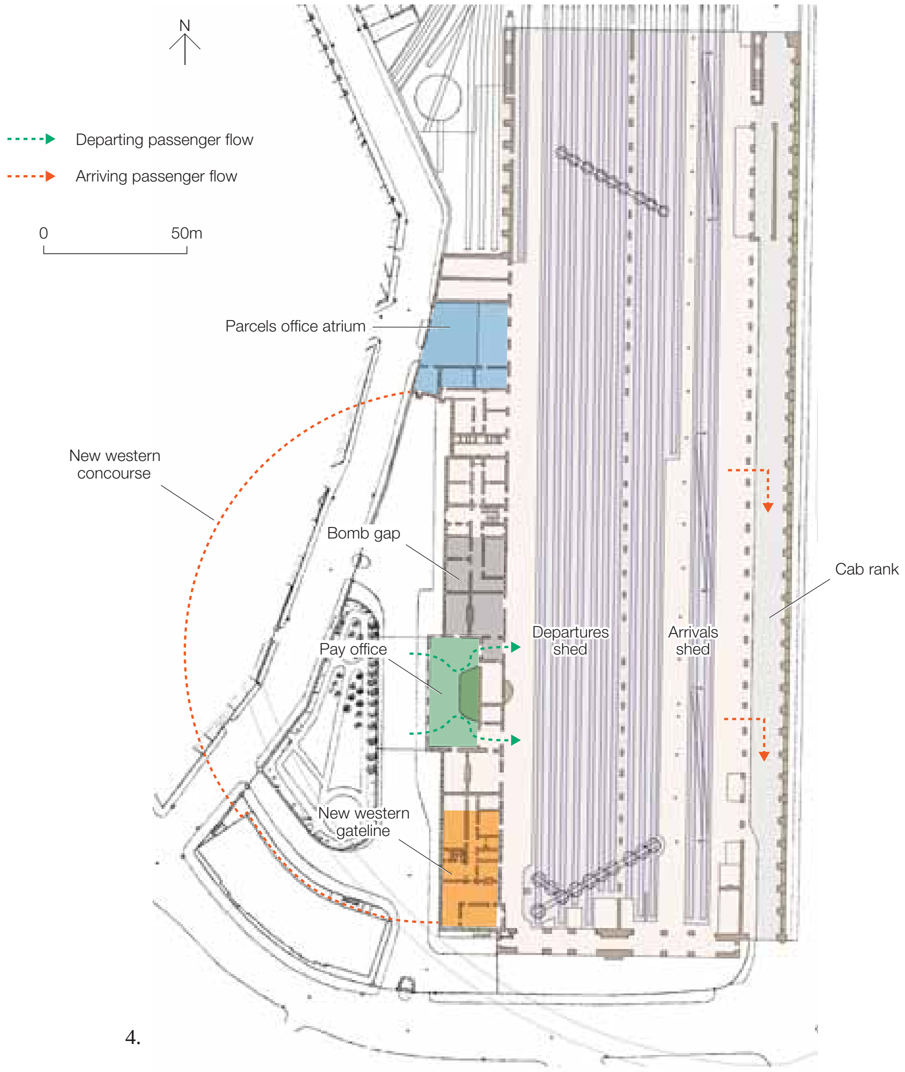
1. The newly-opened King's Cross terminus of the Great Northern Railway.

2. Plan at platform level, 1852.

3. Bomb damage to the WR and trainshed in 1941.

4. Key plan.

5. Historic cross-section of the trainshed, showing the structure.



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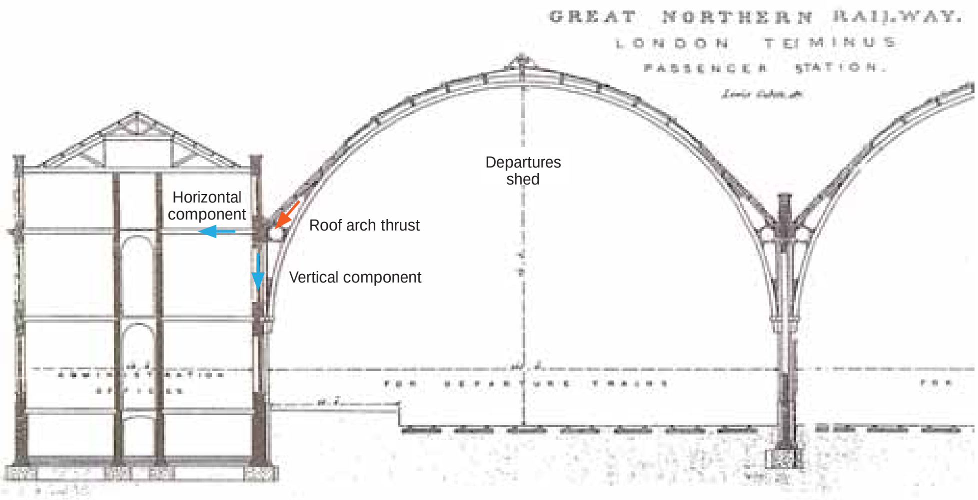

5.

- make the adjustments necessary to achieve key modern requirements such as fire safety, lift access to all floors, and building services
- ensure that the structural performance was adequate for 60 more years of use.

Design approach (principles)

Original structural diagrams (Fig 5) showed clear load-paths from the arched roof of the trainshed through the WR's cross-walls and buttresses to the foundations, but change upon change had muddled this clarity. The building's structural operation was hard to understand, let alone assess and credibly analyse. To avoid "analysis paralysis" a coherent design principle was needed.

Three important philosophical principles had to be established – how to:

(1) establish the fitness for purpose of existing elements

(2) integrate new structure into the existing where changes were required (either because of existing problems, or because of new requirements)

(3) safely make the change from an existing structural configuration to a new one.

Adequacy of existing structure

The structure of the WR buildings had, broadly speaking, worked acceptably for 160 years. The 1941 bombing had been a major structural test but also demonstrated some robustness, in that the damage was restricted to areas directly affected by the bomb (ie no "disproportionate collapse").

To require the client to spend significant sums on additional structural works to strengthen something that seemed to be working adequately would rightly be treated with scorn. Such works typically result in some loss of original heritage fabric, and consume additional physical resources with consequent environmental impact.

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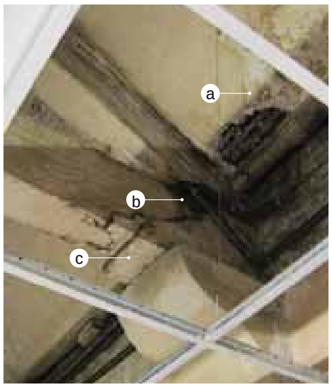

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8.

The structure was thus considered to have been proved in service and could be relied upon to perform satisfactorily in the future, provided that:

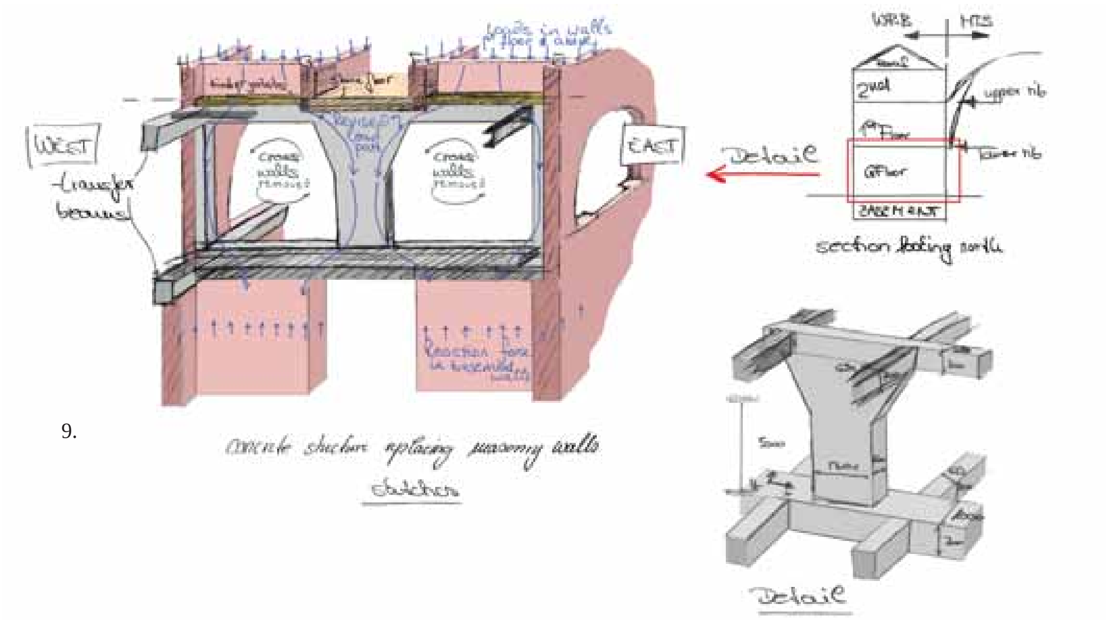
- any flaws the original design exposed in use were rectified
- there was no adverse change in the magnitude or point of application of loads on the structure (previously or proposed)
- there had been no unacceptable deterioration of structural elements from fire or moisture damage, dry or wet rot, rust, abrasion or other action
- there had been no reduction in structural capacity due to structural reordering over the life of the building
- there was no change in other performance requirements (eg fire resistance).

With some exceptions these conditions were found to be met over most of the building. Crucial to successfully implementing this approach is confidence that the existing structure is in good condition, and determining this fell to the contractor, Vinci. Arup produced a set of "assumed existing structure drawings", documenting from various sources what was expected throughout the building. When the actual structure was found to be different from that assumed, or its condition had deteriorated (Figs 6-8), this was brought to the team's attention and rectified. Vinci's proactive approach in this respect was vital to resolving several issues, particularly around the Pay Office.

Integration of new structural elements

These were introduced for many reasons in the station masterplan, but in all cases the team kept the bigger picture of load-paths in mind. This seems self-evident but, astonishingly, there were areas in the existing building where this seemingly obvious principle had been ignored (Fig 13). Load-path assessments had to include:

- determining the most likely vertical and lateral load-paths through the existing structure, and understanding how structural modifications would interrupt these
- designing new structure to achieve both strength and stiffness equivalent to any elements that it replaced
- paying particular attention to any secondary action an element may be performing, eg as floors often form critical lateral restraints on masonry walls to prevent toppling or buckling; where these were removed, either new structural elements were installed to provide restraint or the walls' stability was carefully assessed
- developing in principle the steps required to make the change from the old configuration to the new, including an indication of the temporary works required to support the interim configurations when the old structure had been removed but the new had not been introduced.



9.

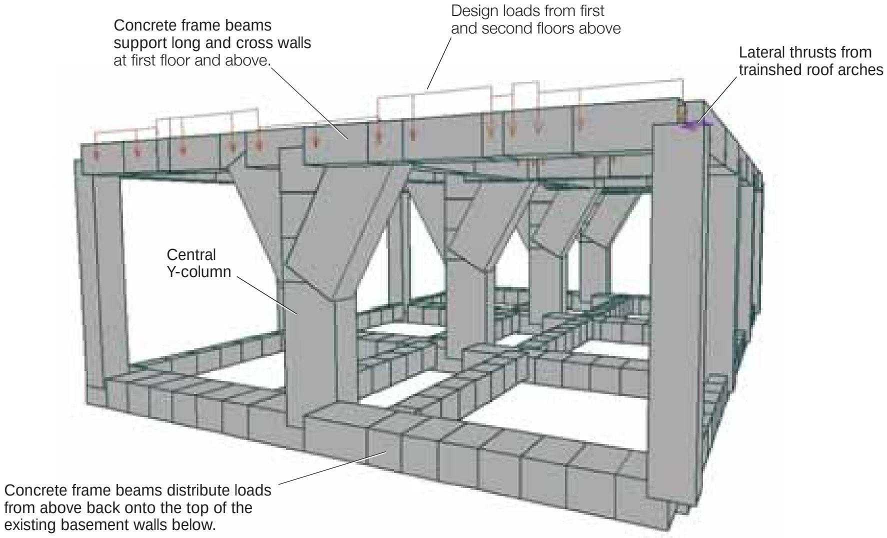
6. Flaw in the original design exposed in service: a) cracks in overstressed masonry pier.

7. Deterioration: a) signs of water ingress from blocked gutter above; b) rotting of timber truss members; c) cast iron truss shoe.

8. Reordering: a) timber truss members; b) wrought iron drop-rod; c) a hanger rod supporting the floor below has been cut – the floor sagged by 150mm.

9. Concept sketches for reordering at new gateline.

10.



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12.

Significant works
Structural work was needed throughout; the following are some of the significant aspects.

New western gateline

Recreating passenger movement lines similar to those of the 1852 original set a big challenge for the design team, in that passengers would move from the new Western Concourse through ticket gates within five bays at the south end of the WR building. This would require supporting all the existing structure from the first floor and above, gutting the internal structure beneath to allow a new concrete frame to be built without longitudinal and cross-walls obstructing passenger movement, and then lowering the overhead structure onto the new support.

Encouraged by Network Rail, Arup developed a three-dimensional concrete frame solution, to be inserted between the ground and first floor levels only. Loads from the first floor-level walls flow around this open frame and are redistributed back into the walls of the basement beneath (Fig 9). The total amount of load is essentially the same as the existing, and the frame spreads this out onto the top of the basement walls so that it goes back into the existing structure more or less where it was before. This minimised the amount of demolition and reconstruction required, reducing cost, programme and risk and preserving historic fabric.

The central (large) Y-shaped column is critical functionally, aesthetically and structurally. JMP and Arup modelled the gateline area in 3-D to optimise the shape (Figs 10-11). Its smaller lower section maximises sight-lines for both passengers and gateline attendants, while the flare above provides support along the line of the spine walls either side of the corridor at first floor level, thus avoiding deep transfer beams that would have been visible through the historic window openings in the façades.

10. Optimising form and function: architectural rendering by JMP.

11. Optimising structure: 3-D analysis model.

12. Fitting out of the gateline area, showing completed structure.

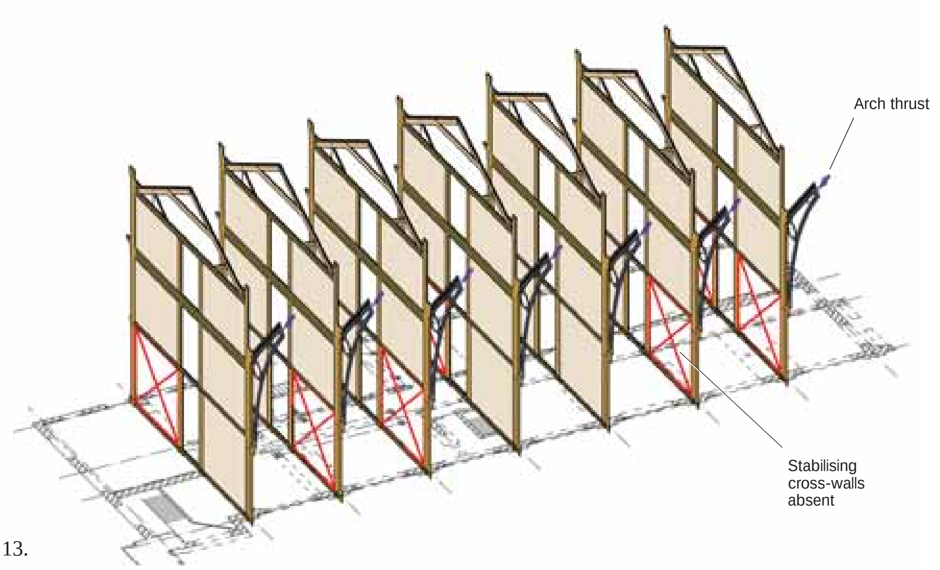
Arup's review of the lateral stability of the buildings under the main trainshed roof arches showed this area to have been compromised by previous modifications (Fig 13). The new concrete frames were designed to achieve the strength and stiffness needed to support the roof under the new and heavier cladding loads.

The proposals made substantial demands on the temporary works. The masonry cross-walls between ground and first floor that provide the critical load-path for thrusts from the main trainshed roof to the foundations, already compromised by ad hoc alterations, would be removed completely so as to install the new concrete frames.

Substantial temporary works would be needed to act as stilts supporting the first and second floors of the building while the ground floor structure was removed and replaced. These stilts would also need to be braced to provide lateral support to the main trainshed arches. With thousands of passengers using the platforms here every day throughout the construction period, the consequences of something going wrong would be serious.

Vinci, its subcontractor McGee, and temporary works designer Arnold Burgess Partnership approached the task with unruffled confidence, installing a system that performed faultlessly (Fig 14). Enormous steel beams would suddenly appear at seemingly inaccessible parts of the building (making holes in the roof to crane in pieces being unacceptable in the listed building).

The demolition and construction crews worked in incredibly difficult conditions, principally due to the piecemeal 1970s-era modifications which meant that no regularity of approach to temporary works or construction operations was possible. The ordered arrangement of the complete gateline (Fig 15) reveals little of the heroics required to install the structure.



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15.

13. Previous removal of the crosswalls compromising the lateral stability system.

14. Braced steel temporary works stilts to support the first and second floors above; tops of the basement walls that will support the new concrete frame are visible.

15. Completed gateline structure.

16. Not the only mystery at King's Cross Station!

17. JMP's aspiration for allowing public access to the atrium.

18. Refurbished atrium.

19. Exposing the atrium space.

16.

17.

18.

19.

Parcels Office atrium

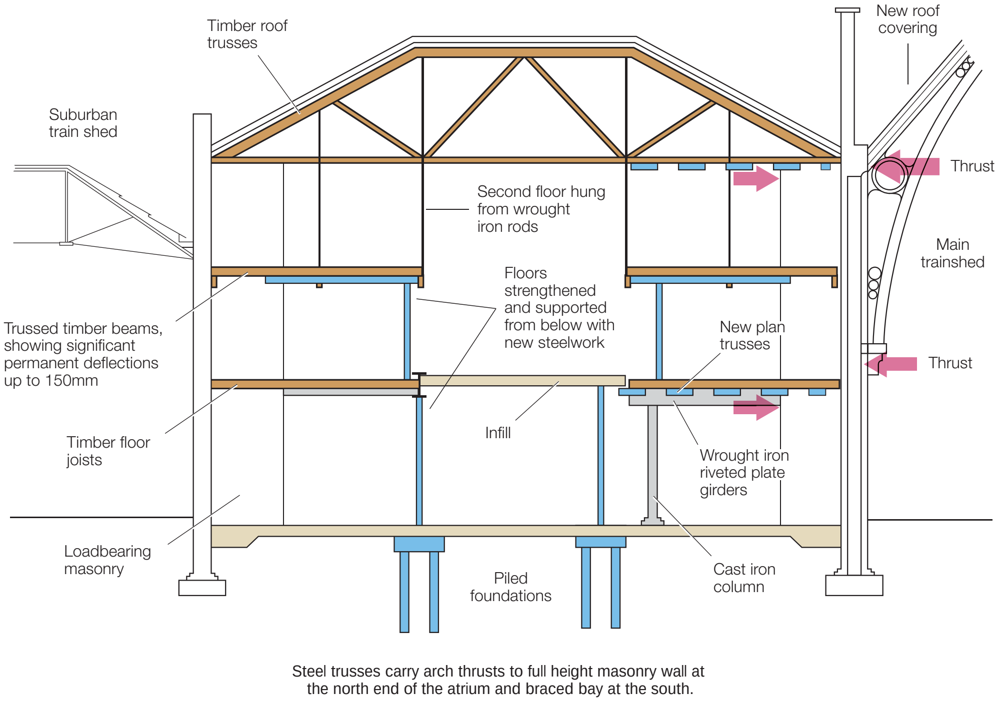
A luggage trolley seemingly disappearing into one of the station walls beneath a sign for "Platform 9¾" attracts countless *Harry Potter* fans posing for photographs (Fig 16). But the walls of the real platform 9 enclosed a real secret: for many years, the atrium in the former Parcels Office in the WR was boarded over, forgotten by all except a few who climbed a ladder above the left luggage desk and performed a few acrobatics to get through the trap-door above. The refurbishment included plans to make this area accessible to everyone in the form of a pub (Figs 17-18).

An internal atrium bringing natural light to deep floor plates was highly revolutionary for the 1850s, and the construction had several other unusual features. For example, to provide column-free space for the ground floor parcels depot, the first and second floors were originally hung from the timber roof trusses with wrought iron rods.

Developing an understanding of the existing structure was vital, and this began with the removal of partitions and cladding, exposing the atrium to full view for the first time in many years (Fig 19).

As the structure was revealed, it became clear that it had undergone several modifications. Some areas previously hung from the roof trusses had settled a very obvious 150mm or so. In some places the hangers had been cut and then columns (generally cast iron) introduced below, although in what order was unclear!

The increased live load caused by change in use to pub made appraising the strength of the existing structure necessary. This showed that in many areas, additional strengthening would be required, eg for the timber roof trusses to continue to hang the second floor. It was therefore decided to support the second floor from structure below.



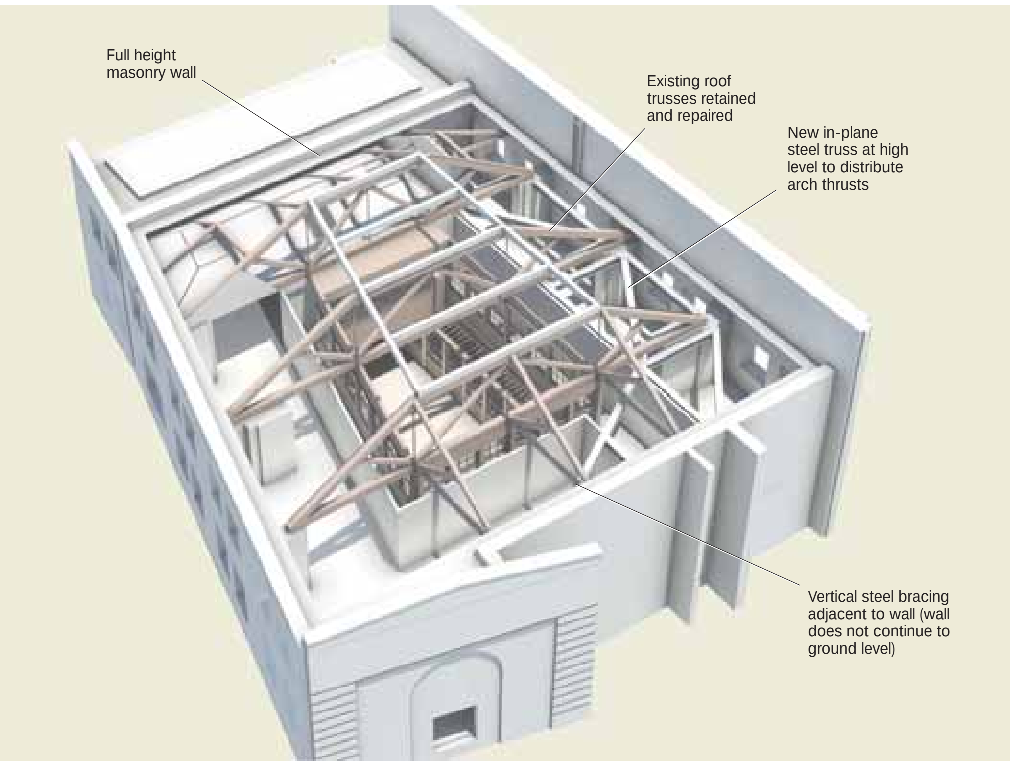
20.

20. Section through the pub atrium showing load paths after the modifications.

21. Architectural visualisation of the loft structure.

22. Strengthening the first floor:
a) existing timber floors retained;
b) existing riveted iron girder;
c) existing floor strengthened by wedging it off the top of new steelwork;
d) new in-plane truss installed below existing floor.

23. Strengthening the second floor:
a) new twin steel beams parallel to historic joist, picking up loads of existing timber floor;
b) existing iron joist;
c) existing iron cruciform stanchion;
d) new steel post placed parallel to historic stanchion.
Placing new structure parallel to old means that the new works are reversible.



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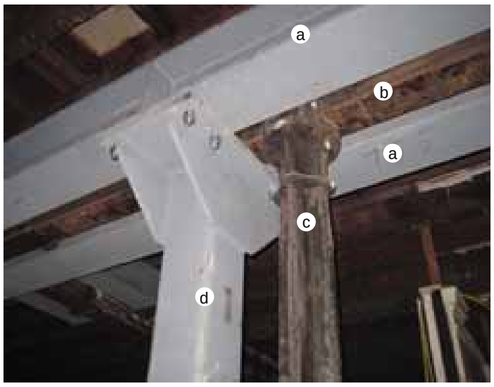

23.

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26.

24. Pub occupying the strengthened floors adjacent to the atrium. The diagonals of the new in-plane steel truss stabilising the main trainshed roof can be seen in the ceiling.

25. 1941 bomb damage, showing the fallen girder, rubble on the balcony, the old ticket office with masonry parapet, etc.

26. Old booking hall in 2007:
a) "Badminton court" floor above;
b) cantilever balcony fully enclosed in wired-glass lean-to;
c) ducts and plant fill the space above a mezzanine floor inserted at first floor level in the 1970s.

Another important consideration was lateral stability. The atrium had no cross-walls and the only apparent way to resist thrusts from the main train shed arches was buttressing action from short masonry piers. Calculations showed the buttresses to be just sufficient to provide lateral stability for the existing main train shed roof with only a very small factor of safety against overturning, so a new load path was needed for the heavier new roof covering (Fig 20).

The general philosophy behind the strengthening was to ensure minimal impact on the listed structure which, where possible, was justified for the new use.

Modifications to areas needing strengthening were designed to be reversible, with the existing structure left in place and new steelwork installed below or alongside. Similarly for connections clamps, not bolts, were generally used to attach the new steelwork to the existing girders.
This approach resulted in a bespoke structural arrangement, requiring details to be considered from the very start of the design (Figs 21-23).

Pay Office

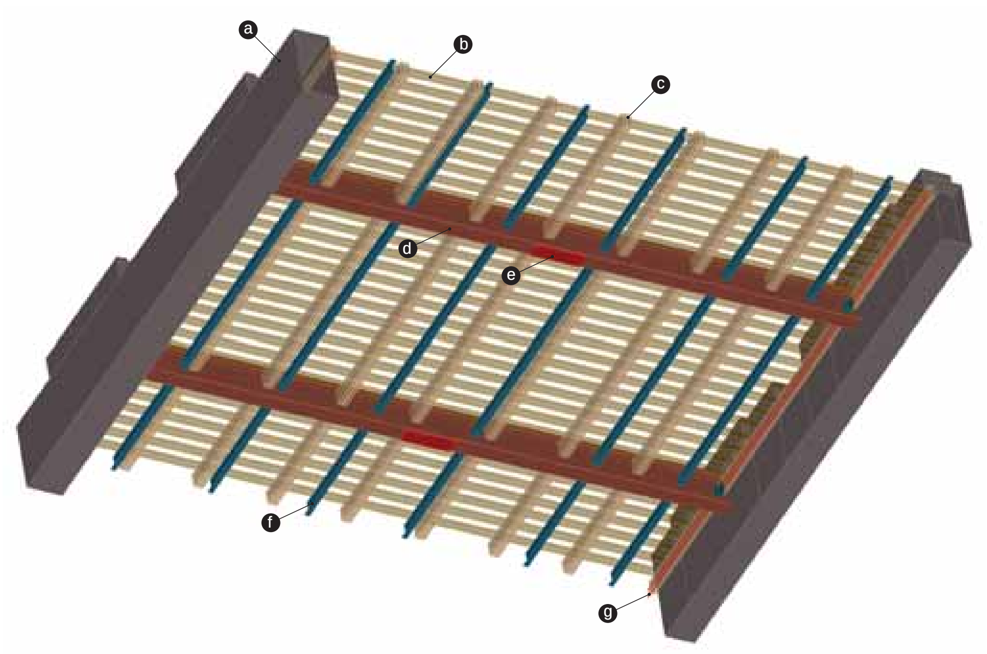
Time had been cruel to Lewis Cubitt's impressively tall (originally 12m) column-free Pay Office. The north-east corner was damaged by the bomb (Fig 25), and alterations were made in the 1970s. By 2007 the space was a rabbit-warren of partitions, mezzanines, plant and ductwork (Fig 26). JMP's vision was to restore this space to its original function and grandeur, stripping out the clutter and restoring two of Cubitt's original elements – the floor above the Pay Office ceiling, and the first floor level cantilever balcony along the east wall.

"Badminton court floor"

To create the grand space beneath, the floor over the Pay Office had impressively long spans for the period: six 12.5m riveted wrought iron girders (a new technology at the time) supporting primary joists under the common joists and floorboards. Originally an open-plan office, it was at one stage used as a badminton court, and the name stuck. The floor was distinctly bouncy, which must have been wonderful for badminton players but suggested some investigation into its condition and capacity.

Key to Figs 27-29

a) Existing walls
b) Common timber joists (deck-boards above not shown for clarity)
c) Primary timber joists
d) Existing plated wrought iron girder
e) New strengthening plate to augment central splice plate in wrought iron girder
f) New cold-formed metal beams to augment overloaded primary joists
g) New tie-rods for resilience



27.

28.

29.

27. Upgrading the "badminton court" floor. Much design work translated into minimal requirements for new strengthening elements.

28. New lightweight steel section relieving load on overstressed timber joists.

29. New resilience ties at the ends of existing iron girders.

A survey identified weak points in the primary timber joists and the bottom flange splice connections in the girders. The girders had plentiful sectional capacity but the only lateral restraint against buckling was from the primary joists butting up against the girder web.

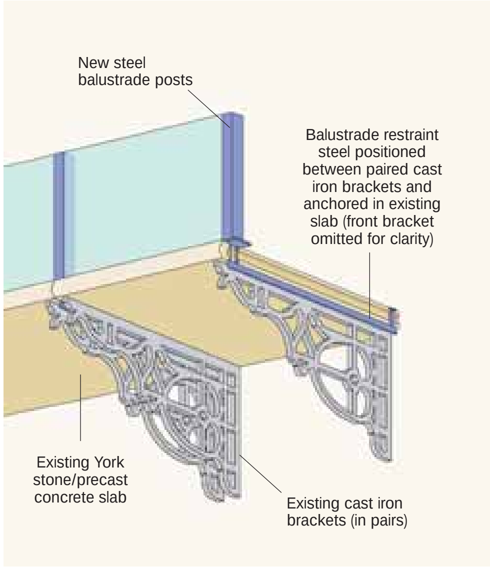
The existing floor is 10m above ground, making access for repairs difficult, so Arup and Vinci developed a solution that took full advantage of all the existing structure (Figs 27-29). This involved assessing everything down to the rivets in the splice plates, but gave confidence that only the lower flange splice-plates in the girders and one layer of timber joists needed strengthening, the former with additional splice plates and the latter by inserting lightweight cold-formed metal beams to relieve load from the existing joists and enhance lateral restraint to the girders. The parts to be installed were light enough to be brought into position by hand, without any complicated lifting arrangements.

Photos of the bomb damage (Fig 25) show that the northernmost girder fell from its bearing when the north-east corner of the hall was destroyed, but was lifted back into place during reconstruction. The area of floor supported by each girder suggested the need for additional resilience measures, so ties were provided between the girders to "catch" a girder should it somehow lose its bearing at either end (Figs 27, 29).

First floor balcony

The balcony in the Pay Office forms part of the first floor corridor that originally ran the full length of the WR, and consists of York stone floor slabs supported on cast iron brackets cantilevering from the rear wall of the Pay Office. The principle of "proved in service" was applied here too, avoiding the need for expensive load-testing.

The principle challenge for the new works, therefore, was to create a new handrail to modern loading standards. The original had long since been replaced by the wired-glass "lean-to" fixed back to the rear wall that fully enclosed the balcony (visible along the right-hand side of Fig 26). Opening up the balcony again would mean that the new handrail had to manage without restraint fixing to the wall, but also it couldn't be allowed to put a bending load into either the original stone slabs, or the precast planks that had replaced some stone slabs dislodged by the bomb.



30.

31.

32.

As JMP developed the architectural design in discussions with English Heritage, it became obvious that any solution must have minimal visible effect on the exposed historic brackets. Vinci suggested using posts and horizontally spanning glass above the balcony slab to avoid structure along the visually exposed leading. This in turn inspired Arup and JMP to develop a detail that used the space between each pair of brackets to hide a return leg underneath.

This resolved the horizontal handrail load into a vertical push/pull that could be much more easily accommodated via discrete fixings through small holes in the existing floor slabs (Fig 30). After installation the new leg beneath the balcony visually disappears between the brackets (Fig 31).

A view of the booking hall after restoration (Fig 32) shows Lewis Cubitt's grand space. The contrast with how it was in 2007 (Fig 26) is very satisfying.

Conclusions

From 2012, passengers taking a train from King's Cross once again make their way to the west side of the building, to the site of Lewis Cubitt's garden now enclosed by the new Western Concourse roof.

The well-heeled still arrive by cab; others by bus, Underground, or foot. All can purchase tickets in the original Pay Office, now restored to the splendid open space originally conceived. If they have time they can wait in one of the many new passenger amenities, possibly the first class lounge in the former bomb gap. They can even fortify themselves with a "swift half" in the pub in the rediscovered atrium near Platform 9¾.

When their train is ready they pass through the WR building to the platforms following passenger movement lines set by Cubitt 160 years before. The 21st century King's Cross will be busy, with passenger numbers exceeding 1850s' levels by orders of magnitude, but new facilities and the restored holistic clarity to passenger experience will ensure a high level of service despite the increased demands.

The WR is again at the centre of the station's function. A great deal of structural work was needed, some involving the removal of historic fabric. This was challenging to achieve safely, as well as requiring close attention to the conservation principles that govern works like this in protected buildings.

Much else was also required to undo the numerous piecemeal changes, and restore and re-open the building to a wide variety of users. It is hoped that, as a result, future generations find as much to enchant them at King's Cross station as so many have found in the past.

30. Balcony proposals.

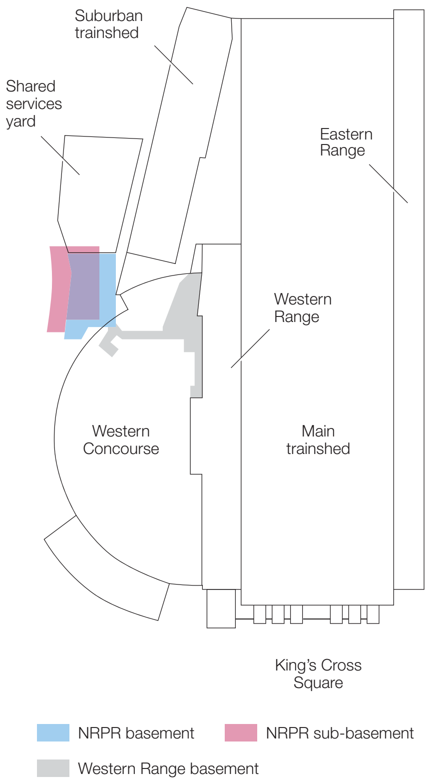
31. Existing cast iron brackets being refurbished.

32. The restored booking hall.

Servicing a Grade I refurbishment

Author
Simon King

1.



2.

Historical context: heat and light

When King's Cross opened on 14 October 1852, the WR building was heated solely by coal fires. These would have consumed over 40 sacks or approximately 1000kg of coal per day, equating to some 1.6M tonnes of CO_2 per annum being released into the atmosphere – one more contribution to London's then heavy pollution.

Similarly, the only lighting source was gas. King's Cross did not receive an electrical supply until nearly 35 years later, when the original pipes serving the gas lighting were used as wireway for the new electrical cables. During the WR refurbishment, some of these pipes were uncovered with the vulcanised-rubber insulated cables still within – fortunately no longer live!

Initial findings

During the station's numerous partial refurbishments over its 150-year life, the mechanical, electrical and public health (MEP) services had been subject to piecemeal additions and modifications and were in desperate need of total renewal. The heating system was a mismatch of gas boilers, electric space heaters, and DX (direct expansion) heat pump split units, none working in unison and thus very unreliable and inefficient.

During the initial site investigation, Arup found that the main LV (low voltage) switchboard supplying most of the electrical services was over 45 years old, having been manufactured by Ottermill in 1962. It had been modified many times over the years to cater for the ever-increasing demand, and was long overdue for replacement. Further investigation uncovered an even older LV switchboard in a room under the main north stairs, manufactured in 1933 by Bill Switchgear and containing rewireable fuses. This was in remarkably original condition, possibly due to the fact it was supplying an area of the station that had undergone little modification (Fig 1).

Design considerations

As noted already in this feature on the new King's Cross, refurbishing this live operational Victorian railway station presented an array of challenges for the designers. The constrained site in the middle of one of London's busiest commuter hubs, the need for public safety, the requirement to maintain business as usual and accommodate stakeholder requests, the many heritage considerations – all these were highlighted and factored into the MEP design from the outset.

During the space planning stages, careful consideration had to be given to the location of the major MEP services, paying particular attention to the installation (how the equipment could be got into the building) and access for future maintenance/removal. And, although Network Rail needed up-to-date services appropriate for its 21st century railway station, these had to be seamlessly integrated with what was appropriate to the historic aspects of the station.

Horizontal and vertical distribution possibilities, with minimal disruption to the fabric, needed to be explored.
Also, incorporation of a secondary/essential services distribution system to provide the station with greater resilience would be a key factor.

Network Rail plantroom (NRPR)

It was decided very early that a station this size would require an energy centre, and that for this the only viable location would be underground. The developer Argent wanted to purchase some land north of the Concourse (an area known as the "Milk Dock"), and the team negotiated for Network Rail to construct a subterranean plantroom there prior to Argent taking ownership. The deal was completed and King's Cross had its energy centre (Fig 2), but it had to be connected to the WR building and the new Concourse.

