ISSUE 2 2010

The Arup Journal

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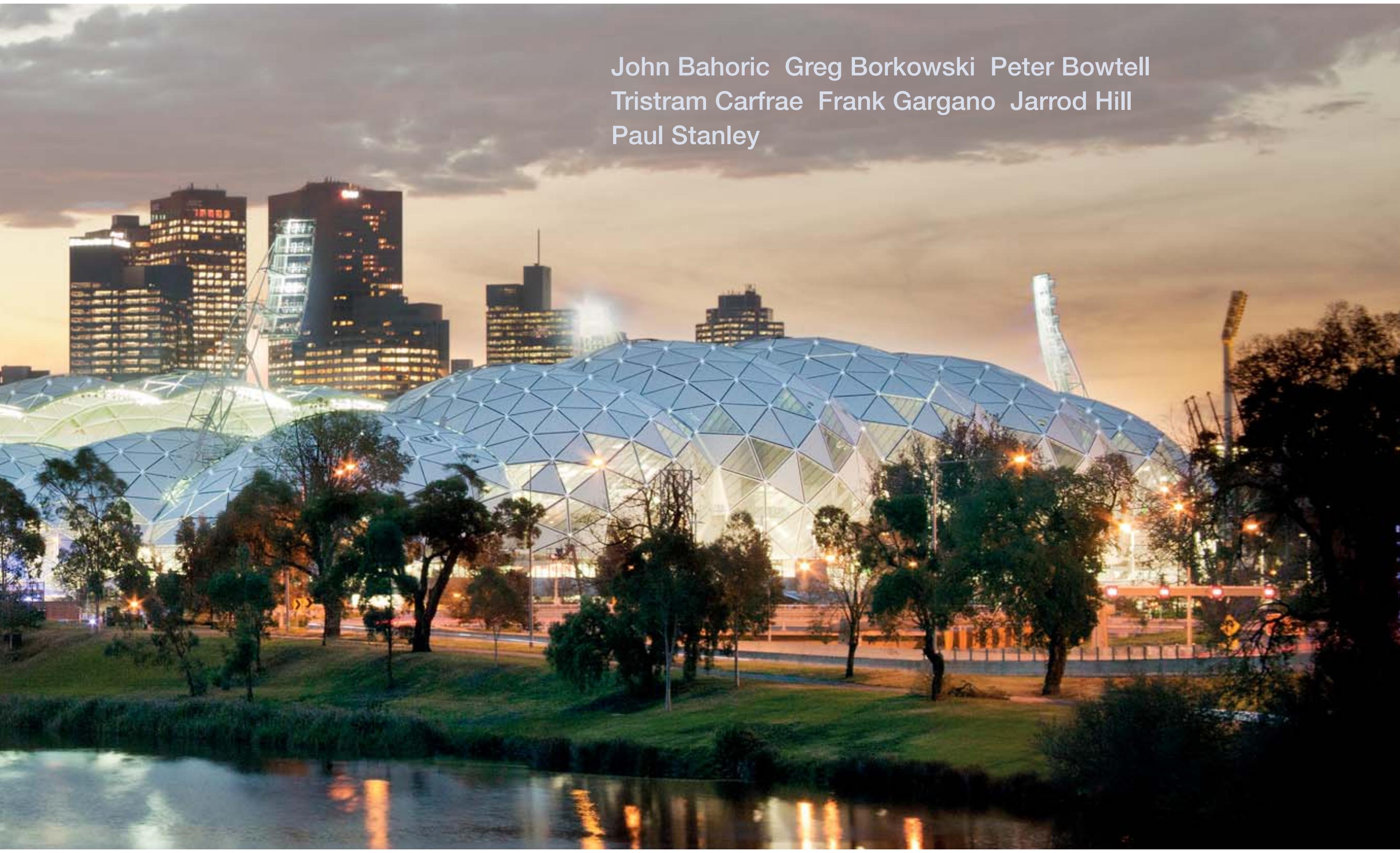
1. AAMI Park on Melbourne's famous Yarra River.

AAMI Park, Melbourne

> "The stadium is the latest jewel in the crown of Melbourne's sporting infrastructure, and will be the new home of soccer, rugby league and rugby union in Victoria. Victorians love their sport and AAMI Park is the latest addition to a first-class suite of sporting infrastructure that is the envy of any city in the world."
>
> **James Merlino**, Victoria Minister for Sport, Recreation and Youth Affairs

John Bahoric Greg Borkowski Peter Bowtell Tristram Carfrae Frank Gargano Jarrod Hill Paul Stanley



Awards

2008 Be Inspired Award of Excellence in the Innovation in Commercial or Residential Building category (Bentley Structural Awards)

2010 Structural Engineering Steel Building Design Award and Large Project - Architectural Steel Design (Australian Steel Institute Awards)

2010 shortlisted for Award for Sports or Leisure Structures (Institution of Structural Engineers)

Overview and inception

There is no other place in Australia that lives and breathes sport like Melbourne. As the traditional heartland of Australian Rules football, the city's sporting venues are typically oval-shaped to accommodate AFL in the winter and cricket in summer.

Melbourne, however, also boasts a passion for codes that play on a rectangular pitch, and AAMI Park fills a major gap in the city's sporting infrastructure, providing soccer, rugby league and rugby union teams with Melbourne's first purpose-built, rectangular-pitch stadium.

Key dates	
Project conception	2004
Design commencement	2005
Start of construction	September 2007
Opening Match*	7 May, 2010
At a glance	
seating capacity	31 000
roof structural steelwork	1080 tonnes
steel roof members	4156
bolted roof splices	2512
structural bolts in roof	11 408
Tenants	
Melbourne Storm	Rugby league
Melbourne Rebels	Rugby union
Melbourne Victory	A league (soccer)
Melbourne Heart	A league (soccer)

*Australia v New Zealand, rugby league Test

Formerly known as the Melbourne Rectangular Stadium, and delivered by Major Projects Victoria (MPV – Victorian State Government), the world-class AAMI Park facility features a sports campus, elite training centre, and sports administration complex. It brings spectators closer to the action, and enhances the development of the codes in the Melbourne market.

With 31 000 seats, AAMI Park adds to Melbourne's suite of sporting and entertainment venues (Fig 2), complementing the existing Rod Laver Arena (15 000 seats), Docklands Stadium (52 000 seats), and Melbourne Cricket Ground (100 000 seats), to complete the provision of venues for all sizes of major events.

History and background of precinct

Melbourne's sporting precinct is steeped in rich history. The 1956 Olympic Games saw the start of Melbourne's ascendance as one of the world's leading sporting cities. The Melbourne Cricket Ground was transformed into the Olympic stadium, and across the road new facilities including the Olympic pool were built – right in the heart of the city. Located on the south-eastern edge of the central business district (CBD), along the banks of the Yarra River, the precinct is surrounded by parkland but close to major public transport infrastructure.

The existing venues were all state-of-the-art in their day and AAMI Park continues that tradition, further enhancing Melbourne's claim to be Australia's sporting capital.

2. AAMI Park, MCG in background, and Rod Laver Arena to the left.

3. Uninterrupted views from the stands at AAMI Park

The precinct currently includes:

- Melbourne Cricket Ground (MCG), venue for the 1956 Olympics, 2006 Commonwealth Games, 1992 World Cricket Cup Final, and various international and domestic sporting fixtures including the AFL Grand Final and the Boxing Day Test Match
- Melbourne Park, including Rod Laver Arena and Hisense Arena, home of the Australian Tennis Open
- The Lexus Centre, originally constructed for the 1956 Olympic Games swimming events and now the training venue for the Collingwood Football Club (AFL)
- Olympic Stadium – originally constructed for the 1956 Olympic Games, now home of Athletics Victoria, and the former home of the football codes accommodated at the new stadium.

Arup's role

Arup's structural design for the project included the concrete and steel bowl structures, the steel roof, and the light tower structures. Arup also provided civil engineering design, pitch and turf consultancy, pedestrian modelling, initial façade advice ,and specialist wind engineering from its research and technology group.

The structural engineering showpiece of the stadium is its roof, a highly efficient structure that is both functional and visually exciting – an engineering-based solution to an architectural challenge.

The roof geometry was also driven by the requirement to maximise natural light and ventilation, both for spectator comfort and the health of the playing surface. Arup in conjunction with Cox Architects and Planners developed the roof concept, and undertook the design development and the detail design.

The concept was built on previous Arup knowledge of sporting infrastructure around the globe, while the detail design drew upon local knowledge of sports stadia gained during the design and construction of the MCG Northern Stand[1].

Evolution of stadium roof forms

The structural engineering design of stadia has evolved in tandem with the technology and tools that have enabled the designs. Early grandstand roofs comprised trussed systems supported by columns at the perimeter, with the trusses typically manufactured from local timbers. Inevitably, the columns in front of the crowd obstructed views of the playing action.

Later grandstand roofs eliminated the use of columns in front of the crowds, giving unobstructed views. The MCG Great Southern Stand (1992) is an example of a steel cantilever structure that protects crowds from the elements. Cantilever roofs have further evolved, as demonstrated by the MCG Northern Stand where a cable-net and mast structure is used to support the roof, providing a more efficient structure (Fig 4).

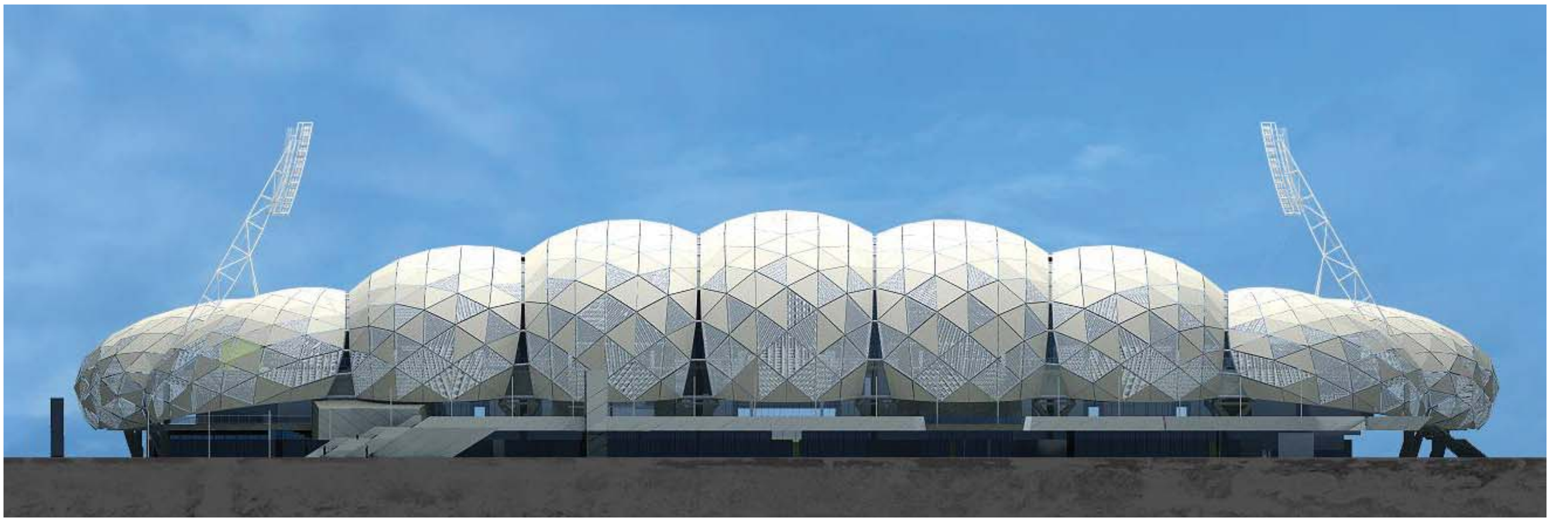
The City of Manchester Stadium[2, 3] uses a cable-stayed system to support its roof structure, allowing further structural efficiencies (Fig 5), while at Khalifa Stadium, Doha, Qatar[4], the inherent efficiencies of arches have been utilised (Fig 6). The Beijing National Stadium[5], in turn, employs a sophisticated system on interconnected planar trusses to provide a column-free environment over the crowds (Fig 7).

4. MCG Northern Stand.

5. City of Manchester Stadium.

6. Khalifa Stadium.

7. Beijing Stadium.



8. The roof consists of 20 geodesic shells.

AAMI Park (Figs 8, 9), by contrast, draws upon the principles of the geodesic dome, first popularised by Buckminster Fuller. The AAMI Park roof design extrapolates these principles to achieve a highly efficient structure that utilises multiple load paths to share load and ensure that each element of the roof contributes to the carrying of load to the supports.

Foundations

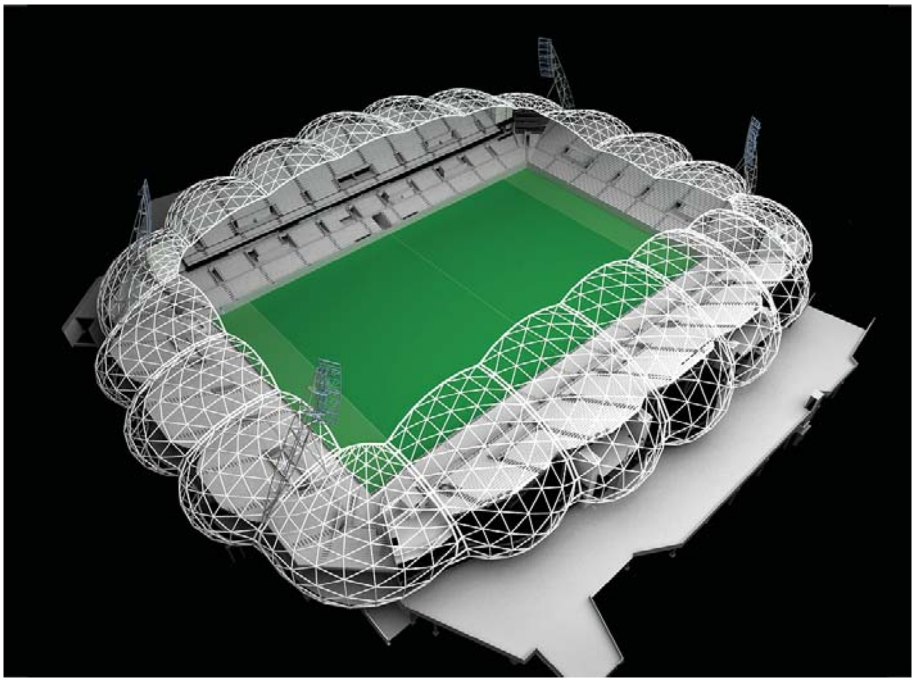
The site geology comprises an ancestral infill valley, formed in the Silurian Age Melbourne Formation bedrock, and infilled by a sequence of inter-bedded sediments and Older basalt (Tertiary age), underlying Newer Volcanics basalt.

The basic foundation section includes:

- fill material (pavements, rubble, gravels) to a depth of up to 3.5m
- Jolimont Clay (stiff to very stiff silty clay of high plasticity) to a maximum depth of 6m
- Newer Volcanics (basalt); the depth to this layer varies from 3-9m across the site.

Due to the expected varying depths to basalt, the original foundation design combined pad footings and bored piles, both bearing on the basalt to reduce any differential settlement issues.

Pad footings were to be adopted in areas where the basalt was close to the surface, and the bored piles where the basalt was deeper. During initial site works, however, the basalt layers were found to vary considerably over short distances, so all the foundations were installed as end-bearing concrete bored piles, to eliminate any abortive excavations.



9. Isometric roof and bowl model.

The concrete bowl

The seating bowl structure is built from a combination of in situ concrete, post-tensioned concrete, precast concrete, and steel, and is divided into six separate sections, jointed at strategic locations. Horizontal stability systems to resist earthquake and wind loading are provided by a combination of services cores and shear walls.

A 13m radial grid (perpendicular to the playing pitch) was adopted to integrate with the 26m width of each of the roof shells. 300mm deep hollowcore floor slabs with 125mm structural topping were used as the typical floor system; this gave adequate spanning capabilities, reduced formwork requirements on site, and improved construction speed. Non-rectangular sections of the floor plate were designed as reinforced concrete, to eliminate the on-site issues that would have been involved with non-rectangular hollowcore panels.

In situ reinforced concrete was also adopted around all the stability cores to provide structural integrity for horizontal loads, and to eliminate the need for corbels on concrete walls. (Corbels increase construction time and cost by adding construction items and interfering with conventional jump-form core systems.)

10. Steel rakers being constructed.

The reinforcement cages were prefabricated on site and lifted into position, allowing reinforcement fixing and formwork processes to occur simultaneously, again reducing construction time.

The lower seating bowl structure is a suspended reinforced concrete raking slab, spanning from the pitch retaining wall to a circumferential ring beam (parallel to the pitch edge). A retaining wall around the pitch perimeter encloses its playing surface, 2-3m above ground floor level.

The areas below the stadium seating bowl and concourse structures form office space, changing rooms, gymnasium and training facilities, cafes, administration areas, and plant and equipment zones. During construction, the stadium's playing area was used for site storage and handling purposes.

The upper terrace seating bowl structures were built from precast plats supported on raking steel beams (Fig 10). This form of construction is typical for Australian stadia, allowing precasting and steel fabrication to be conducted off site, reducing on-site construction time. In fact the moulds used for the precast seating plats had previously been used to manufacture the MCG Northern Stand seating plats.

The back edge of the seating bowl is scalloped to follow the roof geometry and maximise spectator numbers. The scalloped profile is in structural steel, including beams and raking columns, with cantilever precast seating plats.

Steel roof structure

The 182m long (east/west) and 130m wide (north/south) roof consists of 20 geodesic shells, five along each of the east/west sides, three on the north/south sides, and one in each corner.

The shells are made of 273mm diameter tubular steel sections, rigidly assembled in triangles to form the structure, which is bounded by a 508mm diameter groin member to the sides and front edge, and a 457mm diameter member to the back edge. All are clad in combination metal/glass panels. Four light towers spring from each of the corner shells. The roof weight is approximately 50kg/m², which compares very favourably to other contemporary stadium roof structures (Fig 11).

11. Steel roof under construction.

12. Steel roof structure in place.

The roof is supported by a combination of arching and shell action, catenary and cantilever action. The east/west roofs have an overall gentle upward curve that arches back to the corner shells, while the north/south roofs have an inverted curve that also spans back to the corner shells. Each shell is supported from two points at each groin – by a ball joint connected to the groin at the back corner of each shell, and a raker prop to the back of the seating that works as an axial restraint.

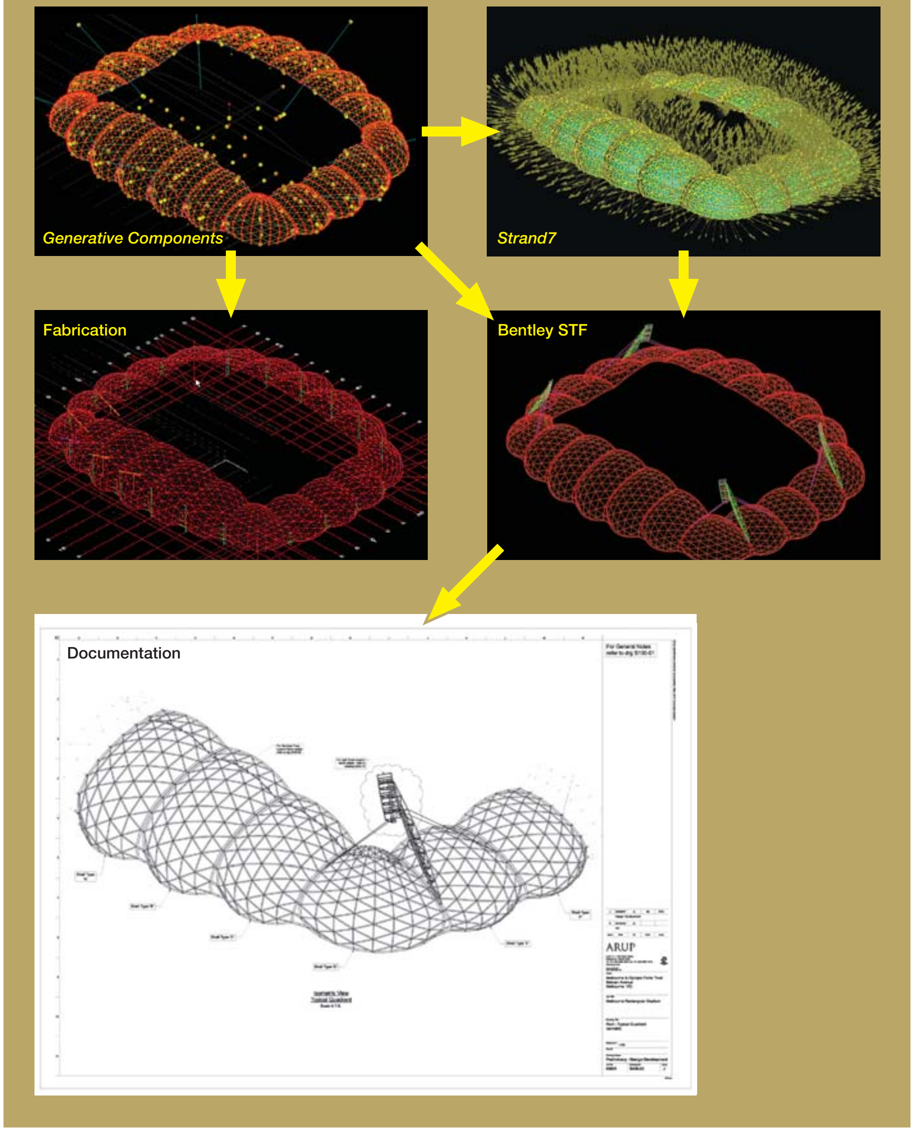
Key to the roof design was measurement of its stiffness, and the estimation of effective member lengths. Traditional code methods for the latter could not be used, as it was difficult to estimate points of member restraint. A second order buckling analysis was used both to measure the effective length of the system for each load case and to come up with a set of forces for member design.