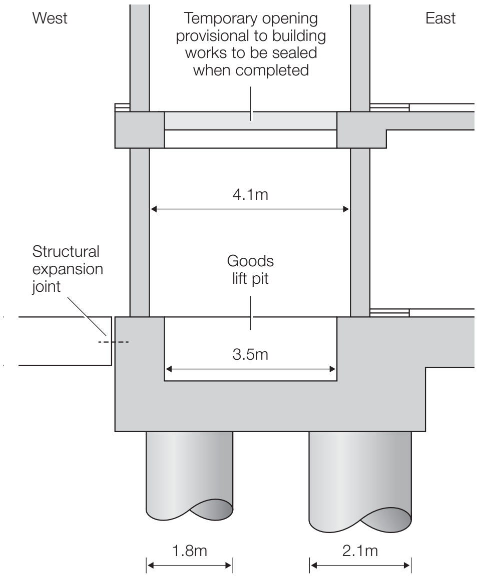
The NRPR is 10m below ground (Fig 3), and needed to be constructed early to enable the diversion of services. It houses most of the incoming services: heating and ventilation, communications, water and gas, and all associated sub-stations, plantrooms and water storage. Corridor and service riser connections were then developed to enable suitable interface with the rest of the station.

1. Bill Switchgear in the Western Range, dating from the 1930s.

2. Location of NRPR.

3. Section through Network Rail plantroom location.

4. Power distribution strategy.



3.

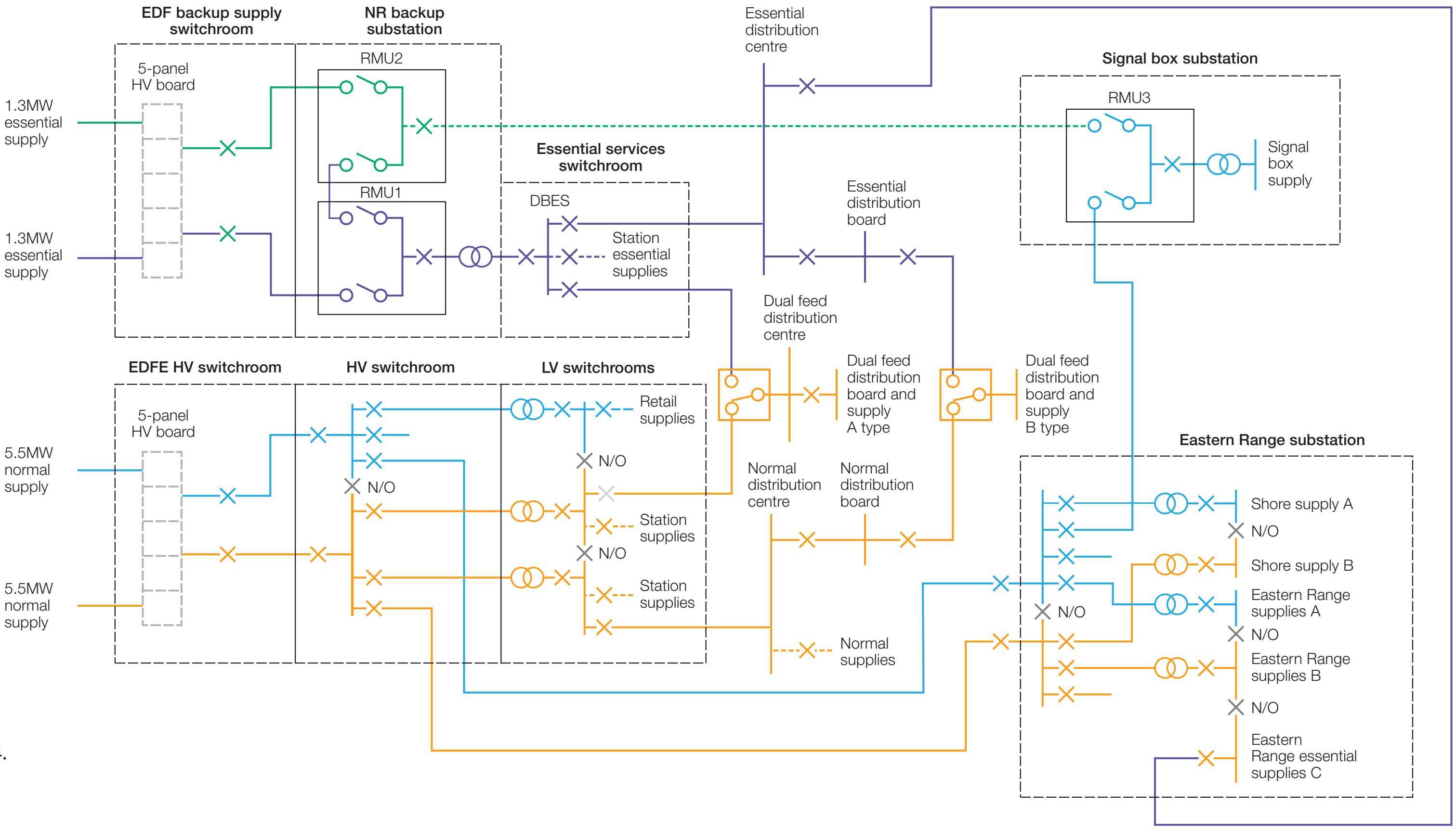
Incoming power supply

A load assessment was carried out for the new station, incorporating all retail requirements and future train shore supplies. This enabled an authorised supply capacity (ASC) to be set at 5.35MW. The incoming supply for the station was designed to be capable of serving this load, and comes from a primary sub-station about 6.5km north-east of King's Cross at Holloway.

Because the primary sub-station receives its power from more than one source, this supply is extremely secure, but the supply from the sub-station into King's Cross, via 6.5km of direct buried cable, is less secure. Maintaining the station's operation is of absolute importance, so it was agreed very early on that generators would be needed to keep it going in the advent of a major power failure, as well as to serve the sprinkler pumps and smoke extract system. Unfortunately, locating industrial-sized generators within a heritage building brings huge logistical issues. Due to the size of the Concourse roof, it would require the world's largest mobile crane to lift such a generator onto the roof of the WR building. Also, generators do not provide anywhere near the level of fault current of a network supply, so it would be necessary to reduce the size of the essential services protection devices. This in turn had the potential to cause discrimination problems as well as increase the size of the essential services distribution cabling, further adding to the congestion problems in the Victorian WR building.

The team therefore proposed to Network Rail that cost could be saved and risk and complexity reduced by using the existing DNO (distribution network operator) supply for the station's essential services, as it originates from a different primary source in London. This was extremely fortuitous, because when electrical power was originally distributed across London, the rail lines heading north out of King's Cross had acted as a physical barrier between east and west. This meant that the essential services supply would be even more secure than with generators – a win/win situation.

An essential sub-station was created in a different zone/sector of the NRPR, providing a diverse source of power (capable of supplying 1.3MW) to maintain the essential services within the station (Fig 4).



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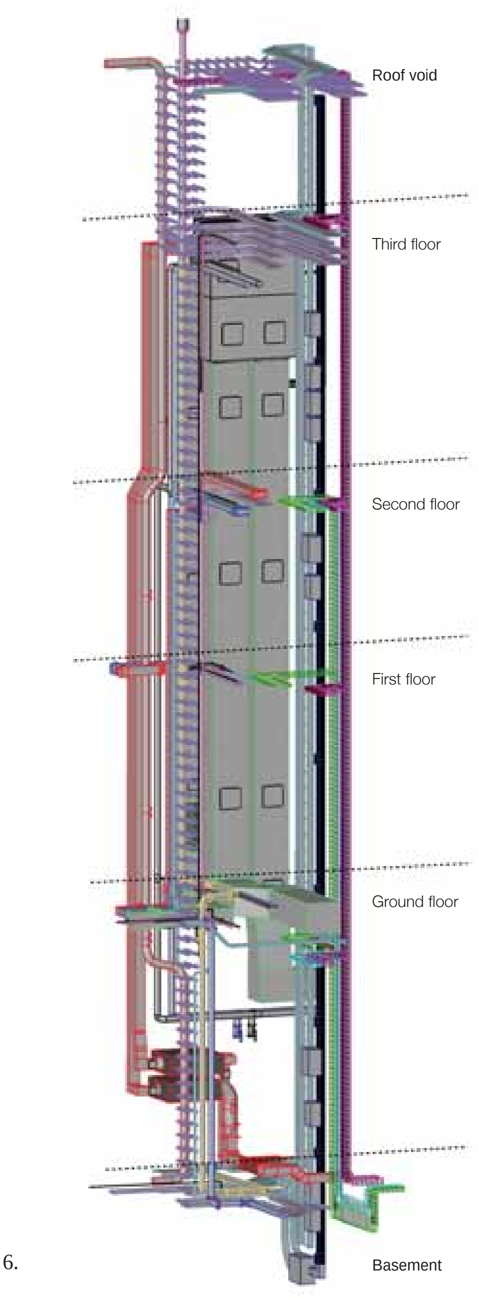


6.

7.

Western Range building
The next stage was to decant the WR building, a process that revealed numerous previously unknown hazards, due to the inability to provide a thorough survey while it was occupied. It was very important to create a services strategy throughout this historically important building without compromising the Grade I listed features, and this involved close liaison with the architects, heritage specialists, and English Heritage itself.

During the space planning, the team also had to consider not only where the main service plant could be located and how the items could be got into the building, but also – and possibly more importantly – the servicing strategy to remove them if and when necessary after construction was complete, with the new Concourse structure now in place against the side of the WR building.

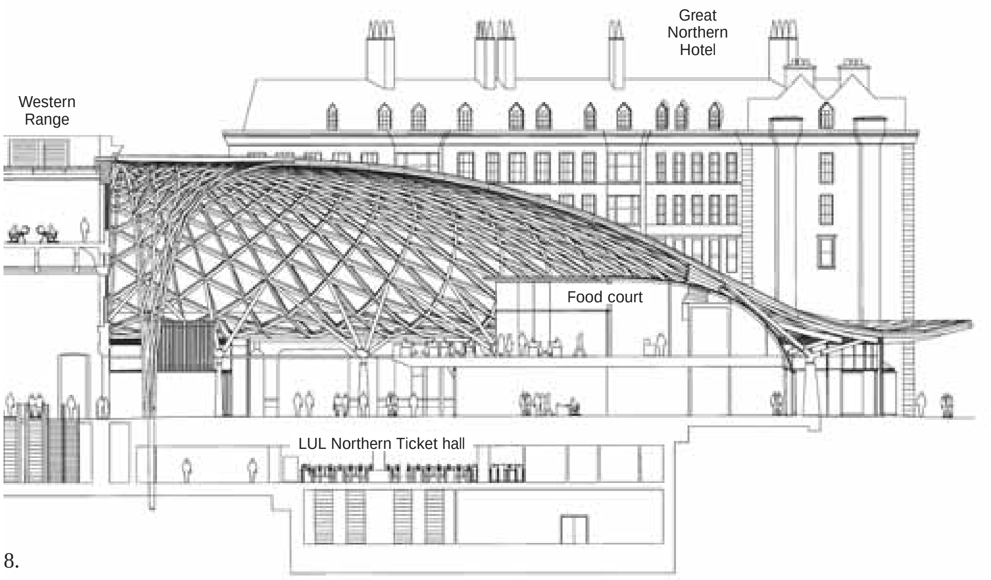
Several external plant decks were required to house the refrigeration equipment that forms part of the building's comfort cooling system. The structure here required significant strengthening to accommodate the plant loads, the largest of which was a plant deck on the roof of the WR's central block (Fig 5).

Several vertical risers had to be created through the building from basement level to the roof voids. This meant significant modifications to the Grade I structure, as well as the loss of some heritage rooms. This was the only viable services strategy and completely necessary for providing the capability for a modern office building, but it proved difficult to convince English Heritage of this (Fig 6).

The WR building has many split levels, making the horizontal servicing strategy extremely challenging. Quite early on, it was decided that the corridor would form the best horizontal path, with the services above concealed by a bespoke accessible ceiling.

One particular problem encountered was that the WR building was intended to house several tenants, each requiring a distribution system dedicated to its particular facility. Arup had already decided to provide floor-boxes within the existing timber floors, as this would cause the least disruption to the historical fabric and be the most aesthetically pleasing by not having dado trunking on the wall or chasing into the existing building fabric. This presented another challenge – how to supply the lighting and floor boxes from the same distribution board?

The solution was to create vertical droppers within the corridor, concealed behind panelling with 45˚ cord holes in the heritage walls to enable the services to reach the floor void between the joists (Fig 7).

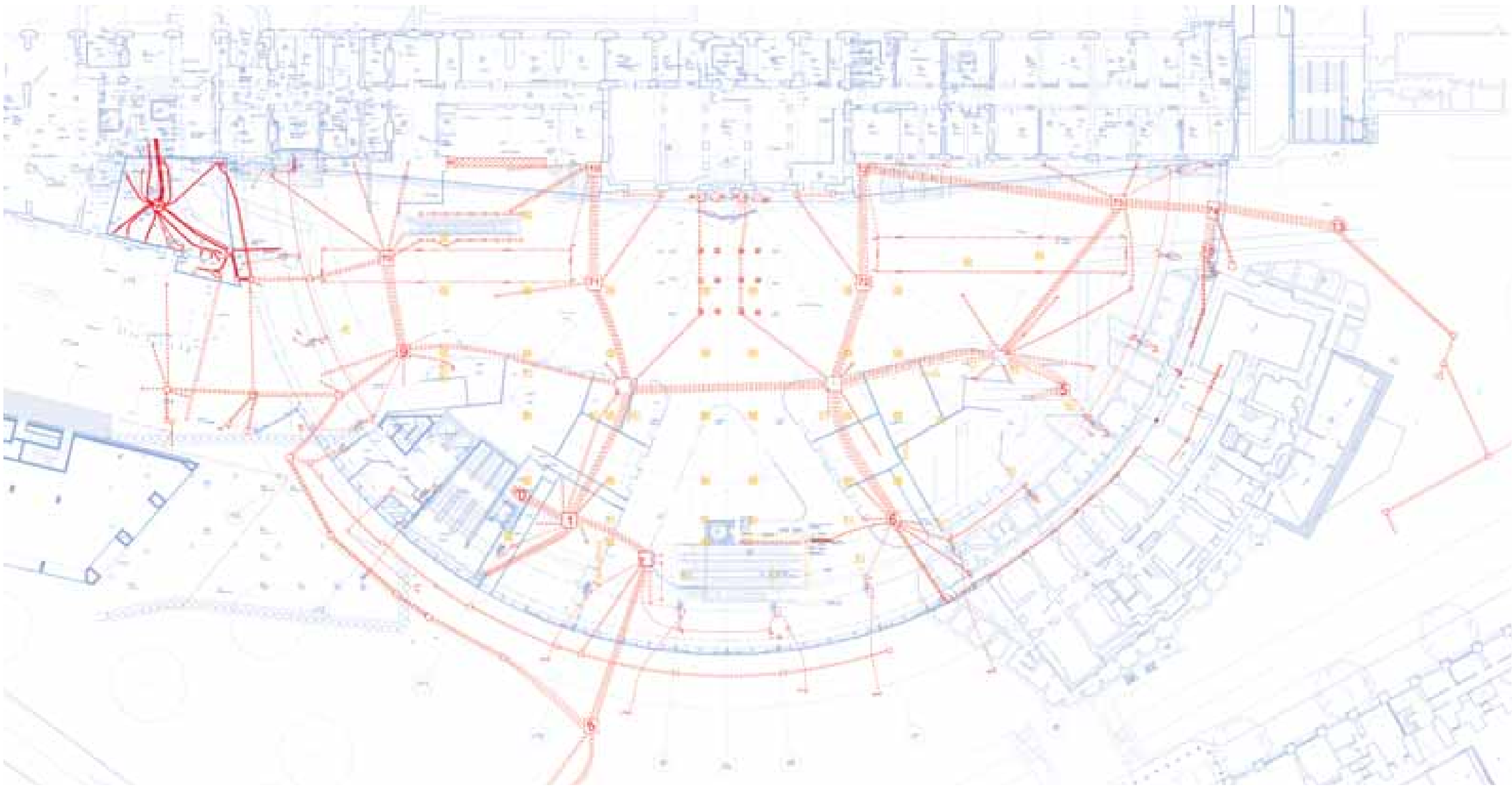


8.

The Western Concourse

The new concourse had its own servicing challenges: to the east is the Grade I listed WR building, to the south-west the Great Northern Hotel (Grade II listed), and 400mm below the finished floor level of the concourse was part of the structure of LUL's Northern Ticket Hall (Fig 8).

Arup managed to obtain vertical connection from the NRPR and created a riser extending from the NRPR's sub-basement level to the food court (mezzanine) level. The concourse floor provided a 320mm service void (excluding finishes) to house all the necessary ductwork to service the multitude of equipment within the concourse. This meant that a network of ducts had to be created with no crossovers (Fig 9).



9.

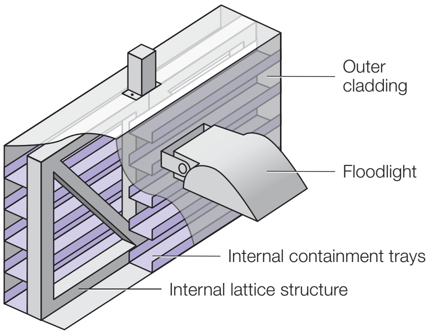
5. Rooftop plantroom under construction.

6. Co-ordinated services in one of the vertical risers.

7. Vertical connections.

8. Section showing the proximity of surrounding structures.

9. The complex network of service ducts beneath the concourse floor.



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12.

The other major issue with the concourse was how and where to run the high-level services. The low level was resolved by the network of ducts, but the high level was different. For architectural reasons, they could not be run on the new diagrid structure, but nonetheless numerous services had to be picked up at high level, particularly around the perimeter, including lighting, emergency lighting, EDNE (emergency do not enter) signs, closed-circuit TV, and PAVA (public address voice alarm).

It was decided that the only way to accommodate such an array, in the confined space, would be to design a boom with an internal wireway, strong enough to support industrial type floodlights (Fig 10). Further input from Arup structural engineering colleagues and the architects refined the solution (Fig 11).

The lattice boom contains 10 cable trays acting as ribs that function as wireways for the cabling, wrapped in an aluminium casing with an EPC (electrostatic powder coating) white finish. Stainless steel flexible conduits run from the rear of this down inside purpose-made box sections to serve the low-level services below.

The end result not only serves as a secure and efficient containment system and luminaire suspension bracket, but also blends unobtrusively with the overall clean concept of the concourse roof (Fig 12).

13.

10. Concourse perimeter services containment system.

11. Perimeter trunking showing the cable trays.

12. Completed containment system.

13. 21st century passenger display units serviced alongside and within the listed building.

King’s Cross Square: The station’s future public face

Authors
Brian Coles Craig Rew

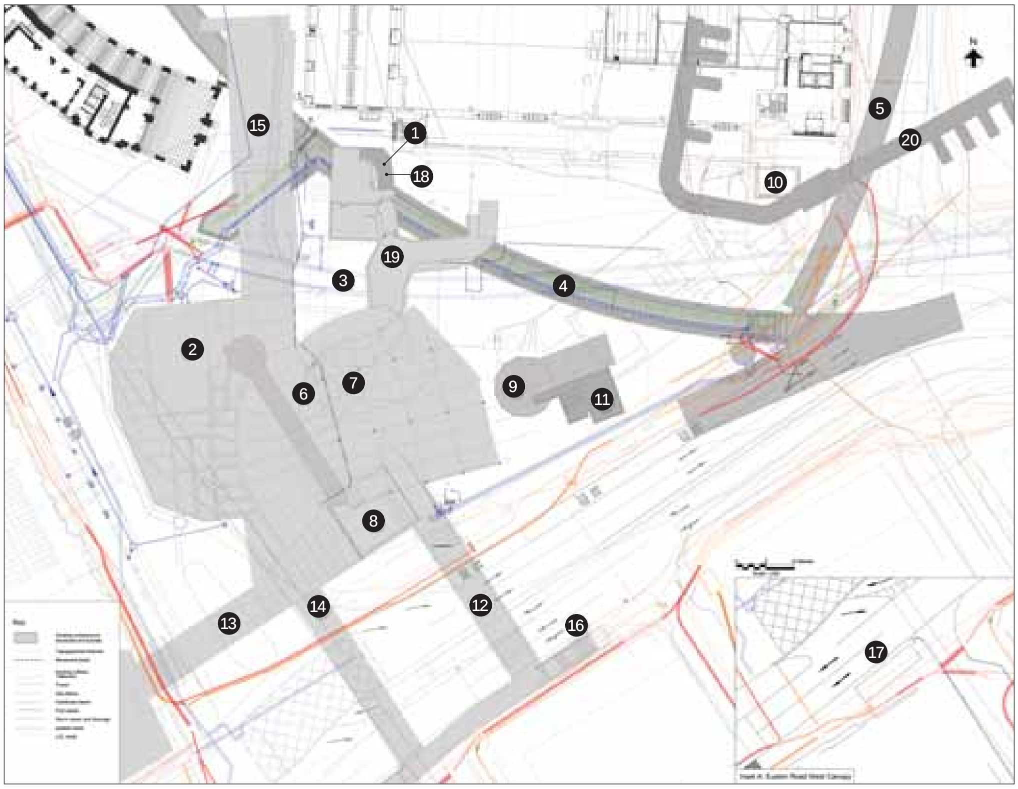
Introduction
Following the London 2012 Paralympic Games in early September, King’s Cross will be ready for the final phase of its redevelopment – demolition of the existing Southern Concourse and the creation of King’s Cross Square. Some 7000m² in total area, this new public space will extend 100m east-west and 70m north-south. It will both greet passengers who arrive at King’s Cross by overground train and then exit the station via the southern arches, and also provide a public thoroughfare for those interconnecting with the station by taxi, Underground, bus and on foot.

After King’s Cross station opened in 1852, the area in front of the Southern Façade (Fig 1) eventually filled up with a collection of low-rise buildings serving both the overground railway after 1880 and later the expanding Underground station beneath, when in 1906 and 1907 the Piccadilly and the Northern Lines respectively opened. The exact composition of the structures continually changed up to 1973 when the now-to-be-replaced Southern Concourse was constructed.

The site above and below ground
As well as the Southern Concourse, five other structures occupy the site. Public access to the Underground station beneath is via two major, 3m wide, staircases with accompanying lift structures. In addition, three ventilation structures (known colloquially as the “Blue Egg”, the “Push Pull”, and the “Rotunda”) enable pressure relief to the deep Tube lines and provide a dedicated emergency access route. All five of these structures are owned by London Underground (LU) and had to be retained in the new King’s Cross Square scheme.

The area under the square is heavily congested, with the King’s Cross St Pancras Underground ticket hall, an abandoned rail tunnel now used to house major gas and water pipes, and also the Fleet sewer, a 19th century brick arch structure still in current use. In addition, a multitude of other utilities are hidden beneath the surface (Fig 2).

1.



Key
1. South-east stairs
2. “Blue Egg” vent shaft
3. Thames Water Utilities Ltd Fleet sewer
4. Hotel curve
5. Blind tunnel for unused 19th century Maiden Line
6. New Tube ticket hall structure
7. Original Tube ticket hall structure
8. Tube ticket hall main stairs
9. “Rotunda” vent shaft
10. “Push Pull” vent shaft chamber
11. London Underground Victoria Line substation
12. London Underground “Khyber Pass”
13. Pancras Road subway
14. Euston Road subway
15. Northern ticket hall link
16. Euston Road east canopy
17. Euston Road west canopy
18. Switchroom E5
19. Access corridor to switchroom E5
20. “Push Pull” vent shaft.

2.

1. Contemporary print of the original aspect of the area in front of the Southern Façade.
2. Plan of existing utilities and below-ground structures at the site.

3.

4.

3. Architect's impression of the completed King's Cross Square looking east.

4. King's Cross Square from the east.

The King's Cross Square scheme
The scheme has two aspects: the delivery of a public space, and the incorporation of existing structures into that public space. From the former perspective, rearranging the way people use the station, and the Southern Façade arches now becoming an exit-only facility had two major impacts on the Square's design.

Firstly, the layout of the paving mirrors a north-south movement direction (Fig 3), drawing people out of the mainline station before they exit the square via entrances to the Underground, bus stops, on foot to the east or west, or re-enter the concourse. Secondly, as the exit into the uncovered area of the square occurs within 5m of passing through the gateline within the station, a new Southern Façade canopy will be constructed to give passengers an extra covered area beyond the original station structure.

All of the five existing LU structures have to be redeveloped so as to provide a coherent architectural form that relates to the rest of the Square, while maintaining all their previous functionality. Two of the locations, the Blue Egg and the Rotunda, introduce retail opportunities for Network Rail.

Arup's role
Architects Stanton Williams won the design competition in 2009 for the King's Cross Square redevelopment. As subconsultant to Stanton Williams, Arup is providing civil infrastructure, structural, electrical, mechanical, public health, pedestrian modelling and resilience services. For the Southern Façade canopy and south-east stairs, Arup is lead consultant with John McAslan + Partners providing architectural services.

Programme
The concept design was completed in July 2011 and the detailed design was delivered in January 2012. Demolition of the existing Southern Concourse begins in mid-September 2012, after which a phased approach to the construction works will be required to allow the refurbished King's Cross to continue to operate unimpeded.

At present four phases are planned. These include part closure of the southern arches, which will be split into a east/west divide, and also closure of the two major staircase entries into the Underground, one at a time. It is anticipated that King's Cross Square will completed within 12 months.

Conclusion

Author
Mike Byrne

The new Western Concourse at King's Cross was officially opened to widespread acclaim by London Mayor Boris Johnson on 14 March 2012. It marked the completion of the flagship element in this £547M station transformation, the final piece of a major transportation hub that includes St Pancras International and King's Cross St Pancras Underground station. These opened in 2007 and 2009 respectively, and Arup had key roles in the design of both.

King's Cross is of course more than just a station. The project is the centrepiece in a transport-led regeneration of what was once one of London's most deprived areas. The station takes its place again as a destination, a place where people will linger to enjoy – perhaps the sheer grandeur of the new concourse, or the surrounding public realm – before travelling on to their destinations.

King's Cross is placemaking in the tradition of the great Victorian stations, and creates a magnificent gateway to London. It will also continue to energise regeneration of the local area and act as a focal point for a new vibrant part of the capital.

The Western Concourse project is at the heart of Network Rail's redevelopment of the station. Designed to handle over 40M passengers per year, the new station provides a much-needed upgrade of the existing facilities while restoring the station to its former glory as a major London terminus. These *Arup Journal* pages can only give a small insight into the huge effort that has gone into the realisation of the project, and the blood, sweat and tears over 15 years of effort by Arup and John McAslan + Partners, since winning the competition to design the new station in 1997.

The innovative solution to the location and design of the flagship Western Concourse owes its genesis to the many challenges faced in redeveloping the original station: Grade I listed structures to be retained; maintaining an operational station with minimum disruption during construction; modernising all the systems and services; and of course the need to delight the modern-day travelling public.

Arup's work also included restoration of the Grade I listed buildings east and west of the station, the inclusion of a new platform, and the final element: the creation of a new public square in front of the existing station, designed together with Stanton Williams. Arup's work has embraced transport planning, multidisciplinary engineering services, security, IT, lighting design, acoustics, visualisation and pedestrian modelling, as well as acting as lead designer for the detail design phase.
But the success of all these projects is due to the collaboration between the design team and client Network Rail, who had the courage and conviction to sponsor a magnificent project – just like the great Victorian railway companies of the past.

Indications from first users of the new station is that King's Cross has achieved all these objectives, and will serve the capital well in this Olympic year and for many to come, just as Lewis Cubitt's original station did after it opened in 1852.

1.

Authors

Nicholas Bailes is a senior engineer in the London office. He was a member of the structural design team for the King's Cross station project.

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Brian Coles is an Associate in the London office. He is the Contractor's Engineering Manager for King's Cross Square.

Andrew Jenkins is an Associate Director in the Bristol office. He led the assessment of pedestrian planning for the Western Concourse.

Mike King is a Senior Associate in the Singapore office. He led the design of the Western Concourse roof.

Simon King is an Associate in the London office. He led the building services design including the overall lighting design for the later stages of the King's Cross station project.

Florence Lam is a Director in the London office and leader of Arup's global lighting practice. She led the concept daylighting and architectural lighting design from the outset of the King's Cross station project.

John McAslan CBE is the founder and a Director of John McAslan + Partners, architect for the King's Cross station redevelopment.

Alex Reddihough is an engineer in the London office. He was a member of the design team for the Western Concourse roof.

Graham Redman is a senior engineer in the London office. He was responsible for the structural design of the refurbishment works for the King's Cross Grade I listed buildings, during the construction period.

Craig Rew is an Associate in the London office. He leads the civil engineering team for both King's Cross Square and the public realm interchange facilities.

Chris Rooney is a Director in the London office. He led the transport planning for the King's Cross station project.

Sarah Tattersall is a senior engineer in the London office. She was a member of the structural design team for the refurbishment works for the Grade I listed buildings.

Ken Wiseman is an Associate in the Hong Kong office. He led the structural design team for the King's Cross station project.

Project credits

Client: *Network Rail Ltd* Architect and masterplanner: *John McAslan + Partners* Principal engineer: *Arup* Other consultants: *Chapman Taylor, Pascall + Watson, Stanton Williams, Tata Group* Key contractors: *Vinci Construction UK, Kier Construction, Laing O'Rourke/Costain joint venture, Carillion, Morgan Est, Osborne, NG Bailey.*

Image credits

Front cover ***6***(1) ***24***(7) ***31***(18) ***33***(24) ***35***(32) Thomas Graham; ***6***(2) Luna Raphael; ***7***(3) ***8***(1-2) ***9***(3-4) ***14***(5) ***15***(6) ***16***(10) ***17***(12) ***19***(16) ***20***(2) ***21***(5) ***22***(9) ***23***(2) ***30***(15) ***35***(31) ***40***(13) ***43***(1) ***45***(1) Hufton + Crow; ***10-11***(5-6) ***12***(1) ***15***(8) ***16***(11) ***26***(1-3) ***27***(4-5) ***29***(10) ***31***(17) ***32***(21) ***39***(8) ***42***(4) *Back cover* John McAslan + Partners; ***12***(2) Alan Delaney; ***13***(3-4) ***15***(7) ***16***(9) ***20***(1, 3) ***21***(4, 6) ***22***(7-8) ***23***(3) ***24***(5-6, 8) ***28***(6-9) ***29***(11-12) ***30***(13-14) ***31***(16, 19) ***32***(22-23) ***33***(26) ***34***(27-29) ***36***(1) ***38***(5-7) ***39***(9) Arup; ***18***(13-14) ***19***(15) John Sturrock; ***23***(1) Andrew Jenkins; ***24***(4) ***37***(4) ***41***(2) Nigel Whale/ Arup; ***27***(2) ***33***(25) ***41***(1) Hulton Archive; ***32***(20) ***35***(30) ***36***(2) ***37***(3) ***40***(10) Nigel Whale; ***40***(11-12) Simon King ***42***(3) Stanton Williams.

The following past and present Arup staff members are among those who made significant contributions to the King's Cross station project:

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Wright, Paul Wright, Mehdil Yazdchi, Haroon Yousuf.


King's Cross

One New Change

Location
City of London, UK

Authors
Michael Devriendt Tim Fairbairn
John Hirst David Rutter


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2.

3.

4.

5.

1. The US Air Force *F-117* "stealth fighter": the architect's visual inspiration for the One New Change roof profile.

2. Architect's impression of One New Change, looking east from St Paul's.

3. Public area on the roof.

4. Location plan.

5. New Change Passage.

Introduction

In 1994 Land Securities plc, London's leading property development and investment company, acquired the site and building of One New Change (ONC), in the heart of the City of London. In due course the principal tenant, the legal practice Allen & Overy, decided to move its offices about 2km north-east to Spital Square, and this left ONC with substantial vacant possession.

Land Securities arranged for a limited, invited competition to redevelop of the site. Atelier Jean Nouvel, supported by Arup, won this competition in 2003 and design started in earnest in 2004. In his competition entry, Jean Nouvel referenced the US "stealth fighter" (Figs 1-2), and in fact subsequently unveiled a model of the aircraft as part of his presentation to the City of London Corporation's Planning and Transportation Committee.

Location

The site is directly opposite St Paul's Cathedral and is thus extremely sensitive, particularly as the building that previously occupied it – a 1950s Portland stone and red brick construction originally constructed for the Bank of England – had been criticised for being out-of-date.

The new single block of One New Change is bounded to the north by Cheapside, to the east by Bread Street, to the south by Watling Street, and to the west by New Change, which curves around the front of the eastern façade of St Paul's (Fig 3).

The overall building form is a clear response to the constraints imposed by St Paul's Heights and viewing corridors, together with site boundaries, daylight guidelines, and rights of light issues. The design is full of subtly intersecting planes and irregular geometry – particularly at roof level, where plant areas are extensively screened and a public terrace provides a completely new view of St Paul's (Fig 3).

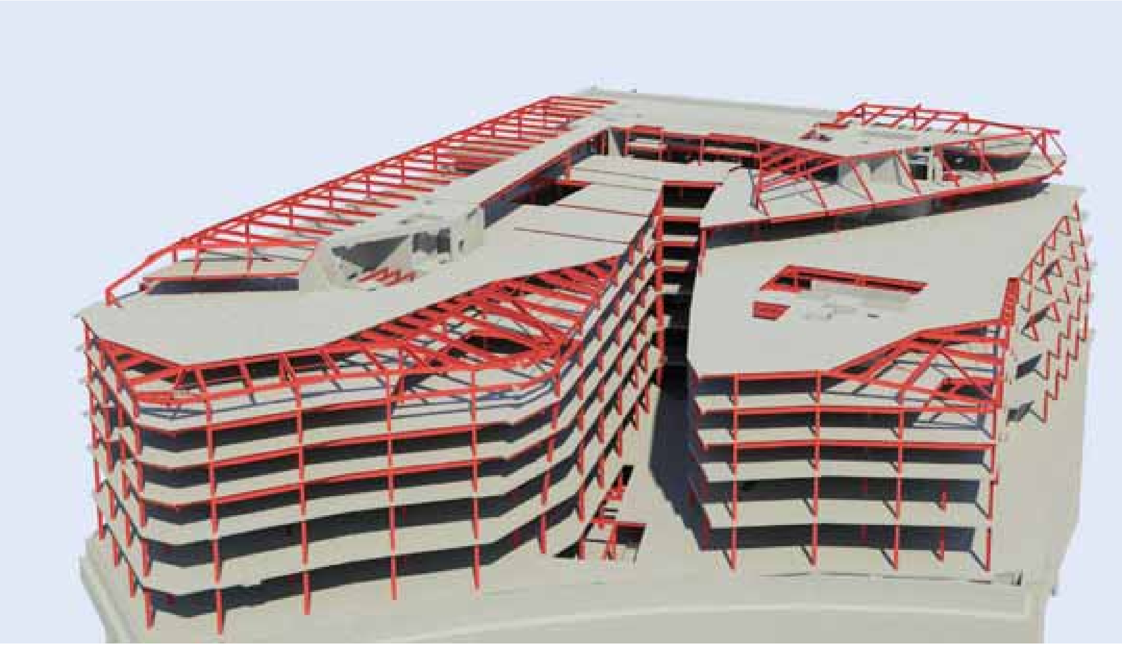
The accommodation includes over 20 000m^2 of retail space in the lower ground floor, ground floor, and first floor levels. A further 30 000m^2 of office space is above on levels 2-6. The new thoroughfare "New Change Passage" runs east/west, aligned with the Cathedral and providing both direct and reflected views of it.

The pedestrian routes that bisect the retail level at ground floor (another runs north/south between Cheapside and Watling Street) are effectively pedestrian streets. The City's chief planner, Peter Rees, has said of ONC: *"This isn't a shopping mall. This is the City's high street reborn."*

Office superstructure

The upper office floor structure is fairly conventional in principle. The floors are framed primary and secondary fabricated steel beams acting compositely with a 130mm, normal-weight concrete slab laid on profiled metal decking.

To optimise the floor-to-floor heights, which was particularly critical due to the St Paul's height restrictions, the services are integrated within the depth of the beams by using fabricated plate girders with a combination of circular and rectangular holes typically up to 900mm wide (unstiffened) and 500mm deep in the 750mm deep sections.



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6. The “street” from New Change, modelled in the *Revit* program.

7. Cranked architectural “blade column” modelled in *Revit.*

8. Cranked column at the central atrium.

9. The atrium on opening day.

The office floor grid is notionally a combination of 9m x 17m and 9m x 9m. However, the structure at New Change Passage and for most of the perimeter follows the inclined planes and faceted cladding of the building envelope.
The surface geometry and the client requirement to keep the internal spaces uncluttered necessitated complex structural geometry with inclined columns and cranked beams. The inclined columns are restrained by floor beams and via shear studs to the floor slab. Out-of-balance forces are transferred to the concrete stability cores.

The whole structure was modelled in 3-D using the Autodesk *Revit* program (Fig 6). This was essential to enabling the structure-cladding interfaces to be verified, and the model was supplied to the cladding contractor. It was also used for structure/services co-ordination and for 4-D modelling, which also included the construction programme.

Around the central atrium are four architectural “blade columns”. These box sections, 300mm x 1.2m, were fabricated from 30mm thick steel plate with a central stiffener and were splice connected by welding on site. The blade columns are also inclined and cranked at floor levels throughout their height; fin plates facilitate connection to the incoming floor beams (Figs 7-9).

10.

At the top of the building (Fig 10), the cladding wraps around the perimeter edge and covers a large section of the roof. This "fifth façade" is supported by inclined beams at shallow angles, and these are often cranked to adapt to the geometry of the cladding (Fig 11). The coordination with the building services at this level was particularly critical, given the shallow headroom in some areas and the increased solar gain through the skylights.

At roof level are two very large building maintenance units (BMUs) for cleaning the extensive areas of horizontal and vertical façade. One unit is fixed and the other mobile, tracking around the northern and eastern edges of the building. The mobile BMU is the largest in Europe, with a reach of 42m, and weighs 80 tonnes (Fig 12). The track supports are integrated into the roof plane to preserve the integrity of the "fifth façade".

The almost – and occasionally completely – vertical façades comprise double-glazed cladding and, on the west elevation only, a third glass outer layer, which combine to provide a thermal-regulation-compliant skin using both solar control and insulation. The glass is fritted with a combination of red, light grey, dark grey and beige colours to "reflect and respect" the Portland stone, concrete, and red brick of the neighbouring buildings (Fig 13).