Virtual 3-D design process

The design team worked within a virtual 3-D environment from concept stage through to construction (Fig 13). Parametric modelling was used to define the roof structure because of its ability to test alternative geometric configurations, and to accommodate the final preset geometry for fabrication and construction purposes.

During concept stage, initial studies of the roof and shell geometries were undertaken with Cox Architects and RMIT University's Spatial Information Architecture Laboratory, using a combination of *Catia* models and 3-D CAD.

13. Virtual design process.



Parametric modelling

The parametric model was developed using Bentley's *Generative Components* software after concept design, when basic geometric principles were agreed between Arup and Cox Architects (Fig 14). Parametric modelling enabled revised geometry to be speedily generated and imported into the structural analysis model to study structural geometric efficiencies. The parametric modelling software created the centreline wireframe models, which were used by the structural engineering design team and by Cox Architects for coordination and approval.

Structural optimisation

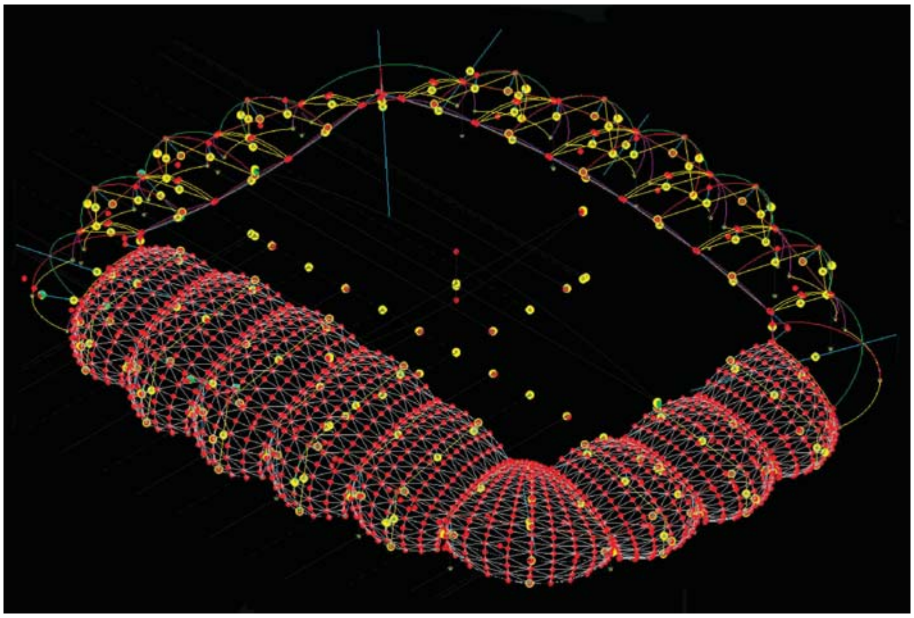
Arup's structural design team utilised in-house optimisation software together with *Strand7* analysis software to study the structural efficiency of the roof geometry. A total of 24 models, with variations in shell curvatures and heights, were studied to determine the most efficient geometry. By optimising the structural size required for each of the 4156 roof members, the most efficient structure was determined, giving steel tonnage savings (Fig 15).

To sum up, the virtual 3-D design process comprised:

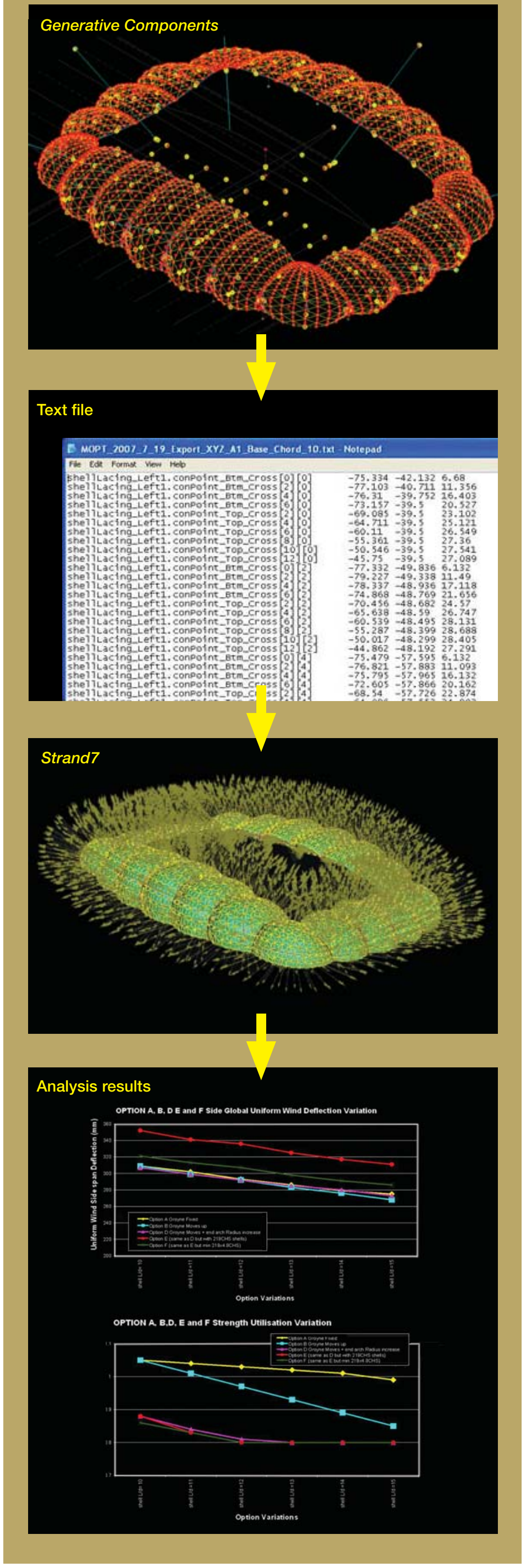
- generation of 3-D parametric model geometry
- importing of initial members and nodes into *Strand7* analysis software
- application of loads and restraints to the structural model, and analysis for stress levels and steel tonnages
- production of alternative 3-D geometry by the parametric model, the revised node geometry being imported into the analysis model, allowing member properties, restraints and loadings to be used from the previous analysis model
- analysis of revised model to compare stress levels and report steel tonnages
- testing of the geometry's structural efficiency by modifying and testing differing overall arch shapes and local shell shapes; by testing a number of shape variations, the final geometry was chosen
- analysis of final geometry by optimisation software to determine final member section sizes.

Project documentation and steelwork drawings were generated from the parametric geometry, after input into Bentley structural software. The parametric model was also used to make allowance for the self weight deflection of the structural steelwork at the front edge of the roof. The contractor used this preset model as the primary set-out for the roof geometry, and this information was then used to prepare the steelwork shop detail drawings, and for steelwork fabrication.

14. Parametric modelling.



15. Structural optimisation process.



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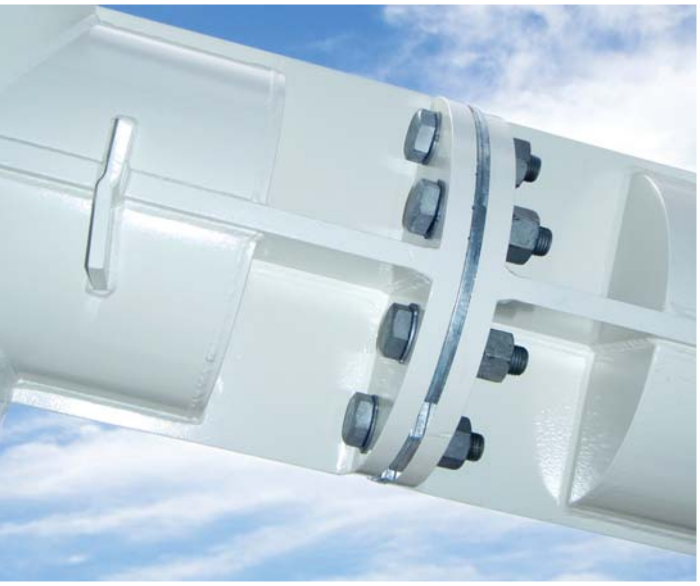


16. Bolted splice connection.

Roof steelwork erection

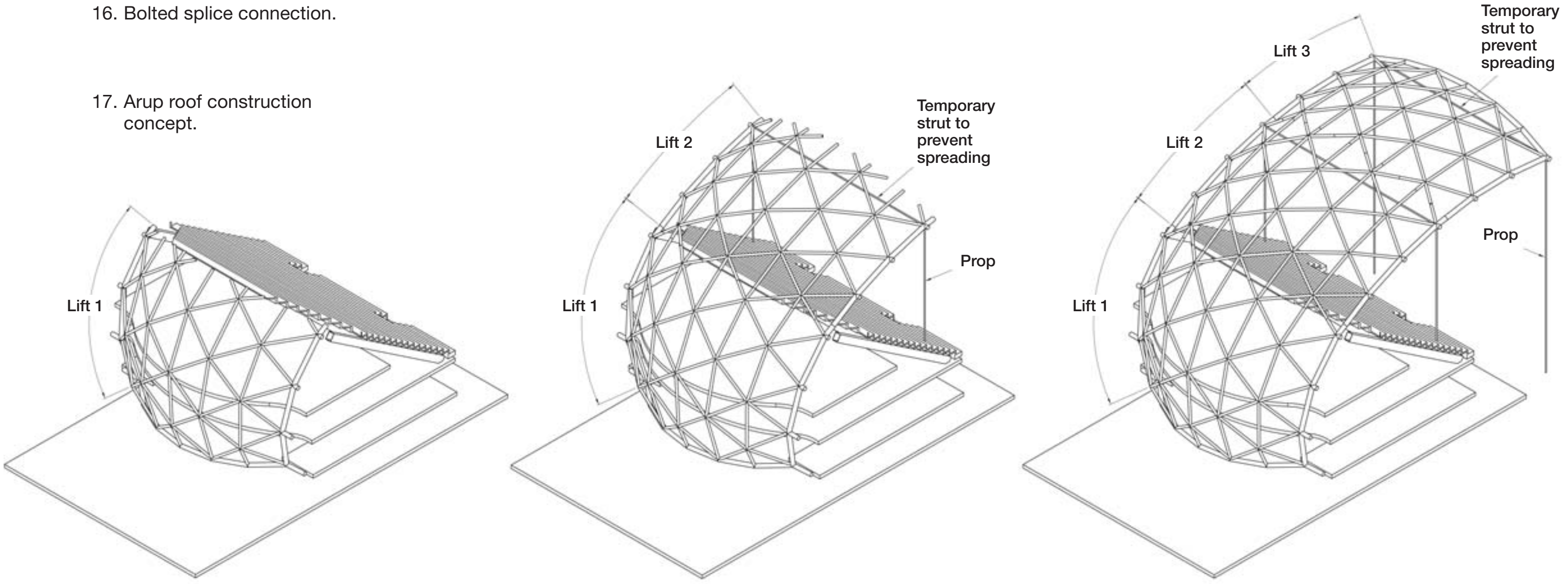
The design of 20 individual interconnected shells allowed the contractor to appoint three separate fabricators, reducing the overall construction time. The roof steelwork was fabricated off site (two fabricators were in Melbourne's south eastern suburbs, the third in Tasmania) allowing works on the concrete bowl structure to progress. Each shell was split into transportable sizes, allowing steelwork to be painted and delivered to site (including being ferried across Bass Straight from Tasmania). Bolted splice connections were adopted in preference to on-site welding (Fig 16).

The roof erection procedure adopted by the contractor differed significantly to the original Arup concept (Fig 17), which included the delivery of the largest possible prefabricated sections for welding into shells on site, prior to large crane lifts.

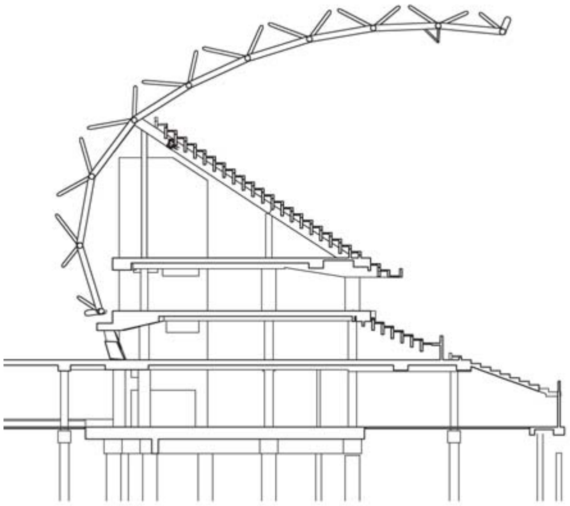
The contractor's preferred scheme relied heavily on site bolting, with connection plates adding weight to the structure. The scheme also added complexity to the structure, requiring mating end plates at connections, with zero tolerance.

Arup developed a bolting and shimming procedure to ensure that the contractor's preferred scheme could achieve the structural design intent (Fig 18).

17. Arup roof construction concept.



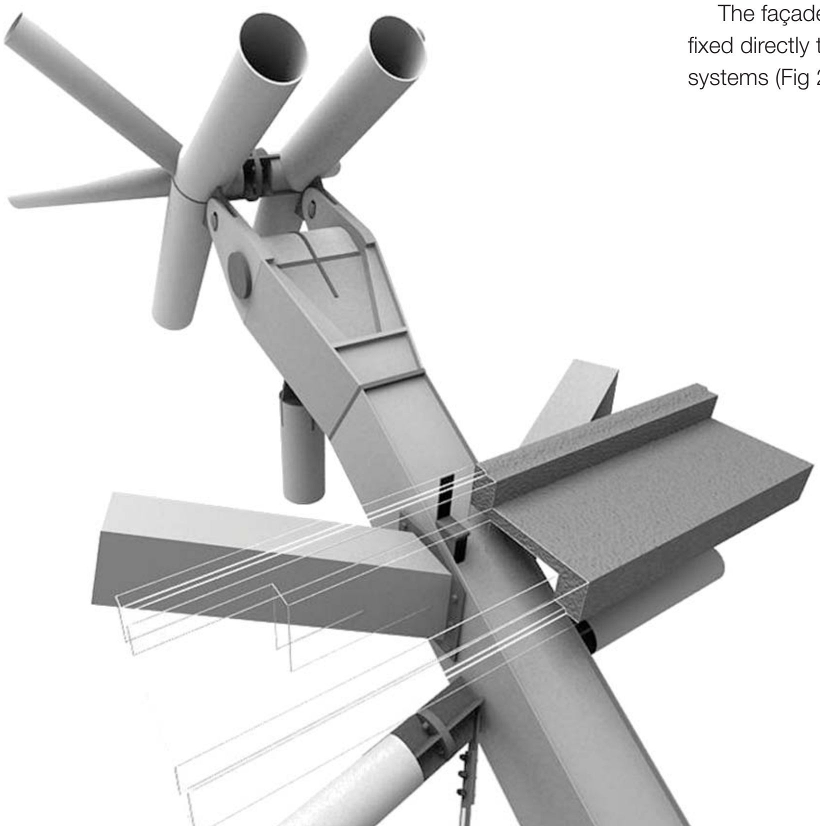
18. Construction of shell roof, October/November 2009.

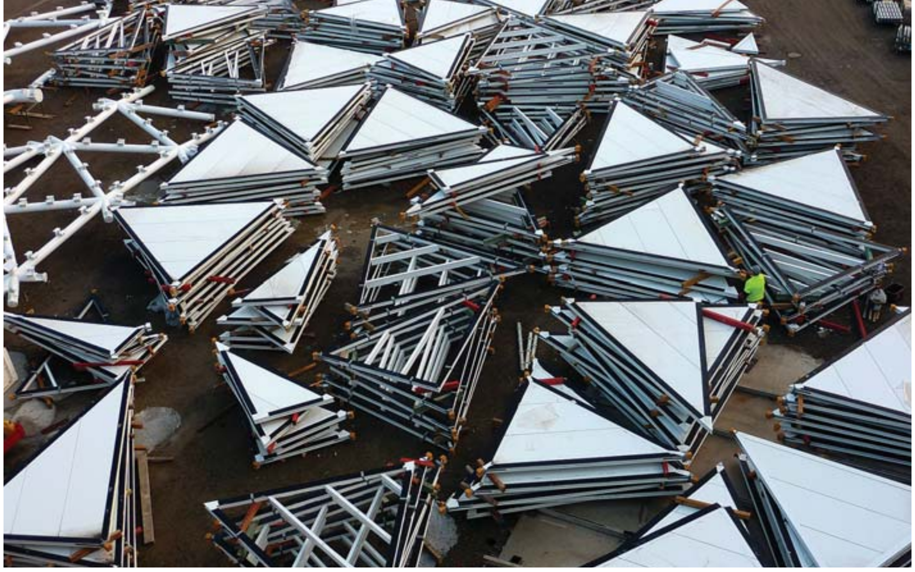


19. Typical section at groyne, showing connections.

20. V-column supporting vertical loads.

21. Connection at back of seating bowl.





22. Façade elements.

Roof/bowl interface

Each of the 20 steel roof shells is connected to the concrete structure at the bottom corner, and at the back of the seating bowl (Fig 19).

The base connections allow rotation via ball-and-socket details, while transferring axial loads and shear forces into the concrete structure. All vertical load is transferred to the concrete structure at the base connection. V-shaped columns are designed to integrate with the 13m structural floor grid (Fig 20).

The connections at the back of the seating bowl transfer axial thrust into the raking steel beams used to support the seating bowl.

Each connection is detailed with a slotted hole to prevent bending moments being transferred into the steel structure, and to eliminate any axial load being transferred to the steel and concrete columns (Fig 21).

Façade installation

The façade is a combination of triangular glass and aluminium sandwich panels (Fig 22). The glass panels comprise approximately 20% of it, positioned at strategic locations in line with internal concourse spaces to allow patrons views of surrounding parkland. The lightweight aluminium sandwich panels allow enhanced thermal and acoustic performance of the stadium. They are self-supporting between the triangular panels of the primary steel frame, eliminating the need for the secondary and tertiary layers of steel often part of the design of traditional cladding systems.

The façade panels were assembled and sealed on site prior to being lifted and fixed directly to the steel structure, eliminating the need for secondary steel purlin systems (Fig 23).

23. Installation of façade panels.

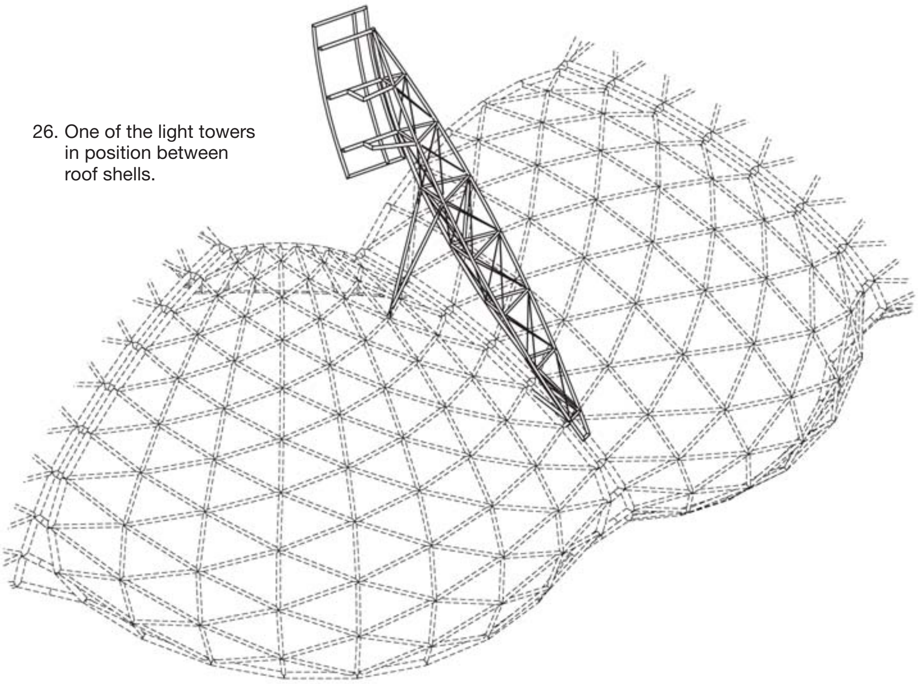
Light towers

The four light towers are supported directly on the roof structure. Each comprises a “main frame” truss section with front props to the roof structure, and a “head frame” section to fix the light units (Figs 24-26).