11.

12.

13.

10. The "fifth façade".

11. Cranked beams at the top of the building.

12. Building maintenance units on the roof; the further one is the larger of the two.

13. "Reflect and respect".

14. Future provision for retail connectivity: ground floor to level 1.

15. New Change Passage, looking east.

14.

The retail floors

The retail area of the building occupies the first and ground floors and what is titled the "lower ground floor", though it is a true basement level some 6m below ground level. The ground and lower ground floors fulfil the essential function of propping the perimeter retaining walls. Good axial stiffness was a key attribute and reinforced concrete the preferred material.

For the retail floors the team chose a 9m x 9m base grid – slightly larger than in many retail buildings but compatible with the office planning grid above, with which it needed to co-ordinate.

As with all retail projects, the building has to be adaptable throughout its life for tenant requirements. This is frequently achieved by allowing for new openings to be formed in any structural bay and with any orientation, but here, to increase the efficiency of the structure and material usage, and take advantage of the square grid, the team decided, in consultation with the client, to design the floors as two-way systems.

This necessitated identifying where future adaptations could affect structural behaviour. This was carried out with Land Securities and its retail experts, and the investigation showed that potential locations for additional vertical circulation were actually quite limited. The final design was executed on this basis, with complete analysis of the alternative scenarios, and this permitted a substantial saving in reinforcement quantities (Fig 14).


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16.

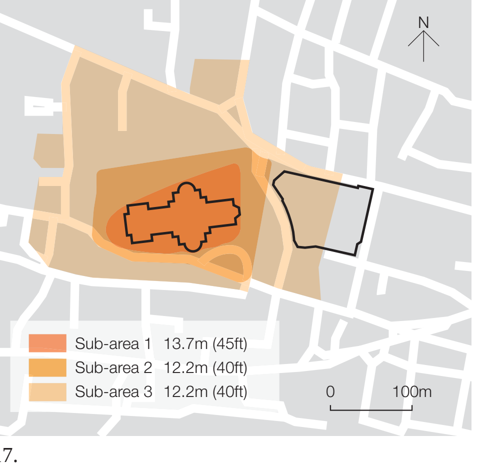
The Depths
London was an outpost of the Roman Empire and this heritage is preserved below ground.

"St Paul's Heights" is well known to anyone involved with building in the City of London. The concept was devised in the 1930s by the then Surveyor to the Fabric of St Paul's "in response to growing concern that important views of the Cathedral would be obscured by the 'lofty' structures being erected in the vicinity"[1,2], and St Paul's Heights subsequently influenced the design of a multitude of structures in the City.

Few, however, are or need to be familiar with the requirements of St Paul's Depths. Historically, damage had occurred to the Cathedral as a consequence of foundation movement from several sources, and in 1935 an Act[3] was passed with the express purpose of protecting it. This placed statutory requirements in relation to deep groundwork within the prescribed "St Paul's Depths" area to protect the fabric from further damage. ONC was required to conform to the Act.

St Paul's, which is only about 60m west of the site (Fig 16), is founded on shallow foundations within the Brickearth, the silty layer that overlies the river terrace deposits which contain the shallow aquifer.
The basement of the new development extends into the London Clay and encroaches on the prescribed St Paul's Depths area (Fig 17). This is the first time that excavation to such depth had been proposed within the prescribed area and hence it was necessary to demonstrate, in accordance with the Act, that the excavation would not cause damage to the Cathedral:

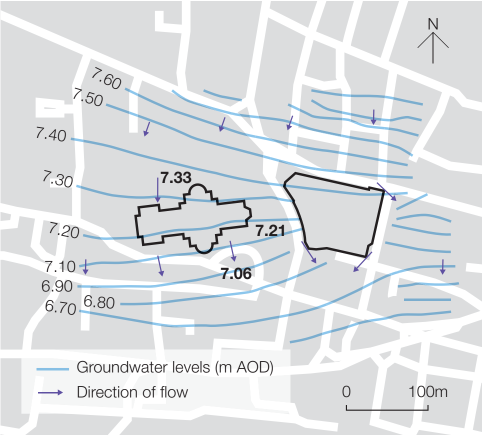
"*... And whereas in the execution of works involving deep excavations in the vicinity of the Cathedral the removal of sand and gravel and the pumping of water tend to result in subsidence of the foundations and risk of danger to the structure of the Cathedral: And whereas for the avoidance of unnecessary risk of disturbance of such foundations and structure it is expedient that control should be exercised as by this Act provided with respect to excavations and the pumping of water therefrom in the vicinity of the Cathedral...*"[3]



17.

16. The excavation at night.

17. Extent of St Paul's Depths. ONC is in Sub-Area 4. Approval is required under the St Paul's Act if construction work takes place below 9m AOD (above Ordnance Datum).



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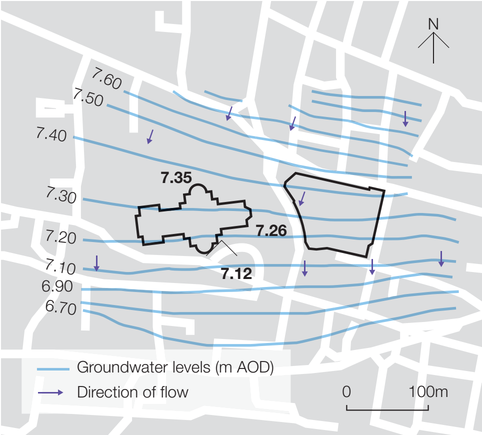


20.

Although no pumping of the aquifer was envisaged, the possibility that a rise in the shallow groundwater level might cause a change in the Brickearth's moisture content and result in structural movements to the Cathedral had to be considered. Groundwater modelling and ground movement assessments were therefore necessary to demonstrate that the proposed development had minimal effect on the groundwater regime in the shallow aquifer.

Before construction started, the groundwater in the shallow aquifer flowed south towards the River Thames beneath the existing buildings occupying the site footprint. However, construction of the new basement secant walls for the new development caused this groundwater to flow around the basement ,potentially affecting groundwater levels at St Paul's. The key question was whether this adjusted flowpath would result in a change of groundwater regime at the Cathedral's foundations.

The original groundwater flow was therefore modelled using field observations, and then the model adjusted to replicate the effects of the new obstruction (Fig 19). These modelled findings were then monitored against actual groundwater levels in the shallow aquifer throughout the construction of the new basement. This confirmed the validity of the modelling and that groundwater levels do not fluctuate significantly beyond the natural seasonal variation (Fig 20).

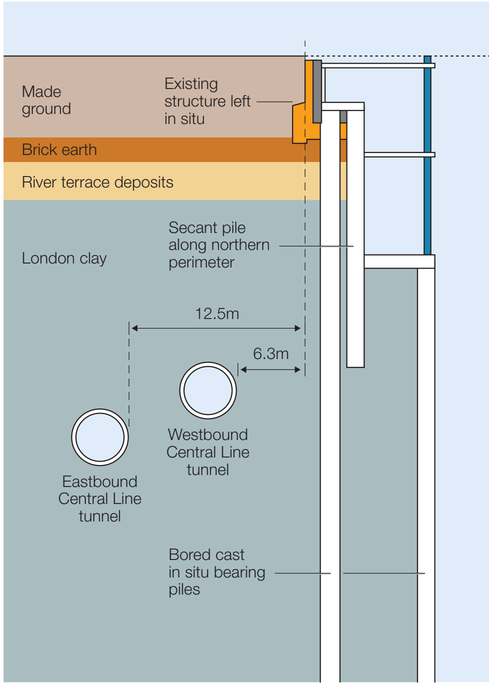
Assessment of ground movement due to the basement excavation also indicated that this would have negligible effect on St Paul's, and this was confirmed by precision surveying and movement monitoring.

Basement construction:
Not only but also...

Not only did the substructure design have to contend with an Act of Parliament concerning St Paul's, it also had to address the east and westbound London Underground (LU) Central Line tunnels that run within 7m of the northern site boundary. These are of cast iron, have an internal diameter of 3.78m, and a crown level of 20m-25m below ground. Fig 21 shows their positions relative to the site and the new basement. It was thus clearly essential that the effects on surrounding buildings and structures of movement of the new development, both during construction and after completion, be kept within acceptable limits. These effects needed to take into account the demolition, the excavation of the basement, and the construction of the new building.

The principles adopted to limit movements are simple in concept. For the ground conditions at the site, movement depends on change in stress and therefore load, so it was decided to reload the ground with the new building load. A raft was therefore preferred. Secondly the perimeter walls need to be supported horizontally by stiff props inserted as quickly as possible. Reinforced concrete slabs provide the stiffness and top-down construction enables the props to be installed as quickly as possible.

While the principles are simple, the actual applications rarely are. Top-down construction requires support to the higher level slabs as excavation progresses, but as a raft at low level cannot provide this, the slab is supported by steel columns plunged into bored concrete piles. To maximise efficiency, these piles are incorporated into the overall foundation solution – a piled raft.



21.

18. Building materials, textures and colours, separated in time by three centuries.

19. Groundwater levels around St Paul's as modelled to predict the effect of ONC's construction.

20. Actual groundwater levels measured during construction.

21. Positions of Central Line tunnels relative to the ONC substructure and basement.

22. Entrance to New Change Passage.

23. View looking south-east along New Change.

24. Calculated and measured movements of Central Line tunnel.

Early in the project Arup set up regular meetings with LU to seek its approval for the proposed works, initially preparing an approval in principle (AIP) document defining the methodology for appraising LU's assets. Following LU's approval of this methodology, a detailed assessment report appraising the effects of the project on LU's assets, including consequent additional stress and strains within the linings, was prepared and submitted by Arup. The results were compared with case studies of deformations to LU tunnels from nearby works and an inspection of the tunnel was carried out by Arup to verify the basis of design.

The team included, as part of the assessment, an appraisal of the impact of the works on track geometry and clearances between the tunnel lining and rolling stock. These results were compared with a track geometry and tunnel clearance survey commissioned by Land Securities and carried out by LU. The conclusion was that no significant impact was anticipated on LU's assets.

While the Central Line was considered to be the most sensitive adjacent structure, it was also necessary to look at potential effects on adjacent buildings including St Paul's Choir School, immediately opposite the south-west

Challenges of the site

The site posed a myriad of challenges, which included:

- an existing perimeter retaining wall close to the new basement line, including heavy vault walls from the building's Bank of England history...

... so the new secant piled wall moves from inside to outside the existing wall, depending on location.

- a basement access ramp which cuts through most of the propping floor slabs...

... so the slabs were designed to allow for these, while retaining the propping action.

- concrete stability cores, which are not amenable to construction using plunged steel columns...

... so these cores were designed to be constructed within purpose-made separate caissons.

- the need to break though and remove heavy concrete and steel grillage foundations, together with a logistics preference to excavate as much as possible within an open excavation...

... so the lower ground floor was selected as the first slab for the top down construction phase.

Initial testing and assessment of proposals and construction sequences was carried out using simple elastic analyses. Once developed, the overall system was tested using a complex 3-D finite element analysis in *LS-DYNA*.

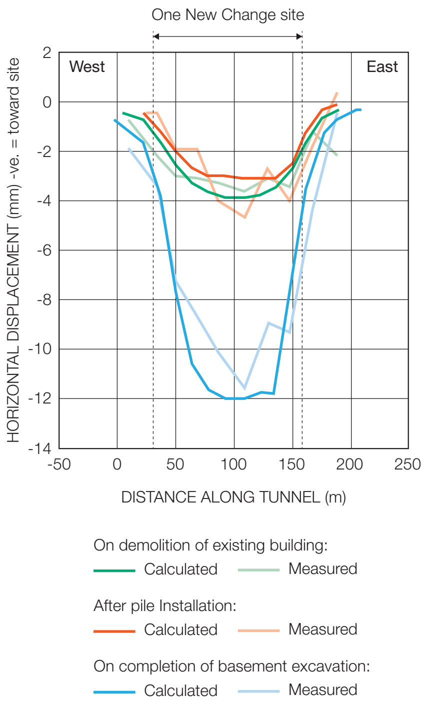
22.

23.

corner of the development on New Change, and of course the somewhat more distant but still comparatively close Cathedral itself.

A comprehensive monitoring system was therefore implemented. For the Central Line tunnels, this comprised both real-time and manual monitoring instrumentation, as specified by Arup to confirm that any movements were in line with the earlier calculations in the assessment report. Trigger values were specified, while an emergency preparedness plan (EPP) defined the actions to be carried out by the project team in the event of triggers being breached.

As construction progressed, Arup reviewed the monitoring results to ensure no unforeseen movements occurred to LU's assets. Good agreement was generally found between the observed response and the earlier calculated movements (Fig 24). A pre- and post-condition survey by Arup confirmed that the condition of the tunnels had not been affected by the project works[4].



24.

Geothermal ground source heat scheme

Together with Land Securities, the team set the target of meeting at least 10% of the building's energy demand from renewable energy sources.

An early appraisal identified ground source energy systems as being the most appropriate approach, and that a combination of both closed and open loop systems would meet the required energy target.

The system comprises continuous circuits of fluid-filled pipes installed within 189 of the total of 219 load-bearing piles that were founded in the London Clay (Fig 25 *overleaf*). The fluid is circulated continuously through the loops within the piles, transferring heat to and from the ground, depending on the time of year. The ground under the building acts as a thermal mass.

During the summer, water at temperatures between 30-44˚C is circulated through the loops in the piles, to be cooled by 3-5˚C by the relatively cool ground. This temperature drop is used to cool the building. In winter, by contrast, water at -4˚C to +5˚C is circulated through the loops in the piles, and warmed 3-5˚C by the ground to provide heating to the building. Temperatures at the surface of the piles are predicted to reach around 2˚C as a minimum and 35˚C as a maximum under these conditions.

The open loop system comprises a pair of wells, one for extraction and one for re-injection of the groundwater, installed to a depth of 130m in the chalk aquifer.

A comprehensive prior desk study was carried out to consider the permeability and likely occurrence of fissures in the chalk beneath the site for the purpose of demonstrating the feasibility of the open loop system, and agreement from the UK government Environment Agency was secured at an early design stage to allow the detailed design to be developed.

The open loop system works in conjunction with the closed loop system in the piles. Water extracted from a well in the north-east corner of the site passes through a plate heat exchanger before being re-injected through a well of similar depth in the south-west corner (Fig 25).

There is no overall net abstraction of water, and water temperatures will be nominally affected locally around the re-injection well only at a depth of some 100m.

The effect on the supporting surrounding ground of temperature variation within the pile was assessed by carrying out finite element analysis in LS-DYNA. The analysis accounted for coupled thermal-mechanical-consolidation behaviour and included thermal conduction and expansion, pore pressure generation, and nonlinear soil material behaviour. The results demonstrated that the proposed temperature variation had negligible influence on pile capacity.

The system can provide 1700kW of heating and 1800kW of cooling, with an estimated saving of up to 800 tonnes of carbon per year. The use of ground source heat schemes as part of the project, and team working between client, project manager, consultants and contractors, was recognised in 2009 when the project team won the Institution of Civil Engineers Fleming Award. It is the largest commercial application of ground sourced energy technology in Europe.

Conclusion

One New Change opened on 28 October 2010 amidst a flurry of interest from city workers and the London media, with around 20 000 customers visiting on opening day. All 60 retail units have been let, with tenants including *Banana Republic*, *Topshop* and *Reiss*. The British celebrity chefs Jamie Oliver and Gordon Ramsay both opened restaurants in the complex. Office tenants include K&L Gates, Friends Life and Chicago Mercantile Exchange.

Stuart Fraser, Policy Chairman at the City of London, said:

"One New Change will significantly enhance the City as a tourist destination, as a place to live and, most importantly, as one of the world's leading financial centres – a financial centre in which the top firms and the top talent from around the world continue to want to be based."

25.

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25. Ground source heating and cooling scheme.

26. Cladding textures.

27. One New Change from St Paul's.

27.

Awards

ICE Fleming Award for excellence in geotechnical design and construction 2009

MIPIM *Architectural Review* Future Project Awards 2010 – mixed-use and overall winner.

RIBA Award 2011

Best Built Project, London Planning Awards 2011/12

Authors

Michael Devriendt is an Associate in the London office. He led the geotechnical design for One New Change.

Tim Fairbairn is a structural engineer in the London office. He worked on the design of the superstructure of One New Change, and was also Resident Engineer on site for much of the construction phase.

John Hirst is a Director in the London office. He was Project Director for One New Change.

David Rutter is a senior engineer now in the Madrid office. He led the design of the superstructure steelwork for One New Change.

Project credits

Client: *Land Securities plc* Architect: *Atelier Jean Nouvel* Associate architect: *Sidell Gibson Partnership* Structural, geotechnical, external public health, security and façade consultant: *Arup – Mark Adams, Graham Aldwinckle, Jenna Andrews, Bruce Arthur, Daniela Azzaro, Trevor Baker, Alice Berry, Sara Bird, James Bown, Roseanne Boyce, Russell Brincat, Tiago Cabecinha, Aoife Carolan, Kashmir Cheema, Andrea Cremese, Marie-Paule Curtet, Kamil Daoud, Cormac Deavy, Michael Devriendt, Tim Dijkman, Mathieu Jacques De Dixmude, Matt Ellis, Tim Fairbairn, Arjun Flora, David Gill, Amrita Glazebrook, Claudia Groth, Gerardina Guarino, Isobel Byrne Hill, John Hirst, Mark Hutchison, Gavin Jack, Simon Jobbins, Simon Jughard, Wieslaw Kaleta, Raymond Lai, Alistair Law, Ryan Law, Alaric Lee, Chris Lyons, Allan Macdonald, Robert Malies, Ciaran Mallon, Maithini Manoharan, Julian Maranan, Agata Marut, Karen Mayo, Christopher McCormack, Andrew Moise, Chris Moore, Jeremy Morris, Paul Morrison, Hossein Motevalli, Edith Mueller, Corinna Neupert, Duncan Nicholson, Rob Nield, Tony Noad, Amie Nulman, Paul Nuttall, Ben O'Brien, Sheyda Okke, Chris Oram, Ed Palaganas, Rajan Parikh, Richard Powles, Sreejit Raghu, Caroline Ray, Mark Reed, Lindel Reid, Joao Rio, David Rutter, Ali Ryder, Rupert Samuel, Jon Shillibeer, Harry Spencer, Danny Swannell, Bartomiej Szymczyk, Nina Tabink, Sebastian Thieme, Jomel Uy, Rupesh Varsani, Edward De Villiers, Rebecca Vivian, Jessica Wade, Olivia Wall, David Whitaker, Jim Williams, Colin Winant, Jamie Wood, Alistair Wylie, Mehdi Yazdchi* Construction manager: *Bovis Lend Lease* Cost consultant: *Davis Langdon & Everest* Building services engineer: *Hoare Lea & Partners* Geothermal subconsultant: *Geothermal International*.

Image credits

1 *US Air Force (public domain)*; 2 *Atelier Jean Nouvel*; 5, 13, 15, 18, 22-23, 26-27 *Hufton+Crow*; 3, 9-10 *Land Securities plc*; 4 *Nigel Whale*; 6-7 *Arup*; 8 *Tim Fairbairn*; 11 *Jim Williams*; 12 *Sidell Gibson Architects*; 14, 17, 19-21, 24-25 *Luna Raphael/Nigel Whale*; 16. *Bovis Lend Lease.*

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Evelyn Grace Academy

Location
Lambeth, Greater London

Authors
Keith Jones Duncan Steel James Whelan

Background
ARK Schools[1] is a UK education charity, and forms part of the international children's charity ARK (Absolute Return for Kids). The parent body was founded in 2002 "by a group of leaders in the alternative investment industry who decided to pool their skills and resources to improve the life chances of children" [2].

Since its establishment, ARK has developed a growing range of health, welfare and education projects in the UK, Southern Africa, India and Eastern Europe, benefitting over 200 000 children in the intervening 10 years.

ARK Schools works with the UK government academies programme[3] to raise standards in inner-city schools, by:

- setting up a network of outstanding, non-selective, inner-city schools (ARK Academies)
- supporting ARK Academies to provide extended educational and enrichment opportunities for pupils
- training potential Principals to prepare them for senior leadership roles in challenging urban schools
- running a leadership programme targeted at the best middle leaders within complex urban schools
- operating a specialist programme (ARK Plus) which opened in November 2009 to provide focused academic and behavioural support for year seven pupils.

Arup's role
In 2005, Arup was appointed as part of ARK's framework to deliver its Academies programme, and in due course the firm was appointed as multidisciplinary engineering designer for four Academies: Globe, Burlington Danes, King Solomon and Lambeth. This last was subsequently renamed Evelyn Grace Academy (EGA) after the sponsor's mother and grandmother respectively.

Lambeth is an inner city area of south-east London, listed in the 2007 Index of Multiple Deprivation[4] as the capital's fifth most deprived borough, and 19th most deprived in England. In 2005, 50% of schoolchildren in Lambeth had to leave the borough to be educated. EGA is located within Lambeth's Coldharbour Ward, one of most deprived areas of the UK, with:

- an above-average population with a long-term limiting illness, especially between ages 0-15, and the largest population in Lambeth of residents in poor health
- a high proportion of children in lone parent families, and a low proportion in married families
- a low economic activity rate amongst 16-24-year-olds, due to large numbers of full-time students who do not work.

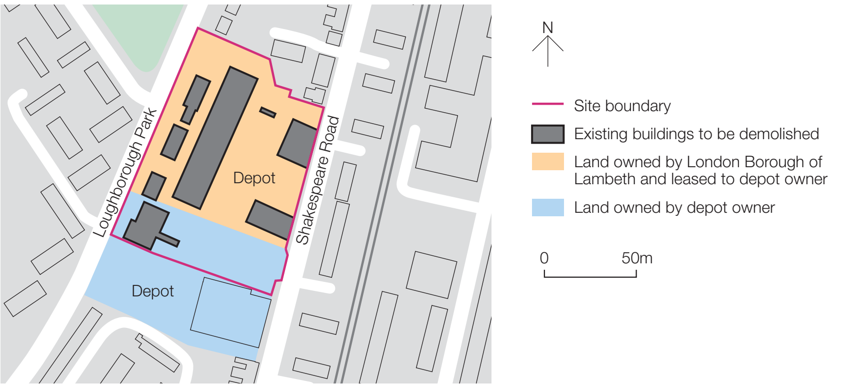
The key stakeholders in establishing EGA were ARK as education sponsor, the government Department for Education and Skills (subsequently the Department for Children Schools and Families, and now the Department for Education), and the newly-appointed School Principal. The design team comprised Zaha Hadid Architects, Davis Langdon (cost consultants), Capita (project manager), and Arup as SMEP engineer and CDM (construction design management co-ordinator) – a defined UK-specific role that relates to health and safety in design.

Concept
The brief for EGA was to establish a 1200-pupil secondary school based around the "small schools within a school"5 model. Thus there are two schools for students aged 11-14 and two for pupils aged 14-19, all under the overall leadership of the School Principal. The project was to achieve a BREEAM (Building Research Establishment Environmental Assessment Method)[6] "Very Good" rating.

The Academy actually opened for business in 2008, with year 7 pupils using temporary accommodation in a nearby council-owned site that was only available for one year. The original plan was for the next year's intake to join the original pupils and all move together into the new building, but due to a procurement delay, the Academy had to use temporary accommodation on the new site for a further 12 months.

The site area is small compared to that for many secondary schools. The architectural challenge was to fulfil the full programme/brief without filling the whole site with buildings to the perimeter, and still create an open and welcoming school that also links the two residential streets that bound the site, Loughborough Park to the west and Shakespeare Road to the east (Fig 1).

The site was also subject to planning constraints relating to building height, as it is surrounded by two-storey terraced housing. Some notorious high-rise estates (Fig 2) near the site serve as a reminder of how previous town planning decisions had blighted the area and how important and transformational EGA had to be. The brief was achieved using a modern aesthetic (Fig 3) and with a gross internal floor area of 10 745m^2.



1.

2.

3.

1. Plan of the original site.

2. The urban context.

3. Architectural design concept expressed in the completed building.

4.

Site constraints

The site was occupied by a refuse vehicle depot, with buildings for vehicle maintenance and offices together with hardstanding for parking. Liaising with the local council, the Arup team established that possibly two redundant buried fuel stores were present, and undertook a detailed geochemical survey to identify hazards in the ground and develop a remediation strategy to render the site suitable for school use. The tanks were eventually found and excavated by the contractor, and pockets of contamination from fuel and oil leaks discovered. All contaminated soil was removed from site.

There is a level change of 1.3m between Loughborough Park and Shakespeare Road and, given that the school buildings effectively traverse the site and that being step-free was an aspiration, the site had to be re-profiled and several short freestanding retaining walls used in the landscaping.

Arup worked closely with the architect to determine appropriate levels for the buildings and the various external spaces in a way that balanced the cut-and-fill requirements across the site and significantly reduced the amount of traffic removing material.

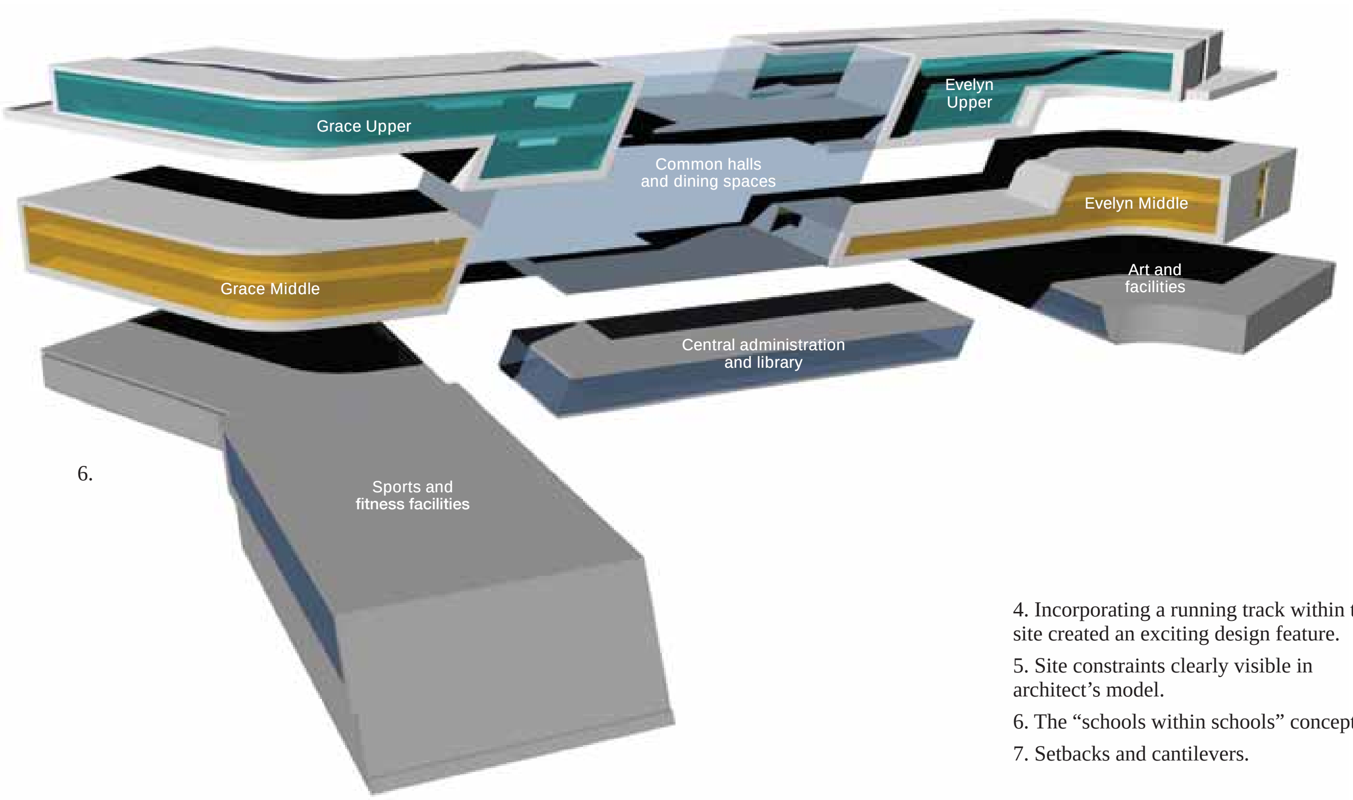
5.

A detailed ground investigation showed the underlying soil to comprise made ground mixed with alluvium over London Clay with thin layers of Terrace gravels present in some areas. Groundwater was evident in some of the trial pits so the team monitored the water level to gain a better understanding of the variation and establish a design water level.

This was important for the design of the sunken areas, and for advising the architect whether or not a simple polythene damp-proof membrane (DPM) would suffice. The water level was very close to the typical ground slab formation level, leading the architect to specify a full tanking system as the DPM.

The site location had challenges for the site team. As well as the proximity of the two residential streets, the presence of low bridges constrained delivery vehicles. In addition, the contractor had limited space on site for materials handling, and this was compounded by the fact that temporary accommodation for the year 7 and year 8 pupils had to be erected on the south side of the site.

This temporary accommodation also meant that construction had to be phased with the external works to the south being constructed after the pupils had moved into the new school buildings.



6.

4. Incorporating a running track within the site created an exciting design feature.

5. Site constraints clearly visible in architect's model.

6. The "schools within schools" concept.

7. Setbacks and cantilevers.

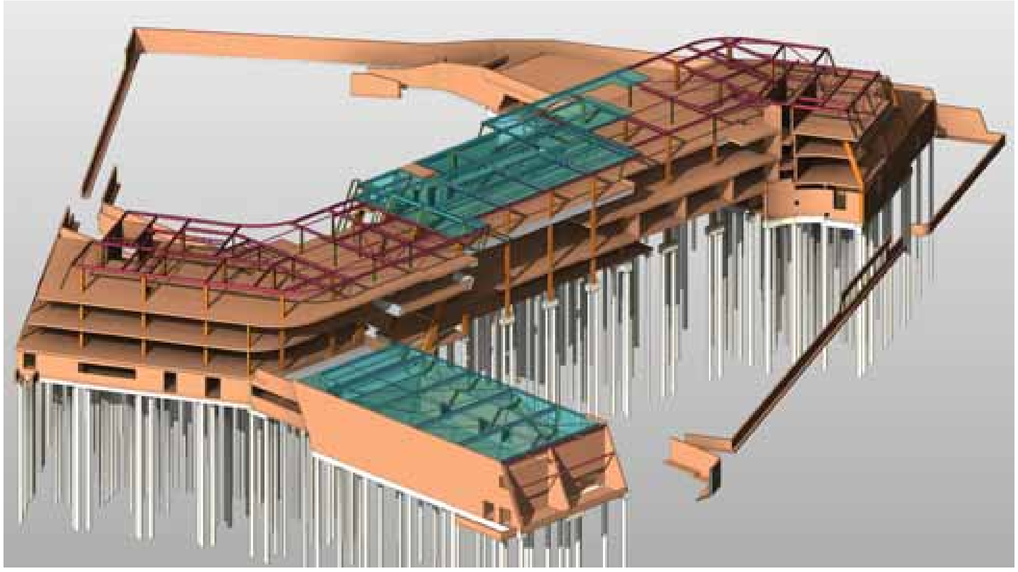
7.

Structure

Arup's biggest structural challenge was to help realise the architect's vision within the constraints of buildability and budget. The aim was to achieve the most economical possible structure, allowing the budget to be targeted on aspects of the design that would better improve pupil outcomes.

The architect's concept was a three-storey building in which the different schools (stacked vertically and horizontally) were differentiated by articulating the façade and offsetting the floorplates relative to each other (Fig 6) – "schools within schools". This involved several setbacks and cantilevers, which presented significant structural challenges (Fig 7). Arup quickly settled on an in situ reinforced concrete slab with generally a flat soffit as the preferred solution, principally for three reasons:

- The cantilevers were easy to achieve compared to steelwork.
- For aesthetic reasons the architect wanted to expose the structure where possible.
- There was a benefit in exposing thermal mass and reducing the energy consumption.



8.

9.

The choice of concrete had, however, one major drawback. This was its weight, and it mattered for three reasons. Firstly, the foundations became larger; secondly, in some locations there was little choice but to adopt transfer structures and the increased weight led to these being deeper and heavily reinforced; and thirdly, there was increased slab edge deflection, compounded by the effects of creep in concrete.

The latter impact mattered because the architect's façade design of stick-system curtain walling with large areas of glazing was very sensitive to deflection of the supporting structure. The slabs were therefore sized and reinforced primarily to limit the slab edge deflection. Where possible, edge beams were added but, due to the presence of the setbacks and cantilevers, only in certain locations.

The façade contractor qualified his price on there being a firm limit of 8mm differential settlement, which meant that in some locations Arup had to further stiffen the slab with concrete columns and cross-walls. The end result did not compromise the architecture significantly and allowed the contractor to proceed without delay or much additional cost.

The relatively heavy column loads from this three-storey concrete building led to a piled foundation solution using CFA (continuous flight auger) piles into the London Clay. Unfortunately it was not possible to get the benefit of a ground-bearing slab due to groundwater being present near the slab formation level. The Arup team foresaw that the contractor would be challenged to maintain an adequate and dry subgrade during construction, and so adopted a suspended ground floor slab, further adding to the size of the foundations. In total, the contractor needed to install 280 CFA piles (Fig 8).

Initially the team wanted to maintain a concrete structure throughout, to both minimise interfaces between subcontractors and give the architect a consistent soffit finish, but due to space planning constraints at the top floor, it was impossible to maintain all columns through to the roof. This meant longer roof-spans, and coupled with the impact a heavy concrete roof would have on the transfer beams, led to the choice of a steel-framed roof with profiled steel decking. The roof structure is designed to work very hard, given the significant amounts of mechanical plant that it has to support.

The other main structural challenge was the use of inclined columns (Fig 10). To keep within the client's budget, the scope of the inclined structure had to be limited. Early on, and working with the architect, the Arup team opted to rule out inclining any concrete shear walls and limit the inclined columns to those most visible, ie either side of the running track, using experience from previous projects with the same architect in the design. The lateral thrusts the inclined columns impart are resisted by tying them into the slab diaphragms and by designing the lift shafts and vertical concrete walls to resist the effects of bending between floors.

10.

8. *Revit* image of the structure, including piling.

9. Architectural expression of "schools within schools".

10. Construction of inclined columns.

Building services

To minimise the scale and provision of mechanical plant, natural ventilation was the aim wherever possible. However, as this was an inner city location with a main road on either side, in some areas the acoustic stipulations of *Building Bulletin 93*[6] restricted the amount of natural ventilation that could be used.

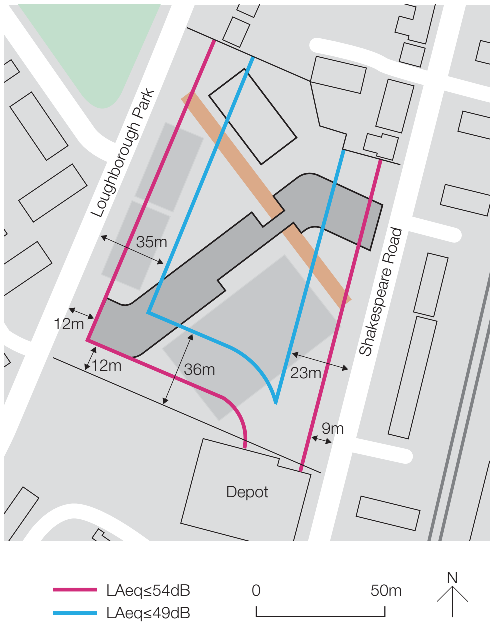
Fig 11 shows the three significant acoustic zones across the site. Areas inside the blue boundary, with an external background noise level of <49dB, can be fully naturally ventilated through the façade. Areas within the red boundary, with an external background noise level of <54dB, can have only limited openings in the façade, while those areas outside the red boundary can have few or no openings in the façade.

This led to the development of several different ventilation strategies to suit these acoustic restrictions, while at the same time meeting the overheating criteria set out in *Building Bulletin 101*[7]. Some classrooms are fully naturally ventilated, some have mechanical extract to assist the flow of air through the façade openings, and others are fully mechanically ventilated.

To allow both high- and low-level openings, the façade has a combination of trickle vents and opening windows, depending on its configuration. In naturally-ventilated classrooms the windows are under full control of the teacher, whereas in the assisted natural vent rooms the windows are automatically opened to a preset level, but have a key switch that allows the teacher to override the windows opening.

These different ventilation systems required a simple building user's guide to be created for each type of room, showing graphically how each room functions (Fig 12).

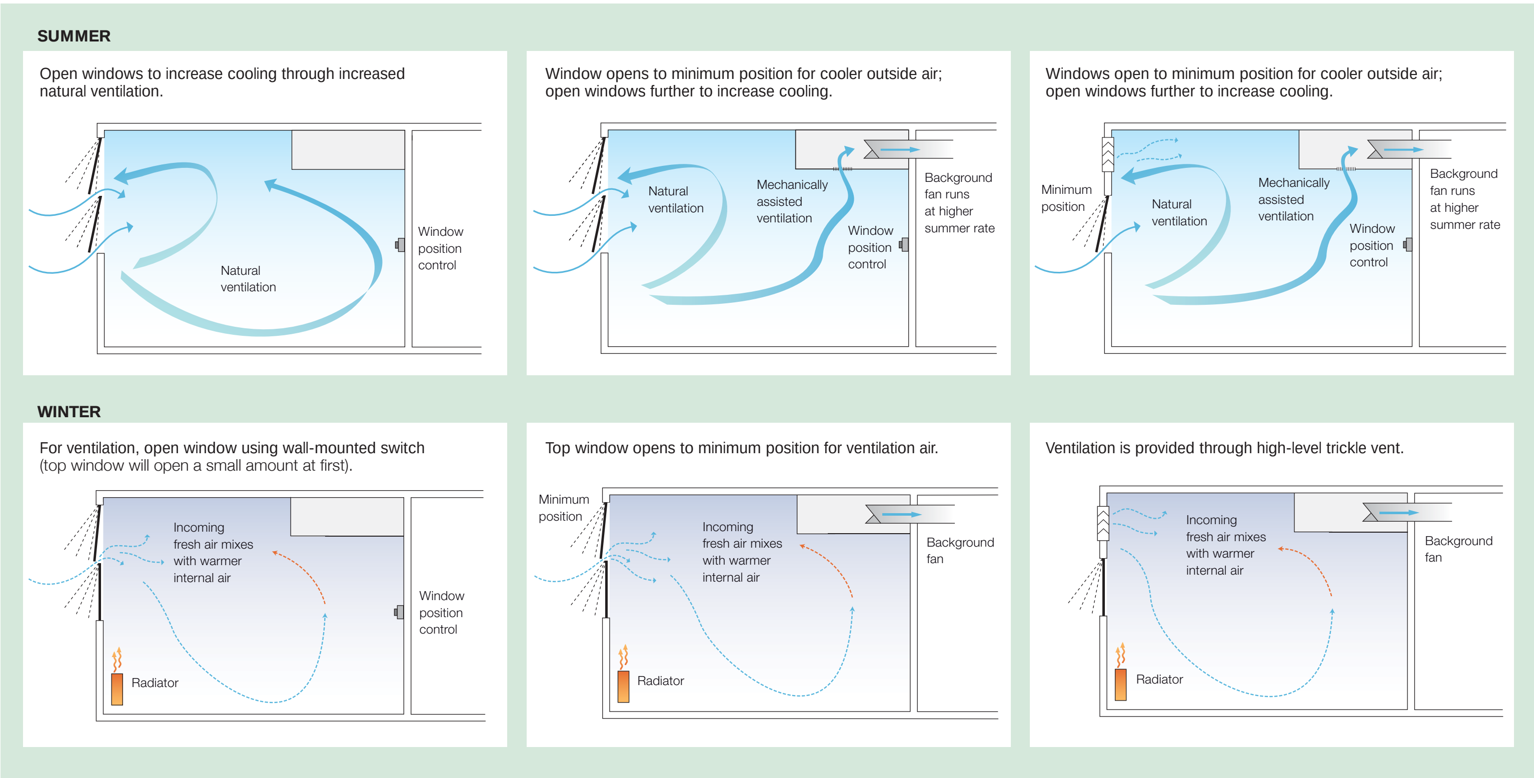
A significant amount of passive cooling could be gained by exposing the concrete soffit in the majority of classrooms. Most of these were designed for the pupils to use laptop computers, and to have low heat gains. Some areas such as the IT suites, however, have a high concentration of computers and consequent higher heat gains, so here additional cooling was required. This was achieved by using ductwork-mounted cooling coils as a way of lowering the temperature of the air locally before it enters the room.



11.

11. Three significant acoustic zones.

12. Summer and winter ventilation strategies for the three different room types.



12.

One of the Greater London Authority's planning conditions was to achieve a 20% reduction in carbon emissions through the use of renewable technologies. The most cost-effective solution was a 250kW wood pellet biomass boiler, supplemented by gas-fired condensing boilers. The biomass boiler can run continuously during periods of high demand, but be switched off at low demand, when the gas boilers can operate more efficiently.

The lighting design concept was kept simple to match the language of the internal fit-out. Continuous rows of ceiling recessed or suspended luminaires from the same range are used throughout classrooms and corridors to further emphasise the lines of the structure. This meant that most of the lighting could be in the form of energy-efficient linear fluorescent lamps.

The lighting control system uses absence detection and daylight dimming to reduce energy consumption. Here, the teachers maintain full control of the lighting, switching on when entering the rooms and then dimming up or down to the required level. After a few minutes the lighting level automatically dims if sufficient daylighting is present, which is the case in most rooms due to the extensive areas of large windows. The teacher can switch off the lights at the end of the lesson, but if they should happen to be left on, the absence detection function will automatically turn them off after a set period.

Water consumption throughout the building is reduced by the use of low water-use taps and WC cisterns, and by linking the solenoid shut-off valves to the lighting control system so that water supplies can also be turned off when areas are unoccupied. Storm water attenuation is required on site to reduce discharge to the sewer during heavy rainfall. Surface water is collected in the build-up to the artificial sports pitches that cover much of the external landscape. This restricts water flow to the underground attenuation tanks which then discharge to the sewers.

All energy use is monitored and recorded by the Building Management System, which takes information from sub-meters in the electrical, gas, water and heating systems to gain accurate information about the energy consumption by each. The low-energy services design, coupled with a high-performance façade system, allowed the UK Building Regulations Part L target of 20% improvement on the notional building to be achieved both with and without the biomass boiler included in the performance calculations. The project also achieved an Energy Performance Certificate with a "B" rating, well below the benchmark set for a building of this type.

13.

13. Continuous rows of ceiling recessed lighting.

14. The Brixton £5 note.

15. "Schools within schools", but a unified school population.

16. Ample daylighting.

14.

The "schools within schools" concept led to an arrangement of corridors that did not necessarily line up between floors, requiring many of the services risers to be offset. In addition, the need to accommodate a school of this size in a building of restricted height meant that the floor-to-ceiling heights were limited, which made services coordination very complex. Arup's 3-D services models in *CADuct* were adopted by the contractor and turned into full working 3-D *Revit* services models in order for them to produce installation drawings. By working with the contractor at the beginning of construction to help co-ordinate his 3-D services model, Arup was able to assist in producing accurate installation drawings, which led to much faster and more efficient services installation.

Outcome

The new building was completed on time and on budget in 2010. As well as achieving the BREEAM "Very Good rating", it was the first project designed by Zaha Hadid Architects to be completed in England. It received the acclaimed RIBA Stirling Prize for Architecture in 2011, and was also highly commended at the BCIA (Building Controls Industry Association) Awards in 2011 – quite an achievement for a building procured via design-and-build, which so often places cost and programme certainty over end-product quality. This is testament to the collaborative approach taken by Mace, the main contractor.

The Academy fast became iconic within Brixton and appears on the latest Brixton £5 note, a local "currency" available to be spent in local businesses (Fig 14). Most important, however, is the reaction of school staff and pupils, exemplified by the ARK testimony: *"The Arup team worked with us from the start to turn our vision into reality. Arup helped us create a school that meets all our aspirations and inspires its staff and pupils. The whole school community is proud of Evelyn Grace Academy."*

15.

16.

Authors

Keith Jones is an Associate Director in the London office. He was Project Director for Evelyn Grace Academy, and has also worked with Zaha Hadid Architects on the CMA CGM Marseille Tower and KAPSARC.

Duncan Steel is an Associate in the Bristol office. Previously based in London, he led the structural engineering design team for Evelyn Grace Academy.

James Whelan is a senior engineer in the London office. He was Project Manager and led the electrical engineering design team for Evelyn Grace Academy. He has also worked with Zaha Hadid Architects on the CMA CGM Marseille Tower and London Aquatic Centre projects.

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(7) DEPARTMENT FOR EDUCATION AND SKILLS. *Building Bulletin 101*. Ventilation of school buildings. DfES, 2006.

Project credits

Client: *ARK Education* Architect: *Zaha Hadid Architects* Structural, mechanical, electrical, and public health engineer, and construction design management co-ordinator: *Arup – James Addley, Adam Alexander, Jenna Andrews, Scott Bambling, Chris Barker, Chris Barrett, John Bennett, Peter Berryman, Steph Brewood, Kevin Burke, Duncan Campbell, Tony Campbell, Greg Chandler, Judy Coleman, Rob Constable, Ryan Coulin, Dominic Coyle, Mathieu Jacques De Dixmude, Charles Dye, Adel Enderson, Nigel Erhardt, Michael Forrest, Duncan Gray, Ian Griggs, Katy Hallums, John Higginson, Isobel Byrne Hill, Andrew Holland, Mark Hutchison, Keith Jones, Simon Jughard, Mitsuhiro Kanada, Charles King, Will Laird, Kevin Luske, Robert Malies, Agata Marut, Ed Matos, Gary McCarthy, Steve Mitchell, Guri Neote, Corinna Neupert, Shane O'Riordan, Sheena Patel, Kevin Pawadyira, Bethan Phillips, Richard Reid, Mike Roberts, Nick Rushton, Harry Spencer, Duncan Steel, Michael Stephen, Karen Warner, James Whelan, Jim Williams, Colin Winant, Craig Winter, Darren Wright, Toby Wright, Mike Young, Jeff Yuen* Quantity surveyor: *Davis Langdon* Project manager: *Capita* Main contractor: *Mace*.

Image credits

1, 11 *Nigel Whale*; 2 *David Richards*; 3-4, 7, 9, 13, 15-16 *Hufton + Crow*; 5-6 *Zaha Hadid Architects*; 8, 10 *Arup*; 12 *Luna Raphael/Nigel Whale*; 14 *Brixton Pound*.

1.

Tall buildings

Author
Farrah Hassan-Hardwick

Tall buildings make an important contribution towards meeting the ever-increasing demand for working space and living space in the world's major cities. With growing urban populations, clogged transport systems, and an acute shortage of affordable land for development, one logical step to a sustainable future is to build upwards.

The skylines of many leading world cities, and those contending for such recognition, are often defined and punctuated by tall buildings, which have historically displayed economic wealth and status. An example from Renaissance Italy is the statuesque towers built in the 14th century in San Gimignano, many of which still exist and continue to attract millions of tourists, and act as a reference point for striking architecture and design.

The drivers for such dominant skylines range from land scarcity, social need, and high real estate values to commercial opportunity and corporate demand. Accommodating large numbers of people in a small footprint puts less pressure on green space and local transport infrastructure, while reducing suburban sprawl. For business, consolidation of staff can result in a stronger corporate culture and lower operating costs.

Innovative engineering strives to make today's tall buildings energy efficient and environmentally sound, while providing high standards of comfort and safety for the communities that occupy them.
Arup continues to work with virtuoso architects in designing some of the most technically innovative and inspiring tall buildings in the world, often with unusual, elegant, and even surprising forms that on occasion reflect local architectural styles.

Excellence in design is key to achieving long-term viability, and the primary drivers underpinning the design process are economy and efficiency, and optimum use of space. Tall buildings are increasingly mixed-use, for reasons of planning, risk management, and value maximisation. They should generate higher than average rents, driven by the prestige of occupying an iconic building, the natural light, and the striking views afforded from the upper floors. The trade-off, of course, is higher construction cost per unit area.

The tall buildings with which Arup is currently involved in London show that the overall quantum of development increasingly comprises residential use plus a mix of commercial, leisure, and retail. This reflects central London's robust viability over the last three years, driven by huge overseas demand for safe-haven investment. The driver for economic efficiency, viability and design process that leads to a striking and interesting form will incorporate high-tech façade engineering, low energy environmental systems, natural ventilation, and elegant open public spaces – a combination of sustainability with functionality and performance.
This repertoire of tall buildings brings a new dynamic and dimension to London's flourishing skyline.

Such "cities in the sky" offer a rich focal point for their communities, providing employment, living, leisure, and entertainment. In addition, careful design of the relationship at ground level between vertical elegance and streetscape is crucial to sustaining and enhancing people's connection with both dimensions of their built environment, reaffirming a sense of place and identity. Arup's portfolio of tall buildings continues to define the skylines of the world's global cities.

Author
Farrah Hassan-Hardwick is an Associate and the business development leader in the London office.

1. Arup-engineered tall buildings on the London skyline, *l-r:*
30 St Mary Axe (completed 2003)
Heron Tower (completed 2011, see pp85-92)
Shard London Bridge (in the distance) (completed 2012, see pp93-99)
(photo: Hufton + Crow).

1.

The Leadenhall Building

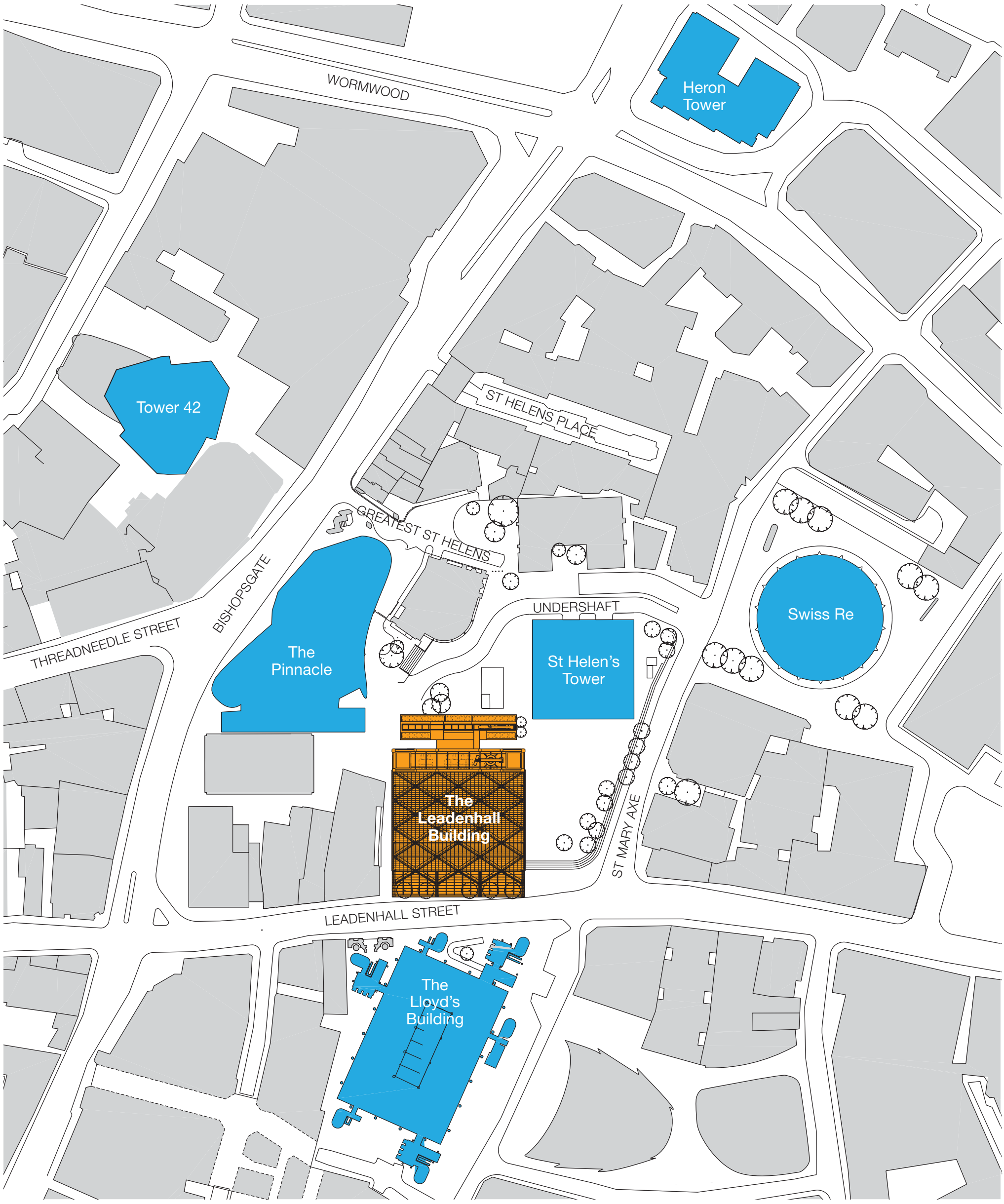
Location
City of London

Authors
Nigel Annereau Damian Eley
James Thonger

Introduction
This 225m tall office tower is located on Leadenhall Street in the City of London, directly opposite the Richard Rogers/Arup 1980s masterpiece the Lloyd's building, and within a "cluster" of other tall buildings that also includes 30 St Mary Axe (the "Gherkin"), Heron Tower (pp85-92), Tower 42, and the Pinnacle (pp77-84) (Fig 2 *overleaf*). The Leadenhall Building will provide 56 000m² of prime office space over 42 floors.

The project began in July 2001 when the then Richard Rogers Partnership (now Rogers Stirk Harbour + Partners) and Arup won a limited competition to develop the site of the 14-storey 1960s P&O building at 122 Leadenhall Street for British Land. Planning permission was granted in 2005 and demolition of the existing building commenced in January 2007.

Reflecting the client's desire to complete the new building as quickly as possible, the project was at that time procured under a construction management form of contract with Bovis Lend Lease, but the 2008 economic downturn led to it being put on hold in 2009. At this point, the existing building had been demolished and the first phase of foundations completed.



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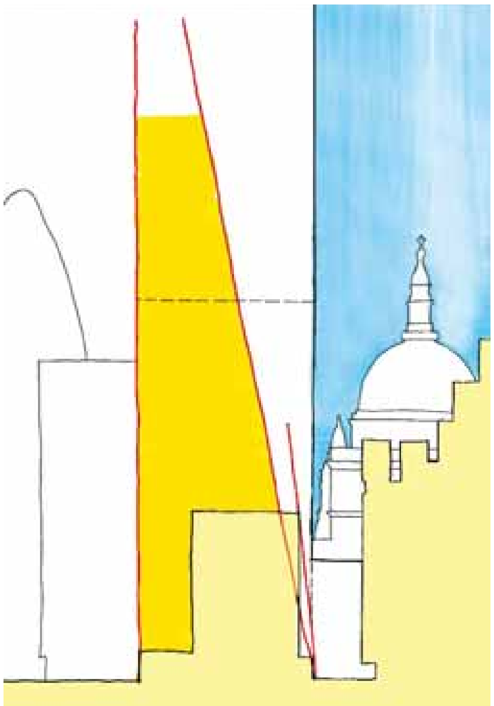

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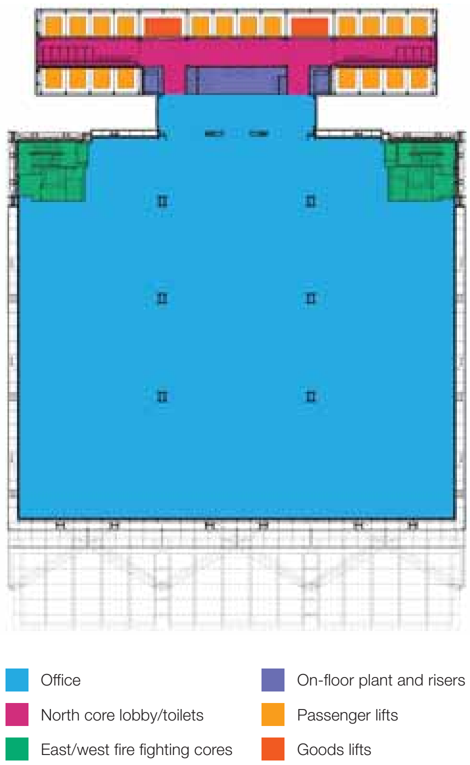


4.

In 2010 the project was resurrected. The piling and raft foundations were completed as an advanced works package under the existing construction management arrangements, and at the same time, preparations were made to tender the remainder of the works in January 2011 as a lump sum design-and-build contract; Laing O'Rourke was duly appointed in August 2011. The project is due to be completed by May 2014.

The building form

As with other celebrated projects designed by Rogers Stirk Harbour + Partners, the Leadenhall Building combines distinctive ideas about its relationship to its context with provision for highly flexible and open office space. The basic design decision regarding its iconic wedge shape was led by townscape considerations, but was also closely integrated with a structural solution that features architectural steelwork detailing of the highest quality.

The distinctive triangular form was developed in response to concerns about the position of the tower behind St Paul's Cathedral when viewed from Fleet Street. Leaning away from St Paul's, the building's silhouette can be much taller than would otherwise have been possible in such in a sensitive location (Fig 3).

1. The Leadenhall Building viewed from the south-east.

2. Site plan.

3. The building is sloped to reduce its impact on the view of St. Paul's from Fleet Street.

4. Typical floor plan.

5. Building section.

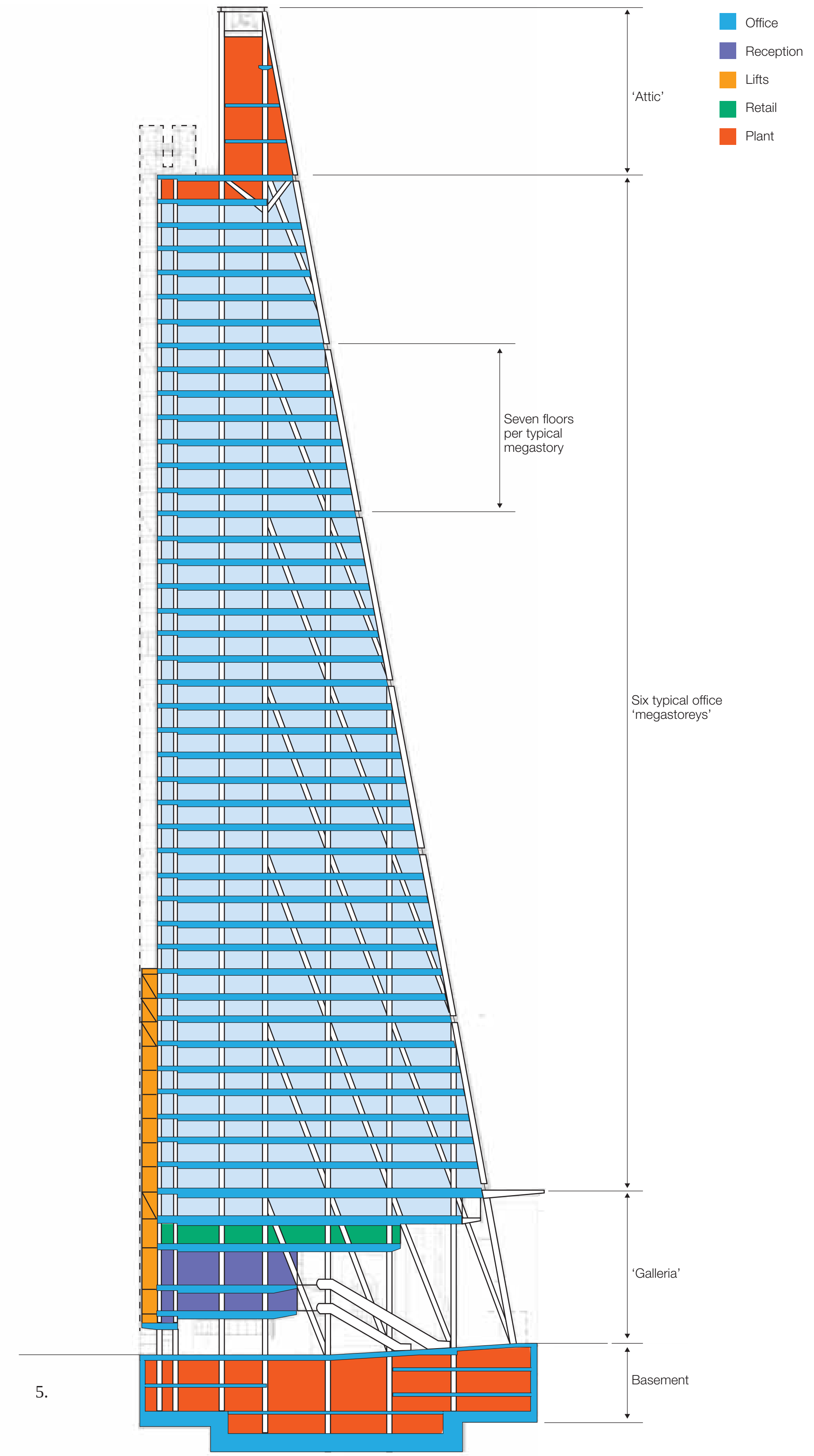
The upper floors of the building consist of two distinct zones, the primary office floors and the north core, connected by a relatively narrow linking section of floor (Fig 4). The huge office floors are rectangular in plan, 48m wide and up to 43m deep, and virtually column-free – the unusually large column grid (16m x 10.5m) means that only six internal columns are required on the largest floors. Furthermore, the perimeter columns are outside the cladding line and almost all of the services and lifts are located in the north core, with two secondary fire-fighting and escape cores located at the north-east and north-west corners of the main office floors – all features that make the floors extremely flexible for internal space planning.

The building's triangular geometry in profile and the layout of its perimeter braced structure (the "megaframe") enable seven floors to fit within a 28m height, with each floor 750mm less wide than the one below. The typical floor build-up within each 4m storey consists of a 150mm deep concrete slab over 700mm deep fabricated steel beams. A zone of 150mm is provided for raised floors, and most of the services pass through holes in the steel beams. This ensures that a 2.75m floor-to-ceiling height is maintained throughout.

A passive constrained layer damping system is designed into some of the long-span beams to reduce the bounciness of the floors. (Arup originally designed this cost-effective solution to the common issue of footfall-induced vibration in 2001 for Plot 1 (now the Ernst & Young office) in the "More London" development on the South Bank.)

The "attic" and the "galleria"

The megaframe structure organises the building elevation into eight equal "megaframe" storeys, the middle six of which contain the office floors. At the top of the building, within the uppermost megastorey, the generators, boilers and cooling towers are spread over four floors in the area known as the "attic" (Fig 5).



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The lowest megaframe storey is known as the “galleria”, a largely open space and accessible to the public. To the north, it is linked to the short cul-de-sac called Undershaft, while to the east and south it opens completely out onto St Helen’s Square and Leadenhall Street respectively. Within the galleria, two hanging banks of escalators bring visitors from Leadenhall Street to the main entrances and lift lobbies at the first and second floor levels (Fig 6).

The third and fourth floor levels are suspended within the space of the galleria below the level 5 structure, which is the first level that occupies the full floor plate. The level 5 structure in turn also projects through the south side of the building to become a 10m cantilevering wind canopy over Leadenhall Street.

Calming the wind

The galleria canopy is designed to help reduce the windiness experienced by pedestrians at the base of the building; the need for wind control in surrounding public areas is a common design issue with tall buildings. Prior to the planning application, Arup undertook a study which demonstrated that the introduction of several measures would make the windiness of the environment meet usual acceptability levels. These include the canopy over Leadenhall Street, 50% glass screens around two sides of the galleria, and carefully positioned landscaping, including trees. These studies were carried out using RWDI’s wind tunnel facilities in Canada (Fig 7).

After planning permission was granted, Arup continued to test different options in the RWDI wind tunnel in Dunstable, UK. As a result, the team was able to show that the glass screen on the west side of the galleria, together with minor improved landscaping, provided sufficient shelter and that the screening on the east and south sides could be completely removed (Fig 8). This enabled the galleria to be much more openly connected to the adjoining public spaces of St Helen’s Square and Leadenhall Street than originally planned, improving connectivity and enhancing the public’s experience of the building.

6. The “galleria” viewed from Leadenhall Street.

7-8. Wind tunnel test model showing the development of the wind mitigation measures:
7) planning scheme; 8) final design.

9. The north elevation of the building is animated by 20 passenger lifts.

10. The public walks under the bottom of the lifts when entering the galleria from the north.

11a. The megaframe structure surrounds the office on all four sides.

11b-d. Storey-height K-bracing stabilises the floors between the megaframe node levels.

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The north core

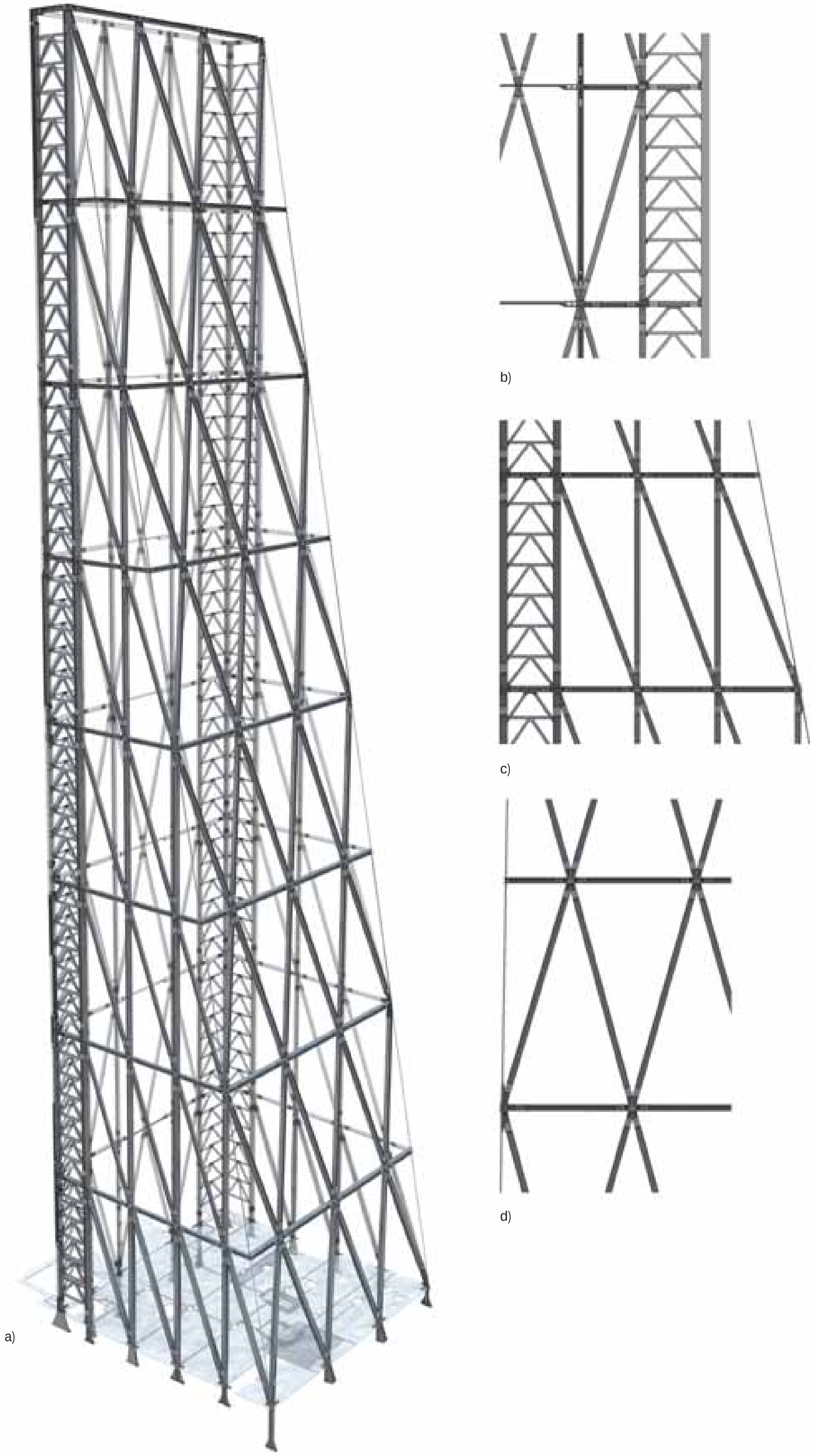
The north core contains the passenger lifts, toilets and most of the services risers and on-floor plant in a slender structure separated from the main offices by the narrow linking floor plate, thus maintaining the legibility of the megaframe around all four sides of the building. On the north elevation, the primary beams, columns and cladding of the north core form a backdrop to the 20 passenger lifts and two goods lifts, which travel up to 200m within cantilevered suspended glass lift shafts. The passenger lifts are arranged in three banks: four low-rise, eight mid-rise, and eight high-rise lifts. They are entered at first or second floor level, with lift pits elevated to steel "crash decks" below first floor level (Figs 9-10).

The high-rise passenger lifts will travel at speeds of up to 8m/sec, making them the fastest panoramic lifts in Europe. Between the three banks of passenger lifts are the two goods lifts, which descend past the crash decks into the basement.

The megaframe

The megaframe structure is a braced diagrid, surrounding all four sides of the office zone and typically located within the externally ventilated façade. It is arranged on a large scale, dividing the building elevations into the eight, seven-storey modules. Each megaframe storey is therefore 28m above the previous one. These large distances mean that, to brace the columns between the stiff node levels, a secondary stability system was also required. This takes the form of chevron or "K-braced" panels, and is located in the northernmost bays of the east and west faces and the end bays of the north face, around the east and west fire-fighting cores (Figs 11a-d).

The long internal floor spans direct much of the office floor load to the perimeter. As a result, the megaframe columns are designed to carry a substantial portion of the building's weight and can therefore naturally



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also resist the wind loading with minimal additional material. Uplift forces to the foundations are also minimised.
The megaframe is significantly stiffer than many stability systems for buildings of this height, and as a result the accelerations caused by wind are less than 75% of the levels recommended in *ISO 10137*[1].

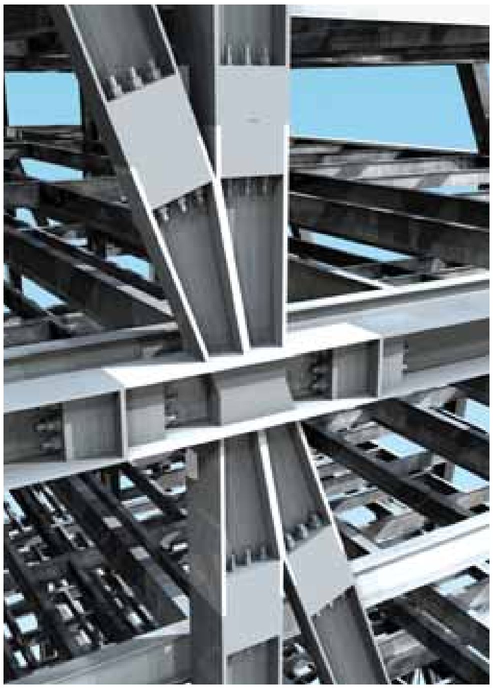
Placing the megaframe outside the thermal envelope meant that its design had to allow for increased differential temperatures.
In some places, the office floor beams are connected to the megaframe via sliding bridge bearings. These allow small horizontal movements to occur freely, so that the megaframe can expand and contract without transferring damaging forces into the weaker floor structures behind.

The "node" connections
The greatest challenge in the structural design was undoubtedly the megaframe connections. Typically, six megaframe elements come together at each joint, in a variety of geometries, and the connections transfer forces of up to 6000 tonnes in at least three different directions simultaneously. The design had to ensure that as well as being practical to build and cost-effective, the megaframe as a whole would present an appropriate and consistent aesthetic. This made it necessary for the connections design to be developed very much in parallel with, and often slightly before, that of the members themselves.

The solution was to connect straight megaframe members to separate "node" pieces via prestressed bolted connections. Typically 6m x 3m and weighing up to 30 tonnes, the nodes provide the geometrically complex transitions between the different elements through welded joints between carefully oriented plates.

The weaker bolted splices are moved away from these points of intersection to the linear members, where the stresses are lower and the geometry more regular, and there is more space for bolts (Fig 12).

The bolts themselves are actually high-strength threaded bars, up to 76mm in diameter, pretensioned by <200 tonnes to ensure that the joints never open up under the design loads. By using these very large bolts, and with compact tensioners, a greater capacity within the joint could be achieved than with more conventional fixings.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As a result, all the site connections can be made entirely by bolting within the profile of the members. There are no outstand elements or site welds at any of the node connections. The bolts transfer their prestress to the ends of the members and nodes via "bolt boxes" (Fig 13) – stiffened plates welded between the flanges of the megaframe sections.

Design of the megaframe nodes
The design process for the nodes progressed through a number of stages. Initially, diagrammatic sketches and simple hand calculations established the lines of force through the joints and ensured that the critical ones had the required capacity. This established the principles (Fig 15).

During the scheme design, the steelwork contractor William Hare was brought into the team, under a pre-construction services agreement, to provide advice on buildability and assist in modelling the nodes.

Each joint type was developed using simple analysis models to refine the structural design and optimise the flow of forces through the connections. Each joint was also modelled in a 3-D *Tekla* CAD model. *Tekla* is designed particularly for modelling steelwork fabrications, and these models were invaluable in helping to identify and resolve difficulties in fabrication, and to further refine the joints from an architectural perspective.

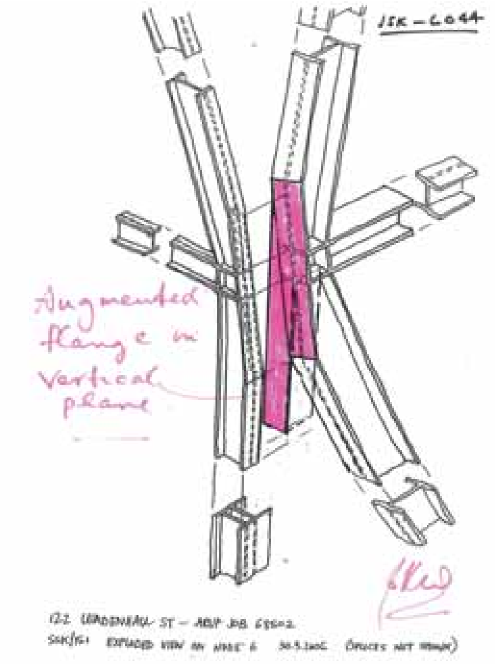

14.

12. The megaframe "node" connections are connected to the members themselves via the "bolt box" splices.

13. Early trial mock-up of the post-tensioned "bolt box" connections.

14. An installed node.

15. Initial hand sketch of the south corner node, showing how the plates are oriented to carry the primary forces through the joint.



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For the final analysis, the *Tekla* models were converted into detailed finite element models. They were analysed using *Nastran* software, supported by Arup-written tools that make it easy to search for high stress concentrations. Separate algorithms also extracted minimum weld size requirements along every joint, and enabled single pass fillet welds to be specified in the majority of locations (Fig 16).

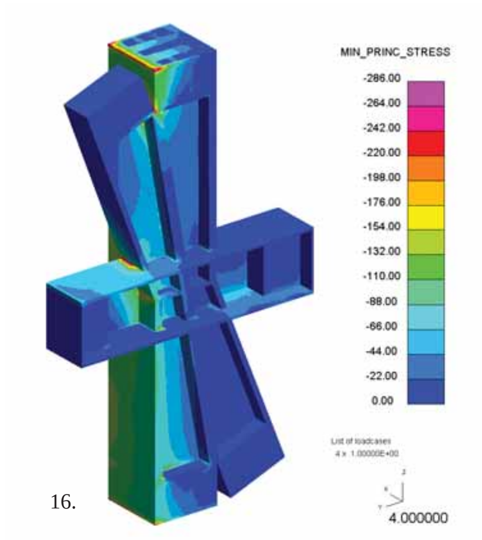
When the building was re-tendered to new contractors in 2011, Arup produced traditional 2-D drawings showing plate and weld sizes and types, supplemented by exploded diagrams clarifying the anticipated fabrication sequence for every node type. This reassured the tendering contractors that these complex elements could be made, and meant that a competitive yet reliable price could be obtained for the client. The steelwork fabricators were also able to use the 3-D *Tekla* model to further interrogate and develop the design and calculate material quantities quickly.