Both the main frames and head frames were spliced into two transportable-sized sections. The lower section of the main frame was connected to the roof with the front props in place, while the two sections of the head frame were bolted to the other part of main frame on the ground and then lifted. Fixing the head frames on the ground allowed any alignment issues to be safely resolved prior to erection, therefore reducing crane time.

24. AAMI Park and Olympic Boulevard.

25. Testing the lights.



26. One of the light towers in position between roof shells.

Sustainability

The efficiencies from the structural design process generated a structural steel weight of approximately 50kg/m^2 (not including cladding), a tonnage approximately 50% of the norm for stadium roofs of similar size. Not only is the roof structure lightweight, it also eliminates the need for secondary steelwork purlins to support the façade. The triangular panels forming the façade system fix directly to the structural frame.

The roof interface with the concrete structure is an example of multiple use of the structural systems. The 20 individual shells are supported at each back corner by the ball joint on raking concrete columns. These columns also support the concrete floor system, which is scalloped to match the profile of the bio-frame geometry. Each shell is also propped at the back of the seating bowl, so that the steel beams supporting the upper seating terraces also become roof support.

In addition to the structural efficiencies, the stadium design also allows rainwater to be collected from the roof structure, for use in seating wash down and toilet flushing.

Value

Value results for AAMI Park from the structural engineering concept and design processes therefore include:

(1) Parametric modelling allowed variations in geometry to be tested quickly to provide the most structurally efficient form.

(2) Structural optimisation determined minimum steel tonnages for the roof geometry.

(3) By combing parametric modelling and structural optimisation, the engineering design team provided value in both steel tonnage savings and design time savings.

Pitch and turf

The brief for the playing surface appeared simple; design a FIFA and IRB-approved flat playing surface that can be used to host football (soccer), rugby league, and rugby union. The challenge for the design was the frequency of use for sport and entertainment – more than 50 events per year. The playing surface would have to endure high wear throughout the year with minimal recovery between matches.

Arup identified early in the project that three key elements had to be addressed in the design to ensure the pitch could withstand the high intensity of use:

(1) sunlight: a minimum of four hours of direct sunlight on every section of the playing surface

(2) ventilation: adequate air flow across the playing surface to assist with breaking the mildew process

(3) routine maintenance/turf replacement: the proposed profile should be designed so that the playing surface could be readily maintained and allow for a successful turf replacement regime.

The natural turf playing surface is 130m x 76m with a 3m wide perimeter synthetic grass surround (Fig 27).

The surface is based on United States Golf Association (USGA) putting green construction, with a 300mm rootzone sand layer overlying a variable depth drainage gravel blanket. The top 100mm of the rootzone sand layer is amended with peat moss additive.

The USGA putting green construction methodology relies on the creation of a perched water table at the interface between the rootzone sand layer and the drainage gravel blanket. Once this layer is saturated, any additional water passes through to the gravel drainage blanket below.

The system allows for a very well-drained surface, while providing a moist environment below the surface to promote turf growth and health.

Couch was selected as the turf because of its low thatch accumulation, high vigour, and rapid recovery after wear. It is also conducive to over-sowing, and supports the rye grass well. Rye grasses were chosen after two years of trial; they feature excellent wear tolerance and recovery from injury, improved summer stress tolerance, and active winter growth.

Due to the flat playing surface, drainage is by infiltration through the profile, and is collected in the underlying subsurface agricultural drainage network. Working with AGCSA Tech, Arup produced a detailed specification for construction of the profile.

To enable collection of the infiltrated water through the profile, a ridgeline was formed in the subgrade in the middle of the playing surface along the length of the pitch.

Infiltrated water runs along the sloped subgrade layer until collected by subsurface agricultural drains spaced at regular intervals and connected to larger collector drains that fall to the perimeter trunk drainage network. The subsurface agricultural drains are in a traditional “herringbone” configuration.

Pedestrian modelling

Arup provided pedestrian planning advice for the external podium and forecourt areas. Safety being a primary factor in pedestrian movement, Arup’s work enabled architects and stakeholders to make informed decisions regarding the appropriate sizing for the podium level, the forecourt area (including ticket facilities), the two main podium stairs, lift locations, placement of furniture, and overall operational requirements.

With the aim of maintaining patron flow at all times, dynamic simulation techniques were used to test vertical circulation, queue zones, and ticket facilitates. The simulations allowed the team to test, in a virtual environment, the behaviour of all 31 000 spectators, both before a game and after the final whistle. Arrival and departure profiles were captured to reflect different types of game (soccer and rugby) and different types of ticket purchasing behaviour. The models were then analysed to quantify the amount of time patrons have to stop because of the design (“stationary time”). The concept was based on the notion that slowing a crowd is actually a positive outcome from a cost and operational perspective, but slowing people to the point where they have to stop begins to create frustration and potential hazard.

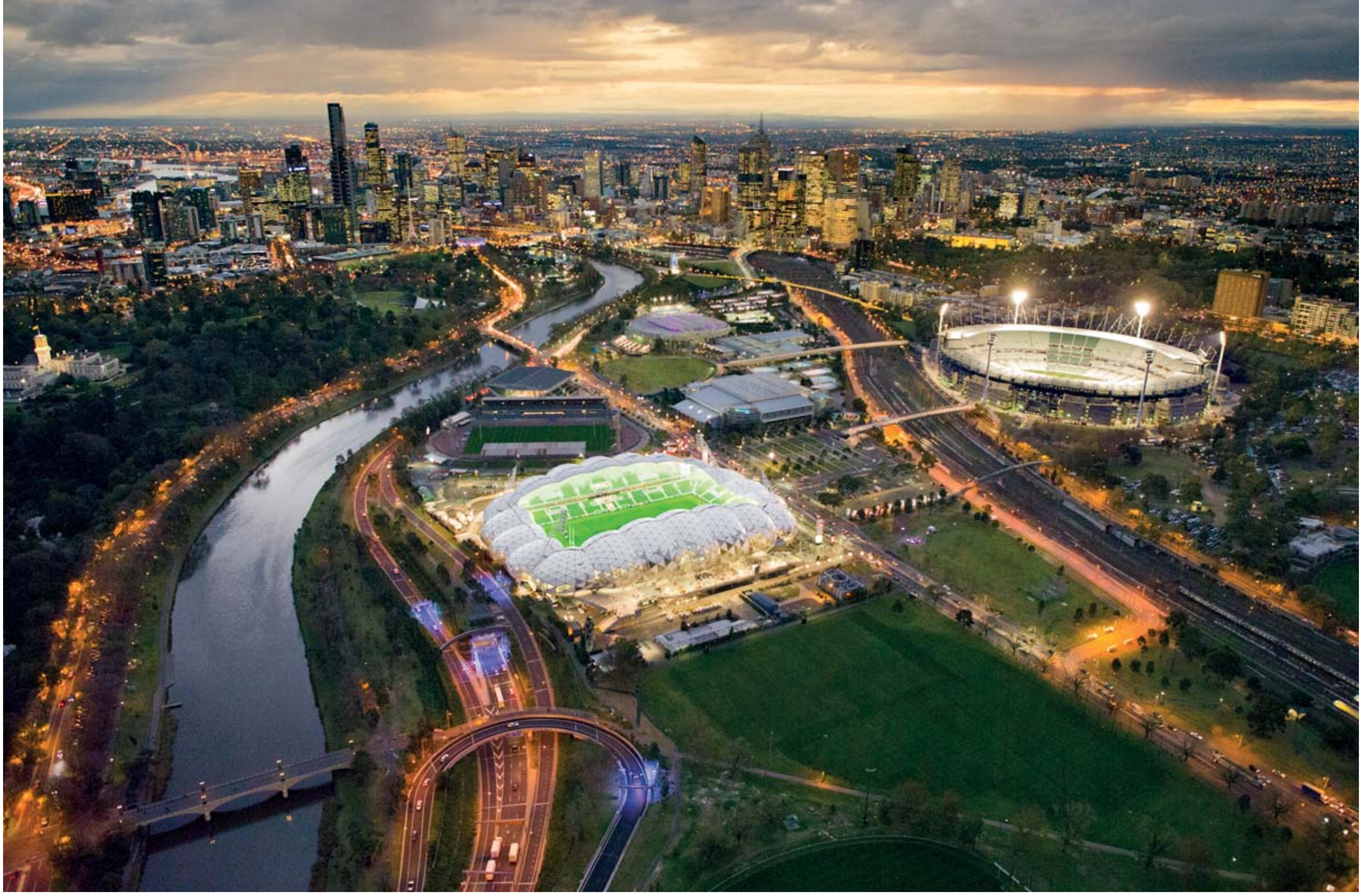
The pedestrian planning team, aided by the simulations, were able to help engage with the design team and key stakeholders to drive improvements in the design process, and expedite important decisions.

Some of the key challenges for spectator movement were around the main east/west stairs from podium to forecourt, and the relationship of the forecourt with the surrounding facilities and transport options. Early designs tested showed the stairs to be too narrow, creating large queue formations at their tops where they flow into the stadium. If, on the other hand, the stairs were too wide, people would enter the forecourt too quickly and create issues at the busy street level. The key was to determine the right balance.

As a result of Arup’s analysis the stairs were widened and reshaped, the forecourt was increased by moving the whole stadium, lifts were relocated to provide clear passage for those with restricted mobility, and proposed furniture was moved to maximise clear walking area in the forecourt. The end product is a smoother, more comfortable, more reliable spectator experience (Fig 28).

27. Playing surface being installed, April 2010.

28. AAMI Park in use.



29. AAMI Park opening night.

Conclusion

The opening of AAMI Park in May 2010 (Fig 29) brought to a close more than five years of effort by Arup's design and engineering teams for the structural and civil engineering, pitch and turf, façade and pedestrian modelling.

The stadium roof concept developed by Arup with Cox Architects and Planners resulted in a cutting-edge structure that requires 50% less steel than typical stadium roofs of the same size. The design team worked in a virtual 3-D environment from initial design through to construction, using 3-D parametric modelling together with optimisation and analysis software to deliver efficiencies to the structure.

This stadium represents the next generation of structurally efficient design, and sets a new benchmark for other stadium projects around the world.

John Bahoric is an Associate of Arup in the Building Structures Melbourne group. He was responsible for the roof structure design for AAMI Park.

Greg Borkowski is a senior engineer with Arup in the Building Structures Melbourne group. He was responsible for concrete bowl structure design and coordination of structural site issues for AAMI Park.

Peter Bowtell is a Principal of Arup and leads the Melbourne office and the Buildings practice in Melbourne. He was Project Director for AAMI Park.

Tristram Carfrae is a Principal of Arup, an Arup Fellow, and a member of the firm's Main Board. He is based in the Sydney office. He developed the structural concept for the AAMI Park roof.

Frank Gargano is a Senior Associate of Arup in the Building Structures Melbourne group. He was Project Manager and lead structural engineer for AAMI Park.

Jarrod Hill is an engineer with Arup in the Infrastructure Melbourne group. He was responsible for design of the pitch and turf for AAMI Park.

Paul Stanley is a Senior Associate of Arup in the Infrastructure Melbourne group. He was responsible for the pedestrian modelling for AAMI Park.

Credits

Arup client and architect: Cox Architects and Planners **Facility management:** Melbourne and Olympic Park Trust **Project management:** Major Projects Victoria (MPV) **Structural and civil engineering, pitch and turf, façade and pedestrian modelling designer:** Arup – Mark Ayers, Jarrod Hill, Andrew Alsop, Mark Arkinstall, John Bahoric, Greg Borkowski, Peter Bowtell, Tristram Carfrae, Peter Duggan, Alex Edwards, Frank Gargano, Graham Gedge, Peter Gillespie, Martin Holt, Anthony Ivie, Daniel Lambert, John Legge-Wilkinson, Sean Maher, Alastair McConville, Brendan McNamee, Conor Monaghan, Jin Pae, Tanya Price, Jochen Ristig, Paul Simpson, Nathan Smith, Peter Smithson, Charles Spiteri, Paul Stanley, Rod Veal, Doug Wallace, Ashley Willis **Mechanical & electrical engineer:** Norman Disney & Young **Contractor:** Grocon Constructors **Illustrations:** 1, 2, 24, 29 John Gollings; 3, 8-23, 26-28 Arup; 4 Peter Hyatt, 5 Arup Associates/Dennis Gilbert, 6 Arup/Midmac/Sixco, 7 Christian Kober; 25 John King.

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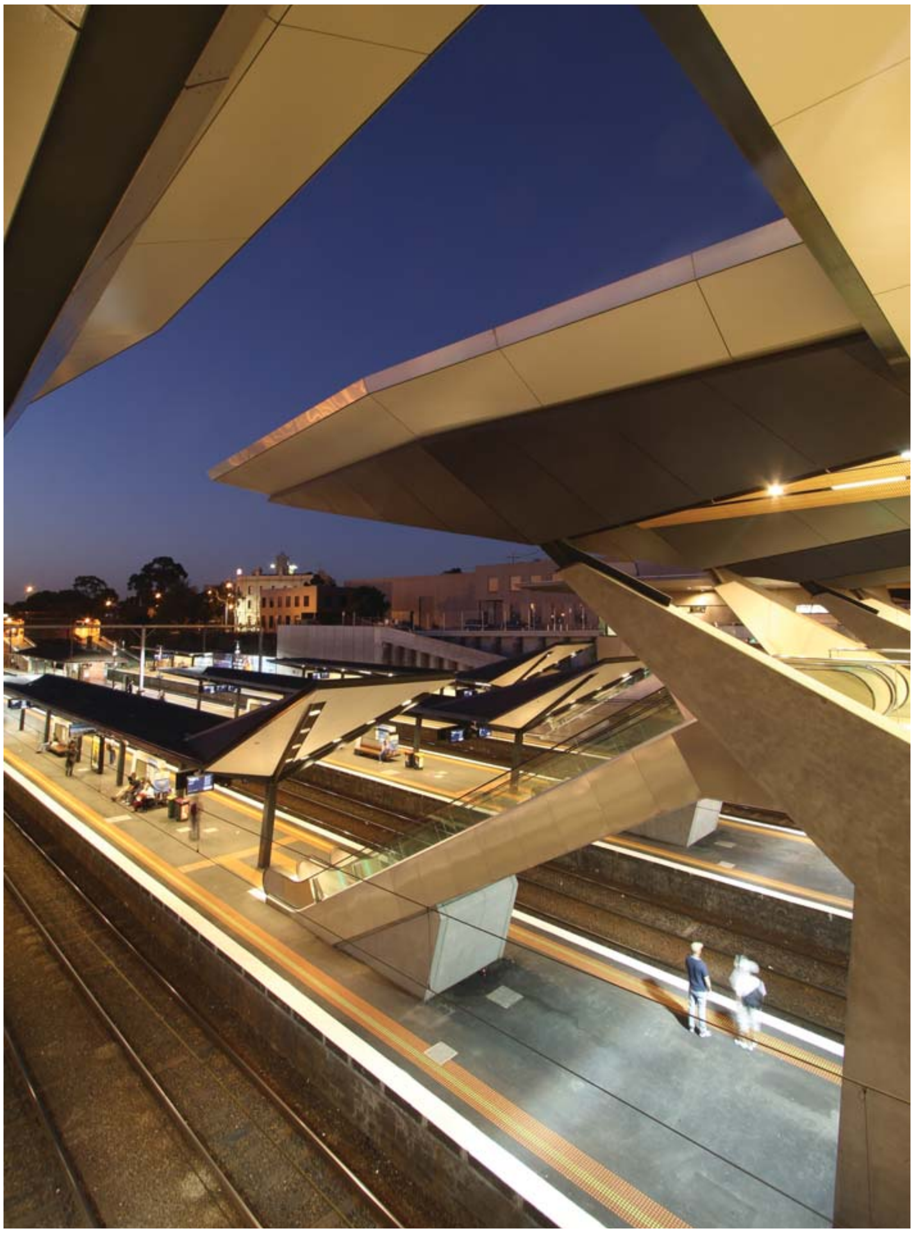
North Melbourne station redevelopment

Joseph Correnza Patricia Culhane Marco Furlan Jochen Ristig Paul Stanley



1. The finished station from the concourse level above platform 6.

> “Arup was able to come up with innovative design solutions for various site constraints and challenging project needs. These design solutions enormously helped to achieve minimal disruptions to commuters during construction and overall project outcomes.”
>
> Ranabahu Wickramasinghe, Project Director, Department of Transport.

The project

With some 2M travellers annually – a number expected to double in coming years – North Melbourne is one of the city’s premium rail stations.

The first passenger station at this site, with two platforms, was built in 1859, and in its current configuration the station opened in 1886.

The six platforms are in a cutting some 8m below the station building, which is located at street level. The platforms are close to freight line routes and to suburban train stabling, and near the entry to the Melbourne City Loop, the underground railway that runs beneath Melbourne’s central business district (CBD). North Melbourne station is one of the main interchanges for City Loop passengers connecting with both suburban and regional trains.

In May 2006 the Victoria Department of Transport announced a A$39M redevelopment for North Melbourne station, and engaged Arup as the lead consultant. Faced with multiple challenges of construction in a live rail environment, the firm devised a unique design solution that has been used as a benchmark for subsequent projects.

The scope encompassed a new concourse structure over the city end of the platforms, with lifts and escalators connecting the concourse to all six of them. This new station building provides better urban integration of the station precinct, additional platform shelter, resurfacing to the platforms for greater safety, additional CCTV to enhance security, and upgrades to passenger information display screens and public address communications.

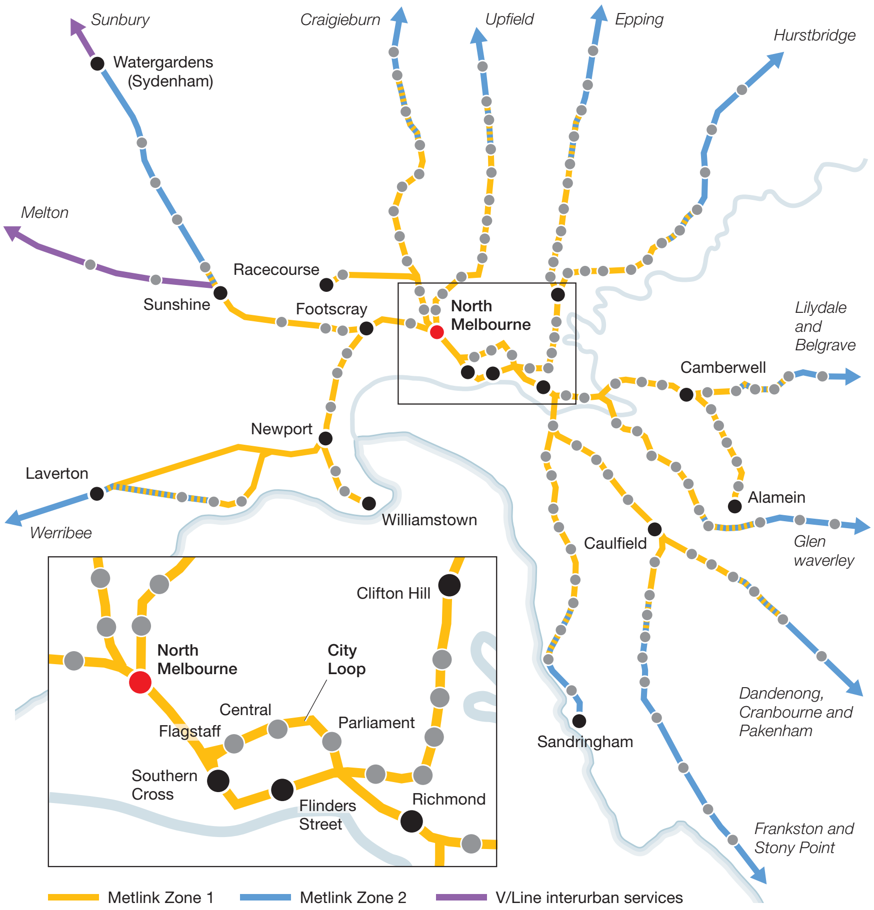
A further key element of the design was to acknowledge and retain the existing heritage listed station facilities and overpass structure.

Client requirements

The Department of Transport’s project drivers included improved convenience for interchanging passengers, and station accessibility for all passengers, with improved amenity.

Another important driver was to encourage more passengers coming from the city’s suburbs to interchange between trains at North Melbourne station in order to travel through the City Loop to its CBD stations of Flagstaff, Melbourne Central and Parliament. The City Loop is functioning close to capacity already and the number of trains going through the tunnel cannot be increased significantly.