Following Laing O'Rourke's appointment as the main contractor, the steelwork package was awarded to Watson Steel Structures, whose capabilities in accurate machining of joints enabled Arup to make better use of bearing contact in the design and thereby further reduce the welding content of many of the nodes, and simplify the shimming strategy (Fig 17).

16. Finite element analysis models were used for the final design of the nodes.

17. A ground level node being machined. Accurate machining of the megaframe results in less welding and fewer shims.

18. Megaframe bases cast into the perimeter retaining walls.



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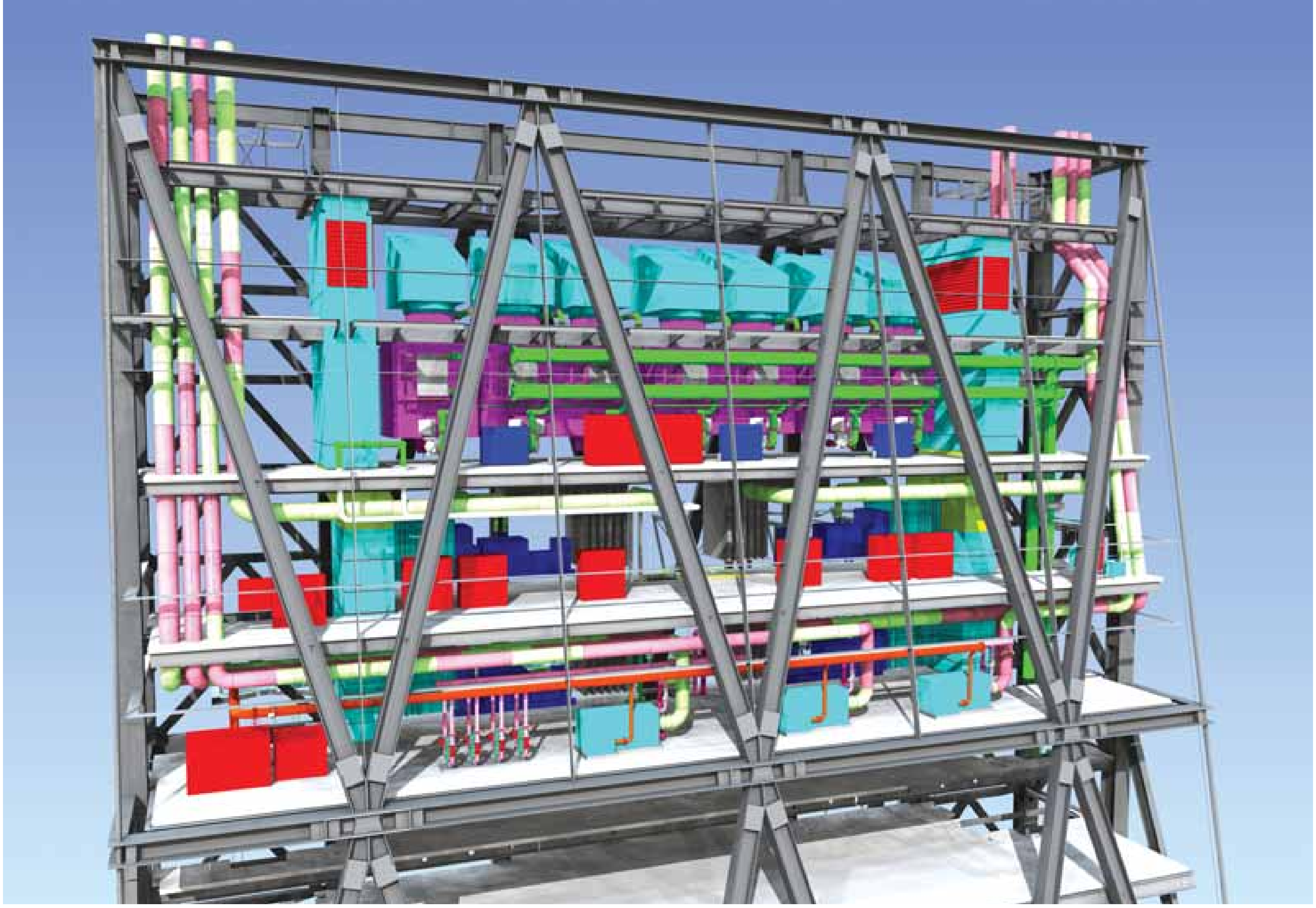
Substructure and foundations

The 14-storey 1960s P&O building had a three-storey basement, but the new building required more volume below ground and so a fourth level was introduced. To reduce the danger of undermining adjacent perimeter structures, the extra basement level was confined to the site's central area while the third basement level raft was designed so that it could be built first and give support, together with some minor temporary works, to adjacent structures. This minimised the temporary works needed to construct the lowest basement storey.

The superstructure arrangement led to very high loads under the megaframe at the very edge of the site, as well as under the six internal columns. This contrasts to most buildings with a central concrete core, where the largest foundation loads tend to occur under the core. Here, the loads are supported by large diameter bored piles founded in the London Clay and, since the megaframe lands at the very edge of the site, these large perimeter piles must be eccentric to the megaframe. They are therefore linked to the internal column piles via a 2.7m thick raft slab covering most of the site. This thickness reduces to the south where, by virtue of the building shape, the column loads are considerably less.

The perimeter megaframe columns to the east, west and south sides are supported on new retaining walls cast on the insides of existing perimeter structures. Large base plates and columns are cast into these walls at first or second basement level, so as not to impact on the architectural requirements a ground level (Fig 18).



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Building services

Two of the most notable characteristics of the Leadenhall Building that affected the services design were its significantly reduced roof plan compared with the building footprint, and the almost complete disconnect between the ground floor and the basement. These two unconventional features drove a very particular set of solutions for installing the building services.

All the base building services that require outside air for aspiration or heat rejection are at the top of the building. These include the 100% backup generators, the cooling towers, the boilers, and the tenants' kitchen extract fans. Together with high-level electrical switchrooms and the water system pressurisation units, these systems make up the extent of the "attic" plantrooms (Fig 19).

With a tapered building form each floor plate is different, offering a range of tenancy sizes. However, the building is designed to have just one tenancy per floor, which has made it possible to provide the office fresh air supply on a floor-by-floor basis instead of the more conventional centralised supply typical in tall buildings.

This enables the landlord to turn off individual floors when not in use, and to meter the associated energy use on an individual floor basis. It also enables each tenant to reschedule their fresh air supply rate if required, without affecting other tenancies. Each air handling unit is controlled by volume flow rate feedback, to ensure a constant fresh air supply regardless of the differential wind pressure between the supply and extract louvres.

Each floor also has its own plate heat exchangers for both heating and chilled water so that, as with the air handling systems, the floors are individually metered and pumped. This also allows tenants' own installations to be hydraulically separated from the main building systems, avoiding risk of contamination from the tenants' to the landlord's systems, or of tenants' hydraulic flow changes affecting the balance of the landlord's hydraulics.

As a result, each tenant can choose the most appropriate HVAC system for their needs, from variable volume DC fan coil units (the system assumed for the Building Regulations energy efficiency calculations) to chilled beams or chilled ceilings.

The building form does not readily lend itself to the future addition of extensive tenant plant, so the installed systems are highly flexible.

In addition to 100% power backup generation, the building is fed electrically from two separate 33kV substations, each capable of supporting the full building load. There is space in the basements to install additional tenants' generators and chillers, and a dedicated space for a tenants' cooling tower in the attic.

The chilled water and electrical distribution systems have been designed to enable tenants to install a high energy-use space such as a computer suite without having to install their own additional cooling systems. This is achieved by building a spare capacity of 1000kW into both systems, which can be delivered to any tenant's floor up to a maximum of 300kW per floor.

19. The rooftop plant rooms are distributed over the four attic floors.

20. The lower levels of the existing P&O Building were demolished first, enabling foundation construction to progress in parallel with later demolition.

21. Site progress, mid-June 2012.

22 (next page). The north core frame was designed for prefabrication as tables with the services and slab already installed.

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Bottom-up demolition

The P&O building was similar to its contemporary and still-standing neighbour, the 28-storey St Helen's Tower (previously the Aviva Tower and before that the Commercial Union building). They were both designed by the Gollins Melvin Ward Partnership (now GMW Architects) and shared the then-fashionable design feature of having most of the superstructure floors supported at their edges by hangers suspended from above by post-tensioned trusses fixed to a stocky central core.

As already noted, the original requirement was to complete the new building quickly, and so the demolition strategy for the P&O building was designed to enable the new perimeter foundations to be installed simultaneously and thereby save months from the overall construction programme.

The demolition contractors, McGee, initially demolished only the lower half of the suspended floors, and then placed a temporary steel platform between the remaining superstructure and substructure. This temporary platform was strand-jacked to a level clear of the masts of the piling rigs and attending cranes, allowing the substructure demolition and first phase of foundations around the perimeter to be completed while superstructure demolition continued in parallel.

The second phase of excavation, piling and foundation work in the central part of the basement occurred once the existing core demolition was complete (Fig 20).

Accurate construction

Being able to rely on accurate machining of steelwork components during fabrication has had a significant influence on the construction process, enabling larger elements to be prefabricated and reducing the requirements for shimming on site.

The megaframe splice connections were originally conceived with tapered or site-adjustable shims in the joints, to achieve the necessary fit-up of the 28m long megaframe members. Through accurate fabrication, however, these could be replaced by a single shim, pre-fixed to the steelwork. This minimised the requirements for site adjustment, reducing the risk of shims being dropped at height, diminishing waste, and speeding up construction (Fig 21).

The north core primary structures also benefited from greater accuracy in fabrication. They were prefabricated into three table structures per floor level, and lifted into position with many of their services and floors pre-attached, again accelerating the erection process and reducing waste (Fig 22).

The Leadenhall Building has an inherent tendency to lean towards the north by about 160mm during construction, due to its shape and the orientation of the diagonal elements in the megaframe.

This is being corrected during erection through a process known as "active alignment", in which the diagonal megaframe members on the east and west faces are subsequently shortened so as to bring the building back into its correct alignment. Since the amount of shortening is decided after much of the structure has been erected, this will mean that the pre-set can be adjusted if necessary to reflect the actual movements on site.

Conclusion

The Leadenhall Building's highly distinctive building profile, amongst its existing and new neighbours also under construction, will enhance London's skyline and offer tenants very large and virtually unobstructed office floors. And at the ground floor, a unique and dramatic space is being created for the enjoyment of the City of London's public.

The manner in which the engineering of the structural steelwork and the building services has been integrated into the architectural concept and details is unprecedented for a building of this scale. Indeed, the detailed architecture of this building is often inseparable from its engineering, and has been realised through Arup's very close collaboration from the outset with both the architect and the numerous fabricators.

22.

Postscript

This is the first of two articles planned for *The Arup Journal* about the Leadenhall Building, the second article to follow when the project has been completed. This will describe further aspects of Arup's design, including the lifts and some of the methods of construction in more detail.

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Nigel Annereau is a Director in the London office. He provided overall day-to-day leadership for the Leadenhall project team and led the substructure design.

Damian Eley is an Associate Director in the London office. He was Project Manager and led the superstructure design for the Leadenhall Building.

James Thonger is an Associate Director in the London office. He led the building services team for the Leadenhall Building.

Reference

(1) INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. *ISO 10137:2007*. Bases for design of structures - Serviceability of buildings and walkways against vibrations. ISO, 2007.

Project credits

Client: *British Land Co plc* Architect: *Rogers Stirk Harbour + Partners* SMEP engineer, and lighting, archaeology, acoustics, security, wind engineering, IT/comms, sustainability, and transportation consultant: *Arup* Client representative: *M3 Consulting*
Cost consultant: *Davis Langdon*
Construction manager for enabling works: *Bovis Lend Lease* Demolition contractor: *McGee*
Piling contractor: *Cementation*
Enabling works concrete contractor: *Byrnes*
Main contractor and concrete contractor: *Laing O'Rourke* Steelwork contractor: *Watson*.

Image credits

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The following Arup staff members are among those making significant contributions to the Leadenhall Building project:

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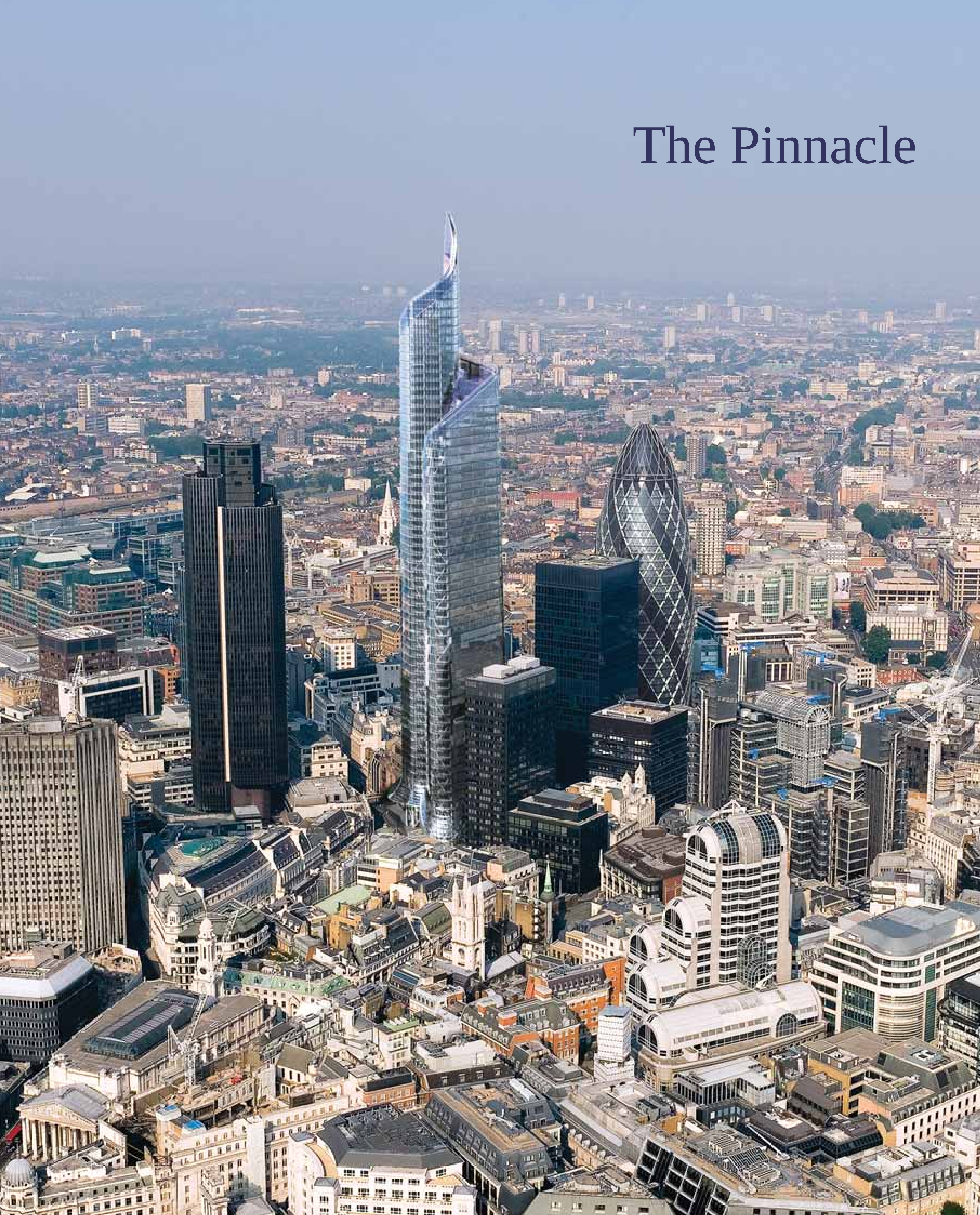
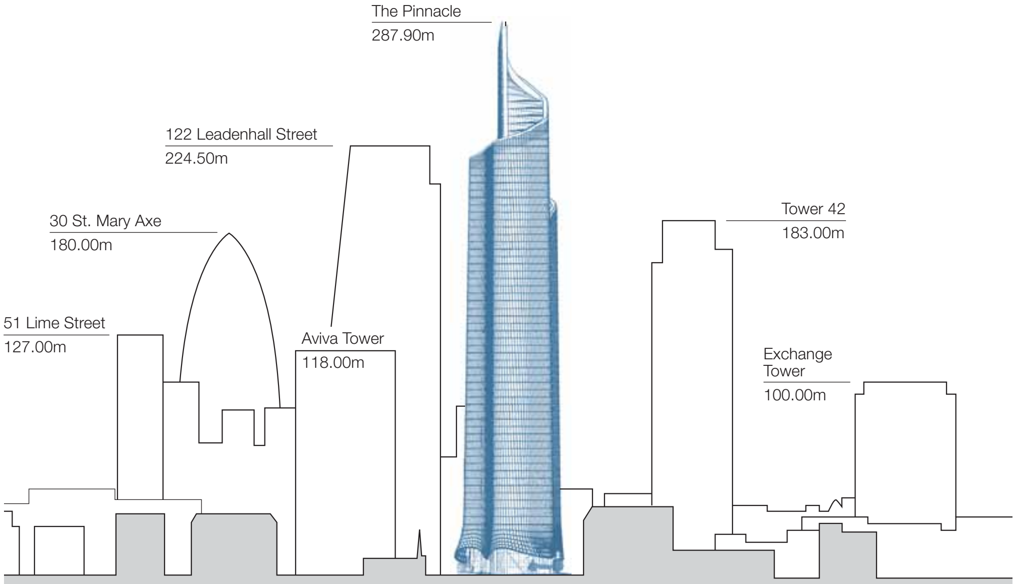
The Pinnacle



Location
City of London

Author
Steve McKechnie



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The building
The Pinnacle will form the apex of the cluster of iconic buildings in the heart of the City that also includes 122 Leadenhall Street (pp67-76), Heron Tower (pp85-92), and 30 St Mary Axe (the "Gherkin") – all engineered by Arup. The sculpted curves of the Pinnacle's design, by architects Kohn Pedersen Fox Associates pc (KPF), will interact with these surrounding structures to unify them and transform this part of London's skyline (Figs 1-2).

The Pinnacle will provide 86 000m² of office space in one of the most sought-after locations in Europe. Its plan form is shaped to make maximum use of an irregular site. The ground floor comprises an entrance lobby with a series of retail units; escalators will lead building users from the lobby to banks of double-deck lifts. Above this will be 54 levels of office accommodation, including two sets of sky lobbies where users will change from express to local lifts. The plant areas are in the three-level basement and on levels 55-58. Levels 59-63 will form a viewing gallery where the public will be able to look out from one of the loftiest vantage points in London (Fig 3).

The geometry of the building is complex, but built around simple principles. The elevations are all formed from inclined planes and cones, so that the surfaces are not warped and all primary glazing panels are the same shape and size. This has kept the cladding costs down, while realising a truly exceptional external geometry that will add new shapes to the City skyline (Fig 4).

Architectural quality was an instrumental factor in the decision by the Corporation of London to grant planning permission for the development and, in turn, Arup's structural engineering design was instrumental in making the architectural design efficient and buildable. The computational design process used to develop the building's structural frame and optimise its bracing system to omit all but the most structurally efficient elements was outlined in a previous *Arup Journal* article[1].

Following lengthy design development, work on site started in 2009 with the demolition of the existing buildings. Piling was completed by June 2010 and was followed by construction of the basement. At the time of writing, fabrication of the superstructure steelwork had started and the reinforced concrete core had reached the seventh floor level (Fig 5).

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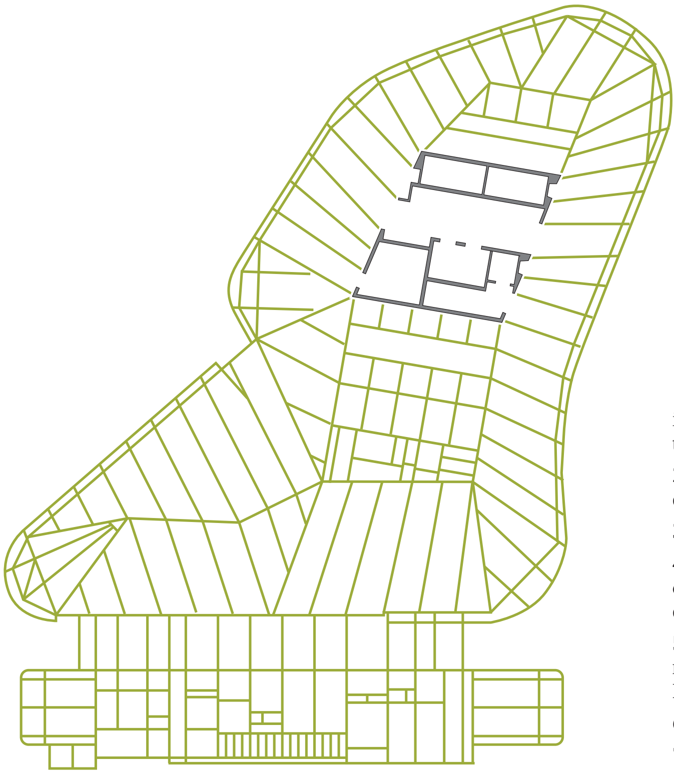

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1 *(previous page)*. The Pinnacle as it is intended to appear amongst other tall buildings in the City.

2. Elevation of the Pinnacle compared to its neighbours.

3. The viewing gallery.

4. The cladding geometry is defined by a series of planar and conical surfaces.

5. Construction progress of the reinforced concrete core, November 2011.

6. Level 12 floor plan.

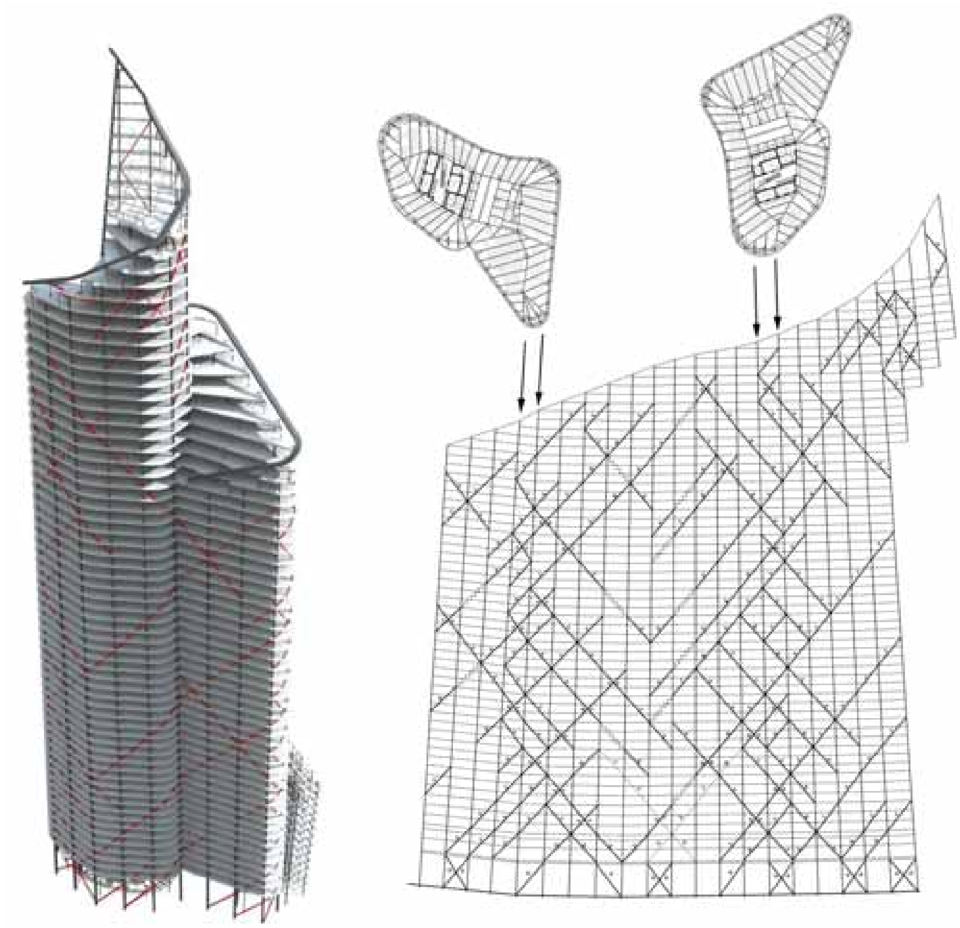
7. Stability bracing.

The structure

The tapering spiral form of the building is supported by a highly efficient steel and concrete superstructure. This squeezes the maximum number of floors into the permissible building envelope while keeping the tonnage of structural steelwork down to a remarkably efficient 135kg/m^2. Slim floor beams combined with minimal column and wall dimensions maximise the lettable area, with complex curves being created from simple straight sections that are easy to fabricate and erect (Fig 6).

The perimeter columns and floors are formed from fabricated steel sections. Floor beams are all 625mm deep, with 400mm diameter web openings to allow services distribution within the ceiling void. Mechanical and electrical equipment fits immediately under the 130mm deep composite lightweight concrete floor slab, between the beams. This allows the building to offer a 2.75m high ceiling, even though the overall floor-to-floor dimension is only 3.85m.

The primary stability structure is formed by linking the perimeter columns with diagonal bracing. This transfers wind loads to the ground very efficiently and harnesses the inherent stiffness of the perimeter columns to stabilise the building (Fig 7).



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These bracing members will be expressed within the office areas just inside the glazing, in the same line as the perimeter columns. This is very efficient structurally and will give visual expression of the structural action to building users. To do this in every column location would, however, take up valuable office space, so Arup used the computational design and optimisation process already noted – a groundbreaking “topological optimisation algorithm” – to define the places where braces could be omitted without compromising the structural performance.

A fully-braced perimeter would have had 760 diagonals and would have taken up office space in 2280 separate locations. The team found, however, that only 362 of those bracing locations were actually needed. The resulting quasi-irregular bracing arrangement will be glimpsed from outside the building and will give it a distinctive visual “grain”, as with natural stone or timber.

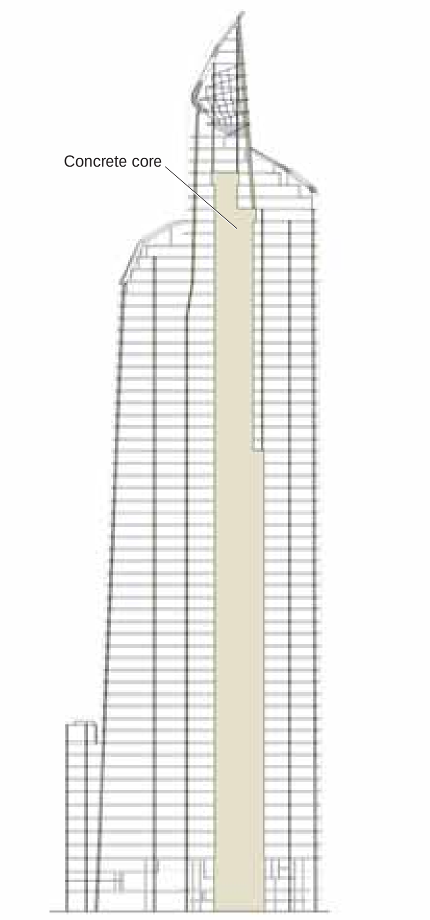
The core

The building structure will be stabilised during construction by a concrete core that is built ahead of the steel erection using self-climbing formwork. The core is designed to be self-stable. Once each new lift of concrete has been cast and started to cure, the shutters are retracted and the whole assembly jacked upwards using the newly-cast walls for support (Fig 8).

This jump-form assembly provides a safe working environment for the operatives building the core, which also provides staircase access up to the workface. The goods lifts and lift motors will be installed before the core is complete using a movable lift motor support that follows the jump form up as the core is completed. This “jump lift” system will be used for access during construction, reducing the need for temporary hoists.

Dynamics

It is often breezy in London and the constant buffeting and gusts of a windy day can make a tall building sway from side to side. Building users in the upper storeys can find this uncomfortable, and on a very windy day it can become “nauseogenic”. In some tall buildings around the world, office workers have to take sea-sickness pills before they go to work on a windy day.



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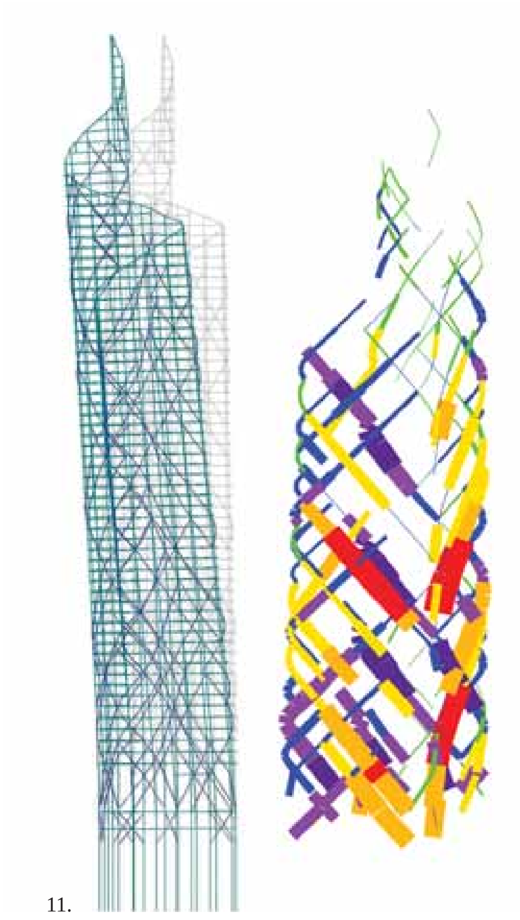

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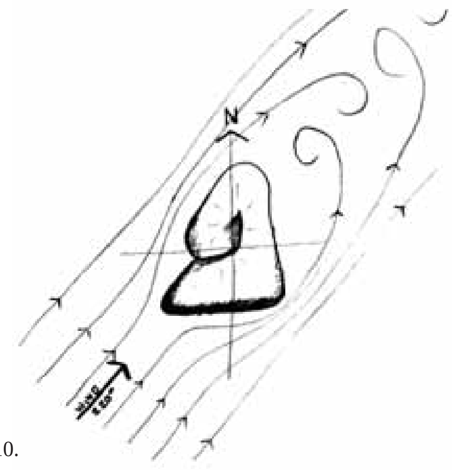

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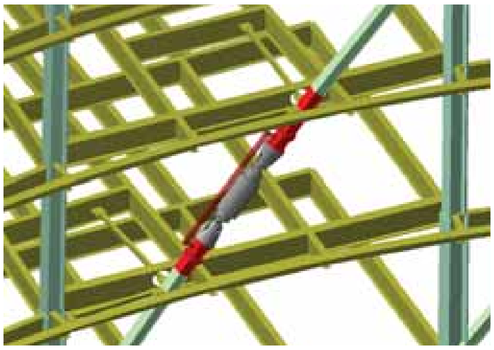
Techniques are now available that allow designers to interpret wind tunnel testing data, and predict and prevent these effects through design (Figs 9-10). Often buildings are made very stiff to reduce the amplitude of the sway, or have a tuned mass damper, like a massive two-storey high pendulum, installed in the upper floors of the building to absorb the energy of motion (Fig 11).

These options, however, are expensive and take up valuable space in a building. Instead, the Pinnacle uses viscous damper units, like enormous shock absorbers, built into the stability structure to absorb the energy of motion of the building, thus ensuring the comfort of building occupants during windstorms (Fig 12). By incorporating the damper units into the structure itself, the team was able to avoid adding steel to the structure, resulting in a saving of 4000 tonnes of steel, which could have cost up to £12M. This new structural technique was made possible by a development of the pioneering structural dynamics work that Arup did to investigate and stabilise the London Millennium (“Wobbly”) Bridge, and new methods of earthquake-resistant design developed in the Los Angeles office.



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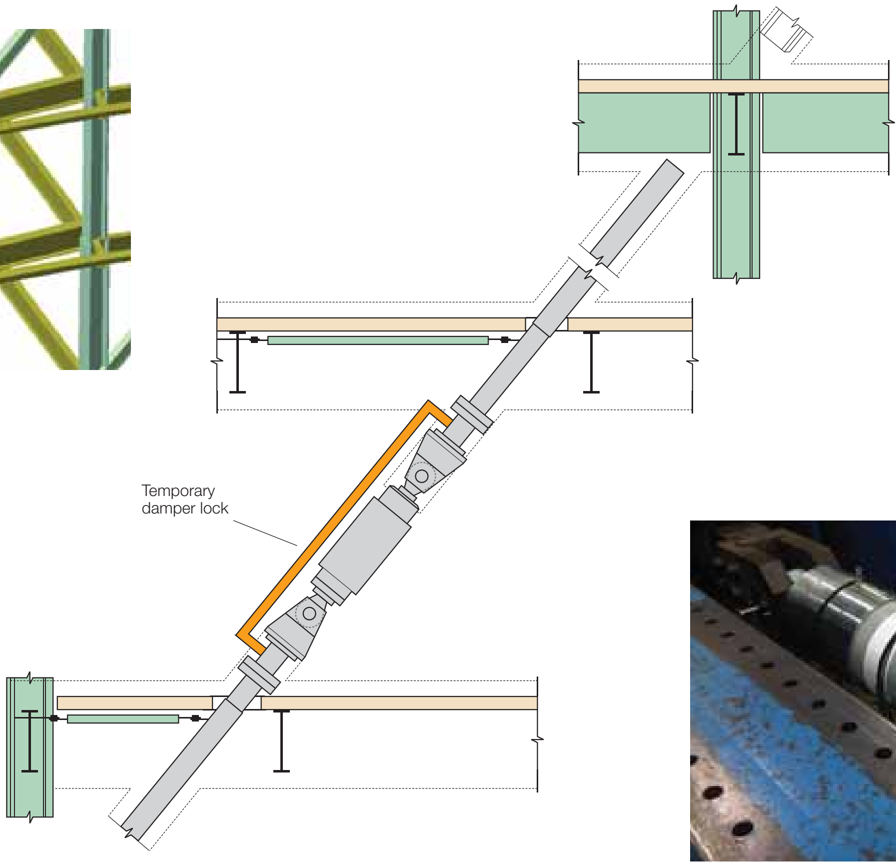


b)

c)

12.

13.

Specialist consultancies

Fire engineering
Arup's fire engineering team saved money for the client with sophisticated time history finite element modelling of the structure's response to fire, and also helped to maximise the net lettable area of the building by gaining permissions for fire escape strategies that are beyond the limits of the prescriptive rules in set in the UK Building Regulations.

Liaison with Transport for London
The Pinnacle is situated on Bishopsgate – one of the City of London's principal roads and a special priority "red route" on which vehicles in the UK are not permitted to stop. This means that the processes to gain approval for temporary roadworks associated with building sites, in this instance from Transport for London (the local government body responsible for most aspects of the transport system in Greater London), are particularly complex and onerous. The Arup civil engineering and transportation planning team was able to help to smooth the process of gaining permissions and planning the works.

Pedestrian wind environment
Tall buildings tend to catch the wind at high level and funnel it down to street level, which can make walking and cycling difficult. The Arup wind team hsa great experience at designing mitigation measures to improve the wind environment at street level, ensuring that pedestrians can move around the streets easily and that the surroundings are a pleasant place to be.

These topics will be dealt with fully in a subsequent *Arup Journal* article.

8. Cross-section showing position of concrete core.

9. Wind tunnel model.

10. Sketch of wind patterns around the Pinnacle.

11. Structural response to wind loading.

12. Viscous damper unit.

13. The Pinnacle as centre-piece amongst its companions, as it will be viewed from the River Thames.

14.

15.

16.

Foundations

The Pinnacle site was previously occupied by a heavy granite-clad building from the 1980s, which had massive under-reamed piled foundations. The number and spacing of these piles meant that there was no space left in the London Clay under the site to put in the new piles that would be needed for the 63-storey Pinnacle tower, and a defect in their original construction meant that they could not be re-used.

The Arup team knew that it would not be possible to remove the under-reams. Instead, using the extensive experience of piling in London and around the world acquired over the years by the firm's geotechnical engineers, the team devised a piling method that avoided the obstructions in the London Clay by founding in the Thanet Sand below instead.

The difficulty was that, on this site, the Thanet Sand is more than 60m below ground level and drilling mud (bentonite) had to be used to stop the pile bore collapsing. When the pile bore is full of bentonite, the bearing surface of the sand gets contaminated and its load-bearing capacity is degraded.

The Arup team overcame this by adding base grouting to the piles. Steel pipes were cast into the piles during construction, and cement grout was pumped at high pressure through those pipes and out into the Thanet Sand below the base of the pile. The grout strengthens the interface and allows the full load-bearing potential of these densely packed sands to be realised.

The resulting piles are, at 65m, the deepest in London and, at 2.4m diameter, the widest base-grouted piles in the world (Fig 14). More importantly, however, the design enabled the client, Deutsche Immobilien Fonds AG, to build the tallest building in the City of London on a site that was severely obstructed by existing piles.

Basement

The reinforced concrete walls and floor slabs of the existing basements on the site meant that over most of the area it would have been impossible to build the new basement using the usual approach of installing a secant piled basement wall and excavating the soil before installing bearing piles. Instead, the team worked with piling contractor Bachy and enabling works contractor Keltbray to develop a novel construction sequence that re-used the walls and slabs of the existing basements and allowed the piling rigs to work without being constrained by basement propping.

First, openings were core drilled through the existing basement slabs at new pile locations. Back propping of the existing ground level slab then allowed piling rigs to work from ground floor level, piling through the basement using temporary casings (Figs 15-16).

Once piling was complete, the existing walls were stabilised by an intricate arrangement of props, soldiers and waling beams installed progressively as the existing basement slabs were demolished (Fig 17). The lowest slab of the existing basement remained in place, to stabilise the foot of the existing walls, and forming the blinding for the new lowest (B3) slab. As the new basement walls and slabs were cast, the props were removed in an incremental process that transferred the loads to the new slabs (Fig 18).

This was all achieved with exceptionally small movements of the soil around the site. Arup's geotechnical engineers modelled the basement demolition and reconstruction process in 3-D to demonstrate to adjoining owners that their properties would not be adversely affected. Readings from the network of monitoring points on surrounding buildings and roads confirmed the results of the analysis (Fig 19).

14. Base-grouted pile, 2.4m diameter.

15. Back-propping of the existing basement lid slab to allow piling rigs to work above, at ground level.

16. Stitch drilling through the existing basement slab to allow construction of piles.

17. Stabilising the existing basement walls, June 2010.

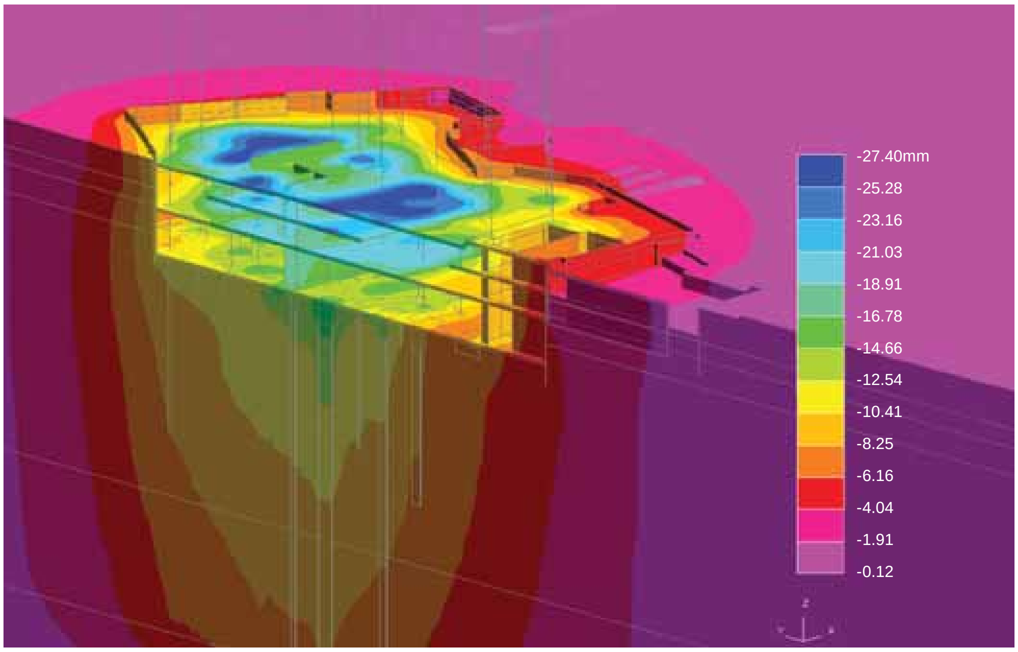
18. Basement progress, September 2010: Steel tower columns erected on pile heads at B3 level before the casting of basement slabs.

19. Predictions of vertical soil movements from the 3-D soil analysis model.

20 *(next page)*. The Pinnacle as it will appear from the north-east.

17.

18.



19.

Conclusion

The Pinnacle project has generated some interesting challenges during the design and construction process, and the Arup team has very much enjoyed finding solutions that helped to make this exciting project possible. Only some have been touched on in this short article, and it is intended to cover aspects of the project in more detail once construction is complete.

As this article was being prepared for publication the design team learned that construction had been paused by its current owner and that the site and the project are up for sale. It is sincerely hoped that a buyer is found soon so that this remarkable building can be finished.

20.

Author
Steve McKechnie is an Associate Director in the London office. He is Project Manager for the Pinnacle project.

Reference
(1) LUEBKEMAN, C *and* SHEA, K. CDO: Computational design + optimisation in building practice. *The Arup Journal*, *40*(3), pp17-21, 3/2005.

Project credits
Client (to spring 2012): *Deutsche Immobilien Fonds AG* Architect: *Kohn Pedersen Fox Associates pc* Structural, geotechnical, transportation, wind, fire, acoustics and security services engineer: *Arup* Building services engineer: *Hilson Moran Partnership Ltd* Project manager and quantity surveyor: *Davis Langdon* Main contractor: *Brookfield Multiplex Ltd.*

Image credits
1-3, 13, 20 *KPF; 4-12, 14-19 Arup.*

The following Arup staff members are among those who have made significant contributions to the Pinnacle project:

Sacha Abizadeh, Ben Ablett, Charlotte, Adcock, Andrew Allsop, Rabin Annauth, Nigel Annereau, Jenny Austin, Imad Ayoub, Nicholas Bailes, Stuart Bailey, Rob Baldock, Mike Banfi, Kathy Beadle, Kate Beattie, Nick Bertram, Dan Birch, James Bishop, George Bowman, Ian Braithwaite, Damien Bray, Jeffrey Brett, Charlie Bromwich, Aaron Brown, Anthony Buckley-Thorp, Claire Bulmer, Rob Burton, Rachel Capstick, Neil Carstairs, Rick Channa, Jonathan Chew, Alecs Chong, Warren Clark, Lucy Clinton, Charlie Collas, Sam Collins, Peter Connell, David Cormie, Paul Cross, Adrian Crowther, Beccy Cusworth, Phil De Jongh, Ahmed Dhorat, Shaun Dixon, Fatma Dogan, Sonia Duarte, Joe Dukelow, Damian Eley, Francisco Fernandes, Errol Fletcher, Emma Forde, Suzanne Freed, John Freeman, Malcolm Fullard, Dan Gallagher, David Glover, Sarah Glover, Peter Griffiths, Sarah Haughton, Nick Hayes, Mark Heath, Alexander Heise, Ashley Henley, Sylvia Hermann, Michael Heywood, Andrew Hibbard, Sean Higgins, Ed Hoare, Martin Holt, Fabien Humphery-Smith, Stuart Inglis, Colin Jackson, Paul Jeffries, Sarah Jones, Allan Jowsey, Tarsem Kainth, Gearoid Kavanagh, Adam Kelty, Katya Kolody, Amanda Kuffel, Andy Lambert, John Lange, Denise Lee, Linus Lim, Simon Lindop, Jonathan Lock, Tony Lovell, Chris Mackichan, Mei-Yee Man, Alastair McConville, Steve McKechnie, Ian McRobbie, Al Meghji, Chris Merrylees, Vahndi Minah, Maral Mitilyan, Hossein Motavelli, Jonny Murrells, Brian Murrihy, Owain Nedin, Chris Neighbour, Rowena Neighbour, Kylie Nixon, Chizoba Nwobodo, Rebecca O'Neill, Ender Ozkan, Henry Painter, Nick Parks, Anesh Patel, Dinesh Patel, Sheena Patel, Eleanor Patterson, Geoff Peattie, Adam Pearce, James Perry, Doug Pickering, Anton Pillai, Piotr Piorko, Aydin Pisirici, Jonathan Portlock, Cladio Pizzi, Juliet Raperport, Robert Read, Craig Rew, Grant Ridley, Charlotte Roben, Emily Roberts, Mark Roberts, Steve Roberts, Azreen Rosedy, Phill Rushen, Scott Sampson, Andrew Scott, Ed Shearer, Hilary Shields, Jon Shillibeer, Vaibhav Singhal, Mark Skinner, Katherine Smale, Rob Smith, David Stow, Vanessa Straker, Ryan Sukhram, Vaughan Sutton, Aoife Synnott, Henry Tayler, Alice Tedd, Pierre Verhaeghe, Harley Wade, Olivia Wall, Paula Walsh, Colin Waters, George Watson, Paul Webber, Ian Westmoreland, Peter White, Stuart Wilson, Ian Wise, Georgina Wong, James Woodcock, Malcolm Wright, Paul Wright, Rebecca Wright, Zhi Zhao.

Heron Tower

Location
City of London

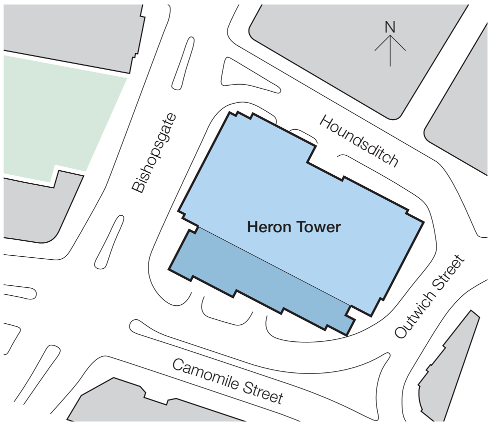
Authors
Dominic Munro Mark Richards Andrew Smith


1.

Introduction

Heron Tower is a new 47-storey speculative office development in the heart of the City (Fig 1) designed by Kohn Pedersen Fox Associates (KPF), and standing on an island site on Bishopsgate, 200m from Liverpool Street station (Fig 2). At 202m to roof level and 230m to the tip of its mast, it is currently one of the tallest completed buildings in the centre of the City of London, approximately 50m x 40m overall in plan, and with a distinctive rectilinear plan form. The total gross internal area, including basements, is around 66 000m².

The aspiration of the client, Heron London Properties Ltd, was for a "six-star" office building, to be one of the world's finest workplaces. The attention to architectural detail and the commitment to high-quality finishes reflect this aspiration. The building sets a benchmark in office design for sustainability, and obtained a BREEAM "Excellent" rating for its overall environmental performance.



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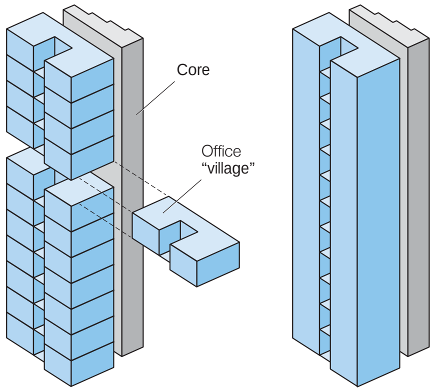
1. North facade, viewed from Bishopsgate.

2. Site plan.



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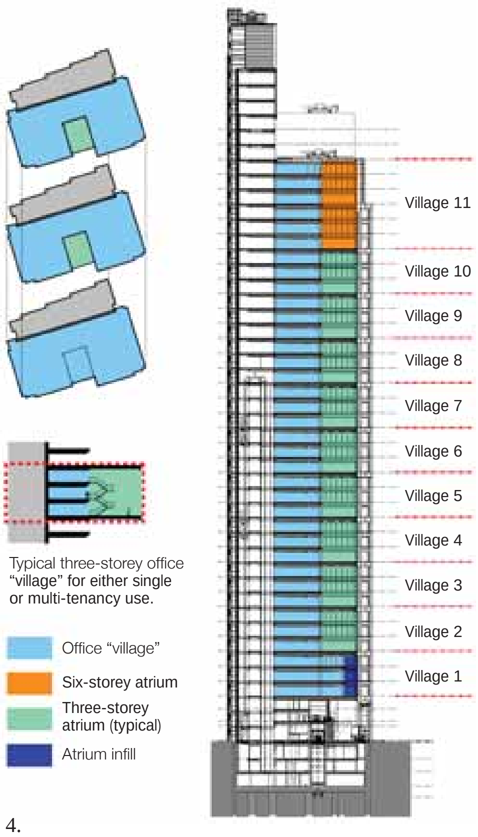


4.

3. The core contains essential services, and protects the office “villages” from solar radiation.

4. Section showing the building’s configuration.

5. The core is placed on the south façade and shades the floor plates from the heat of the sun.

6. East and north façades, viewed from Wentworth Street.

5.

6.

Arup was employed under a full suite of services including, and not limited to, civil and structural, geotechnical, fire, acoustics and vibration, highway, transport planning, CDM, security and communications, and IT.

The engineering and architecture of Heron Tower, its contribution to the public realm and its internal arrangement, have been influenced by the island setting of the site, bounded on all sides by existing highways.

The design responds to this location with an offset core on the south elevation, creating flexible and open-plan office floor plates that are naturally lit by a north-facing atrium. A three-storey "village" concept is articulated on the north elevation, aligning with the internal make-up and modulating the mass of the building (Figs 3, 4).

Responding in this way to the island nature of the site and the significance of the setting, the form of Heron Tower evolved through detailed dialogue between the architect and engineer.

Value through design

- Perimeter structure optimisation saved 900 tonnes of steel, equating to an 8% saving on the overall weight of steelwork without either adding complexity or reducing rationalisation.
- Substantial value stems from a design that incorporates within it a logic that allows basement construction and superstructure erection at the same time. Adopting a steel tube and top-down basement construction helped realise a programme on site that was six months shorter than a traditional bottom-up strategy.
- Arup's fire engineering strategy and detailed analytical studies demonstrated the building's fire performance with reduced fire protection. Accepted by the City of London Building Control, the strategy provided significant savings to the client on the provisions for fire protection to the structure.
- Careful strategies for all aspects of the Arup designs were prepared early in the design process. These strategies formed the basis for design development, and formed a strong base for others to develop their designs. This strategic approach to design influenced the timely delivery to a tight programme.

Responding to the site

The guiding principles sought a building that could stand alone on the local scale, contributing to the overall cityscape profile and to the future consented composition of the tall buildings cluster that also includes the Pinnacle (pp77-84), the Leadenhall Building (pp67-76), and 30 St Mary Axe (the "Gherkin") – all engineered by Arup.

Early ideas for the site considered buildings configured around a central core, a form commonly used for tall construction. This however, alongside the finite constraints of the island site, gave poor floor space efficiency and placed the building façades too close to the highway edge, minimising the benefits to the public realm.

The team realised that a different approach was required, and developed a solution that placed the principal stability element of the building to the perimeter of the office floors using a steel frame "tube", with the lift and stair core offset along one elevation. In addition, placing the core to the south gave an orientation that shields the floor plates from direct sunlight, and an architectural composition in which each elevation is visually different (Figs 5-6).

Another benefit of moving away from the central core approach was to enhance the internal environment with natural north-light penetrating the glazed façade deep into the office floors. The ground level space also benefits from the ability to maximise visual transparency through the building onto the enhanced public realm.

Structural solution

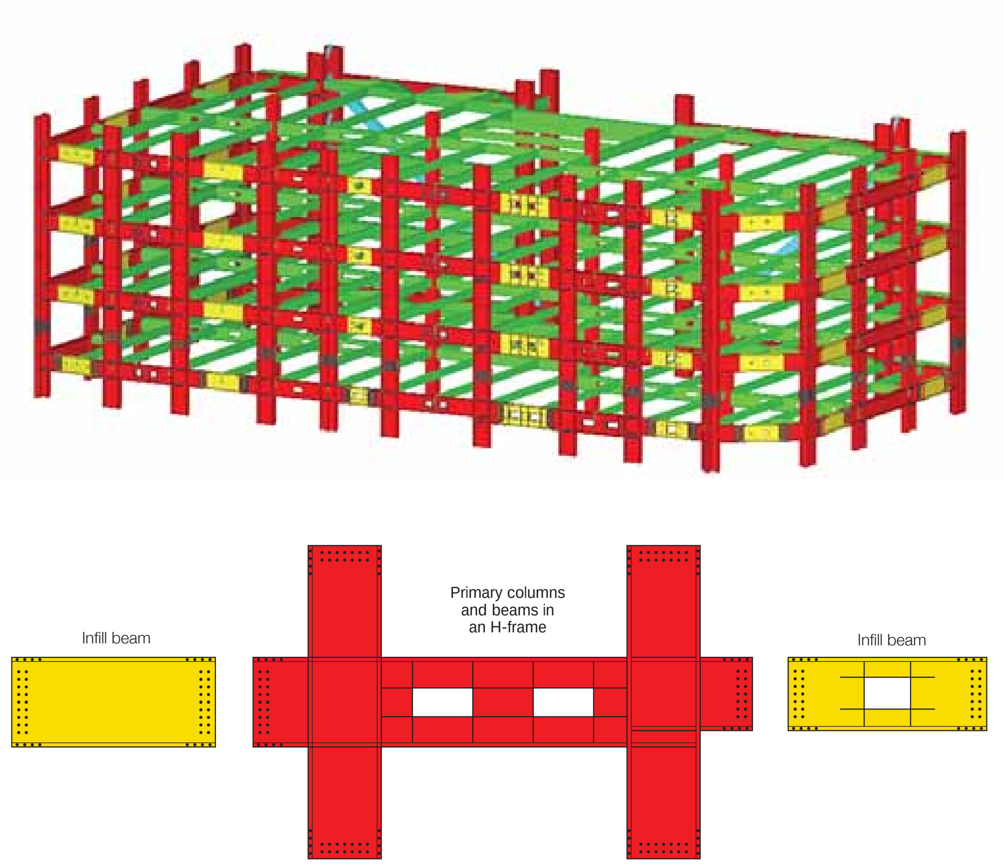
The tube structure derives benefits from efficiencies achieved by placing stability forces on the outer perimeter, combined with the resistance to overturning obtained in part from the building's self-weight. Although the stability tube encloses the perimeter of the office floor plates, the structural engineering strategy incorporates an arrangement that allows the three-storey "village" theme to be defined within the architecture. At the north face the tube form is modified, with diagonal elements incorporated in place of the regular frame pattern provided to the other three elevations. A further architectural detail is possible from the discontinuity of the tube within the north elevation, aligning with the zone of the building that receives north light into the office floors.

7. The “kit of parts” forming the steel frame stability “tube”.

8. South façade, containing photovoltaic cells and glazed lifts, viewed from Camomile Street.

9. Finite element soil-structure interaction model.

10. Excavation in progress.



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The discontinuity in the north side of the tube means that the stability system is essentially a “channel” or “C-section” in plan, with its centre of stiffness closer to the southern side. This complements the building plan shape, which has the south lift and stair core cantilevered off the back of the stability tube, whose centre of stiffness is hence relatively close to the centre of mass of the building. Stability to the south core is provided by the cantilevering concrete deck slabs, with the steelwork framing connected to it and the stability tube for restraint.

The stability tube design as eventually built comprised H-frames with infill connections (Fig 7). To ensure close fit on the column-bearing surfaces, much better fabrication tolerances were needed than were specified in the tender. However, this was proved to be achievable through a trial erection.

All floors are connected to the stability tube, with the inter-village floors (ie those between each “village” group of three storeys) also providing restraint to the north elevation of the tube across the atrium north-light gap. The atrium floors link into the tube structure in a similar way to the inter-village arrangement, but their northern face is separated from the tube over the width defined by the diagonal struts.
To provide restraint to these floors along the north face, a “ladder frame” arrangement is incorporated to the western and eastern flanks, which span vertically between the inter-village floors.

Above the 36th storey the building profile changes, reducing in width to follow a stepped pattern, again on a three-storey incremental basis, towards the 48th storey. This region houses restaurants and bars offering views across London, with the uppermost floors occupied by lift motor rooms and plant space.

The structural arrangement also changes over these storeys, taking a different form from the stability tube layout below.
Here, the stability system comprises bracing interconnecting each of the floors to form, in effect, a 12-storey braced frame structure on top of a 36-storey tube-stabilised frame, with all load transfer from the top segment delivered effectively into the south side of the tube; the south core columns extend the full height of the building.

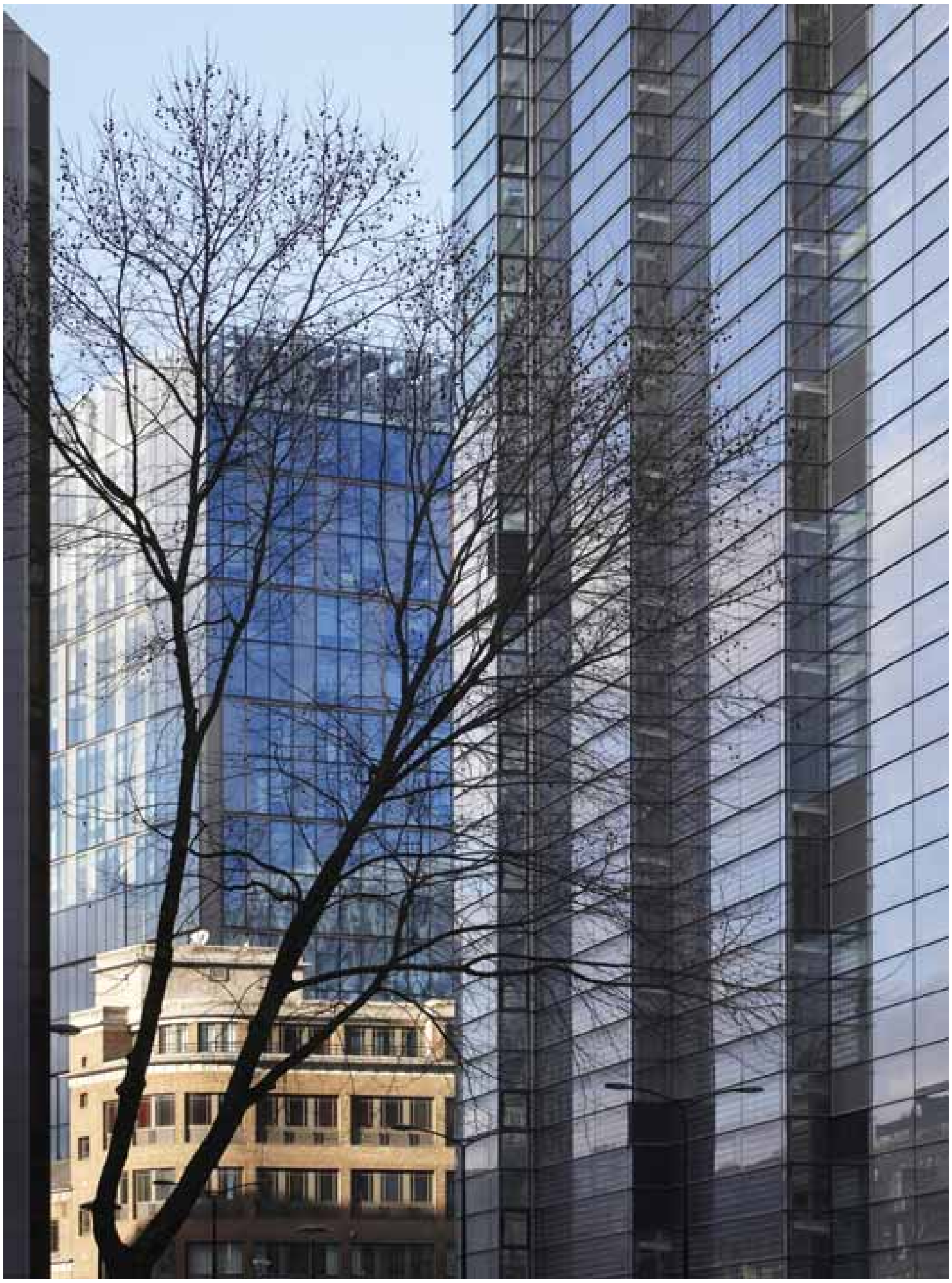
The tube structure was optimised for stiffness under lateral load. This was far from straightforward as many permutations existed of possible locations where stiffness could be added within the tube, with the effectiveness of each option interdependent with the others. Arup developed an iterative computational method for satisfying the stiffness performance criteria, using the cross-strain energy density virtual work approach as a way to evaluate the most effective location for changes to steel plate thickness at each step.

This analysis was linked to *Tekla* software, so that changes to the structural model could be automatically updated. This required substantial work with *Tekla* as the section components on the Heron Tower are not standard, but the valuable relationship with *Tekla* enabled the team to reach a solution.

Foundations and buildablity
Resolving the tube structure approach as it pertained to the basement, the ground conditions, and the need for a construction method to retain the ground, led to a solution that placed the outer stability frame over a continuous secant piled wall. Columns within the area of the tube, and those to the south core framing, could then be placed over a separate system of foundations, allowing the dominant part of the stability forces to remain relative to the secant pile wall.

A natural logic to the structural engineering emerged from these decisions, which associated the dominant elements of the tower stability frame with the earliest phases

7.



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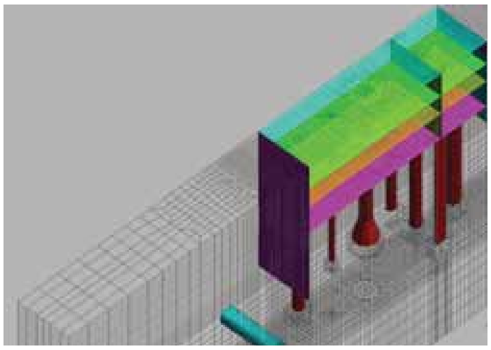

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10.

of the new basement construction activities. With the ability to start construction of substantial elements of the tower stability early, relative to the basement, and with the knowledge that all other columns would receive only vertical forces, strategies for top-down construction became attractive. And, with the understanding that top-down is a process involving assembly of the basement floors with advancing excavation, construction of each floor in sequence with increasing depth benefited the stability and strength of the perimeter secant wall.

The logical outcome was to align the sequence to accommodate basement construction concurrently with assembly of the steel frame, further gaining efficiencies to the build time.

The inner and core columns, supporting a great proportion of the building, require their own dedicated foundations to accommodate tower construction alongside the basement top-down. With these columns needing to be in place for the full depth of the unexcavated basement, the solutions derived – given the ground conditions – consolidated into two categories: (a) dedicated piles to accommodate all loads regardless of construction stage, or (b) a foundation that could respond to the sequential construction and thus the incrementally progressive load demand.

The first of these involved piles extending to the chalk at a depth of about 70m from ground level, but the second could be achieved with a composition of piles to receive the forces from the earlier stages of construction, later combined with the lowest basement level slab distributing forces to the ground as a raft. The latter solution was adopted, with the eventual benefit that no part of the basement or foundations goes deeper than the London clay, around 35m below ground level.

The capacity of these foundations mostly drove the strategy for buildability, with the sequencing chosen to reflect logical steps around the top-down approach. The team analysed and designed the foundations taking each construction phase into consideration, together with careful determination of the forces applied from the tower to account for the range of activities occurring in time (Fig 9).

11.

1) Lower capping beam

Reinforced concrete beam constructed over head of secant pile wall; king post wall behind retaining undisturbed ground to pavement and road beyond.

Function: Receives stability tube and ground floor framing.

2) Ground floor steel beams

Construction of ground floor steelwork, connected to three-storey columns placed with the shafts to main large diameter piles and supported via lower capping beam.

Function: Facilitates construction of ground floor slab.

3) Stability tube framing

Construction of stability tube framing up to second floor (three-storey height length); base of frame placed over lower capping beam; construction of second floor framing also carried out at this stage, with ground and second floors in place before commencing top-down excavation of basement.

Function: Forms platform to tower base, comprising ground and second floors; props secant wall at ground level.

4) Slab construction and upper capping beam

Reinforced concrete slab construction to ground and second floors; slab construction comprising concrete on metal profiled deck, with shear studs to steel beams; slab completes diaphragm function of these floors.

Ground floor slab and upper capping beam form integral element at their interface.

Function: Completes base segment of the tower.

5) Basement levels

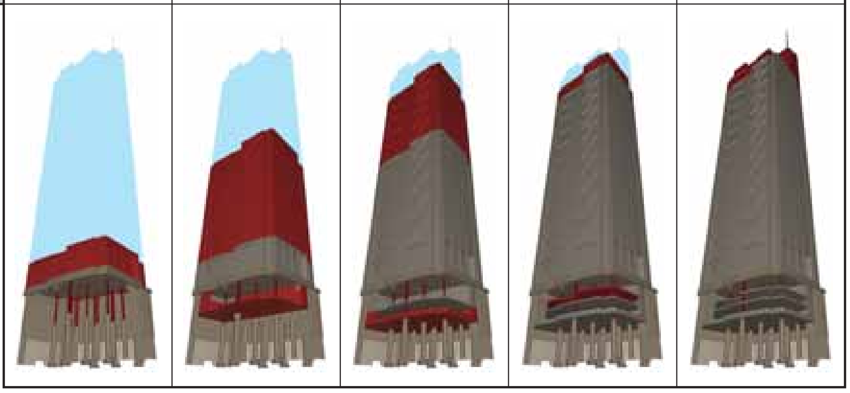
With the ground and second floor structures in place, incorporating the completed tube structure up to the second floor, basement excavation and superstructure construction can begin:

- excavate to level B2 (two levels below ground) and construct B2 reinforced concrete slab
- construct liner wall between B2 and ground floor
- excavate to underside of B3 (basement raft) and construct raft and remaining liner wall
- construct basement level B1.

Function: Each successive basement slab provides for propping to excavation, with the liner wall integral to stability of tower construction.

12.

	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Key stage	Construction of ground and second floors and associated tube structure	Excavation to level B2; construction of B2 slab, liner wall and spine wall to ground	Excavation to level B3; construction of B3 raft, liner wall, and spine wall to B2	Construction of level B2 slab	Complete tower construction
Key design item through construction	Stable base to tower, integral with capping beam delivering stability forces to secant wall	Unrestrained column length to basement; delivery of stability forces from tower to liner wall and spine wall system	Load share between building pile foundations and basement raft at B3	Unrestrained column length in basement	
Basement excavation	Existing basement level	Excavation to level B2	Excavation to level B3 raft soffit	Excavation complete	Basement complete
Limit of superstructure construction	Complete ground and second floor structure before excavation begins	Level 18	Level 32	Level 36	Complete frame



13.

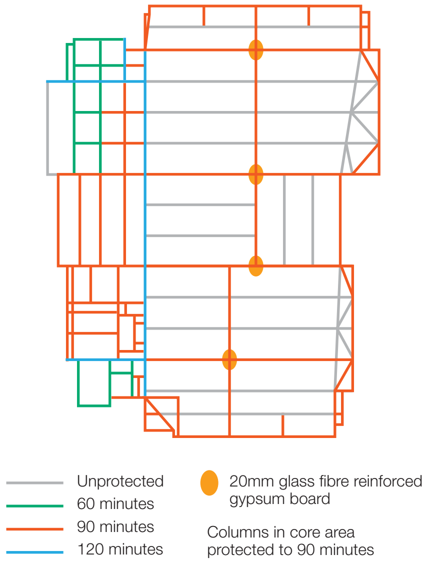
11. West façade, showing the office façade (left), the sky lobby and stair façades (right), and the spire.

12. Basement construction sequence.

13. Construction sequence of the primary components.

14. Fire protection times of primary beams of typical atrium floor.

15. North and west façades.



14.

15.

This analysis involved replicating the phasing using a finite element soil-structure interaction model of the basement and associated force sequences from the tower. The outcome was a detailed understanding of the effect and distribution of the forces, and the load share that takes place between each of the foundation parts through all construction phases, as well as over the long term. With the key constructional decisions made, the construction sequence was intuitive (Figs 12, 13).

With the finished building occupying the full site and bounded by a congested road network, the steel frame's construction speed and crane time were of critical importance. The erection of the perimeter tube was studied in depth, comparing double-storey lifts of columns against the single-storey interconnected H-frames already described (Fig 7). The latter had the advantage of being stable in one direction, and reduced the number of site connections by one per lift.

The sections were delivered to site in 18 tonne units on bespoke trailers and lifted directly into place. Prefabrication played a vital role in the contractor's construction programme and significantly reduce his programme risk and that of the client.

Fire engineering

Arup designed the building's fire engineering strategy, and undertook detailed analytical studies to demonstrate fire performance with reduced fire protection. Accepted by the City of London Building Control, the Arup-devised structural fire protection strategy provided significant savings to the client; for example, on a typical floor all the secondary beams are not fire-protected while the primaries only require 90 minutes' protection.

Heron Tower has two atria, one three-storey and one six-storey. Occupants on all the floors connected to either atrium will be evacuated simultaneously. The tenant will be given freedom to enclose the atrium or not. There is no smoke reservoir in the top of the atrium to delay the time it takes for smoke to re-enter the office accommodation at the upper levels, so *BS5588: Part 7*[1] would normally require the uppermost levels of the atrium to be separated from the office accommodation by smoke-retarding construction. In the case of Heron Tower, the tenant is give freedom to keep the office open to the atrium if they so desire, hence the top level could be open to the accommodation rather than being provided with smoke separation.

CFD modelling was undertaken to assess whether the upper storeys of the three- and six-storey atria needed to be enclosed in order to prevent smoke spreading back onto the upper storeys and protect evacuating occupants at these levels. The assessments compared a fire on a floor with no atrium with a fire spreading smoke in a three or six-storey atrium to the top floor open to the atrium.

The results showed that the visibility criterion was the first to exceed the agreed limits, but conditions in the three or six-storey atria single-storey model were always found to be significantly better than conditions in the "benchmark" single storey. The atria thus did not need smoke to be separated from the upper office levels, as there was no reduction in the level of occupant life safety in the building from smoke spread. This methodology, the type of models run, the input data, and acceptance criteria were previously agreed with the District Surveyor.

16. North façade, viewed from Bishopsgate.


16.

Conclusion

Heron Tower was completed and opened in March 2011. In addition to the 36 floors of office space and restaurants and bars both on the ground floor and at the top, the building accommodates the UK's largest privately owned aquarium. The building was favourably received, with comments including those of Kieran Long in the *Evening Standard*: *"It is the building's decent relationship with street level that I think makes it interesting and praiseworthy... this is an office building looking to the future of the city around it."*

In April 2012 Heron Tower was named Best Commercial Workplace at the British Council for Offices London & South East Awards. Commenting on the award win, Peter Ferrari, Managing Director of Property Development at Heron International, said: *"From the building's exceptional location at the heart of the City, to the emphasis on quality and design, right through to the unique features such as the aquarium in the lobby and the high speed, fully glazed, double-deck lifts, Heron Tower is a truly special building and we are delighted that this has been recognised by the British Council for Offices Awards."*

Authors

Dominic Munro is an Associate in the London office, and led the substructure design for the Heron Tower project.

Mark Richards was an Associate in the London office. He was Project Manager for Heron Tower.

Andrew Smith is an Associate in the London office, and was senior engineer for the Heron Tower project.

Project credits

Client: *Heron London Properties Ltd* Architect: *Kohn Pedersen Fox Associates pc* Structural, civil, geotechnical, fire, acoustics and vibration, highway, transportation, CDM, security, communications, and IT services engineer: *Arup* Building services engineer: *Foreman Roberts* Quantity surveyor: *Davis Langdon* Project manager: *Mace Ltd* Main contractor: *Skanska Construction UK Ltd*.

Image credits

1, 5-6, 8, 11, 15-16 *Hufton + Crow;* 2-3, 14 *Nigel Whale;* 4, 7, 12-13 *Arup/Nigel Whale;* 9-10 *Arup*.

The following Arup staff members are among those who made significant contributions to Heron Tower:

Ikechi Ajoku, Andrew Allsop, Stuart Bailey, Paul Baralos, Monika Beyersdorff, Graham Bolton, Nick Boulter, David Boyd, James Bradley, Ian Braithwaite, David Brede, Harry Bridges, Darren Briggs, Simon Cardwell, Jonathan Chew, Ken Coffin, Clare Courtney, Stuart Cowperthwaite, Helen Crosby, Paul Cross, Pat Dallard, Michael Davis, Brian De Mello, Sonia Duarte, Stephen Duffy, Ian Feltham, Anthony Ferguson, Tom Fernando, Graeme Flint, Jue Jue Foo, Ben Francis, Rob Garrad, Nick Gillespie, Lesley Graham, Helen Groat, David Hadden, John Haddon, Barnaby Hall, Genevieve Hallam, Mark Heath, Alexander Heise, Andrew Hibbard, John Higginson, Andrew Holland, Kate Horsfall, David Hsu, Rory Huston, Stuart Inglis, Stuart Jenkins, Richard Johnson, Vicent Jurdic, Richard Kent, Andy Lambert, Barbara Lane, Mani Manivannan, Barbara Marino, Lisa Matthews, Karen Mayo, Damian McAuliffe, Tim McCaul, Dominic Munro, Luis Navarro, Rob Nield, Sotirios Nikologiannis, Joe Nunan, Hayden Nuttall, Bryan O'Mahony, David Oppenheim, Ender Ozkan, Dinesh Patel, Joe Paveley, Adam Pearce, Adam Pellew, Pietro Perelli-Rocco, Anton Pillai, Adrian Popplewell, Mark Poynter, Kash Qadeer, Nina Quarshie, Jim Read, Mark Richards, Charlotte Roben, Denis Romanov, Thomas Ronholt, Manan Shah, Sarah Sivyer, Andrew Smith, Jim Stewart, David Stow, Ryan Sukhram, Vaughan Sutton, Ciaran Thompson, Paul Thompson, Cristina Vanella, Suzanne Walker, Mick White, Matthew Wilkinson, Mike Williams, Paul Williams, Derek Woodcraft, Philip Wright, Peter Young, Tay Young, Jason Zawadzki.

Shard London Bridge

Location
London Borough of Southwark

Authors
Graeme Flint David Healy Adam Monaghan

1.

Introduction
Designed by Renzo Piano Building Workshop (RPBW) and, at 310m, Western Europe's tallest building, the Shard London Bridge is a model for densely-packed, low-energy, mixed-use development. Located above the transport hub of London Bridge station, the Shard's lower levels house a retail area and 25 floors of commercial offices, the mid-levels contain three floors of restaurants and a 17-level hotel, while the top of the building comprises high-end residential apartments and public viewing galleries. The mixed variety of uses and complex geometry of the Shard, with floor plates and structure that differ on every level, presented some unique environmental and servicing challenges.

Sustainability
The conceptual design for the Shard (previously known as London Bridge Tower) was completed between 2000 and 2002, and thus predated the 2003 introduction of the first prescriptive planning policy in London to require a percentage of a building's energy needs to be provided by on-site renewable generation[1]. This was also before the 2006 edition of *Approved Document L2A* of the Building Regulations (conservation of fuel and power)[2].