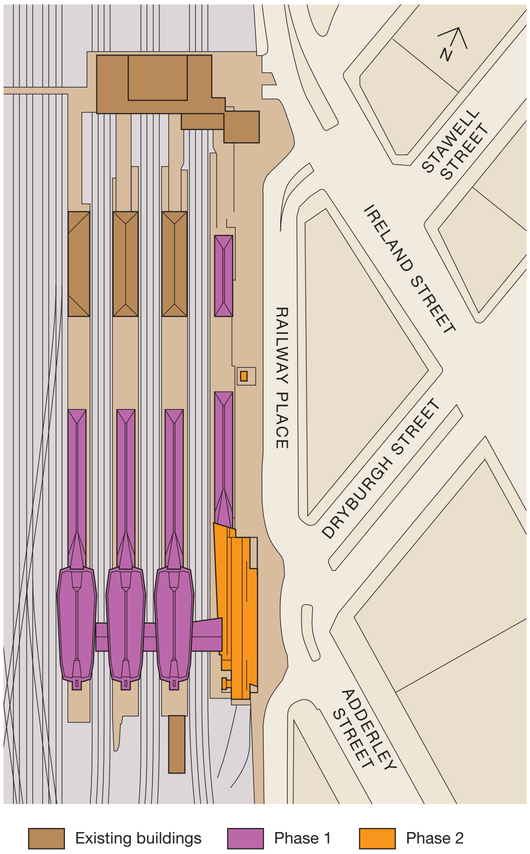
2. The new station entrance and station building from the forecourt on top of the embankment.



3. The Melbourne metropolitan rail network.

Improving the interchange facility meant that passenger numbers going through the Loop could be increased without increasing the number of trains through it. This improvement to the interchange capacity at North Melbourne and reduction in the need for all trains to pass through the City Loop met rail operational requirements and supported a new regional and metropolitan timetable.

In addition to this, there was an overall driving vision that embraced integration with the surrounding urban environment, improved intermodal connectivity with buses and taxis, ease of maintenance, and vandalism control.



4. Site plan: existing heritage listed station facilities in the north-west corner and new platform canopies, concourse roofs, and station building in the south east.

The team decided that the project should be divided into two phases, and devised a two-stage schedule. Phase 1 was to involve the opening of the concourse structure for interchanging passengers, and Phase 2 the delivery of the new station entrance building.

Arup instigated a complete rethink of the station design, consulting constantly and closely with the rail authorities to find innovative solutions to working in the rail corridor while maintaining operations and minimising rail and passenger disruption.

Intensive workshop sessions were held, allowing the designers to agree with all stakeholders – including, importantly, the accredited rail operator – on the best solutions within short timeframes. Arup received positive feedback on these sessions from all involved.

Early and constant interaction with the client and operator was fundamental in arriving at the final solution – an all-encompassing strategy that resulted in minimal disruption and construction in a fully operational rail environment.

5. Rendered architectural image of the new concourse structures viewed from the south (concourse roofs, concourse deck, stairs and lift shafts).

Engineering design

As lead consultant, Arup acted as design manager and delivered all engineering disciplines (except for signalling) – structural, civil, rail, fire, building services, communications, security and pedestrian planning. The firm was also responsible for co-ordinating and managing all sub-consultants, including architectural (Cox Architects), town planning, environmental, cost estimating, investigative surveys, disability management, heritage, and building surveying services.

Structural design

The station design includes a 6m wide concourse deck that links all platforms to the new station building, with access to the surrounding environment. Access to the concourse is provided by two escalators and one lift for each platform, with additional stairs on platforms 1 and 6. The station building has to satisfy the requirements of a premium station for staff and passengers: toilets, waiting room, booking office, staff office and amenities and mobility (compliance with Australia's 1992 Disability Discrimination Act).

The key design drivers for the deck were impact loading and constructability. Australian Standard *AS5100*[1] requires the main structural supports – in this case the concourse supports (one concrete pier and one lift shaft in the centre of each platform) – to be subject to a static load equivalent to that of a derailed train (3000kN parallel to the tracks, together with 1500kN perpendicular to the tracks at 2m above the rails). As the existing alignment of the rail tracks was not to be modified, the new station superstructure had to be designed accordingly. The existing platform structures similarly were not modified.

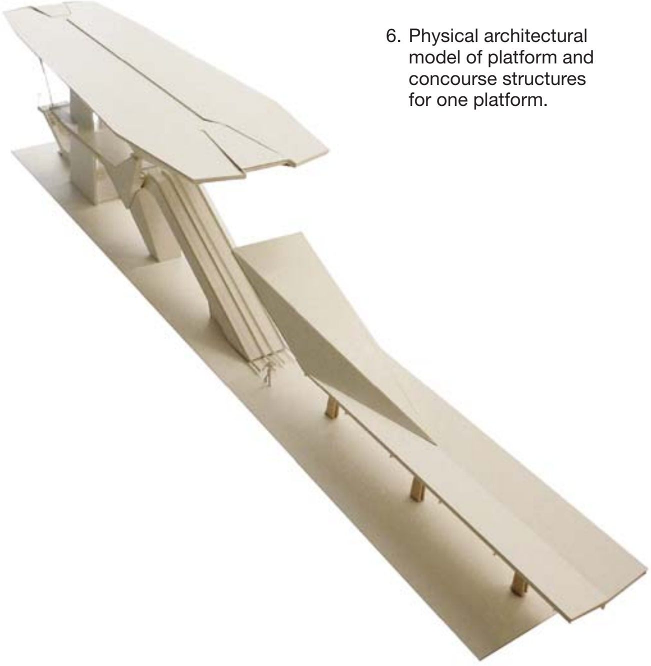
The new access points at the opposite ends of each platform were designed to rail and DDA standards despite very tight clearance constraints. Where the concrete pier and the lift shaft landed on the platform, the available platform width was less than 7.5m, limiting the overall dimensions of these structural supports. Ultimately, the lift shaft side walls could only be 200mm thick, while the main concrete pier was tapered at its base to allow enough clearance for passing passengers. These functional constraints and clearance requirements were used as a basis to develop and define a form for the structure.

The lift shaft was therefore designed as a composite box, comprising precast concrete side walls with steel ladder frames on the door side and back face to facilitate the use of transparent glass cladding for maximising passive surveillance, thus increasing safety and comfort for patrons.

The ground conditions were difficult, with areas of low-capacity clay. To resist the impact loading, shear keys were introduced under each main pier, along with ground beams that connected the lift shaft and pier footing. For the impact condition, an ultimate assessment of the soil capacity was undertaken that allowed large deflections, but avoided progressive collapse.

The main steel support for each typical platform concourse roof was initially designed as two parallel three-dimensional triangular trusses, which avoided the need for a complex secondary steel layer to achieve the final cladding profile. The form was developed in close collaboration with the architect and was designed to integrate structural requirements, finishes, and fabrication from the adoption of repetitive simple geometry.

The station building was constructed on top of an embankment adjacent to the platforms with a 6m high retaining wall. This area was highly constrained, and cantilevered bored piles with reinforcement ratios higher than 6% were designed to accommodate an existing major gas main by limiting lateral deflections of the embankment, as well as an access road for maintenance vehicles passing under the building.



6. Physical architectural model of platform and concourse structures for one platform.

Building services, communications, security

Of the building services component, the lighting design was subject to stringent regulations from the client. At the start of the concept design, all station lighting on the suburban and regional network was provided via high pressure sodium lamps, due to their long life and low maintenance requirements. Given the high importance of this interchange station and the growing preference towards white light for public comfort and safety, the use of either fluorescent or metal halide lamp sources was required.

As North Melbourne was considered the pilot station for the use of white light in Melbourne, considerable design input was required to determine the appropriate standards for lighting levels of white compared to yellow light. Issues addressed include providing appropriate lighting levels across the platforms, up to and including their edges, limiting glare onto the rail corridor, access and maintenance of luminaires, architectural design, and functionality.

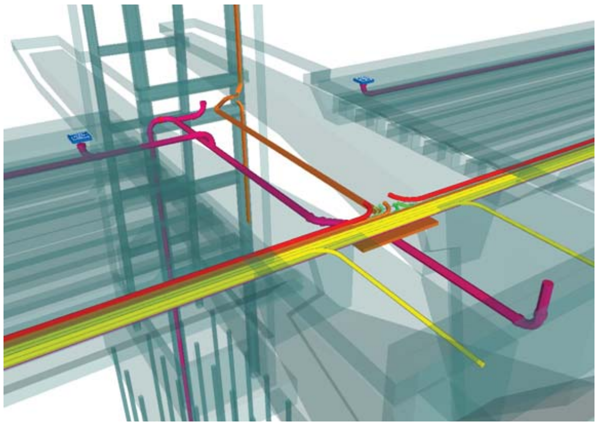
The design of the platform was initially completed using T5 fluorescent lamps (ie lamps with $^{5}/_{8}$in/15.9mm) diameter ends), and subsequently refined during construction to T8 (1in/25.4mm diameter) lamps due to their better performance at lower ambient temperatures, such as those experienced over night in Melbourne. The T8 solution required larger luminaires, increasing the on-site co-ordination needed between engineers, architects and contractors.

Site constraints and constructability issues meant that there were only limited opportunities to conceal electrical and communications cabling within void spaces, so 3-D modelling of the concourse deck was needed to ensure that all electrical conduit requirements could be physically installed within the structure.

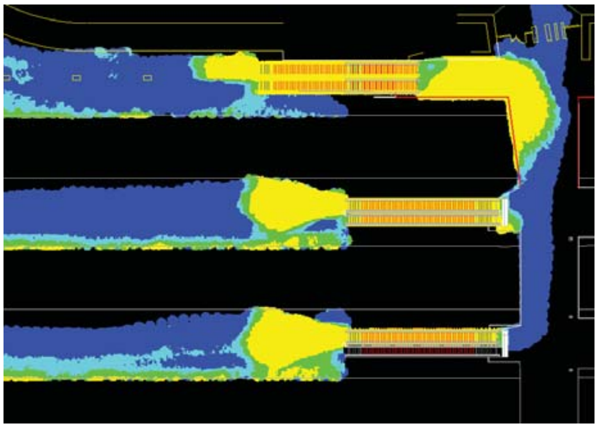
An IP-based digital CCTV system was included as part of the station upgrade. Here, the key driver was to improve patron security and allow for CCTV footage to be recorded for post-incident review and storage at an off-site location for 30 days, which was achieved.

7. Finished platform canopy roofs with 6m high retaining wall and access road in the background.

8. Finished station from the concourse level above platform 4.



9. 3-D integrated structures and services model.



10. Graphic output of *Legion* model showing queuing density.

Pedestrian modelling

Arup's pedestrian planning team assessed the impact of demand and timetable changes at North Melbourne station, so as to understand the benefits and implications of the proposed upgrades on the station performance.

Existing passenger movement patterns in the station were assessed, in the light of the current timetable and projected demand growth out to 2021.

Arup's modelling estimated how key elements – vertical transportation capacity, egress, concourse and platform congestion – would perform, and thus could determine the likely issues and constraints facing the station in base and future years.

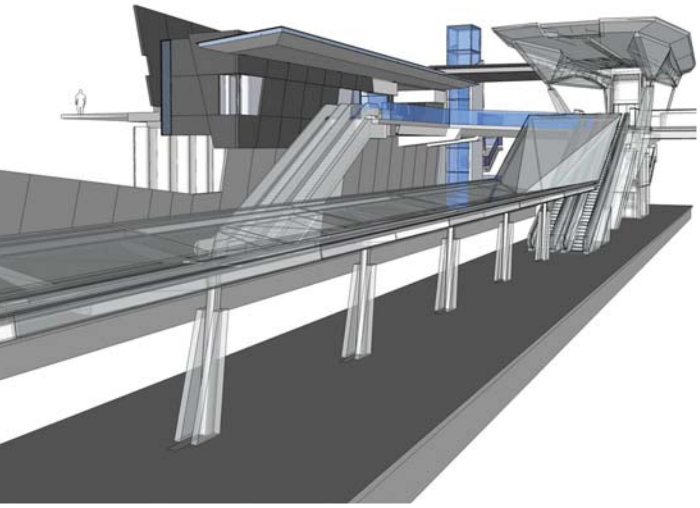
The platform width constrained the ability to accommodate two recognised transit width escalators (2 x 1000mm tread). Instead a combination of one 800mm and one 1000mm was used. Arup's dynamic modelling demonstrated that the combination of escalators was suitable, and that queueing in the interchange zone due to passengers disembarking from two simultaneously arriving trains would subside without affecting train operation.

Through an iterative process with the architect, the concourse width, run-off distances to stairs and escalators, and gateline configuration were established with the aid of Arup's pedestrian planning experience.

Constructability

Prefabrication, modular design, installation procedures, and minimising element weights were key to the design solutions developed. Detailed drawings and strategies were produced for the fabrication, transport, and installation of each element, the installation having to be undertaken within a strict clearance envelope. Sophisticated 3-D modelling was done with various software packages including *GSA*, *Microstation*, and *Navisworks* to suit the applications. The 3-D model had multiple uses, the most important of which were its ability to detect clashes between components, services and the site boundaries, and to demonstrate constructability and geometry definition for the shop detailers.

On many projects, the costs of fabrication, transport and ease of construction are the prime drivers, but Arup knew that when working on active train stations in live-rail environments these costs can be small compared to those incurred by service interruptions and shutdowns. Arup conducted constructability reviews that informed the design, allowing platforms to remain operational throughout construction. The team also developed strategies that permitted construction activities to occur over live rail lines, with the result that disruption to passengers and operations was drastically minimised while the works were being completed.



11. 3-D rendered view of the new station building on top of the embankment from platform level.

12. The main impact-resistant support pier from platform level.

These strategies maintained two key principals throughout the design:

(i) elemental-modular design, and

(ii) separation of construction activities from train operations.

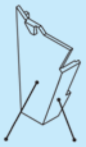
The first of these was achieved by breaking the structure into elements with a maximum weight of about five tonnes. This ensured that the crane capacity from the top of the embankment was adequate and minimised the time an element had to be on the crane hook, a consideration that can be critical for short rail occupation windows. It also informed the use of 150mm thick precast panels for the concourse concrete structures, which acted as lost formwork that could then be filled with in situ concrete to provide final robustness and strength.

Other elements were designed to act in composite (precast plus in situ) due to the space constraints. Additionally, the team aimed to have no externally visible fixings for the precast concrete element connections.

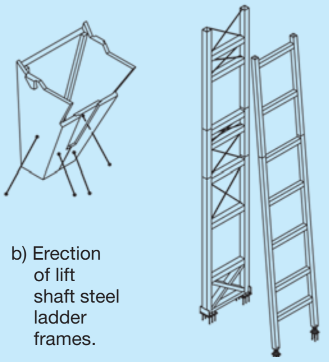
Due to the complex 3-D geometry of the structure, both physical and virtual models were prepared to help the client and contractor visualise and explore the buildability of the proposed geometrics. Arup's 3-D model was used to set out the steelwork and precast concrete works, forming the basis of the shop drawings.

Steelwork elements were pre-assembled on site, with the concourse canopies constructed on top of the embankment, fully clad, and slid into their final positions as finished assemblies. The advantage of this was that no rail shutdown was required, again proving the benefits of elemental design.

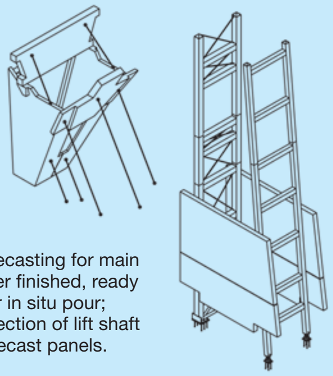
13. Constructability “cartoon” issued as part of the tender package demonstrating the buildability of the structure with minimal disruption to the station operations.



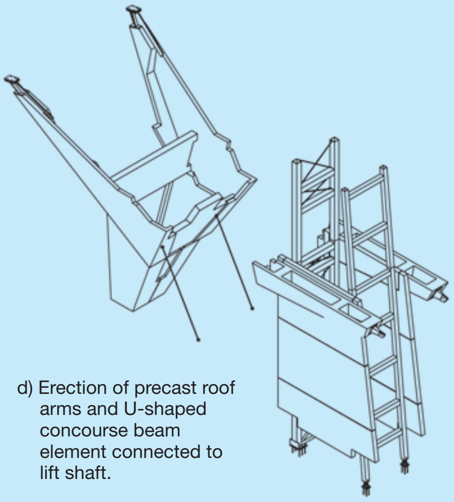
a) Erection of pier precast as lost formwork.



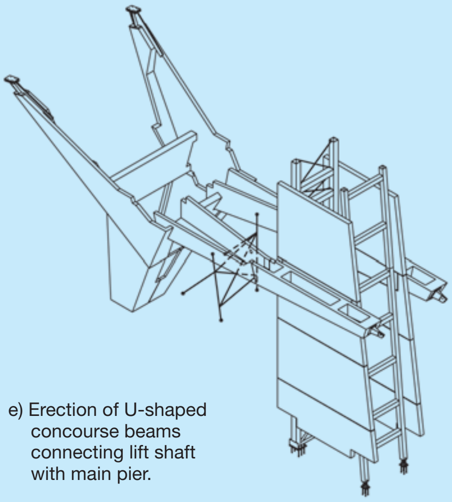
b) Erection of lift shaft steel ladder frames.



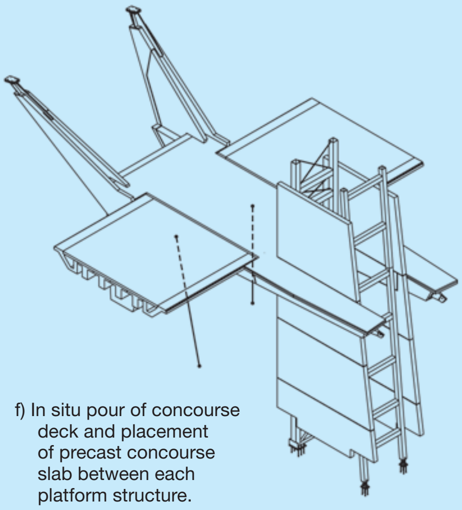
c) Precasting for main pier finished, ready for in situ pour; erection of lift shaft precast panels.



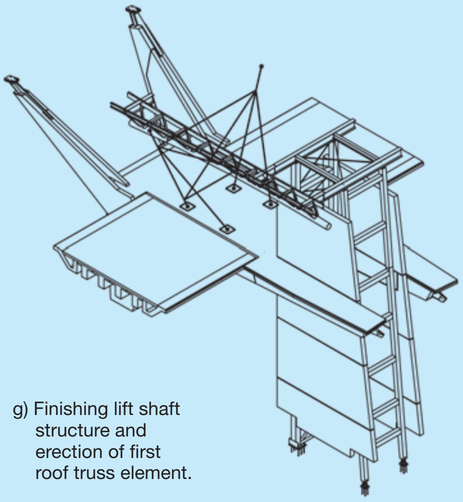
d) Erection of precast roof arms and U-shaped concourse beam element connected to lift shaft.



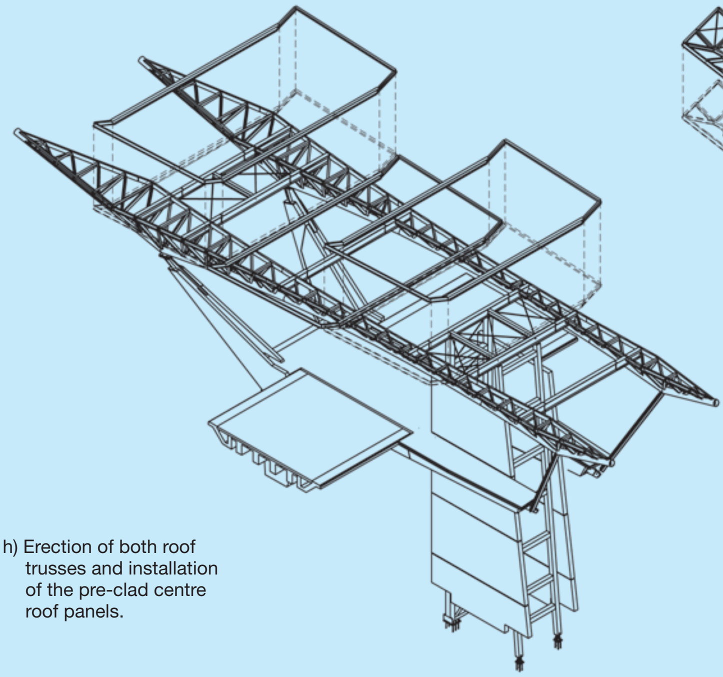
e) Erection of U-shaped concourse beams connecting lift shaft with main pier.