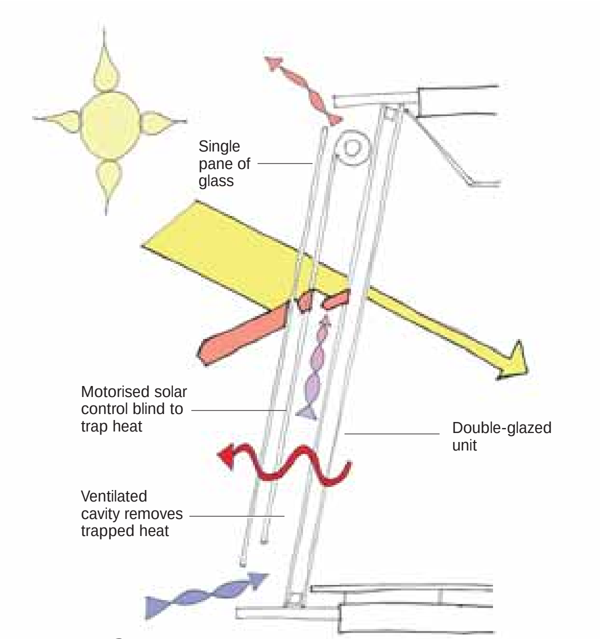
Arup had been engaged as multidisciplinary building services engineer and specialist lighting and communications consultant. Aware of these impending changes, the team set about anticipating the new standards at

1 (previous page). The Shard in its setting south of the River Thames, structurally complete in May 2012.

2. Cross-section through the triple-skin façade.

3. Façade elements being installed near the top of the building.

4.The Shard in late 2011, illustrating ongoing construction of the Spire while the lower levels are largely complete and commissioned.



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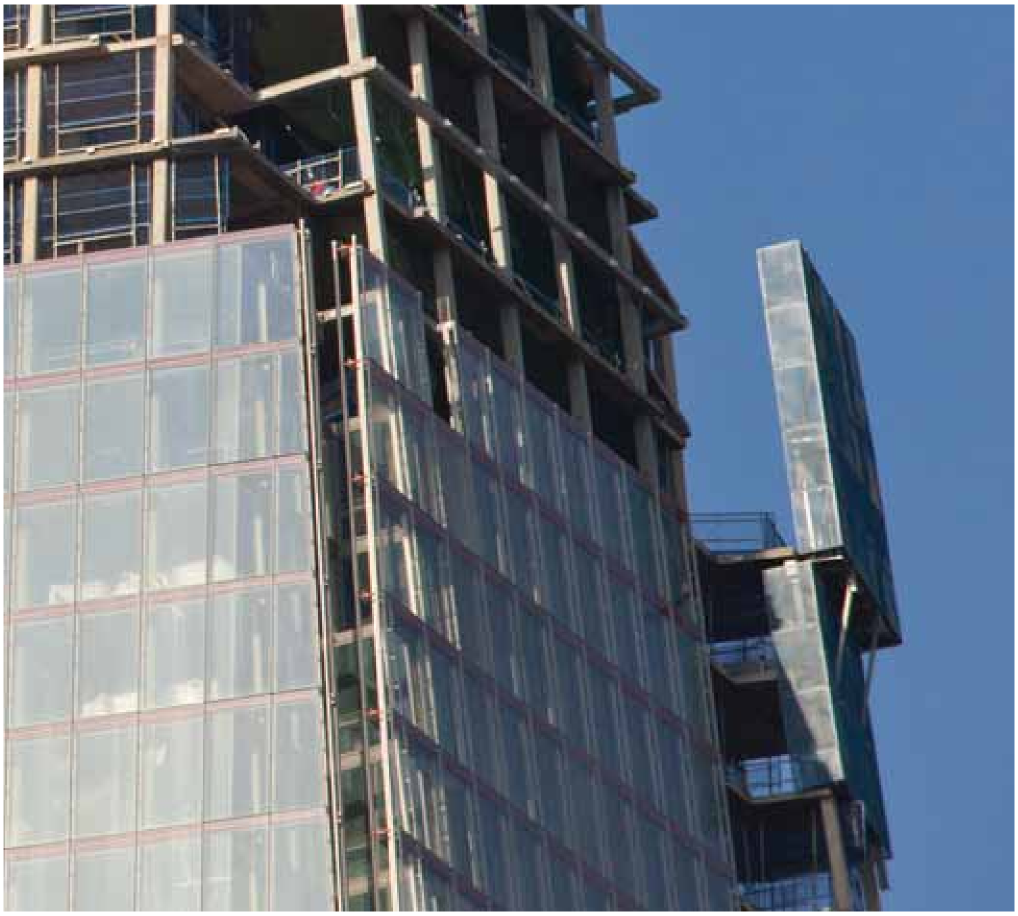

3.

the concept stages so that the building would not be outdated by the time of its construction. These measures substantially contributed to the view of the public enquiry into the planning application, which announced when granting full permission in 2003 that the Shard was a building of the “highest architectural quality”.

The most innovative example of energy reduction – conceived during the initial design stages and rigorously carried through to construction – is the façade. It entirely consists of glazed modules (in excess of 10,000), making the building subject to high levels of solar gain. To counteract this, a triple-skin glazing system is used, comprising a single pane on the outside, then a ventilated inner cavity housing a motorised solar-control roller blind, and finally a double-glazed unit on the inside (Figs 2-3).

An intelligent blind control system tracks the position and intensity of the sun so as to deploy the blinds only when needed.
This minimises the cooling loads, giving an associated efficiency in plant and riser space – a key consideration in tall buildings with limited floor plates and high rental values. Because of the deployable blind, the glazing itself does not have to perform as significant a solar control function, and this allows it to be more transparent. This in turn improves the daylight penetration and gives the building a clear and light appearance, as well as reducing the amount of time when artificial lighting is required.

The triple-skin glazing units have a U-value (an indicator of the extent of heat loss through the façade) of 1.4W/m^{2}K. The aim was for the façade to improve by 25% upon the then regulatory minimum, 2.2W/m^{2}K, and that this would be the façade’s contribution to the expected 25% reduction in energy required by the impending 2006 Building Regulations update compared with the 2002 levels.

Notably, the façade performance is also compliant with the recent 2010 revision to *Approved Document L2A*[3]. While the 2006 edition merely required buildings to demonstrate that they did not overheat (which in an air-conditioned building like the Shard is easily achieved through the appropriate design of the air-conditioning system), the 2010 edition placed limits on the amount of solar gain through the façade.

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The requirement is that the solar gains are less than those through a notional east-facing facade with 1m high glazing across its full width and with a g-value (a measure of the solar radiation passing through the façade) of 0.68, when averaged over the summer months. Many people have assumed that this requirement would herald the demise of fully-glazed façades, but the Shard's active system has an effective g-value (with the blinds down) of 0.12.

The control system is currently programmed to lower the blinds when the incident solar radiation reaches 200W/m^2; under this configuration the solar gains would be slightly more than allowed by 2010 regulations. However, by reducing the solar radiation set-point to 180W/m^2 on certain parts of the façade (lowering the blinds an hour earlier in the morning and raising them an hour later in the evening during peak summer days only), the Shard façade complies with the stringent 2010 requirements – quite an achievement for a building whose design commenced 12 years prior to its planned completion.

Mixed-use building and fire engineering

While its height and iconic shape define the Shard as an unusual building, in engineering terms the variety of space uses also contribute significantly to the design solutions, especially when considering the diverse energy profiles and fire engineering requirements.

Because of the variety of uses within the building and the relationship of the spaces to each other, the fire engineering strategy had to provide an enormous degree of flexibility. If standard design codes for fire engineering had been followed to the letter, the Shard would never have been built, but Arup's design offered robust escape routes and evacuation strategies without compromising the architectural vision or the targets for net floor area.

For mixed-use buildings, regulations typically require designers to provide separate stairs for separate uses. The Shard's viewing galleries, apartments, hotel and office spaces would all have needed their own escape stairs, implying as many as eight sets of stairs – two for each area. The fire engineering design behind the escape strategy, however, reduced these to just three, one of the main reasons being the use of the lifts as a primary means of escape. High-capacity evacuation lifts supplement the stairs, particularly from the restaurants and high-level viewing galleries where there may be more people than the stairs could otherwise cope with. For the lower levels, the stairs are used. The Shard is the first tall building in the UK to use lift evacuation for fire escape in this way.

To create this cutting-edge fire strategy for the Shard, the team drew on Arup's experience of other tall buildings around the world, bringing to the UK market techniques used successfully elsewhere. This involved detailed analysis to establish how wide staircases needed to be, how fast lifts should travel, and how large refuge areas should be – all enabling development of an efficient fire strategy that makes the best use of the building's spaces.

For example, the team employed evacuation analysis to understand how long it would take people to move into the staircases, while in parallel analysing the available safe egress time, so as to establish at what point conditions would become too hazardous for people to remain in each part of the building.

Renewables

Incorporating renewable technologies in cities is often a challenge due to the spatial constraints of dense urban environments. This is particularly the case for tall buildings, whose small footprints and high energy demand tend to exacerbate the situation. However, the Shard's mix of uses have various energy demand profiles that peak at different times of the day, creating an ideal scenario for a combined heat & power (CHP) plant.

CHP involves local generation of heat and electricity (like a small-scale power plant within the building), which can achieve efficiency savings over the use of grid-supplied electricity, due to the reduced transmission losses. The more the CHP operates, the greater the savings, and so a mixed-use building with a more constant heat load is the ideal application to achieve carbon savings.

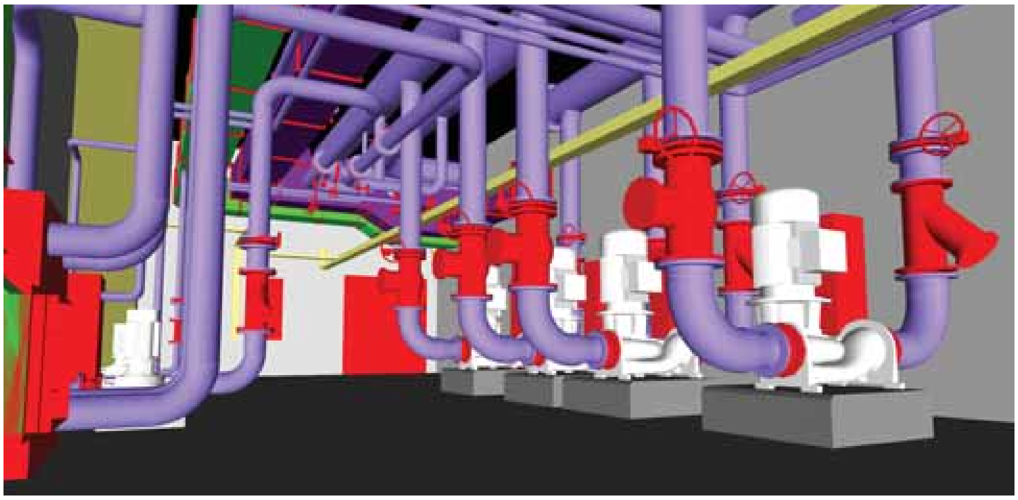
5. 3-D model of condensor water pump sets.

6. Actual installation of condensor water pump sets.

7. The Spire service modules had to be craned into position over 250m from the ground for final assembly.

8. Services for the Spire at the top of the building were assembled off-site in three-storey modules.

9. The completed building.



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Delivery

A key measure of building efficiency is the net-to-gross ratio, indicating how much of the gross area will be lettable once the space requirements for circulation, toilets, risers, plantrooms, and other functional requirements have been taken into account. The higher construction costs (per unit floor area) for tall buildings compared to low-rise means that the net floor area must be maximised, and achieving high net-to-gross ratios is often the key to the financial viability of such projects.

A skyscraper's typical geometry is tall and rectilinear, whose plot at ground level has been extruded upwards to maximise the available area. The Shard's iconic tapering shape makes it anything but typical, and its geometry required a different approach compared with the inherent efficiencies of repetitive and rectilinear floor plates.

This created additional pressures on plant space, and the Arup team worked extremely hard to achieve efficiencies in designing MEP systems that greatly increased the net-to-gross ratio beyond what would otherwise have been achievable. This had a critical role in allowing the building to rise out of the ground at all.

Besides the reduction in plant and riser space due to the innovative façade shading system, the other major contributor was the high degree of co-ordination in the plantrooms' design, to ensure that services would fit with the modest space allocation. To this end, all plant areas were drawn with a 3-D computer-aided design package (Figs 5-6), and these models were then developed by the contractor as part of the off-site assembly

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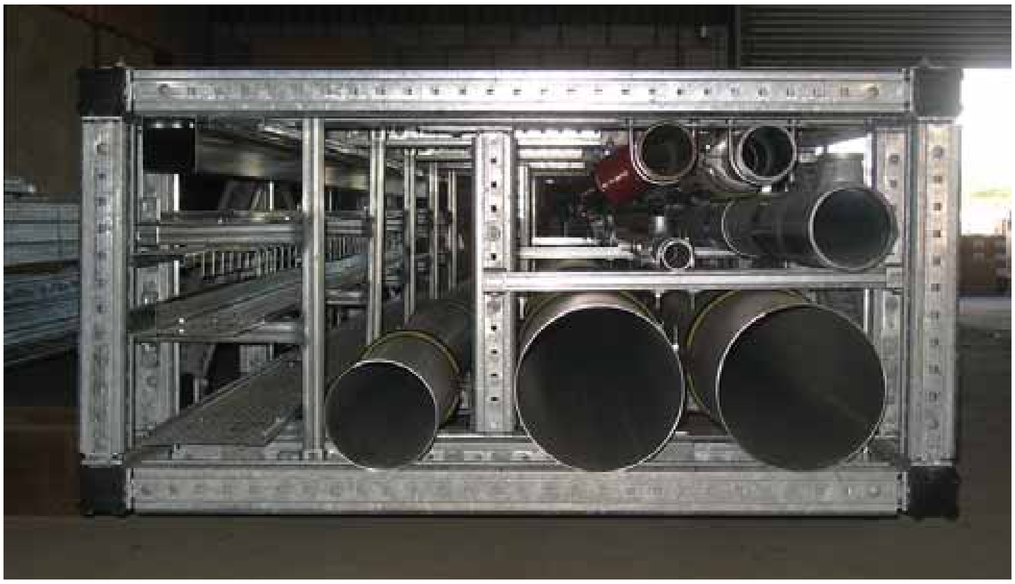

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process, whereby large elements of the services were delivered to site pre-installed on framework and bolted together in situ (Figs 6-7).

While this meant that the team had to release construction information to the contractor much earlier than usual, the benefits were a significantly reduced construction programme and the immeasurable health and safety benefits of large amounts of work being done off-site in factory conditions, especially for the area at the top of the building (the Spire), which extends above the public viewing galleries and is open to the elements (Figs 7-8).

Another aspect of the MEP design to benefit the programme is the arrangement of the plant floors and the servicing strategy. The early concept design identified the value of having mostly separate plant levels for the different space uses: thus the lower office levels are separated from the restaurants and hotel by plant levels, with further plant levels separating the hotel from the apartments, and the apartments from the viewing galleries.

While these intermediate levels also serve to provide pressure breaks for the hydraulic pipe systems, they allow different areas of the building to be independently operated and – crucially for the construction programme – could be independently commissioned. For example, the MEP installation was mostly completed by late 2011 and commissioned up to plant level 30 (just above the office levels), despite the fact that construction of the Spire had yet to be completed. This sectional completion and commissioning of the building meant that it could be finished in an orderly fashion, without the usual last-minute peak in construction activities.

Conclusion

The hotel fit-out began in January 2012 and is scheduled to last for approximately one year. The fit-out of several show apartments and large areas of the offices is already finished ahead of the scheduled practical completion of the shell-and-core works in September 2012.

Project credits
Client: *Teighmore Ltd*; Developer: *Sellar Development Services*; Architect: *Renzo Piano Building Workshop*; Executive architect: *Adamson Associates*; MEP, fire, communications, and specialist lighting engineering design: *Arup*; Structural engineer: *WSP Cantor Seinuk*; Main contractor: *Mace Ltd*.

9.

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Graeme Flint is a senior engineer in the Edinburgh office, and was Project Manager for the fire safety design of the Shard.

David Healy is an Associate Director in the London office, and was Project Manager for the Shard during its construction phase.

Adam Monaghan is an Associate Director in the Manchester office, and was Project Director for the fire safety design on the Shard.

Image credits
1, 3-4, 9 *Thomas Graham*; 2, 5-8 *Arup.*

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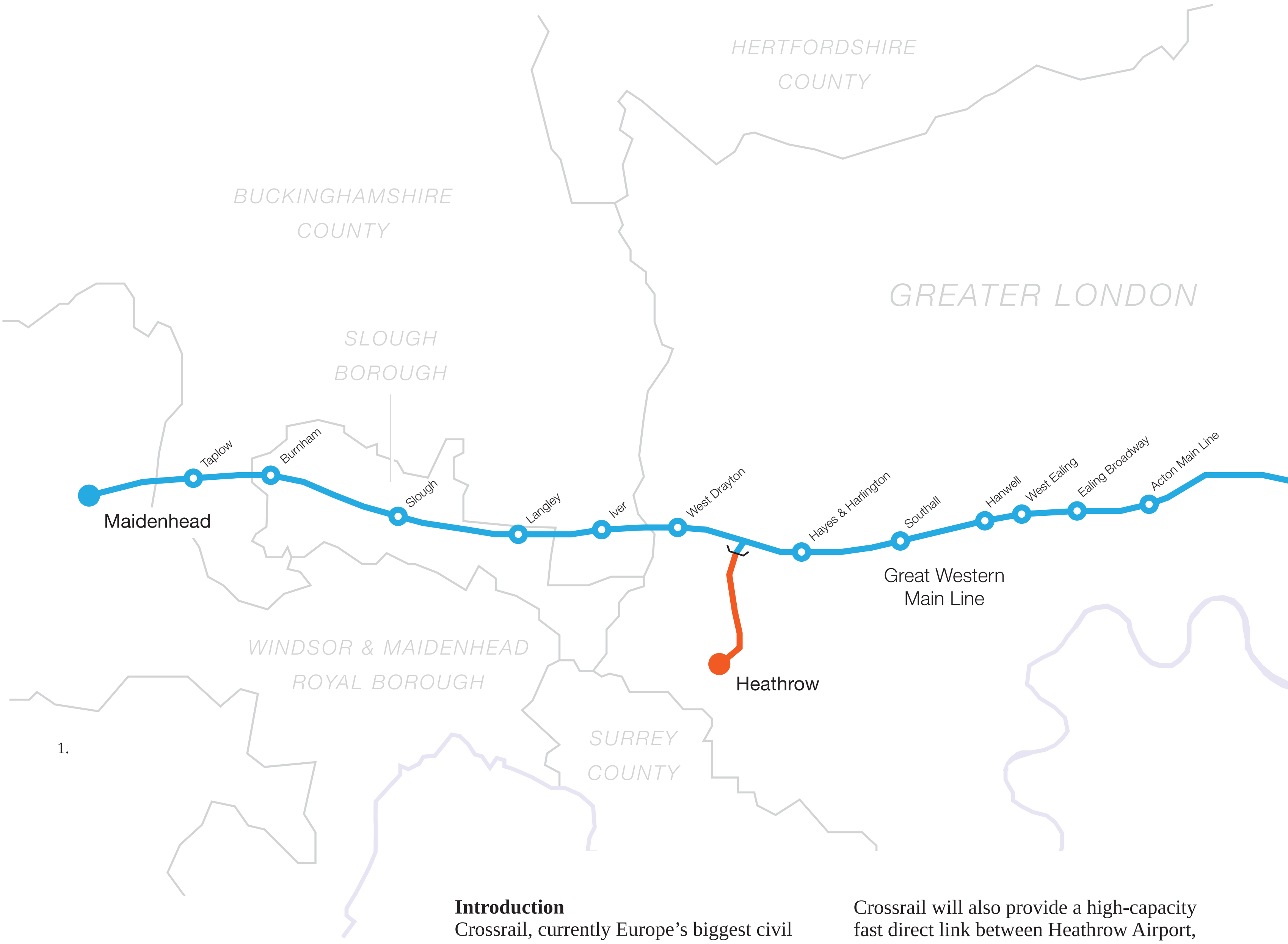
(1) http://en.wikipedia.org/wiki/The_Merton_Rule

(2) OFFICE OF THE DEPUTY PRIME MINISTER. The Building Regulations 2000. Conservation of fuel and power. *Approved Document L2A*. Conservation of fuel and power in new buildings other than dwellings: 2006 edition. NBS, 2006. www.thenbs.com

(3) HM GOVERNMENT. The Building Regulations 2010. Conservation of fuel and power. *Approved Document L2A*. Conservation of fuel and power in new buildings other than dwellings: 2010 edition incorporating further 2010 amendments. NBS, 2010. www.thenbs.com

The following Arup staff members are among those who made significant contributions to the Shard project:

Sacha Abizadeh, Jim Aitken, Ikechi Ajoku, Khaled Abou Alfa, Adam Alexander, Oli Andraos, Paul Andrew, Sam Arogundade, Fawaz Aslam-Pervez, Lloyd Bair, Scott Bambling, Bibi Banjo, Steven Barry, Ben Barry-Otsoa, Stephen Barty, Sam Beaumont, Jason Bennett, Peter Berryman, Hay Sun Blunt, Vicky Boles, Daniel Brace, Kevin Burke, Tony Campbell, Robert Carmichael, Lee Carter, Kitman Chan, Valerie Chan, Ronald Chaplin, Jerzy Chorazak, Paul Coe, Judy Coleman, Matt Collin, Paul Cosgrove, Daniel Costelloe, Martin Coulstock, Dominic Coyle, Arfon Davies, Anna Davis, Vipul Dudhaiya, Saa Dunbar, Guy Edwards, Pip Edwards, Geoff Farnham, Anthony Ferguson, Graeme Flint, Martin Foster, Suzanne Freed, Andrew Freezer, Francesca Galeazzi, Anne Gilpin, Vullnet Gjakolli, Dane Green, David Green, Tony Greenfield, Ross Griffiths, Ian Griggs, Alistair Guthrie, Ben Hall, Margaret Hamilton, David Healy, Rob Henderson, Stephen Hill, Neil Hitchen, Nick Howard, Dan Ingall, Tim James, Rishi Jobanputra, Andrew Jones, Lyudmila Jones, Beijhan Keenan, Amruta Kelkar, Tina King, Chris Kinnaird, Dogan Kozan, Mikkel Kragh, Luke Kubicki, Laszlo Kutas, Will Laird, Barbara Lane, Marina Laskari, Tom Leggate, David Lester, Colin Leung, Kevin Luske, Iain Lyall, James Mackenzie, Melissa Mak, Ed Matos, Toby McCorry, Gordon McDonald, Harriet McKerrow, Peter McKiernan, Stephen McClean, Laura McClellan, Robert Mitchell, Steve Mitchell, Adam Monaghan, Chris Moore, Sandra Murray, Graham Naylor-Smith, Guri Neote, Nick Offer, Simon Oliphant, Teresa O'Neill, Ronan O'Shea, Anthony Page, Kalpesh Patel, Dean Payne, Elisabeth Peacock, David Penn, Richard Pinder, Harris Poirazis, Adam Power, David Pritchard, Wasif Qadeer, Chris Radley, Sylvane Rajaratnam, Laurence Reed, Ricky Reynolds, Stuart Rich, David Richards, Colin Roberts, Mike Roberts, Prakash Sabapathy, Stefan Sadolierski, Amir Saif, George Shantonas, Mueed Sheikh, Any Shen, Martin Shouler, Annalisa Simonella, John Singleton, Rob Slater, Jamie Stern-Gottfried, Les Stokes, Joe Sumners, Tih Nee Tan, Valerie Thomas, Ayman Toema, Julie Wainwright, David Waring, Chris Watts, David Wheatley, John Williams, Mike Williams, Peter Williams, Colin Winant, Craig Winter, Chris Wood, Darren Wright, Tobty Wright, Mike Young.



1.

Crossrail

Planning and designing London's new railway

Authors
Mike Byrne Peter Chamley
Duncan Nicholson Duncan Wilkinson
Graham Williams

Introduction
Crossrail, currently Europe's biggest civil engineering project, is being built under central London to link existing Network Rail lines to the east and west of the capital. When it opens in 2018 it will provide rail services from Maidenhead and Heathrow in the west to Shenfield and Abbey Wood in the east.

Although significant remodelling work is required to the outlying Network Rail infrastructure and stations on both sides of the city, the most intensive construction effort surrounds the 21km of new twin tunnels under the centre of London, with several major new stations being built below ground, integrated with the existing London Underground and Docklands Light Railway (DLR).

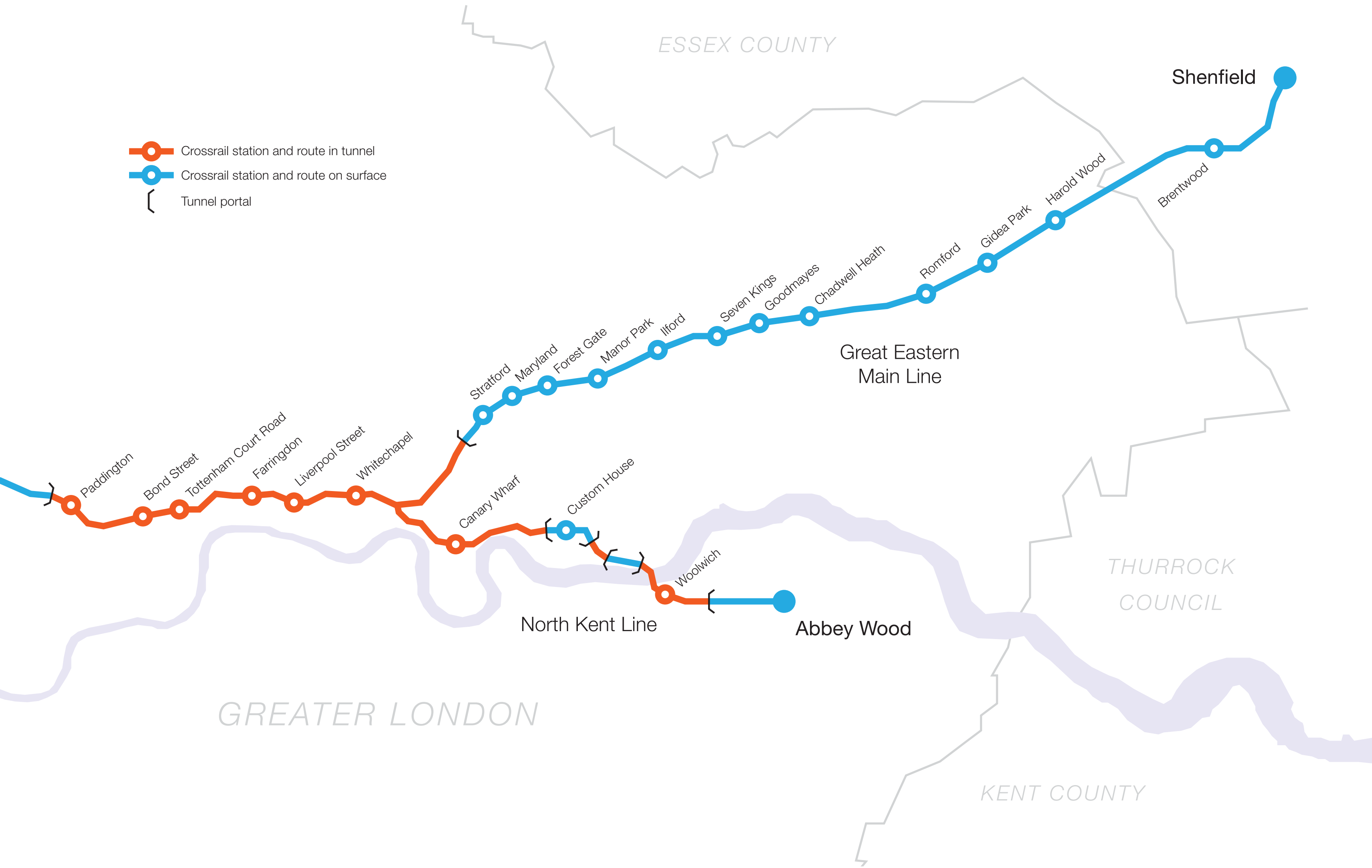
The project will increase London's below-surface rail capacity by some 10%, and should lead to significant regeneration and development, both above the new stations' ticket halls and along the route. This will be a much-needed catalyst to growth.

Crossrail will also provide a high-capacity fast direct link between Heathrow Airport, London's West End, the City of London, and the Canary Wharf business area to the east.

This current phase is being developed by Crossrail Ltd, a wholly-owned subsidiary of Transport for London (TfL), but during its long gestation the project has had many different sponsors within the public sector, and even an Arup-led attempt to sponsor a private-sector delivery vehicle.

This article gives an overview of the history and current state of Arup's involvement in Crossrail. Many people (listed on pp110-111) have contributed significantly to the project, which has been a step change in the design and delivery of major transport infrastructure. The detail of these efforts will be the subjects of future articles in *The Arup Journal* and other learned publications.

Historical development
The idea for a high-capacity rail route under London, linking the overground network to the west and east of the city, was first



mooted in 1943 and was included in the oft-cited 1944 Greater London Plan by Sir Patrick Abercrombie[1]. It was not until 1989, however, that the first real effort was made to develop such a scheme, at which time Arup first became involved. The project was proposed by a joint venture between British Rail and London Underground Ltd (LUL) – the route very similar to today's but without the south-eastern link to Abbey Wood – and a Bill to seek powers to build Crossrail was put before Parliament in 1991.

Significant design work was undertaken to fix the route and the stations, alongside an extensive geotechnical site investigation in 1992 that was designed, supervised and interpreted by Arup. This entailed some 130 boreholes up to 75m deep, and a myriad of trial pits, cone penetration drives and pressuremeter testing holes, but remarkably few services were damaged in the process. This investigation provided most of the geotechnical knowledge for the whole project until about 2006, and even today forms the backbone of what is known for the route's central section.

The extent of this major investigation stretched the entire high-tech soil laboratory testing facilities of the UK, and led to significant advances in understanding London soil behaviour. Against all the odds, the work was completed on programme.

Nonetheless, all this was happening during the last recession and, with the cost of construction estimated at over £4bn, this scheme was finally rejected in 1994. However, the route was now safeguarded and the Department for Transport (DfT) engaged Arup to carry out a study to determine whether there were any "small-scale alternatives to Crossrail". These looked at enlarging London Underground Circle Line stations, breaking the Circle and linking both the northern and southern sections of the route to the overground rail network. However, at over £2bn these proposals were also too costly at the time.

Although Crossrail was deemed unaffordable in 1994, it still had a very strong benefit-to-cost ratio and in 2001 Crossrail London Rail Links (CLRL), a 50/50 joint venture between DfT and TfL, was formed to promote the route. At the same time Arup, picking up on the very good business case and fresh from its success at developing the route of the Channel Tunnel Rail Link (CTRL – now High Speed 1)[2, 3], formed London Regional Metro (LRM), together with AECOM, Royal Bank of Scotland and Berwin Leighton Paisner, to develop a plan to privately finance and develop the scheme. Part of this plan was to re-use the CTRL tunnel boring machines (TBMs) then driving under London.

This proposal provided an open-access rail route funded by property development above the stations and tunnel access charges, but sadly it ran into the sidings in 2004 with the publication of the Montague Report supporting the DfT/TfL proposals[4]. However some of LRM's ideas, particularly the integrated oversite development, were taken into the government-sponsored scheme, and so Crossrail again came before Parliament, this time as the Crossrail Hybrid Bill, in 2005.

1 *(previous page)*.
The Crossrail route.

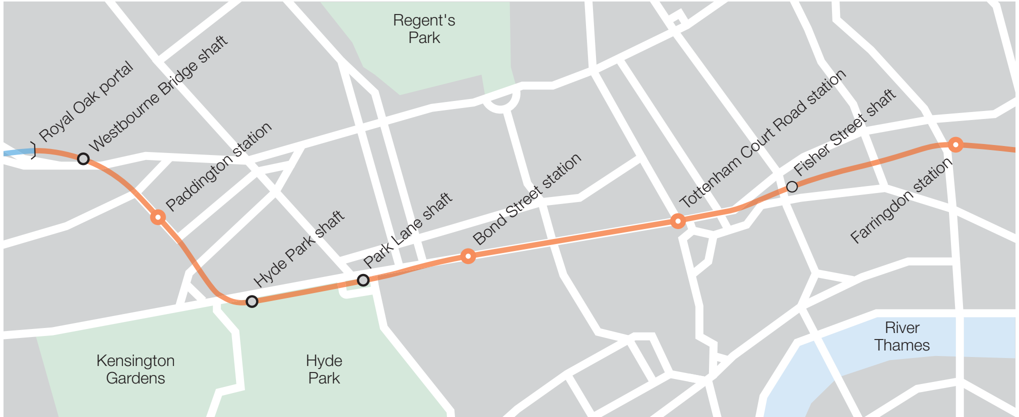
2. Crossrail Section 2, designed by the Arup/Atkins joint venture (MDC2).

3. Reinforced concrete tunnel segment design (typical right-hand ring elevation only shown).

4. Some of the first batch of concrete tunnel lining segments.

5. Assembling the first TBM.

6. Progressive reduction in length and width of the proposed new Crossrail Paddington station box.



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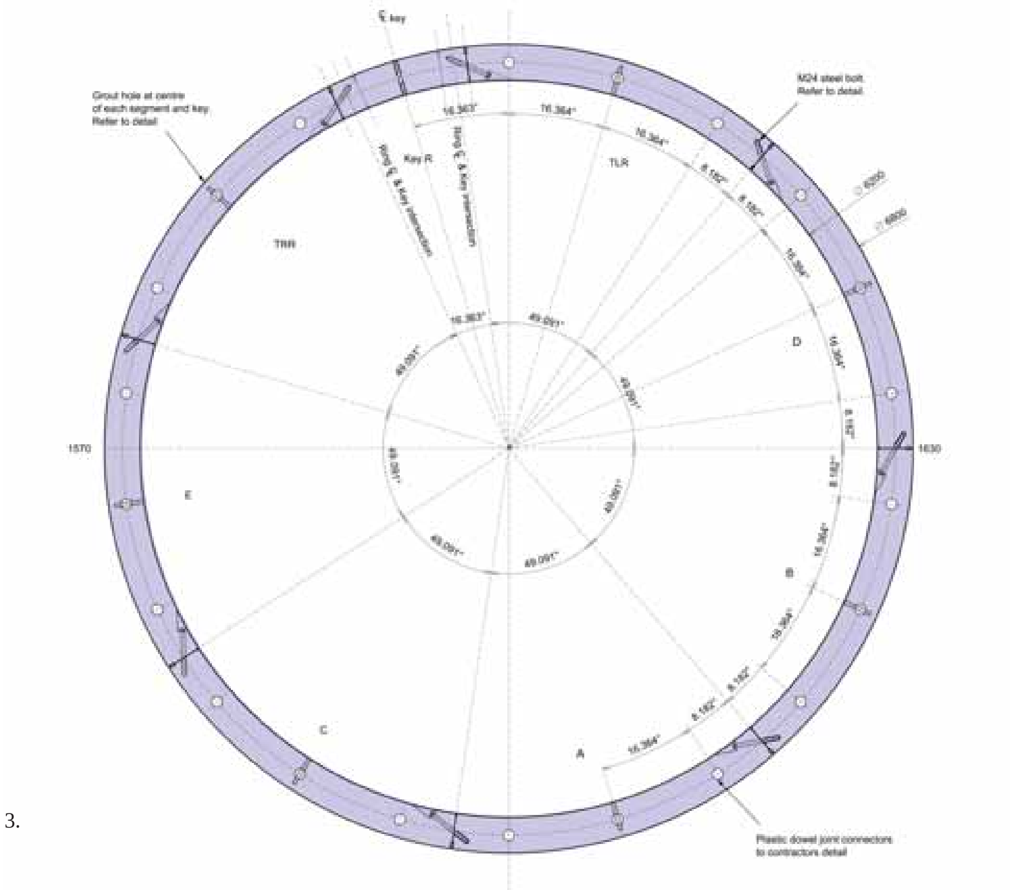


3.

Preliminary design and support to the Hybrid Bill

So as to support the Bill through Parliament, CLRL needed significant design input to update the 1991 scheme and to reduce the significantly escalated costs. To achieve this, it let four multidisciplinary design consultancies (MDCs) covering the whole of the route, and in May 2006 Arup, in joint venture with Atkins (AAJV), was appointed to develop the design for Section 2 (MDC2). This included the western tunnel portal at Royal Oak, some 7km of 6.2m internal diameter twin bored tunnel, the Paddington, Bond Street and Tottenham Court Road stations, and shafts at Westbourne Bridge, Hyde Park, Park Lane, and Fisher Street (Fig 2). The MDCs provided a complete design service, including architecture, civil and structural engineering, geotechnics and tunnelling, building services, environmental, fire, communications and transportation, plus other specialist inputs such as security when required. For Section 2, all these activities were undertaken by an integrated Arup/Atkins team working in a project office.

The strategy then was for the MDCs to develop the designs to a stage where, on the successful passage of the Hybrid Bill, the works could be procured with several design-and-build contracts – assumed to be effectively *RIBA Stage C*.

Section 2 preliminary design

Over the two-year commission from 2006-2008 as MDC2, the Arup/Atkins team achieved a step change in the level and quality of the design, significantly reducing project costs and risks.

4.

5.

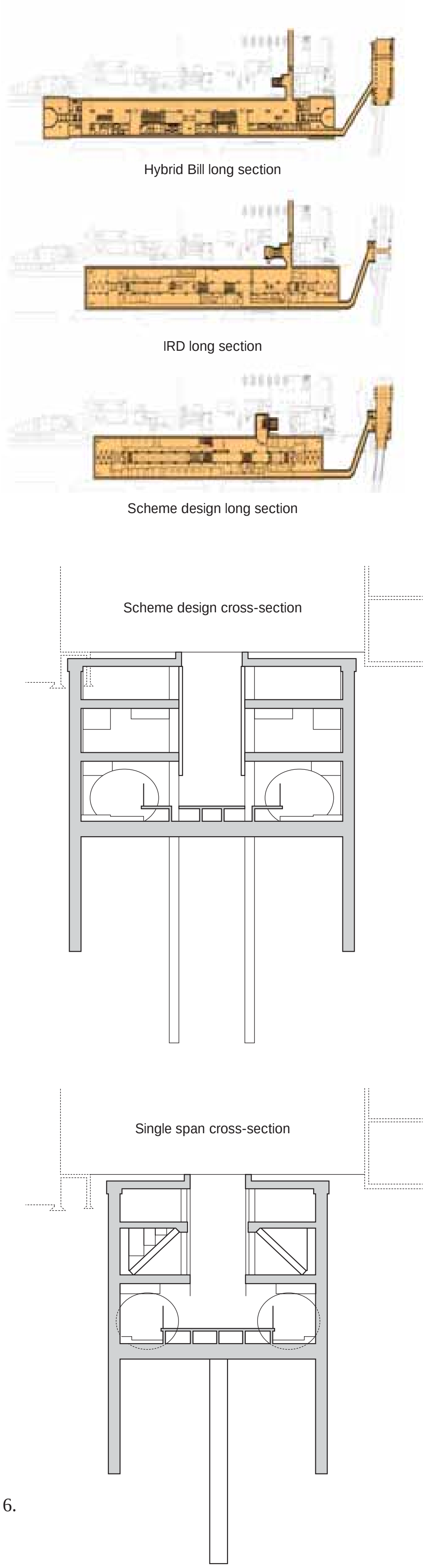
At the Royal Oak portal, the start of the bored tunnel was moved 250m west, thus replacing some 270m of cut-and-cover structure as well as eliminating the need for a major utilities diversion. This change also gave a more accessible site for erecting the TBMs. To the tunnel design Arup brought its experience on High Speed 1, optimising the number of TBMs required and with strategies to reduce ground settlement and spoil disposal by rail. Within MDC2, Arup was also responsible for developing the concrete tunnel segment design, using here the steel and polymer fibre designs employed successfully on High Speed 1 (Fig 3).

At Paddington station, the design progressively removed the need for TBM launch shafts, optimised passenger movement, and integrated the ventilation plan over the platform, significantly reducing the length (300m to 240m) and width (30m to 25m) of the station box (Fig 6). This not only lowered the cost of the box itself but also reduced the impacts on existing Network Rail properties and limited the extensive utilities diversion required in Eastbourne Terrace, under which the station box would eventually be constructed.

At Bond Street and Tottenham Court Road stations, the platforms are 240m long in accordance with the project requirement to accommodate 12-car trains, with track level some 25m below ground. The platforms would be reached from ticket halls at either end of the station via series of shafts and adits. Again through successive design studies, by adjusting the layout and the track alignment within the constraints of the Bill the team managed to rationalise the separate shafts and adits into single boxes.

Also, by adjusting the layout within the Bill limits of deviation, the lowest level of the station box and a ventilation tunnel were removed, while a further development configured the boxes so that the tunnel and station contracts could be independent of each other in the construction programme. *Legion* modelling was used to optimise platform and passageway dimensions to reduce the excavation required and minimise settlement impacts on adjacent buildings.

Progress and passing of the Hybrid Bill
As the MDC2 design development continued, the Hybrid Bill was passing through the committee stages in Parliament, and opportunities to gain private financing for the project progressed.



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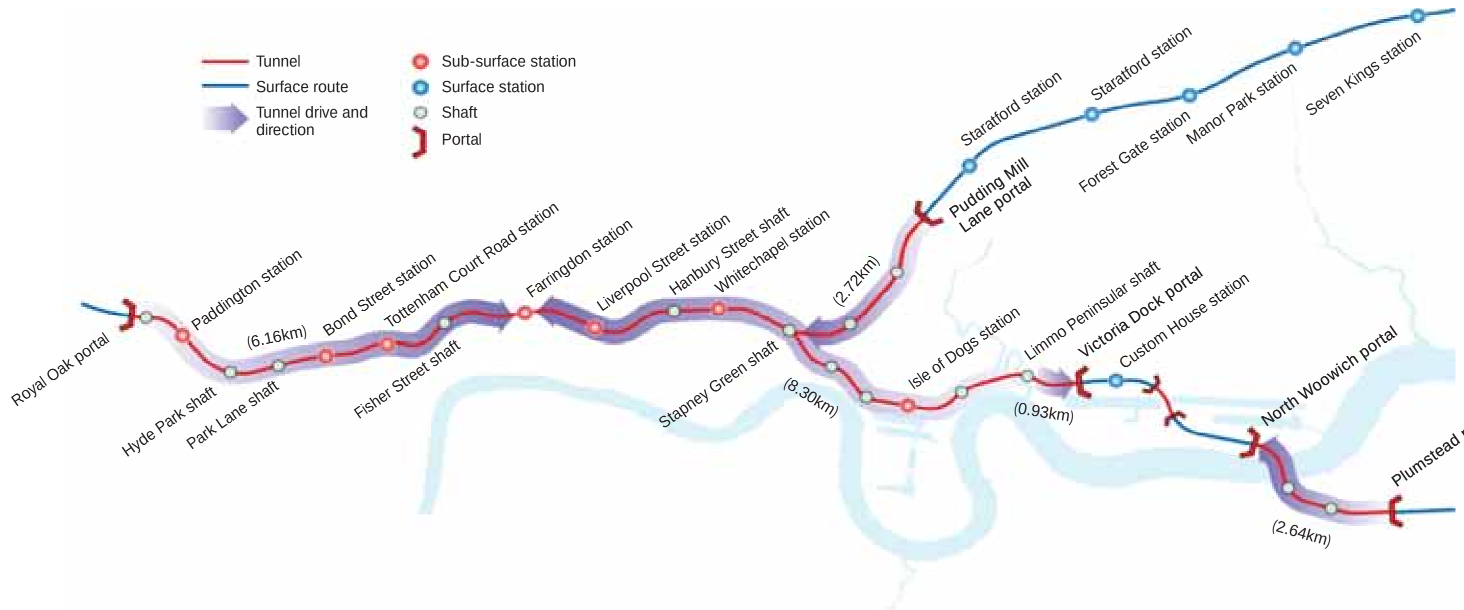
Contributions from BAA, Canary Wharf Group, and Berkeley Homes (now Berkeley) formed part of the overall funding package, which was agreed with the Government in October 2007. As a result the Government announced in its comprehensive spending review that the project would now go ahead.

Canary Wharf Group agreed to design, construct and finance the station in the Isle of Dogs and appointed Arup as designer. Major changes in the procurement strategy for the rest of the central section swiftly followed. Following market testing, it was realised that the UK construction market would have severe difficulties bidding for over a dozen design-and-build contracts with a value of £300M+, so CLRL decided that it would procure an employer's design, and tender the works as construct-only.

Because Crossrail was aware of Arup's close relationship with many major London property development and owning companies, and as it was deemed in the project's interest for such companies to receive very knowledgeable advice, Arup's experts became involved in the process for petitioners who were concerned with the Bill's detail rather than its principle. As technical negotiator, the firm thus advised on issues such as capacity at Liverpool Street station and the detail of the proposed settlement deed being offered to property owners to make it more effective and palatable for them. These expert appearances before the House of Commons Select Committee led to the creation of a dedicated exit at Liverpool Street dubbed the Broadgate Ticket Hall, as well as several improvements to the settlement deed.

Crossrail detail design contracts
The extensive procurement process for Crossrail's detailed design required consultants firstly to prequalify and then bid to get onto the Crossrail design framework. Arup was then – depending upon which categories of the framework the firm was on – invited to bid for the various tunnelling, station, railway system, and rolling stock contracts.

Following the successful partnership as MDC2, it was agreed that Arup would bid jointly with Atkins for tunnels and stations. CLRL wanted to share the work among UK consultancies and "Arup with Atkins" successfully won the largest design package – contracts C122 for the bored tunnels, and C134 for Tottenham Court Road station –



7.

while the smallest station contract, Custom House, was won by "Atkins with Arup". As already noted, Arup was appointed for the civil, structural, geotechnical and building services detailed design of the Isle of Dogs station, as well as being commissioned later by Crossrail for the fit-out design of the Woolwich station box, and more recently the Plumstead stabling facilities.

With the passage of the Hybrid Bill, and the signing of the design contracts, the client CLRL also changed, becoming Crossrail Ltd. The DfT stepped back from the joint venture with TfL to have a high-level sponsorship role and Crossrail became a mode within TfL.

Although this period caused major changes to both the designers and the client body, the process of the Hybrid Bill together with the associated assurances and undertakings fixed much of the project's design, the limits of deviation, and the general and operational requirements of the proposed railway. The detailed design phase thus commenced where the preliminary design left off, but with value engineering exercises to try and reduce cost and risk.

Contract C122: Bored tunnels

Arup's scope

This detailed design contract, awarded June 2009, is significantly more complex than its name implies. Arup's responsibilities cover much more than the detailed design of all the segmentally lined tunnels on the project and rehabilitating the existing cut-and-cover Connaught tunnel for part of Crossrail's route under the Victoria and Albert Dock.

The team is also responsible for the tunnel and track alignment, and the associated permanent way design. In addition, the package includes assessing settlement caused by all underground excavation along the central section from the bored tunnels, the sprayed concrete-lined tunnels for the platforms, shafts and station boxes, etc, together with assessing and mitigating the impacts of any settlement on all buildings and on other infrastructure (roads, Underground and overground railways, water, sewerage and gas pipelines, and underground power and telecommunications).

Finally, the scope includes developing the scheme design baseline from the MDCs of the 21km of tunnels between the interface boundaries with Network Rail, clear of the Royal Oak portal to the west and the Pudding Mill Lane portal to the east, and with the Network Rail surface network south-east of the Plumstead portal.

In places the tunnels are almost 40m below ground and had to be excavated through London Clay, the Lambeth Group, the Thanet Sands and chalk – and thus requiring TBMs capable of dealing with these materials on the various drives.

8.

7. Alignment of the bored tunnels and drive directions.

8. Cutterhead being installed on the first TBM.

9. Space-proofing in the tunnel.

10. Outputs from Arup's project-wide graphic information systems model.

11. 3-D prism targets on building for asset damage mitigation.

Tunnelling programme and strategy

Programming the works led to construction in five tunnelling drives (Fig 7):

- Royal Oak to Farringdon west (Drive X: 6.16km)
- Limmo Peninsula to Farringdon east (Drive Y: 8.3km)
- Stepney Green to Pudding Mill Lane (Drive Z: 2.72km)
- Limmo Peninsula to Victoria Dock Portal (Drive G: 0.93km)
- Plumstead to North Woolwich (Drive H: 2.64km).

Following the strategy from MDC2, an integrated Arup-Atkins design team was established in the client's project office at Canary Wharf, to:

- develop space-proofing within the tunnel, including co-ordination of requirements for rail systems and rolling stock operational space and clearances (Fig 9)
- plan construction sequences
- develop rail permanent way and track and tunnel alignments, including the detailed specification and reference design for the permanent way necessary for procuring a design-and-build contractor for the permanent way
- undertake detailed 3-D modelling of ground movement from the integrated impacts of station box, sprayed concrete tunnel, and bored tunnel excavation (Fig 10)
- carry out the detailed design and specification of the tunnel lining segments to support the different ground conditions and permanent way forms
- evaluate schemes to mitigate ground movement from Crossrail work and its impact on over 4000 buildings along the route, including many listed structures
- prepare inputs for submissions regarding the detailed construction planning, environmental and transportation support services
- prepare works information as part of the contract documentation, assessment of tenders and input to optimum contractor involvement as part of the pre-construction design development.

Ground movement monitoring

Assessing ground movement from the various excavation works and its impact on London's built infrastructure above and below ground required major interface with external stakeholders, LUL, utility companies, and building owners to understand what their assets could sustain as the works progressed and what mitigation measures – renewal, underpinning, compensation grouting, etc – would be needed to protect them.

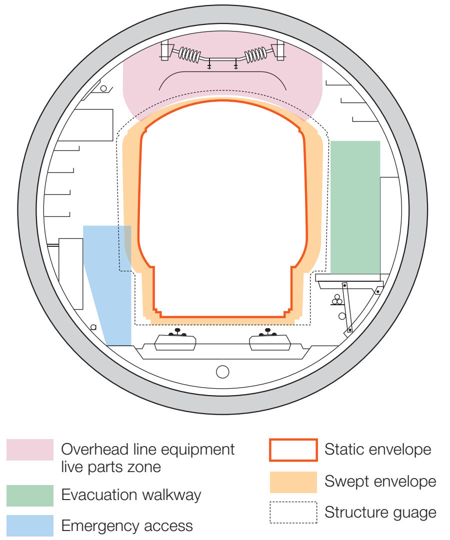
The team developed a set of minimum requirements in terms of instrumentation for ground movement monitoring for the various construction contractors to put in place (Fig 11). The team also calculated and defined the movement trigger levels at these locations for the contractors to carry out mitigation measures to minimise any damage. The overall aim is for the works to be constructed under London such that London barely notices.

Progress

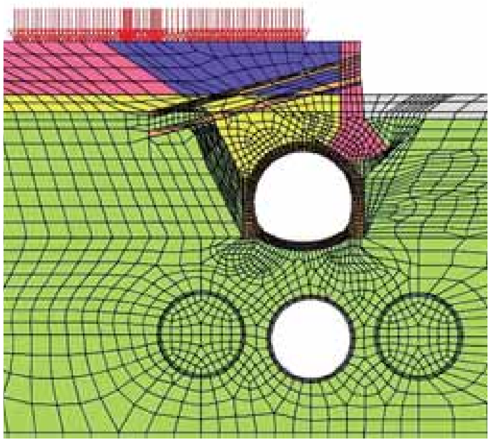
In the second quarter of 2012, the first TBMs began their journey from Royal Oak east towards Farringdon station. Later this year, two more TBMs will be launched in Docklands, heading east under central London to the east of Farringdon. Further shorter tunnel drives will take place in the Royal Docks and east London. During this work Arup will have a site presence to assist the contractors should ground movement not occur as anticipated.

There has been a significant effort on the project to minimise environmental impacts. The Hybrid Bill included significant minimum environmental requirements, assurances and undertakings, and planning obligations. Demonstrating that the design has satisfied these requirements and putting in place procedures to control construction have been major efforts.

The tunnels pass under sensitive recording studios in the Soho and Tottenham Court Road area, and under the Barbican Arts Centre. The team has developed and designed special trackform supported on elastomeric bearings (floating track slab) to minimise transmittal of ground-borne noise from the rolling stock, as well as numerical models of the noise and vibration to demonstrate that the requirements of the Hybrid Bill have been satisfied.



9.



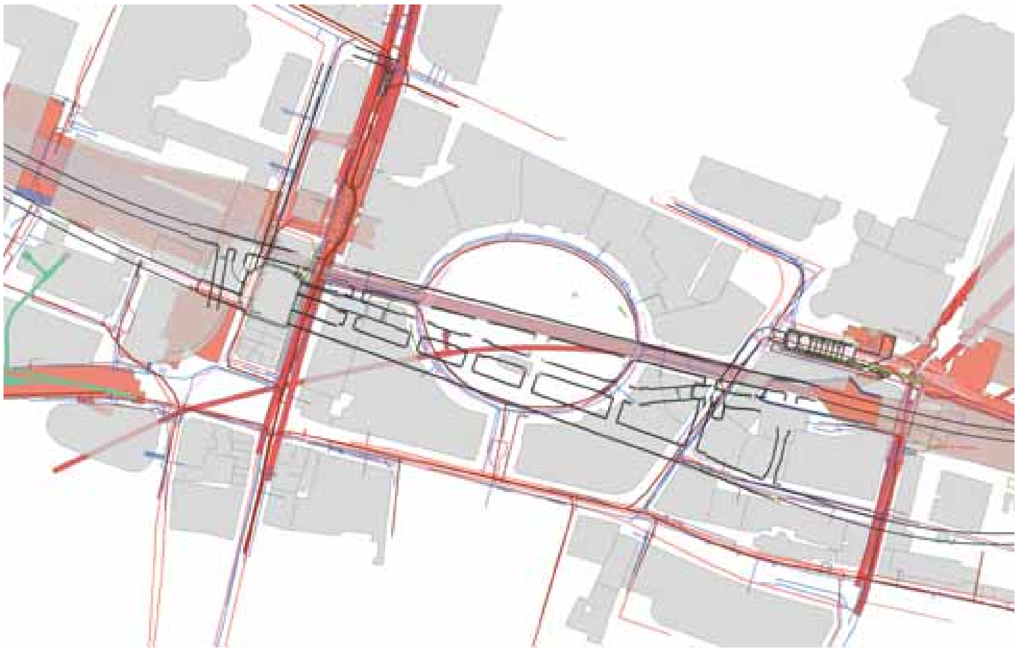
10.

11.

Data handling

As part of this work, the team developed a project-wide graphic information systems model (GIS) to store the underground and overground data – from the results of surveys and building reports to site investigation and utilities information. The database included over 100 attribute fields, and altogether 17 386 "assets" were incorporated into it, including 13 384 utilities, 3284 buildings, 669 heritage structures, 370 underground structures, and 249 overground structures.

This model became crucial to the project and was adopted by the client as the backbone of the project data management. The innovative development of this model (Figs 12-13) was Highly Commended for Technical Excellence in the Ground Engineering Awards 2011.



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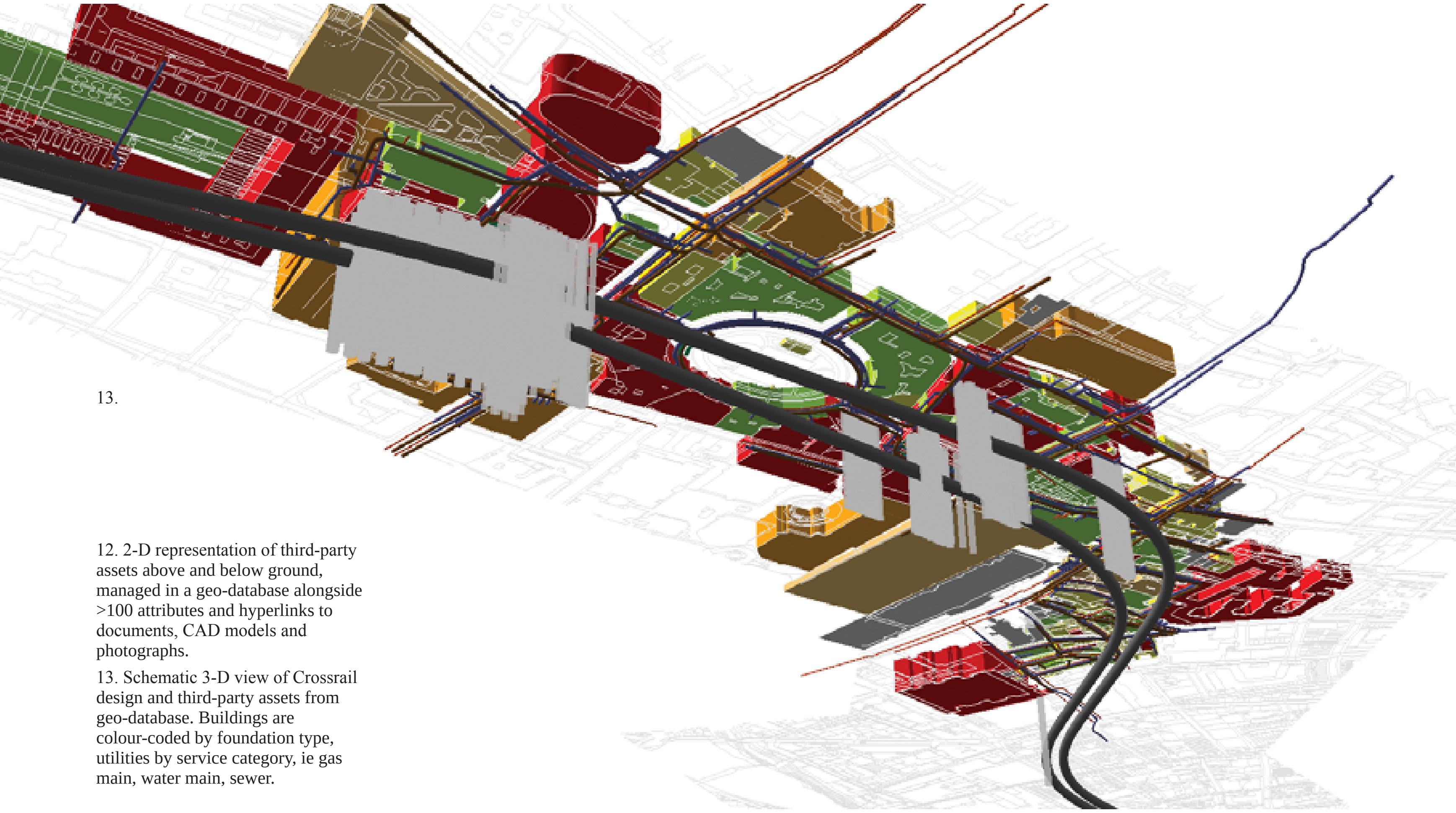


13.

12. 2-D representation of third-party assets above and below ground, managed in a geo-database alongside >100 attributes and hyperlinks to documents, CAD models and photographs.

13. Schematic 3-D view of Crossrail design and third-party assets from geo-database. Buildings are colour-coded by foundation type, utilities by service category, ie gas main, water main, sewer.

14.

14. Escalator descent from surface to trains at Tottenham Court Road Crossrail station.

15. Interface of Crossrail station with the existing London Underground lines and station in the Tottenham Court Road area.

Contract C134: Tottenham Court Road station

Crossrail is unlike any existing underground railway in London. The 200m-long trainsets –which can potentially increase from 10 cars to 12 cars – are the same size as those on Network Rail commuter and inter-city lines. They can carry up to 1500 passengers each, and the service provision is designed to deliver up to 24 trains per hour through the central underground section. As a result, the stations and ticket halls have had to be designed for a much larger throughput of passengers than any LUL scheme. Also, unlike previous schemes, the station ticket halls have been designed to permit future oversite development.

At Tottenham Court Road station, Crossrail interfaces with the existing and frequently overcrowded Underground Central and Northern Lines (Figs 14-15). LUL already had a plan for a major congestion relief upgrade, and this was incorporated into the Crossrail programme to achieve the necessary planning consents through the Crossrail Act powers. Integrating two such complex projects, however, led to underground construction works requiring very high levels of alignment control to thread the Crossrail tunnels through the LUL upgrade works.

15.

16.

At the eastern end of the station, access to Crossrail is through the new London Underground ticket hall at basement level. Due to the potential risks of two contractors working in close proximity, it was decided that the Crossrail structures at this end of the station, known as the Goslett Yard box, should be built by LUL's station upgrade contractor Vinci BAM Nuttall (VBN).

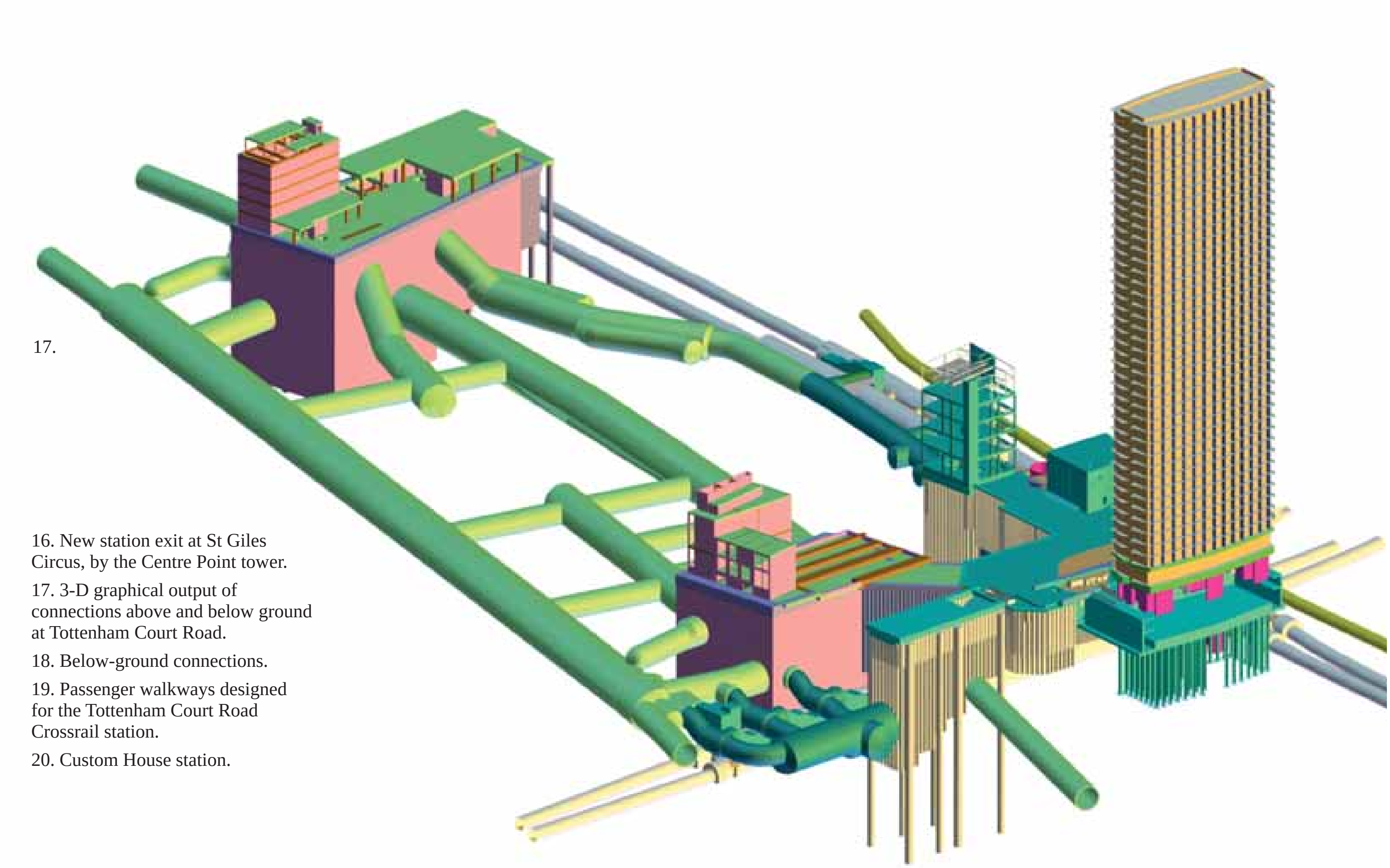
Arup's scope of work has been to develop the scheme proposed as MDC2, integrated with LUL's congestion relief work. The scope includes:

- multidisciplinary detail design of the western ticket hall and platform access structure, a 25m deep box with oversite development
- secondary structures within the tunnels and the Goslett Yard box
- design of the building services and architectural fit-out to *RIBA stage E* for the entire Crossrail station.

Design services include architecture (supported by Hawkins Brown), civil and structural engineering, MEP engineering including specialist lift and escalator advice, fire and security engineering, environmental and sustainability advice, traffic and transport modelling, inclusive access under the UK's Disability Discrimination Act, systems engineering, communications, and cost estimating (supported by Corderoy).

As the detail design progressed the team had to deal with two major replanning studies of the station layout. The first was to deal with buried obstructions not revealed in previous searches, together with a change to the construction strategy that required provision for potential early access to build station platforms in advance of the running tunnels.

The second stemmed from a major cost reduction initiative proposed by the team which determined that direct access to the Central Line was not essential. Removing this link meant that, through careful planning



17.

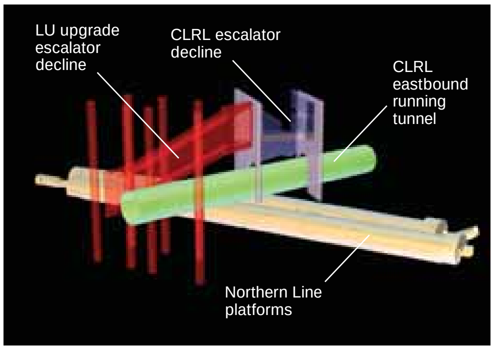
16. New station exit at St Giles Circus, by the Centre Point tower.

17. 3-D graphical output of connections above and below ground at Tottenham Court Road.

18. Below-ground connections.

19. Passenger walkways designed for the Tottenham Court Road Crossrail station.

20. Custom House station.



18.

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and structural engineering, all lifts and escalators could be integrated within the box, thus avoiding the need for the sprayed concrete escalator shafts that were considered high-risk structures to build and were correspondingly costly.

As lead consultant for the station, the Arup-Atkins JV had to co-ordinate and integrate the sprayed concrete tunnel design, the system-wide ventilation and rail system design, and the architectural design (Fig 19) to achieve a pleasant passenger experience in a well-lit and temperature-controlled environment that also could handle the safe evacuation of 2600 passengers from a full 12-car train together with passengers and staff in the station.

Relentless commitment to value engineering led to a design that has steadily been rationalised to achieve the client's requirements at the lowest possible cost.

Crossrail acknowledges the impact its stations will have on their external surroundings, and integration of the new ticket halls has been considered in detail, so as to improve the environment around the stations for pedestrians and passengers alike.

Contract C146: Custom House station
This is the only above-ground new station in Crossrail (Fig 20), and it interchanges with the DLR. Although Custom House is smaller than the station at Tottenham Court Road, Arup's involvement similarly includes architecture (supported by the practice Allies and Morrison), civil, structural, MEP, fire and security engineering, environmental and sustainability advice, traffic and transportation modelling, inclusive access under the Disability Discrimination Act, systems engineering, communications, and cost estimating (supported by the consultancy Faithful+Gould).

The challenges at Custom House are the interface with the DLR, maintaining both full operation of the station and the important access to the exhibition centre ExCeL London. The constrained 20m wide worksite is sandwiched between the DLR and the adjacent main road, and partially overhung by 400kV power lines, effectively requiring the station to built from prefabricated elements, just-in-time delivered to site by flat-bed vehicles.

Construction is expected to begin early in 2013. The potential oversite development is subject to planning negotiations with the London borough of Newham.

Contract C158: Woolwich station
Woolwich station is being partly funded by Berkeley, as the station box provides it with oversite development opportunity, but the commercial deal did not include the station fit-out. This needed to defined, including internal structural work, before the structural box could be finalised.

Following the Arup-Atkins JV work at Tottenham Court Road station dealing with major change, interfacing with stakeholders, and reducing construction and programme risk and out-turn costs, Crossrail Ltd asked the team to undertake the initial *RIBA Stage C* design of the Woolwich fit-out works.

Initial schemes developed to *RIBA Stage C* included one that permitted running trains through the box but without the station in place; the station would then be part of a later Crossrail development. The other was for an operational station. Both these options are currently being developed to *RIBA Stage D*, when it is hoped a decision will be made on the timing of station fit-out.

Canary Wharf station

Over the last two decades since it was created out of part of the derelict former West India Docks on the Isle of Dogs[5, 6], Canary Wharf has become, with the City, one of London's two main financial centres. Canary Wharf Group had always wanted a link to Crossrail, and lobbied successfully for the introduction of a south-east spur connection to the route and a station. Arup was engaged to assist with the petition during the passage of the Hybrid Bill, to promote a design that would reduce the station's environmental impact and improve the overall value it would bring to the area.

The resulting scheme was eventually adopted by Crossrail Ltd, who contracted with Canary Wharf Group to design and build the £500M station. Arup is lead designer, as well as engineering designer for the oversite retail development. Planning permission has been gained by Canary Wharf Group for a shopping centre and a rooftop park over the station, which is sited surrounded by water on all sides, with footbridges to adjacent quays, to the DLR and the London Underground Jubilee Line.

This unique agreement meant that construction could start immediately after final ministerial approval. The first major milestone was completion of the station box in time for the arrival of the TBMs. The station structure is substantially complete and was delivered with a considerable saving on construction costs. Fit-out will be carried out in time for railway operations in 2018.

The new station is located in the 9m deep North Dock and the track alignment passes some 27m below the dock surface. The station was built in a cofferdam 260m long and 35m wide, formed on the east, west and north sides by a *Giken* pile wall formed from 1.2m diameter interlocking steel tubes. These were extended by excavating piles out of the base of the tubes to form permanent piles for the station box. This wall was tied back to a row of anchor piles that also supported a temporary access deck.

On the southern side of the cofferdam the existing Dockland Square development retaining walls were used to form the water cut-off system. The southern side of station box is a 0.9m secant wall constructed from the dock bed once the cofferdam had been pumped out. A row of bored piles with plunged columns was installed along the centre of the box and these were used to support the slabs during excavation below the dock bed, with top-down construction employed from this level. The piles also acted as part of the anchor system to resist the hydraulic uplift pressures.

Construction was supervised on site by Arup engineers who also reviewed the monitoring results against trigger values provided by the design team.

Notable technical features have included:

- the pre-tender trials to demonstrate that the *Giken* system worked and could be integrated with the bored piles
- complex ground conditions with the interbedded clays sand and limestone layers of the Lambeth Group being faulted in places and overlain by the sands of the Harwich Formation at the western end of the box
- the design of the tie back system, which had several stages of preloading to control movements
- a combined solution for temporary and permanent works by boring out the *Giken* piles
- the adjacent Billingsgate and Canary Wharf development buildings up to 40 storeys high and founded on bored piles founded at the same level as the station box
- the installation and commissioning of a reliable instrumentation system
- the use of the Observational Method[7] to compare predicted and measured ground movements; this enabled the berms to be omitted during the final excavation with significant saving of cost and time.

The challenges have been many, not least among them that of constructing the new station in the North Dock very close to some of the most prestigious commercial office space in London, as well as being so far ahead of all other Crossrail projects.

Conclusion

This article is very much a preliminary overview of Arup's involvement with London's most significant new railway within living memory, and the firm will continue to make major contributions to Crossrail through to the opening in 2018. Further articles detailing its progress will be published in *The Arup Journal*.

21. Cross-section through the levels of Canary Wharf station.

22. Canary Wharf station as it will appear.

23 *(overleaf)*. Progress with construction of the Canary Wharf station box, spring 2012.

21.

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Duncan Nicholson is a Director in the London office. He was a member of the geotechnical engineering teams for Contract C122 bored tunnels and the construction phase services, and for the Canary Wharf station project.

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Graham Williams is a Director in the London office. He is Project Director for the Contract C134 Tottenham Court Road station and Project Manager for the construction phase services station work.

22.

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Image credits

1, 3, 6-7 *Arup/Nigel Whale*; 2, 9 *Nigel Whale*; 4-5, 8, 14, 16, 19-20 *Crossrail Ltd;* 10-13, 15, 17-18 *Arup*; 21-22 *Foster + Partners*; 23 *Canary Wharf Contractors Ltd.*

Project credits

1991-92 site investigation
Client: *London Underground Ltd*
Geotechnical engineer: *Arup*

1995 consideration of small-scale alternatives
Client: *Department of Transport*
Economics consultant: *Arup*

2006 planning and environmental assessment
Client: *Cross London Rail Links Ltd*
Transport planning and environmental consultant: *Arup*

2006-08 preliminary design (MDC2)
Client: *Cross London Rail Links Ltd*
Multidisciplinary designer: *Arup/Atkins Joint Venture*

Canary Wharf station
Client: *Transport for London*
Owner: *Canary Wharf Group*
Lead designer and multidisciplinary engineer: *Arup*
Architects: *Foster + Partners (above ground) Adamson Associates/Tony Meadows Associates (below ground)*
Main contractor: *Expanded Piling Co Ltd*

Contract C122 bored tunnels
Client: *Crossrail Ltd*
Tunnel, permanent way and alignment designer, and third party impact assessment: *Arup/Atkins Joint Venture*

Contract C134 Tottenham Court Road station
Client: *Crossrail Ltd*
Lead designer and multidisciplinary engineer: *Arup/Atkins Joint Venture*
Architect: *Hawkins\Brown* Quantity surveyor: *George Corderoy & Co*

Contract C146 Custom House station
Client: *WS Atkins plc*
Lead designer and multidisciplinary engineer: *Arup*
Architect: *Allies and Morrison*
Cost consultant: *Faithful+Gould*.

The following Arup staff are among those who have made significant contributions to Crossrail during the firm's 20+ years' involvement with the project:

Davar Abi-Zadeh, Sacha Abizadeh, George Acuna, Lisette Adams, Edu Aja, Juan Alayo, Maldar Ali, Eden Almog, Sara Anderson, Ryan Andriessen, Richard Armitage, James Armstrong, Marcus Arvidsson, Dave Ashurst, Oktay Aslan, James Assem, Mo Attia, Clive Aubrey, Ian Austin, Imaf Ayoub, Chris Ayres, Grzegorz Babiszewski, Matteo Baffetti, Nicholas Bailes, Amanda Bailey, Ross Bailie, Mike Banfi, Jon Banyai, Mike Barbato, Chris Barker, Phil Barker, Paul Barlow, Daniel Barnes, Oliver Barnett, Andy Barron, Chris Barrett, Bob Barton, John Batchelor, Mark Baxter, Heather Beaumont, Claire Beedle, Simon Belcher, Jonathan Ben-Ami, Jason Benfield, Emma Bennett, Ray Bennett, Sara-Louise Bent, Scott Bentman, Alice Berry, Charles Betts, Olly Bewes, Sara Bird, Chris Birkett, Martyn Biss, Daniel Blackhall, Alice Blair, Sue Blanch, Philip Bogan, Pietro Bologna, Paul Booth, Phil Borowiec, Mark Bostock, Karen Boucher, Anthony Bowden, James Bown, Roseanne Boyce, Paul Braddish, Jale Bradley, Jill Bradley, Andrew 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About Arup

Arup is a global organisation of designers, engineers, planners, and business consultants, founded in 1946 by Sir Ove Arup (1895-1988). It has a constantly evolving skills base, and works with local and international clients around the world.

Arup is owned by Trusts established for the benefit of its staff and for charitable purposes, with no external shareholders. This ownership structure, together with the core values set down by Sir Ove Arup, are fundamental to the way the firm is organised and operates.

Independence enables Arup to:

- shape its own direction and take a long-term view, unhampered by short-term pressures from external shareholders
- distribute its profits through reinvestment in learning, research and development, to staff through a global profit-sharing scheme, and by donation to charitable organisations.

Arup's core values drive a strong culture of sharing and collaboration.

All this results in:

- a dynamic working environment that inspires creativity and innovation
- a commitment to the environment and the communities where we work that defines our approach to work, to clients and collaborators, and to our own members
- robust professional and personal networks that are reinforced by positive policies on equality, fairness, staff mobility, and knowledge sharing
- the ability to grow organically by attracting and retaining the best and brightest individuals from around the world – and from a broad range of cultures – who share those core values and beliefs in social usefulness, sustainable development, and excellence in the quality of our work.

With this combination of global reach and a collaborative approach that is values-driven, Arup is uniquely positioned to fulfil its aim to shape a better world.

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