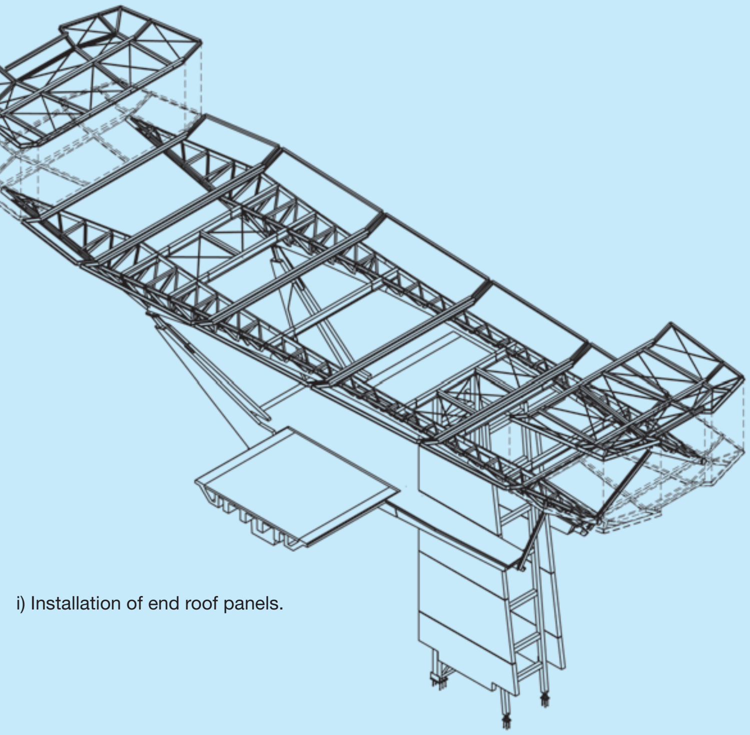
f) In situ pour of concourse deck and placement of precast concourse slab between each platform structure.



g) Finishing lift shaft structure and erection of first roof truss element.



h) Erection of both roof trusses and installation of the pre-clad centre roof panels.



i) Installation of end roof panels.

14. Erection of "crash deck" prior to any construction activity of the new concourse structures.

15. Zone contained by the crash deck where lift shaft and pier foundations are located.

Based on the preference of the chosen contractor, each of the three main concourse roofs was to be constructed in its entirety on top of the embankment, then "skated" across six platforms and into its final position.

Separating construction activities from rail operations was achieved by building a temporary "crash deck" to protect train passengers and rail infrastructure. In the Melbourne network, there had been no precedent for such a protective shield, which was developed with the contractor to suit the final construction sequence. The shield was designed to resist an area loading of 10kPa, which the operator accepted as sufficient protection in the event of any construction element falling toward the rail tracks. Throughout the entire construction phase this deck was not breeched.

The crash-deck allowed the area above it to be treated as a "non-rail" site and the contractor could operate above the deck and overhead wires without disruption of rail services. The station design caters for overhead line electrification with a minimum clearance requirement of 5.75m above rail for suburban trains, and 7.1m above rail for country and freight diesel trains. The temporary crash deck conformed to these dimensional requirements with minimal distance between the top of crash deck and the bottom of the structure. Crane movements were restricted to above the deck. In this way, critical works – even the "skating" of the large concourse roofs – could occur during normal train operations. This strategy also minimised the need for night-time and weekend work, benefiting local residents.

For the platform canopies, temporary vertical hoardings were installed to create a working space within which the foundations could be constructed and then the platform canopies lifted into place. Over the 7m width of the platforms around 1.8m space was allowed either side of the hoarded space for passengers to pass.

Project delivery

This project involved multidisciplinary building and civil design, with Arup's project management team co-ordinating these services to deliver the project brief. Considering the challenging environment and its constraints, a clear delivery strategy was essential to this success. Furthermore, all the engineering design was independently reviewed by another Arup team in the Sydney office.

The project was contractually set up as a traditional construct-only tender. However, once the successful contractor was chosen, a series of value engineering workshops were held to optimise the design for the final construction methodology. Arup and Cox Architects worked closely to develop the building forms, based on engineering principals whilst providing highly functional spatial planning, integration of services and location of amenities.

16. Pier precast elements erected and main reinforcement placed prior to in situ concrete pour.

17. Lifting front lift shaft ladder frame across the rail tracks above the crash deck.

Innovations

Arup's approach to the project delivery involved an extremely high level of integrated design from the outset. Having the rail operator as part of the design team was beneficial, as it meant that the impact of each design decision on the station operations could instantly be reviewed and assessed.

Arup led the constructability planning and undertook workshops that informed the design, leading to the strategy that allowed platforms to remain operational and construction staging to occur over live rail lines. This minimised disruption to passengers and operations whilst the works were carried out.

The strategy involved prefabrication, modular design, and minimising element weights, along with provision of detailed drawings for fabrication and installation within the strict clearance envelope.

Due to the complex nature of the geometry, the structure could only be detailed using sophisticated 3-D modelling. The 3-D model was further used to develop "constructability cartoons" and formed the basis of shop drawings, the testing of pedestrian flow models, and to demonstrate signal sightlines for the temporary and permanent station. This detailed 3-D modelling was invaluable for clash detection, design co-ordination, and definition of site boundaries and clearance envelopes.

18. Crash deck and temporary roof skating structure viewed from the station embankment.

19. Concourse roofs assembled on top of the embankment, fully clad prior to skating into position.

20. Completed concourse structure from platform level.

The team also created 4-D+(time) models to assist in stakeholder and community consultation. The 4-D modelling has subsequently been successfully implemented on other Australian projects including Springvale Road/Rail Grade Separation in the Melbourne suburbs, where site logistics and construction phasing was optimised.

One further Arup innovation was to do acoustic testing to replicate a station environment in the firm's own *SoundLab* installation in the Melbourne office. Limited standards are specified for the public address system in stations, but these take no account of station design and the associated acoustics.

After the testing, Arup was able to specify a system better suited to this particular environment, another procedure that has since been used for other station designs.

Sustainability

Sustainability measures incorporated into North Melbourne station included natural ventilation, maximum use of natural light, and sustainable strategies for heating and cooling, though the rail environment itself tends to act as a constraining influence on sustainability aims. Care was taken to minimise quantities of material used, reduce the resources used during shutdowns, and select components and materials based on durability and long-term maintainability.

This station building is a significant step in the redevelopment and regeneration of the rapidly developing North Melbourne precinct. By drastically improving the buildings' appearance, increasing passive safety through good spatial planning, and improving general usability and commuter comfort, the design team created a station that people are willing to use and are proud of.

Conclusion

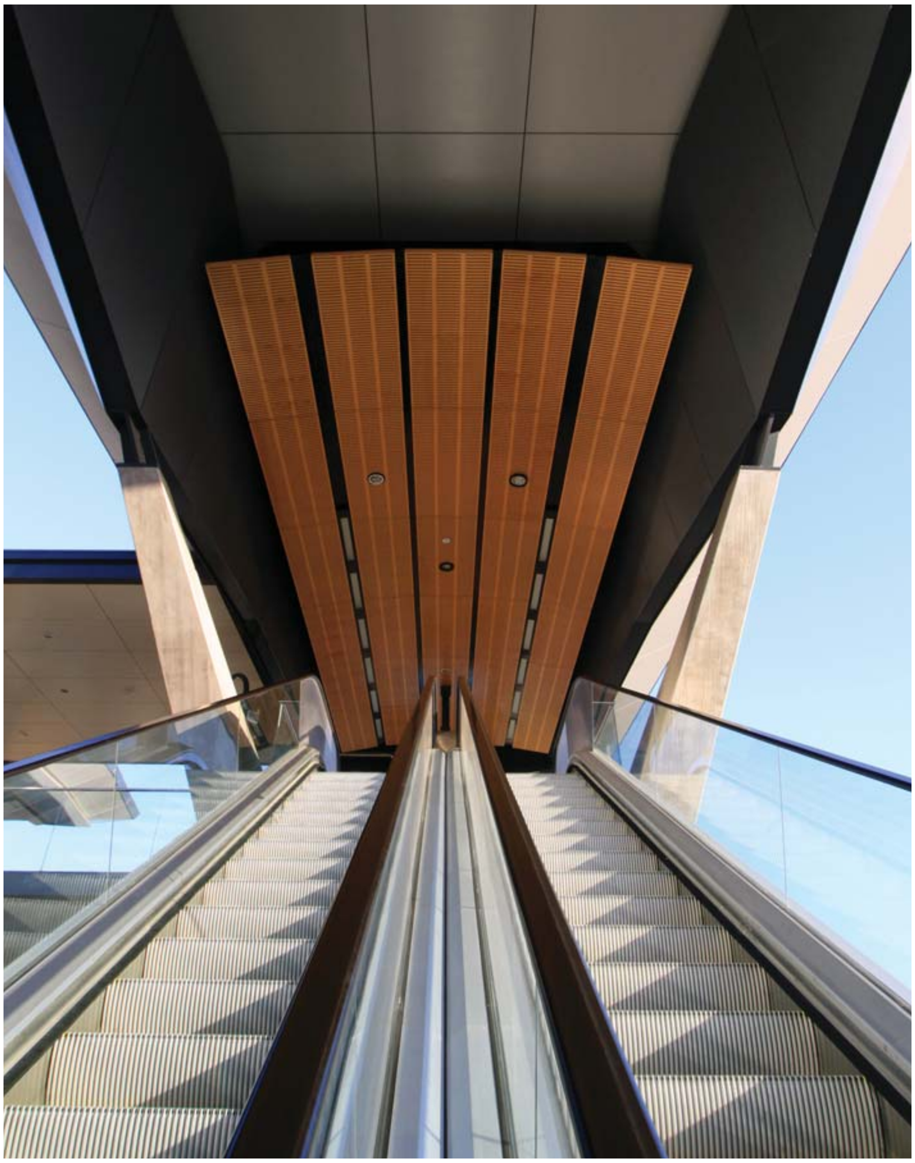
The North Melbourne station redevelopment involved almost all the engineering disciplines in Arup's Melbourne office and was instrumental in enhancing its multidisciplinary offerings across a wide range of other work.

The project's success has been attributed to the highly integrated approach adopted and its success led to Arup tendering for and winning several further station and rail projects throughout Victoria.

Surveys have revealed that transport workers and commuters were pleased with the handling and minimal shutdowns and service disruptions, and are extremely happy with the upgraded new station.

Broader community feedback has also been very positive. The old station was perceived to have aesthetic, safety and usability issues, while the new station is bright, safe, aesthetically pleasing, and compliant to all current building regulatory codes, including the DDA. It is a station that the community is proud of, and is playing an ongoing role in redefining the area.

21. "Bright, safe and aesthetically pleasing": the concourse roof from the base of the escalator.



22. View from new concourse overbridge onto platforms, with existing heritage listed station facility in the background.

Joseph Correnza is a Principal of Arup in the Melbourne office. He was Project Director for the North Melbourne station project.

Patricia Culhane is an engineer in Arup's Melbourne office. She led the design and documentation of the station lighting and electrical and communications works at North Melbourne station.

Marco Furlan is a Senior Associate of Arup in the Melbourne office. He was Project Manager for the North Melbourne station project.

Jochen Ristig is an Associate of Arup in the Melbourne office. He led the design and delivery of the concourse overbridge structure for North Melbourne station.

Paul Stanley is a Senior Associate of Arup in the Melbourne office. He undertook the assessment of pedestrian impacts at North Melbourne station.

Award

Australian Institute of Architects, Victoria Chapter: Public Architecture Award, 2010

Credits

Client: Victoria Department of Infrastructure **Lead consultant, project manager, and civil, SMEP, fire, risk and security, and transportation engineering designer:** Arup – Peter Adcock, Michael Alder, Mark Ayers, Trevor Buckley, Jeff Burleigh, Marina Burneska, Paul Carter, Joseph Correnza, Patricia Culhane, Rhona Tess Distajo, Peter Duggan, Leah Ferrari, Marco Furlan, Sacha Gebbie, Madeline Gray, Paul Guger, Nick Hardy, Liam Heather, Brad Heyme, Jarrod Hill, Paul Janssen, Daniel Lambert, Leann Lee, John Legge-Wilkinson, Andy Lin, Robert Macri, Sean Maher, Cameron McIntosh, Brendan McNamee, Michael Neal, Jochen Ristig, Marzena Rolka, David Shrimpton, Charles Shum, Charles Spiteri, Paul Stanley, Paul Suett, Kajan Tharmarajah, Sean Tobias, Peter Washfold, John Wheadon, David Wintershoven, David Young **Architectural subconsultant:** Cox Architects and Planners **Geotechnical engineer:** Golder Associates **Quantity surveyor:** WT Partnership **Main contractor:** McConnell Dowell **Project manager (rail operator):** Connex **Illustrations:** 1, 2, 7-8, 12, 20-22 Peter Hyatt; 3-4 Nigel Whale; 5-6, 11 Cox Architects; 9-10, 13-19 Arup.

Reference

(1) AUSTRALIAN STANDARDS *AS 5100.2-2004*. Bridge design – design loads. Standards Australia, 2004.

The Denmark Pavilion
Expo 2010 Shanghai, China

Daniel Bosia Mikkel Kragh Michael Kwok Nicolas Sterling

1.

For the Denmark Pavilion at Shanghai's Expo 2010, Arup engineered a new kind of architectural space generated from the flow of structure around a geometric knot.

Introduction

The Denmark Pavilion at Expo 2010 Shanghai China was designed in response to the Expo theme "Better City – Better Life", portraying life in Denmark and celebrating various aspects of Danish culture. A temporary building with a net built-up area of 3000m², it articulates into a continuous geometric knot, forming a looping ramp that serves as the exhibition's backbone. On this continuous flowing display area, pedestrians move from internal, to external, and back to internal spaces around the building – a continuous spiral that rises to a total height of some 11m.

The structure also acts as a velodrome, with bicycles available for public use. This both raises awareness of a green alternative to cars, and promotes a popular aspect of Danish culture. At the centre of the knot is a pond with the statue of Hans Andersen's "Little Mermaid", moved from Copenhagen for the occasion (Figs 1, 2).

The building additionally includes general office areas, a kitchen, and conference space. The main plant areas are in the basement levels, adjacent to the conference and kitchen facilities. Additional plant space is incorporated into the building floor plate through a technical area located in the structural zone, behind a large display wall that runs the length of the pavilion.

Teamwork from competition to construction

The Denmark Pavilion is the second project undertaken by Arup's advanced geometry unit (AGU) with BIG (Bjarke Ingels Group), following a competition for the Copenhagen Aquarium where the team came second. Unlike with the Aquarium, the AGU was deeply involved in the competition-winning concept of the form for the Pavilion.

Arup's first encounter with Bjarke Ingels, founder of BIG, was at the Louisiana Gallery near Copenhagen, where the work of Cecil Balmond and the AGU was on display. Inspired by the knot structures and other complex structural forms, Ingels proposed a collaboration, which took form in summer 2008 with the competition for the Denmark Pavilion at the Shanghai Expo. BIG and Arup conceived a new kind of architectural space generated from the flow of structure around a geometric knot (Fig 3). The structure would coil onto itself, supported only by the ground and its overlapping loops, and sweep out into space to form spans of up to 120m.

Structurally, the concept was for a stiff box with a 4m deep rectangular section, lifted along a smooth knotted centreline. This effectively generates a curved walk-through box girder, torsionally stiff and able to span along a curve. The Weave Bridge[1] in Philadelphia – also designed by Arup and already on site – demonstrated the effectiveness of a walk-through lattice box both structurally and spacially. For the Pavilion, Arup proposed a thin structural skin with internal stiffeners.

The original competition concept was for prefabricated segmental box construction where large pre-welded segments of the knot would be shipped to site on a barge and bolted together, reducing the need for temporary works. Later, the contractor's preference for smaller elements to be delivered to site and assembled in a more traditional way led to a stress-skin monocoque solution, where the frame was designed for strength and the skin for deflections.

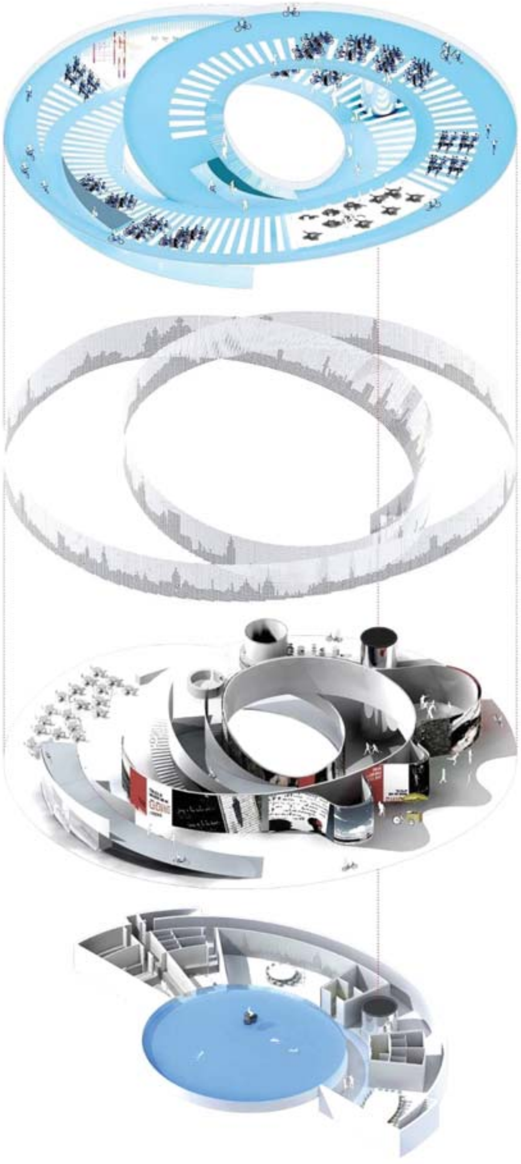
2. Competition image.

Chronology

Competition: 2008
Preliminary and scheme design: September-December 2008
Detail and construction documentation: January-April 2009
Site investigation, foundation and concrete work: May-August 2009
Steel frame erection: September-December 2009
Steel cantilever de-propping: December 2009/January 2010
Opening ceremony: May 2010.

3. Knot geometry.

4. Concept components.



5. Perforations on façade.

Essentially a hybrid bridge/sculpture in its complex curving form, this project was highly unconventional, and fully stretched AGU's expertise in bridge design and façade engineering. In the final structure, cladding and form are one, as originally intended, with the skin of the Pavilion perforated with circular holes emulating the stress patterns flowing across the structural box (Fig 5).

The project also required an unconventional approach to internal climate. Separated from the outside only by its perforated metal skin, the building needed to "breathe" without overheating in Shanghai's hot, moist climate. Arup's environmental physics specialists delivered a fully naturally ventilated building where the flow of air is critical for user comfort.

Finally, to deliver the project in China, Arup's Shanghai office team was of key importance in interfacing with the local design institutes (LDI) and getting the project through the approvals process, as well as developing construction information and following the work on site.

Shanghai office involvement

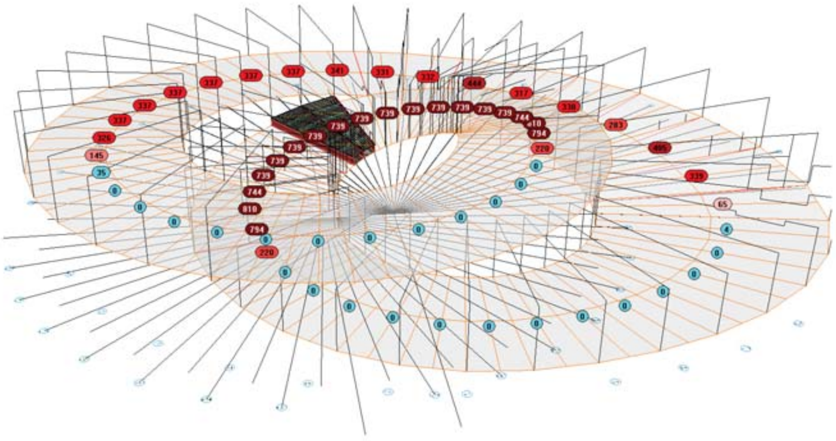
The Shanghai office was first introduced to the project in September 2008, and Arup's team there immediately realised that it would be a fast track schedule, with complete design development by December 2008, detail design and tender by April 2009, and construction completion by April 2010. Like many other iconic buildings in China, the project had to pass local expert panel reviews before construction could start. The design development was carried out by AGU in the UK, and the Shanghai office placed engineers in London to work with the team.

With the London team's support, from the beginning of 2009 the Shanghai team gradually took over the design works to produce the necessary analyses, calculations and drawings to achieve local approval. Working with BIG, the structures team in Shanghai produced all the necessary details and drawings for building the steel structure, while simultaneously the building services team was busy co-ordinating with the LDI responsible for detail design of the MEP systems. Shanghai office also carried out inspections of steelwork fabrication and installation on site to ensure that the complex structures were constructed correctly and completed on time to welcome the tens of millions of visitors.

This project, in its unconventional and innovative nature, is about the individuals that created it, pulled together because of their particular skills or local know-how. It is also about the communication across continents and time zones that made it a seamless flow of design and a success.

Principal quantities

Gross area: 3000m²
Outer ring average maximum radius: 29m
Inner ring average maximum radius: 19m
Box girder average size: 10m wide x 4.5m high
Steel superstructure: 1100 tonnes
Concrete basement and pool: 500m³
Concrete foundation: 300m³
Steel foundation: 163 steel piles
Original total budget: €20M

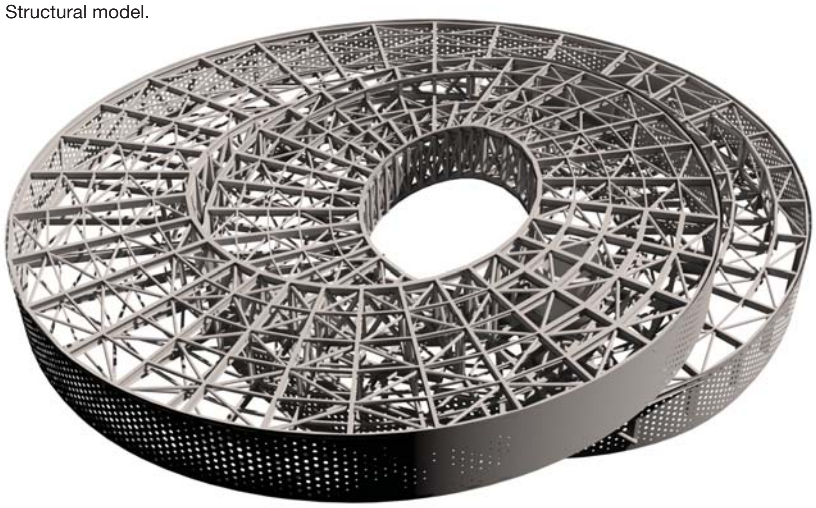


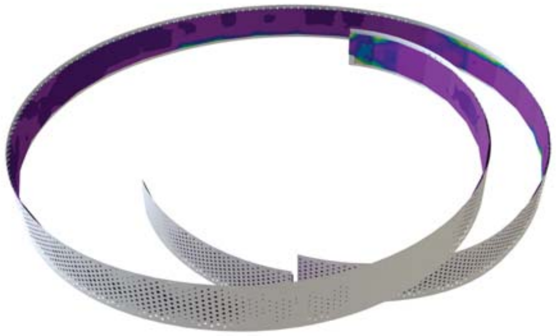
6. Pavilion framing and surfacing warping.

The original design featured a pattern based on Copenhagen's skyline, which is characterised by a combination of low-rise buildings and distinct spires. As the design progressed the concept changed to reflect instead the structural behaviour of the envelope. The stress levels were analysed and translated into densities of perforation (Fig 6).

Where the stress is highest (and the envelope works hardest structurally) the skin is relatively opaque; in areas with lower stress levels it is more perforated. The scale of the perforations (ie the dimensions of the holes in the building envelope) was studied extensively through a combination of virtual models and full scale mock-ups (Figs 8- 10).

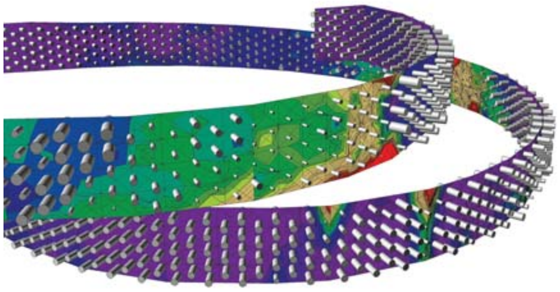
7. Structural model.





8. Structure render and stress diagram mapped onto the outer façade.

9. Perforation density and diameter according to the stress diagram.



Structural and geometric concept

Topologically, the pavilion is a unique continuous body, whose knot geometry creates spatial and structural opportunities focused on the centre, where the Little Mermaid draws visitors. The geometry is a modified logarithmic spiral on plan, formed by the rectangular tube, in section typically around 10m wide by 4.5m high (Fig 7). The first stage of the geometry has its starting point at the vertical core, after which the rectangular tube moves along the ground through a quarter-circle. The second stage launches into a cantilever that rises to 7.5m above the ground, completes the remaining 270°, and connects again to the core, directly above the starting section.

This "looping ribbon" experiences through its structural journey different boundary conditions: touching the ground, interlocking, disconnecting, floating, reaching the core, interlocking again, and finally reaching the ground. Structurally, the knot's box girder comprises two interlocking loops, the outer one cantilevering in space over the entrance to the internal courtyard. The tectonic shift between the boxes looping creates a dramatic effect over the cantilever, and an overall dynamic form.

Exhibition events occur between two parallel façades – the internal and external. The key concept was to keep the outer layer as light as possible and create a "dialogue" between the exterior and the inner exhibition space. The internal façade is closed, and fully braced, while the outward-facing pavilion façade is a perforated, stiffened 8mm thick steel skin, porous and smooth. The holes' diameters and density in the façade were calculated according to the structural stress diagram to create an "informed and graphic structural pattern". In the evening, the façade becomes a "sequenced instrument of interactive light illuminating the passers-by".

10. March 2009: Timber mock-up to test the scale, perforation principle, and lighting devices.

Environmental concept: Natural vs mechanical ventilation

The envelope build-up is a sandwich, with vertical steel stiffeners delivering the required structural strength. Dynamic thermal simulations were used to test the need for thermal insulation, and it was concluded that the effect would be marginal, given the environmental conditions during the summertime Expo event. The building envelope works as a screen between inside and outside with natural ventilation through the perforations. Solar studies were carried out to assess the penetration of direct sunlight into the exhibition space and possible implications on both solar gains and light conditions.

Summer climate conditions in Shanghai are generally challenging, with high temperatures and levels of relative humidity. The Expo bureau expected an air-conditioned exhibition space, and the initial concept featured fancoil units. Two different options were explored and the necessary space was designed into the concept.

But although the programme was extremely tight, the design team decided to explore also the feasibility of a naturally ventilated pavilion while continuing to progress with the mechanically ventilated fancoil-based design.

The process took place at several levels in parallel. The design team analysed natural ventilation rates and the corresponding comfort conditions within the pavilion. The analyses were discussed with the Danish client to agree on what would be acceptable in the absence of standard guidelines for this unusual kind of building. Once the criteria were agreed, the design team entered into a dialogue with the Expo bureau in Shanghai to get permission to proceed.

With the Expo "Better City, Better Life" theme's strong emphasis on sustainable living, the team behind the winning entry had deliberately chosen to showcase and celebrate the Danish way of life, with city bicycles as a central theme and the inside/outside connection as another. The pavilion would allow visitors to experience the exhibition while moving through the space on bicycles. This strong concept did not chime with a design based on an air-conditioned space, where visitors would travel through a cool zone to exit on the roof and return through the cool space again, let alone the notion of conditioning a space that intrinsically needed to be connected with the outside. The team therefore decided to push for a passive design and challenge the perception that an exhibition space should have a tightly controlled environment (though zones occupied by staff (eg offices) and the conference facilities would need to be mechanically controlled).

The client was sympathetic and open to the idea of natural ventilation. Simplified modelling of the pavilion geometry and ventilation openings provided information on likely ventilation rates, and sensitivity studies were carried out to assess the impact of variations in the façade perforation, while the exhibition space was assumed to be open at the ground and roof levels.

11. Perforations in the structure allow light and ventilation to penetrate the building.

12. Exterior view at night showing the open nature of the building.

A dynamic thermal simulation model was set up for the naturally ventilated scenario. Internal gains were modelled in line with the design scenario agreed between design team and client (number of simultaneous visitors, etc). The studies focused on comparing environmental conditions within the exhibition space to conditions experienced outside at the same time. Assessing comfort conditions for such a pavilion space is a cutting-edge research area; progress is being made, but there are no current applicable standards.

The team saw the space as "semi-outdoors", in the sense that visitors would approach the pavilion from across Expo, then sometimes wait outside, and then transit (walk or cycle) through the exhibition space out onto the roof, and finally back down through the exhibition. The approach was thus to focus on perceived conditions as users moved from outside, through the space, and then back outside. The team chose to compare the "operative temperature" in the exhibition space with outside.

This operative temperature takes into account the effect of radiation exchange with the surroundings. The pavilion offers shading from the sun (whether conditions are clear sky and direct radiation, or overcast and diffuse radiation); this is reflected in a lowered operative temperature. It is thus possible that though the internal ambient temperature is slightly higher than outside, it is perceived as being lower, due to the pavilion's shielding. Comfort conditions depend on a range of other factors – humidity, activity levels, and air movement each play a part – but the studies focused on radiation and temperature (humidity levels are virtually identical inside and out).

Studies showed that the operative temperature within the pavilion was likely to be higher than outside for conditions that can be defined as acceptable (or even pleasant). More extreme conditions (outdoor operative temperatures >29°C) occur rarely within the pavilion and far less frequently than outside. The analyses were reported in terms of percentage of the occupied hours exceeding certain operative temperatures and always compared with the outdoor conditions. On this basis the client accepted the passive design concept, and the design team communicated the intentions and the findings of the studies to the EXPO bureau in Shanghai. The technical aspects and the performance criteria were discussed in detail and the definition of the pavilion in terms of indoor/outdoor was clarified and approved.

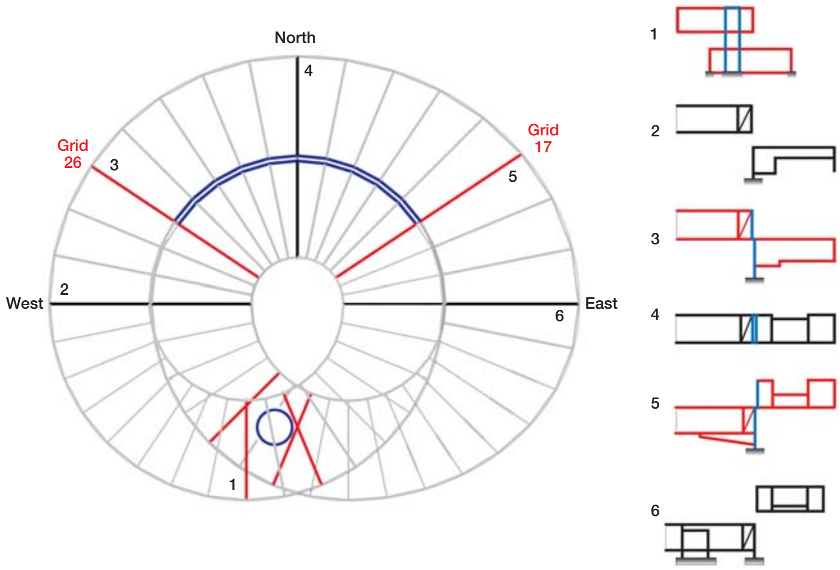
Structural system

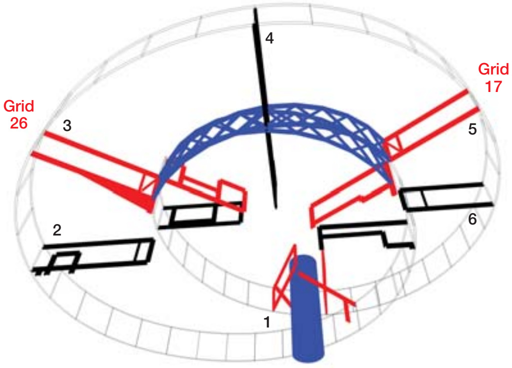
The structural system is divided into three principal parts: (1) the vertical core; (2) the overlapping scissor beams; (3) the transverse C-profiles closed by the structurally active façade, linked by longitudinal horizontal bars and bracing, forming the continuous tube (Figs 13-16).

Vertical stability derives from the core and the scissor beams, where the structure is not supported directly to the ground. A series of transverse frames in 550mm deep steel sections comprise the C-shape, continuous in bending, with the outer perforated façade closing it to complete the tube section. The façade plate is stiffened, curved, and pinned to the frame, and together with the bracing system on the inner elevation provides horizontal stability. The tube is interrupted by ramps, linking the top and bottom flange of the frame.

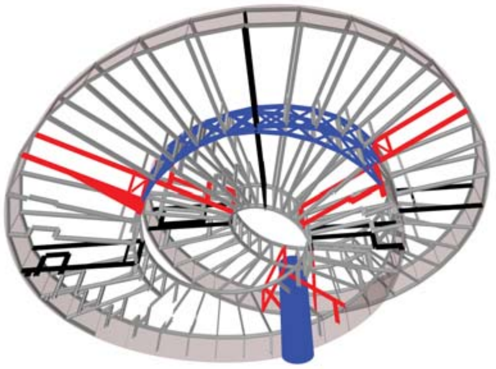
The C-profiles are loaded on their top and bottom members. Longitudinally, the tube acts in bending or bending coupled with torsion to carry the loads to supports. The loads are delivered directly to the foundations where the tube touches the ground; elsewhere, loads are delivered to the core and thence to the foundations.

13. Key structural components.

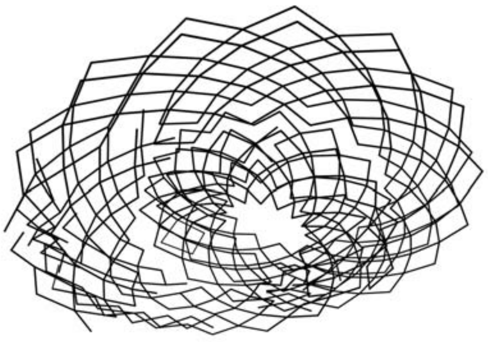




14. Vertical stability: scissor truss and core (blue).



15. Transverse frame: cantilevered critical frame grids 17 and 26 (red); coupled and decoupled frame (black).



16. Horizontal bracing stability.

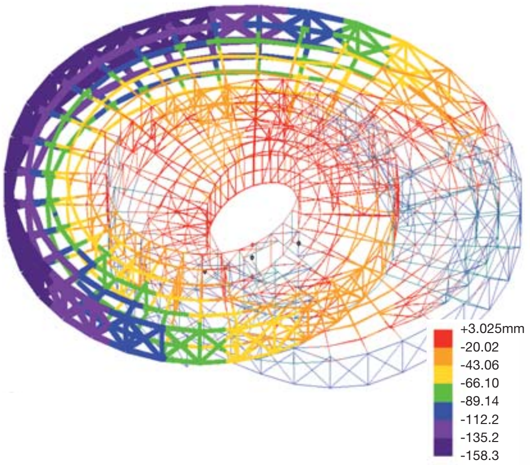
17. November 2009: Steelwork in progress.

Directly opposite the core is the scissor beam area, a set of two connected trusses much stiffer than the rest of the tube. The bottom ends of the scissor legs touch the ground, effectively creating a support opposite the core and so reducing the span of the large cantilever. Between the scissor beam and the core, the outer box is disconnected from the inner box and cantilevers. Transversely, the C-shape is vertically braced on the cantilever part to provide some additional transversal stiffness. The structural box girder benefits both from its torsional stiffness and its curved geometry in plan to control the transverse rotation.

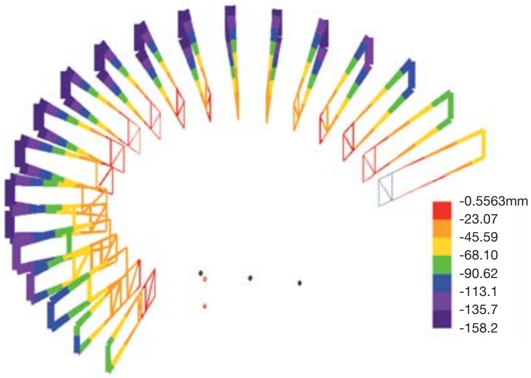
Directly opposite the core, the frames align horizontally. At two points around the curve (grids 26 and 17), the bottom of one frame is on the same level as the top of the other, so that a beam can pass straight through both to link them. Between these two frames is the scissor truss, creating a stiff support around the point where the two sections are level, and reducing the length of the cantilever so as to control deflections and dynamic response.

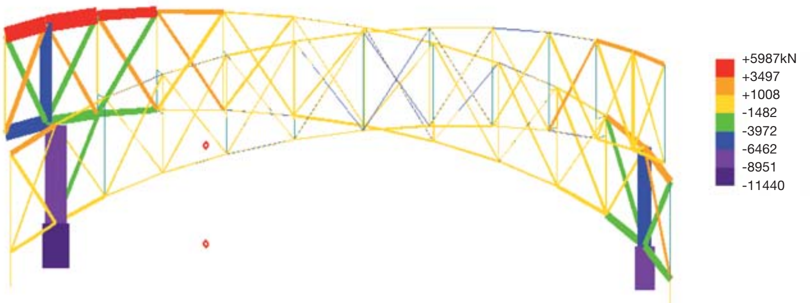
The façade closing the C-profile provides vertical restraint. The stiffness and weight of the external façade panel of a typical segment is equivalent to 1.6m wide cross-bracing, and so in the computer model the structural façade was simulated with 1.6m wide cross-bracing.

18. Global displacement, (1.0DL+1.0LL): *GSA* result.



19. C-frames displacement, (1.0DL+1.0LL), *GSA* result.





20. Scissor truss axial force envelope: *GSA* result.

21. November 2009: first frames erected.

22. December 2009: secondary steelwork finishing, surfacing, and railing.

The key scissor truss element at the overlapping zone (axis 17–axis 26) of the inner and outer transverse frame has a span of 30m between support to the ground. As the support for the outer C-frame, it bears the shear force from floor loading, and has a significant effect on the C-frame's displacement.

The upper and bottom chords of the ring frame trusses are subject to axial force, with the peak at the supports. The elements of the scissor truss have very large axial forces, as they support the structure (Fig 20). The top and bottom beams of the C-frame and the beams fixed at the lift core have large bending moments as they are mainly cantilevered.

As characteristic value, the total dead load is 12 770kN, and the total live load is 15 220kN. In the characteristic combination case (1.0DL + 1.0LL – Figs 18, 19), the maximum value of vertical displacement is 158.3mm at the cantilever part. As a cantilever structure, the frame's span is about 10.5m, bearing the floor and roof loading. The maximum vertical displacement occurs at the cantilever end of the C-frames, dominating the global maximal deflection.

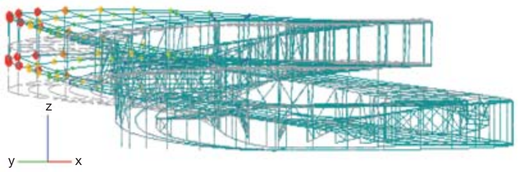
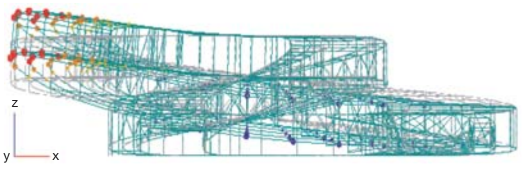
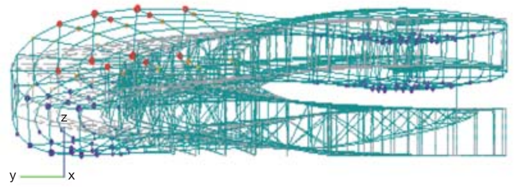
As displacement of the C-frame at axis 24 is relatively large, precamber was necessary to control the deformation. After deduction of the precamber value suggested by the code (DL + 0.5LL deflection), the deformation of the frame satisfied the code's requirement.

Dynamic analysis was used to assess the performance of the building under footfall-induced vibration and crowd loading; the footfall analysis was performed using Arup methodology[2]. The effect of crowd loading was calculated assuming periodic excitation of nodes around the node of maximum displacement of the mode of interest. The applied dynamic load from "group effect" was based on Willford[3, 4].

Human perception of vibration is very subjective; a level that causes one individual discomfort can be completely unnoticed by another. *BS6472*[5] gives a base curve which defines the threshold of human perception. The satisfactory dynamic response is then specified as multiples of base curve magnitude, eg response factor R=4 is four times greater than the threshold of human perception.

23. December-January 2010: Cantilever unpropping.

24. Mode shapes: first three frequencies.

Mode no	Frequency (Hz)	Modal mass (t)	Mode shape
1	2.83	70	
2	3.14	81	
3	4.82	104	

The recommendations used as a basis for the acceptance criteria for the Denmark Pavilion were based on references [2, 6, 7].

Modal analysis was carried out to calculate the dynamic properties of the structure. The total structural mass is 1200 tonnes. Fig 24 shows the calculated natural frequencies and their corresponding modal masses and mode shapes of the first three modes of vibration.

For the calculation of footfall response, the following assumptions were made:

- The total structural mass includes self-weight of the beams and 70kg/m^2 of superimposed dead load. No live load is included.
- Pedestrian mass is 75kg.
- The structure has 1% critical damping.
- The structure was analysed for all modes up to 15Hz to capture the effect of resonant response at frequencies higher than four times the maximum footfall frequency.
- The footfall frequency range is 1.0-2.8Hz. *CCIP-016*[2] recommends maximum footfall frequency of 2.5Hz for footbridges, corridors, and circulation zones of any building. There are no clear references for this type of pavilion, so 2.8Hz was adopted, considering the building's open-plan layout.
- There is no pedestrian access on the bike lane. The footfall excitation nodes on the roof and inside the building always start from 2m from the outer edge of the loop.

The average frequency of people walking is around 2Hz; this can vary depending on factors such as the layout and use of space. In general, people walking faster have the potential to induce greater levels of vibration up to 2.8Hz, though this extreme is unlikely. However, the impact of increasing the maximum assumed walking frequency from 2.5Hz to 2.8Hz was assessed. The R value can increase from R=11.6 to around R=36.7 of local mode. Similarly, response due to the effect of mode 1 can increase from R=4.1 to R=16.3, mainly because the first mode of the structure is excited at its resonant frequency (2.83Hz) by the first (and most significant) harmonic of walking frequency. Frequencies of both the footfall and the structure can, therefore, have a considerable effect on floor vibration.

Dynamic crowd action can be a critical floor vibration scenario from the co-ordinated movement of a group of people. Considering the main use of the Pavilion as an exhibition space, it was to be expected that visitors would congregate in groups inside the building or on the roof area. Normally they would be very unlikely to perform any kind of co-ordinated activities, but rare exceptions could happen of small groups of people trying to synchronise movement. Crowd loading assessment was thus carried out to assess the consequences of any such rare events.

25. View from the ramp.

In this assessment, the dynamic response due to groups of four, 10, and 20 was calculated. This was done for 1% and 5% of critical damping so as to identify the potential benefit of supplementary damping devices. It also assumed that each average 75kg participant would occupy about 1m² at the location closest to the maximum displacement of the first two modes of vibration.

Conclusion

Expo 2010 Shanghai China, and the Denmark Pavilion, opened on 1 May 2010. Initial response was overwhelming, with over a million visitors in the first month.

In addition to Arup's comprehensive contribution to the design of the Denmark Pavilion, the firm also worked on the Expo masterplanning with Rogers Stirk Harbour + Partners, was structural engineering designer for the Korea and Singapore Pavilions, provided structural design review for the UK Pavilion, and joined the expert advisory panel for the façade design of the China Pavilion.

Daniel Bosia is an Associate Director of Arup with the Building London 1 group, and was Project Director in London for the Denmark Pavilion.

Mikkel Kragh is an Associate of Arup in the Milan office, and led the environmental physics and building services design team in London for the Denmark Pavilion.

Michael Kwok is a Director of Arup in the Shanghai office, and led Arup's Shanghai team for the Denmark Pavilion.

Nicolas Sterling is a structural engineer with Arup's Building London 6 group, and was Project Manager and the structural engineering designer for the Denmark Pavilion.

Credits

Client: EBST Danish Enterprise and Construction Authority **Architect:** BIG (Bjarke Ingels Group) **Multidisciplinary engineering designer:** Arup – Daniel Bosia, Gemma Christian, Han Ciao, Toby Clark, Dominic Coyle, Dan Green, Paul Jeffries, Mikkel Kragh, Michael Kwok, Gang Liu, Erik Moore, Nicolas Sterling, Brian Yu, Guang Yao Zhu **Local design institute:** Tongji Design Institute **Contractor:** Maersk, construction management **Illustrations:** 1, 5, 11, 25 Leif Orkelbog-Andresen/BIG; 2-4 BIG; 10, 13-21, 23-24 Arup; 12 ©Arup/Gang Liu; 22 ©Arup/Kingkay Architectural Photography.

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Ropemaker Place, London EC2


1.

Ropemaker Place, a 21-storey commercial development designed by Arup Associates, is the first office building in London to be pre-certified for the US Green Building Council's LEED "Platinum" Core & Shell rating.

Michael Beaven Mick Brundle
Paul Dickenson Robert Pugh

Introduction

Designed by Arup Associates for the UK property company British Land, Ropemaker Place is an 81 218m² commercial development on the borders between the City of London and London Borough of Islington. Ropemaker Place was completed in May 2009, within three years from the initial acquisition of the land in April 2006.

The new 21-storey office building, with ground level retail, defied the economic recession and is fully let in a difficult market. It is the latest in the line of successful commercial office buildings for the same client that includes Plantation Place, Plantation Place South, Triton Square, and Watling House.

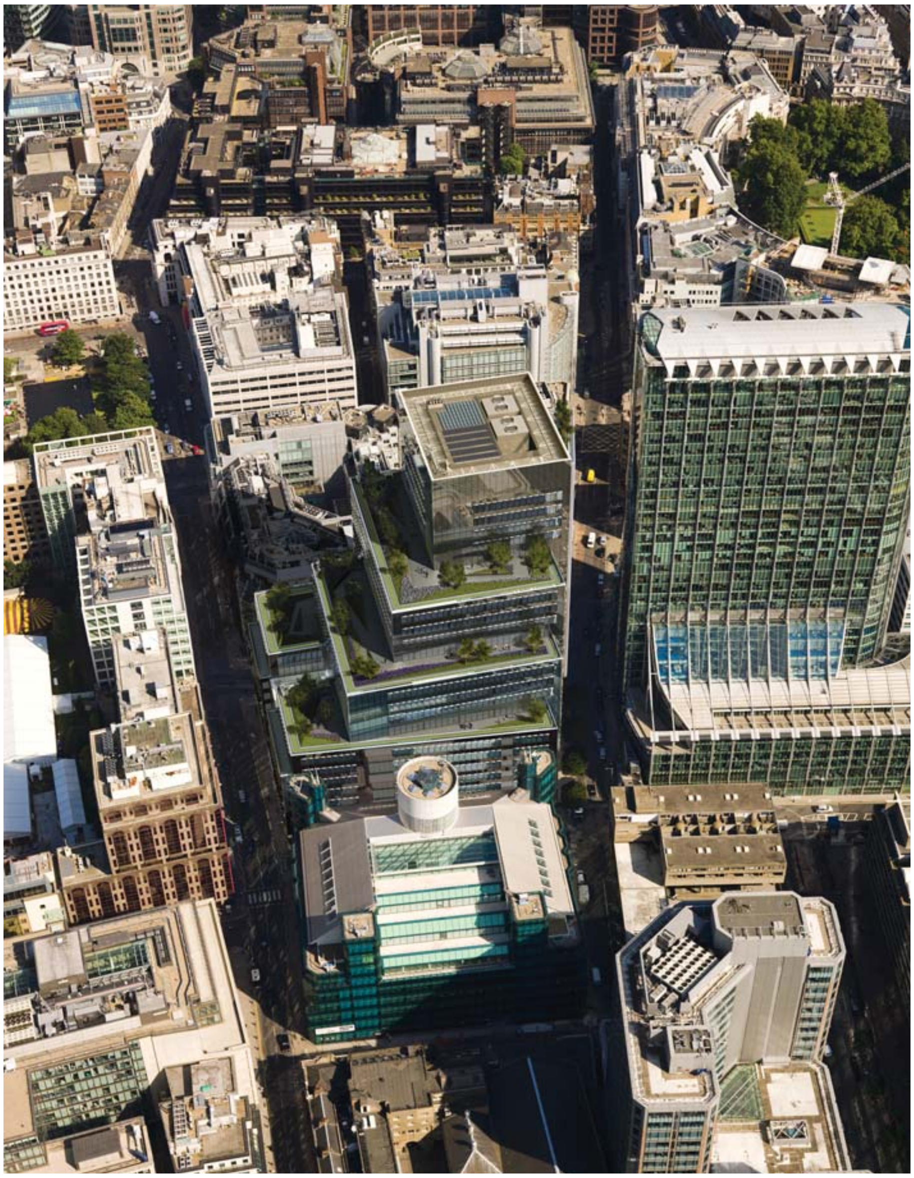
The site of some 0.5ha is bounded by Chiswell Street to the north, Ropemaker Street to the south, Moor Lane to the west and Finsbury Street to the east. The location provides excellent transportation links and convenience to occupiers, as it is triangulated by three London Underground stations and is near to the Barbican Centre with its extensive cultural opportunities. To the east are Liverpool Street station and Broadgate, with the City and its institutions beyond.

British Land purchased the site with the former 12-storey building having been fully demolished to the basement slab, and with an existing planning consent. Arup Associates was asked to review the consented scheme against British Land's base building and sustainability brief and the market requirements for City commercial office buildings, and in particular to build on the successful paradigm of Plantation Place[1], completed by Arup Associates in 2005. This led to a complete redesign that improved the overall massing and simultaneously delivered an increased net office area and a range of floor sizes more attractive to the market, from 3950m² on the lower levels through to 2955m², 2000m², and 1100m² on the upper levels.

The building was to be developed speculatively and – crucially – achieve completion by spring 2009 as a shell-and-core ready for multiple tenant fit-out. The brief was for flexible office and retail spaces attractive to potential tenants and suitable for multi-tenancies. The building had to provide market leading servicing provision with security of supply and resilience, and be adaptable to change.

2. Residential towers in the City of London's Barbican Centre, viewed from a roof terrace.

3. Ropemaker Place in its urban context, showing the overall form of interlocking cubic volumes.



Ropemaker Place provides a total of 55 000m² net office space, 1270m² of retail facilities, and more than 1850m² of roof garden terraces. It builds on British Land's and Arup Associates' ethos of sustainable design and the importance of technical and spatial flexibility for modern office buildings. It was designed to allow for large continuous floors with spacious open aspects, two designated trading floors, a legible circulation, and views over the City of London (Fig 2) and Islington Borough – in all, a desirable working environment of the highest quality.

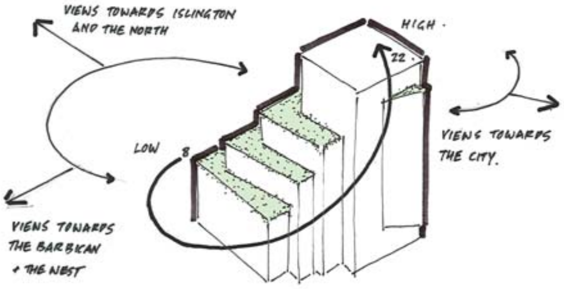
British Land allocated design and construction to only two organisations: Arup Associates as architect, structural, and building services designer (supported with specialist consultancy from Arup and Townshend landscape architects), and Mace as project manager, construction manager, and cost consultant (with its in-house quantity surveyor, Sense).

This close collaboration of integrated teams was an undoubted success for the client. Paul Burgess, Head of London Leasing at British Land, said at practical completion in May 2009: "We are pleased to have reached this important milestone on time and on budget. With Ropemaker we will be delivering our most sustainable development yet in the City. Its ability to help occupiers reduce both operational costs and their environmental impact is combined with a great range of floor plates and a high level of specification to meet operational needs. The roof terrace gardens are of a scale and quality unparalleled in the City and are a wonderful feature for occupiers". Evidently, these sentiments are echoed by tenants, as the building is fully let.

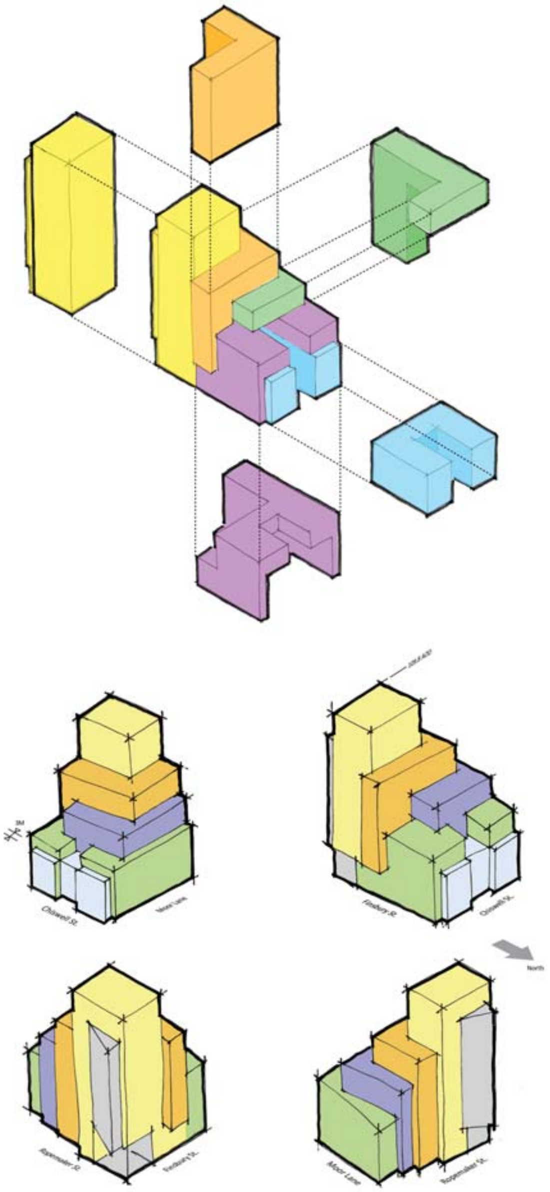
Ropemaker Place is rated BREEAM (Building Research Establishment Environmental Assessment Method) "Excellent", satisfying the entire heating and hot water demand through passive design and renewable energy systems, and offering an array of other sustainable technical features.

The building was also recently awarded the US Green Building Council's LEED (Leadership in Energy and Environmental Design) core and shell pre-certification "Platinum" level – the first office building in London to achieve this.

4. Massing anatomy: cubic elements spiral upwards from north to south.

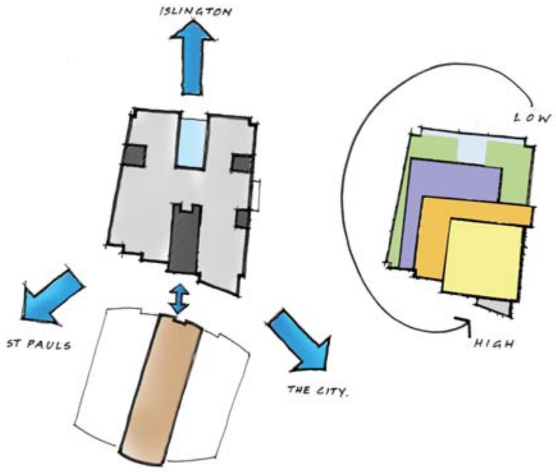


5. North/south section.



6. Massing anatomy: interlocking cubic elements.

7. Spiralling cubic forms and basic core configuration.



Overall form

The overall architectural form was derived from several programme requirements, as well as responding to the local urban realm, rights of light, and daylighting requirements. The building was conceived as six large interlocking cubic volumes, ascending as a series of usable garden terraces, reflecting the larger City scale towards City Point Tower and Moorgate while respecting the smaller scale of the Islington borders. Designating the terraces as usable green roofs consigned all services plant to the basement levels and a roof plant enclosure above the top floor.

Although the site was not within any designated view corridors relative to St Paul's Cathedral, the overall building height was determined by verified view studies, particularly from the Thames South Bank.

These showed that if it exceeded 110.00m above Ordnance Datum, the top of the building would be visible between the western towers of St Paul's – controversial for both planning and heritage groups. This could have added significant unacceptable risk to the programme, so the height was limited to this level.

8. Looking west along Chiswell Street.

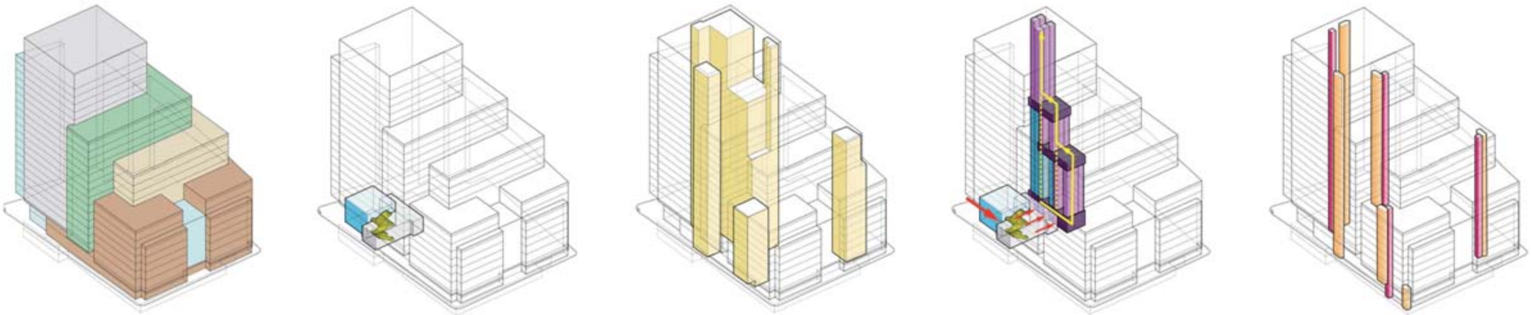
The planning authority also required that the massing along the northern site boundary of Chiswell Street be held at six storeys, with an agreed two-storey setback at the upper levels of approximately 3m from the street frontage, a condition already implemented in the recently-completed block nearby at 10 Chiswell Street (not Arup-designed). The planning authority's requirement was to maintain the overall townscape massing on both sides of Chiswell Street, particularly in views along the street. Initial discussions revealed sensitivities regarding the previous consent on the site, where the mass of a tower element at the north-east corner did tend to be visible from these viewpoints.

One success of Plantation Place was to tune the building's massing and elevational treatment to the immediate and broader setting, so that the creation of these large office floors would not overscale the City context. Ropemaker Place was similarly considered: not an "object" building but one that would be observed as a series of glimpses from the surrounding streets, and be a "good neighbour" to its setting.

Massing exercises determined that the most satisfactory form would be a series of diminishing orthogonal terraces ascending in an anticlockwise spiral from a low six-storey block covering the entire site footprint to a smaller plan 22-storey block on the south-east corner. This arrangement gave the variety already noted of net floor sizes ranging from 3950m^2 on the lower levels to 1100m^2 on the upper, with the opportunity to increase amenity and biodiversity by incorporating gardens on these terraces. Although this overall form broke the existing consent planning envelope, it was supported by the planning authority, as when viewed within the local and broader context it did provide clear townscape advantages.

9. Looking south along Finsbury Street.

10. The south-west corner of Ropemaker Place.



a) Volumetric composition.
b) Entrance hall.
c) Cores.
d) Entrance circulation.
e) Stair cores and firefighting shafts.

11. Principal elements in the building anatomy.

Building anatomy

The main entrance is on the site's south-east corner, diagonally opposite City Point Plaza on Ropemaker Street. This provides a strong urban link to the Plaza and integrates the building into what is essentially a public open space. Pedestrians walking from Moorgate London Underground station to the south, and from Broadgate and Liverpool Street station to the east, have clear sightlines to the entrance which, at over 10m height and fully glazed with an entrance loggia, forms a significant "urban room" in the locality.

The main core containing the lifts, services risers, toilets, and escape stairs was positioned directly off the entrance to the west, allowing vertical connection to all the office floors.

In plan, all cores were pushed to the perimeter of the building envelope, providing uninterrupted floor space with good sightlines, particularly on the lower levels. The main core is oriented north/south directly opposite City Point Tower, against the tall massing and close proximity of which the core's location allows unobstructed views and daylight from the south-west and south-east floors.

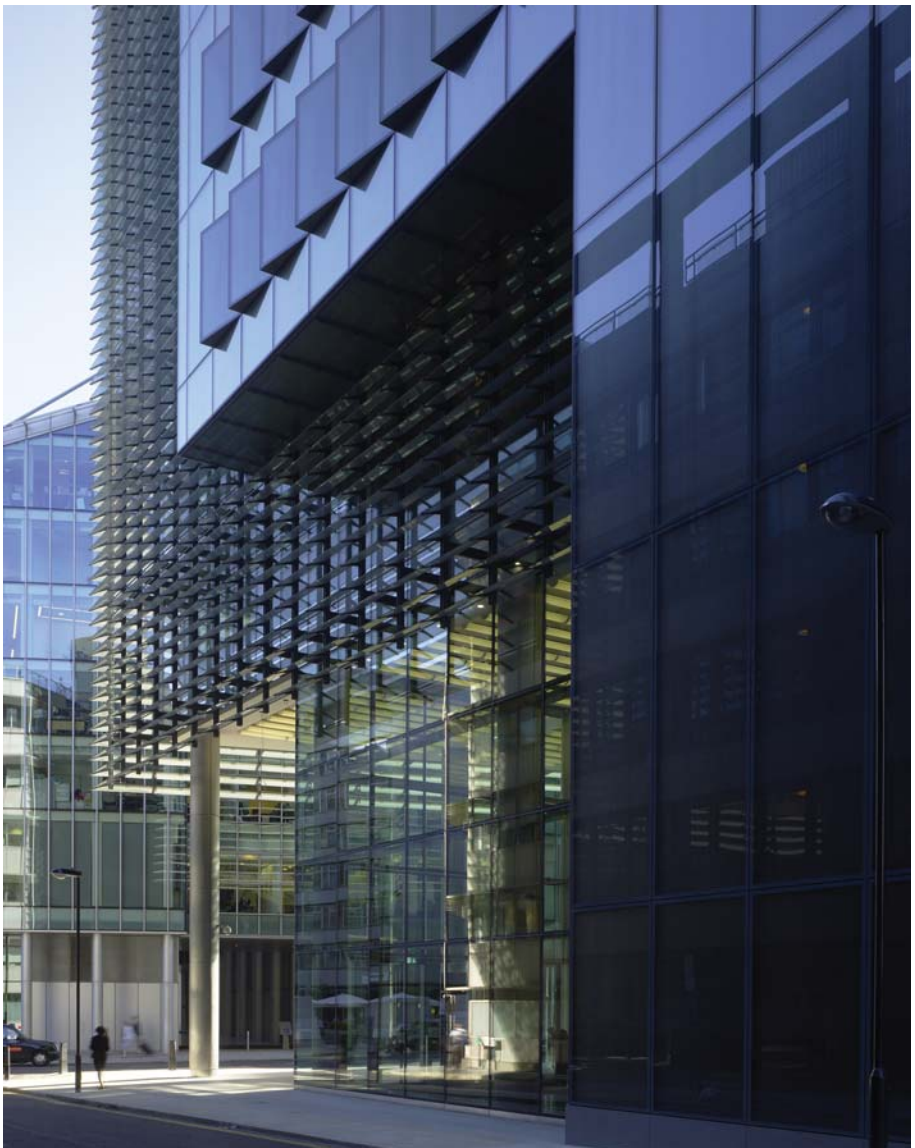
The main core contains three zones of 17 passenger lifts that drop off towards the upper levels and are controlled by an automatic destination service call system for maximum efficiency. The main core also contains two large service lifts for each floor, one of which stops at level 11, allowing a single lift to continue to the upper floors and roof plant.

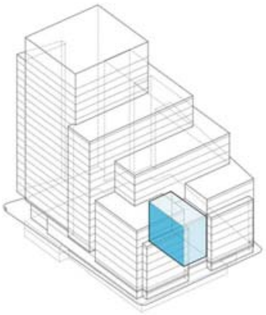
In addition to the lifts, escalators service the large and more intensively populated levels 1 and 2 directly from the main entrance reception. On floors where there are through lifts, what would have been the lift lobby spaces are fitted out as washroom areas. Satellite cores on the east and west elevations provide additional fire-fighting lifts and stairs, services risers, and other ancillaries to the lower levels.

The office floors were planned on a 1.5m grid which, co-ordinated with the base structural column geometry of 9.0m x 13.5m, gives large spans and deep clear office floors. Floor-to-floor heights are generally 3.95m, offering a 2.75m floor to ceiling with a typical raised floor zone of 150mm.

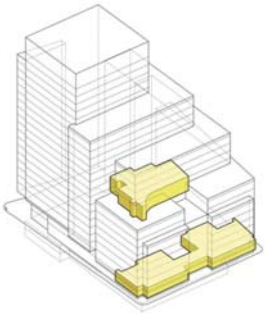
Levels 1 and 2 were designated as dealer floors with enhanced floor-to-floor heights of 4.2m and 4.5m respectively, providing 3.0m floor to ceiling and a 450mm raised floor. The integrated structural services zone incorporating cellular beams is 1050mm deep. Levels 1-16 can be subdivided to a maximum of four separate tenancies.

12. The main entrance on the south-east corner.

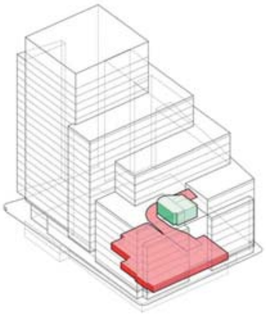




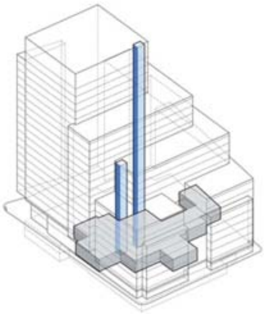
f) Atrium volume.



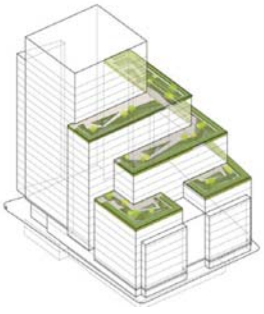
g) Retail units.



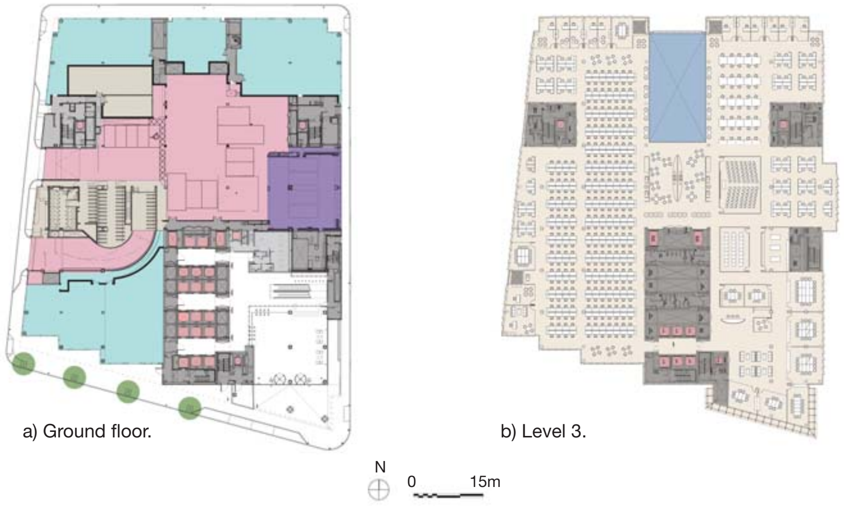
h) Car parking and bicycle store.



j) Service zone and goods lifts.



k) Garden terraces.



a) Ground floor.

b) Level 3.

c) Level 11.

d) Level 16.

13. Typical floor levels.

A top-lit atrium facing north engages the Chiswell Street elevation and provides daylight to the deep floors on levels 2-5. This is designed as a flexible space; depending on whether the surrounding floors are let to single or multiple tenants, the atrium is designed for fitting out as a useful amenity space accessible from level 2. Another possible scenario is that the atrium may be floored over if there is a future requirement for additional net floor area to some or all of the lower levels.

Retail areas along the entire north side of the building at ground level are serviced from the extensive service vehicle dock, increasing retail amenities along Chiswell Street. The south-west corner of the site was originally designated for flexible retail or office use, and has been converted to a separate entrance for a major occupier with access to the main lifts from the west.

Two separate vehicle entrances off Moor Lane access the service vehicle dock and upper basement car park and service areas. This dock services both office and retail and allows parking for 274 bicycles with associated changing and shower facilities. The main stand-by generation is in an insulated room directly west of the dock, the equipment being removable through the service dock if required.

Of the three basement levels, the uppermost contains parking for 55 motorcycles and 23 cars, including for the disabled. The middle and lower basements contain extensive plantrooms and tenant storage space.

14. Glazed atrium roof.

Garden terraces

Green roofs serve important purposes, including absorbing rainwater, providing insulation, creating a habitat for wildlife, helping to lower urban air temperatures, and combating the heat island effect. Arup Associates designed substantial roof gardens for the Wiggins Teape offices at Basingstoke (Gateway 1) in the late 1970s[2]. These were tiered terraces accessed from the office floors and mainly for occupier use, though they were also useful in supporting bird and insect life due to their diversity of planting. Similarly the later Plantation Place, in the City of London, was designed to incorporate on its roof terraces a series of gardens for amenity.

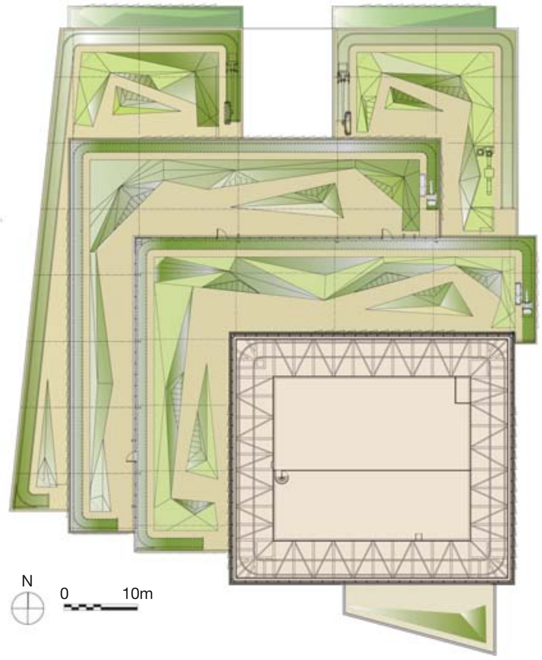
These were all designed with landscape and garden specialists. They are more challenging than, for example, a sedum roof, as they need regular maintenance, and good management and irrigation during dry spells. Well-designed drainage is essential, and extreme care must be taken in the detailed design and construction to avoid the risk of leaks. If substantial planting and mounding are to be incorporated, there are also structural considerations.

An important aspect of Ropemaker's external form is the five ascending landscaped garden terraces that cover most of the available roof, providing a balance between public amenity for the building's occupants and a bio-diverse habitat for insects and birds.

These "green lungs", still rare in City architecture, are the latest example of Arup Associates' interest in the greening of buildings and associated social, environmental, and biological advantages.

16. Typical planting on one of the roof terraces.

15. Roof plan, showing green roof terraces.



The arrangement of the tiered terraces allows views of soft landscape, particularly at long distance from Islington and more locally from the heights of the Barbican tower block residences. As the building's major services areas are either in the basements or at high level, the terraces were designed to be substantially free from mechanical and electrical plant, though they are necessarily shared by the cleaning cradle railway and required maintenance access zones. The cleaning cradles are at the perimeters and, together with hard landscaping for occupier access, created three landscaping zones. The eco-zone was coexistent with the cleaning cradles and tracks and planted with low-maintenance sedum species. These are screened by an undulating continuous planted zone incorporating trees, shrubs and herbaceous seasonal planting. Beyond this and adjacent to the office floors is a hard landscaped amenity zone of pavers, seating, and additional planted beds.

The gardens were set out in plan as a series of triangular forms based on an orthogonal geometry twisted away from the basic north/south building orientation. The planting was selected to reflect the changing seasons and includes native and non-native species common in alpine landscapes, similar in degree of exposure to London rooftops. Over 30 plant species were selected, including trees like birch and dogwood through to box and heather and herbaceous ground cover such as sages, hardy geraniums, and bulbous plants. An irrigation system was installed to offset dry periods and high transpiration rates caused by the more exposed conditions.

At ground level, along Ropemaker Street, semi-mature trees within a natural stone pavement have been planted, providing a much-needed soft landscaped foil to the hard-edged urbanity of the public domain.

Façade design

The site orientation determined that the façades should face directly towards the north, south, east, and west aspects orthogonally. The combination of the interlocking cubic massing and setbacks with the immediate architectural context creates an animated composition of light and shade from the changing sun path, varying with weather and the seasons.

A double-skinned façade, as at Plantation Place, was rejected; budgets were limited and the necessarily deep galleries required for maintenance outside the office interior – preferred by the London market – reduced the net area substantially compared with a single-skin façade. Natural ventilation, which may have made a double skin sensible at upper levels, was ruled out on grounds of cost and noise.

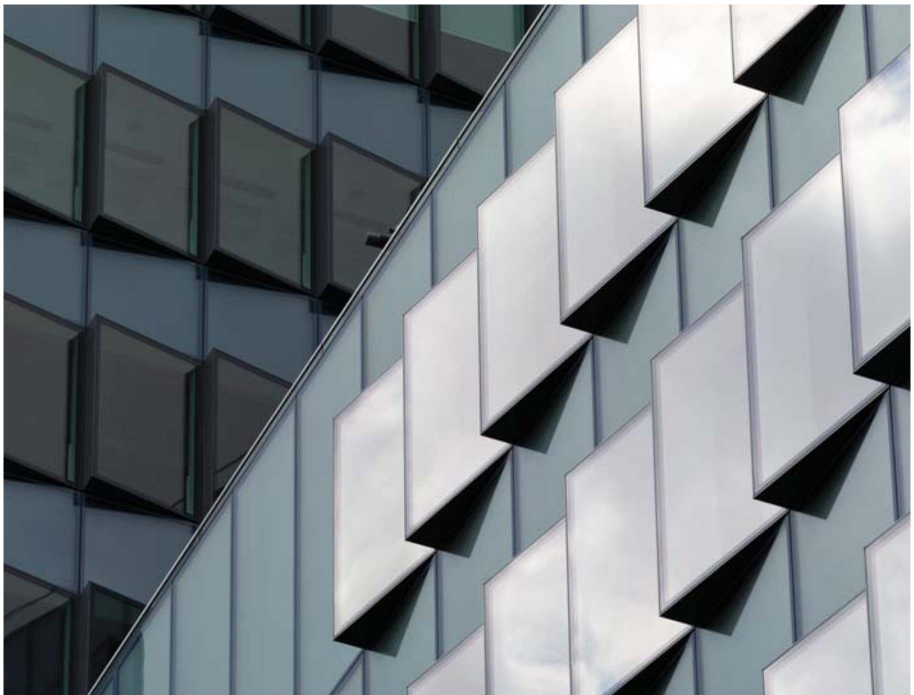
The façade design exemplifies the integration of architectural treatment with environmental performance: a bespoke system of unitised 1.5m wide modular cladding, designed as a series of storey-height insulated cassettes with projecting and tilting vision panels where required, the combination of which reduces the average annual energy consumption for cooling by up to 27% compared to a flat façade. The cladding system was installed from the individual floors using sophisticated mechanical manipulators, and without expensive and time-consuming tower cranes.

Projecting windows

Ropemaker's façade design was key to its environmental strategy. The windows to the east and west project from the flat façade and tilt in the vertical axis away from the sun towards the north to reduce incident solar radiation, helping to reduce peak cooling loads and energy consumption. Similarly the south-facing windows are rotated around a horizontal axis, leaning forward. The rotation allows for an element of self-shading, similar to what can be achieved by louvres and projections. A secondary effect is the reduction of solar transmission of the glazing due to the increase in the solar angle of incidence. The effect of the window geometry varies with orientation and conditions, but annual energy consumption for cooling is reduced in all cases.

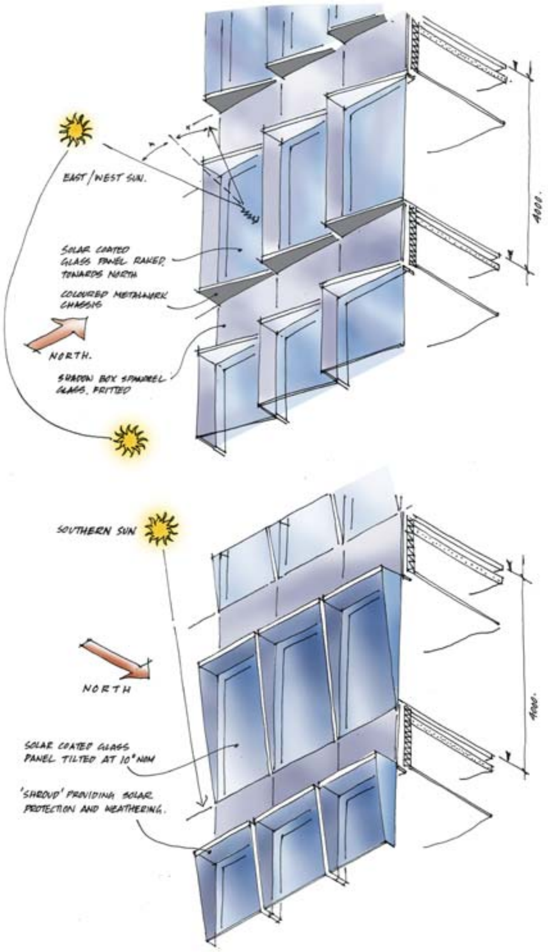
These projecting windows are arranged in serrated compositional blocks that, with the large areas of optical spandrel glass, create additional surface animation and modelling. The building was designed to minimise space heating demand and infiltration losses through the external fabric so that energy use for space heating was reduced; this was achieved through good insulation and airtightness in the building envelope. The use of a double pressure gasket line reduces the air leakage rate to 5m³/hour/m² of façade at a pressure of 50Pa, bettering the UK *Building Regulations Part L* requirement of 10m³.

17. Windows on the east façade.



18. The cill within the window module can be used as a seat.

19. Projecting window cladding: east/west orientation (top) and southern orientation (below).



Internally the cill height of the projecting windows was fixed at 500mm from finished floor level. This provides within the window module a usable surface that invites occupiers to use as an occasional seat (Fig 18), and increases the area of insulated spandrel. The cill was finished with a lacquered timber panel as standard; this can be enhanced if required.

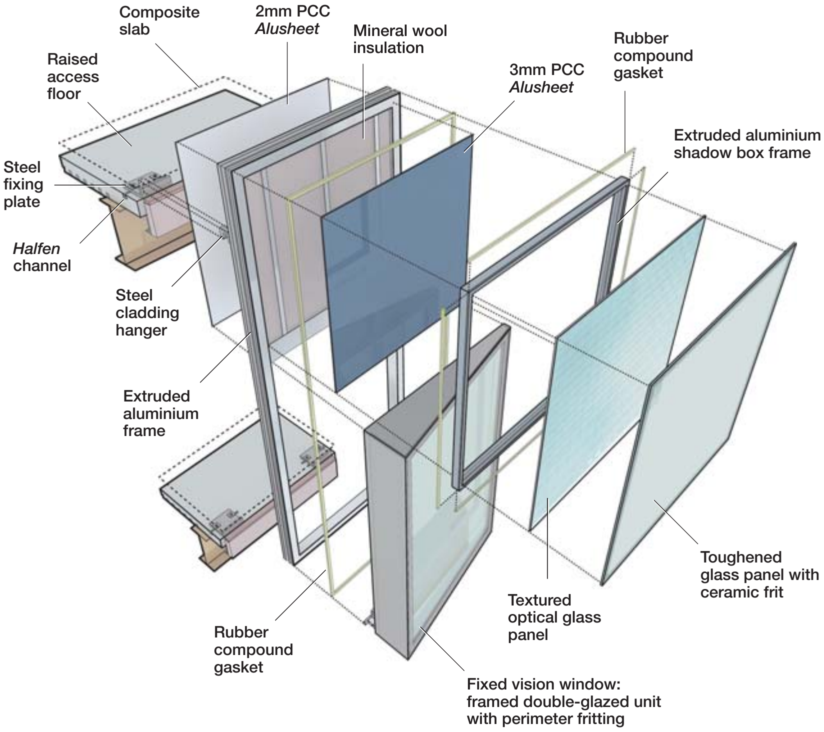
Above the main entrance loggia on the south-east corner a projecting volume, triangular in plan, was provided with a series of external horizontal glass sunshade louvres over 20 storeys in height to attenuate solar transmission. This change to the cladding programme was for architectural and environmental reasons; the windows here are exposed fully to the southern sun with no shading from surrounding buildings, and the change of cladding grain gives the projecting volume additional emphasis on the Ropemaker Street/Finsbury Street corner above the entrance.

Spandrel panels

The insulated glass spandrels that cover over 50% of the building's envelope were constructed as shadow box cassettes, incorporating a special optical glass with back panels, coloured to correspond to the cubic volumes of the massing. The layering of colour based on five different indigo tones into the interlocking cubes further enhances this changing canvas. For each block, a single colour based on the NCS *Natural Colour System*®[3] became the base colour to the opaque spandrel panel viewed through the glass prism.

The spandrels were designed to express depth, light penetration, and reflectivity in areas of the façade where visual "depth" when viewed from the exterior was desirable but vision through the glass from the interior was not required. The "shadow box" usually comprises a double-glazed clear glass unit with a coloured opaque insulated panel some distance behind the glass surface, with pressure equalisation to the exterior through a series of slot vents in the carrier frame. The addition of glass with convex and concave square lenses as the inner leaf of the double glazing gives a more subtle effect.

20. Typical unitised façade cladding with projecting window.



21. The main entrance.

The glass units are frameless and bonded back to the supporting carrier frames by structural silicone, masked by a coloured "frit" band 40mm wide, selected to align as closely as possible to the background tone when viewed through the layers of glass. This "kit of parts" was completed by identically designed opening panels for smoke venting invisibly incorporated into the system, co-ordinated air grilles, high-level plant enclosure screens, and glass balustrades.

The overall visual effect is created by the combined properties of the lens and cladding glass unit and their relationship to the base colour. The optics of the glass dilutes the colour in the encapsulated panel, producing a softer effect analogous to the addition of varnishes to base colour in Old Master paintings. Overlaid on this are sky and context reflections from the immediate surroundings.

On overcast days or in shadow, cloud reflections, the context, and lower light levels create a more muted effect. Direct sun illuminates the spandrel interior and excites the background colour. This is to some extent obscured by light reflections from the lens glass.

Viewing angles acute to the spandrel surface, such as when seeing the building along a street or at high level from the ground, tend to increase reflections and much reduce the percentage of the diffused base tone. Conversely, viewing angles more perpendicular to the spandrel surface decrease reflections and increase the percentage of the diffused base tone. The optical properties and refined detail of the glass facades, together with the interlocking cubic massing, produce an ever-changing appearance, depending on the weather patterns and ambient light of the City sky.

Environment and sustainability

The building was designed on the basis of British Land's office design brief and, from the early concept stage, British Land's sustainability brief, ensuring that principles of sustainable development were embodied in the design and construction from the outset. A comprehensive sustainability strategy was thus adopted for Ropemaker Place, going beyond climate change issues to include resource conservation and social considerations.

Naturally, energy conservation and the adoption of viable renewable energy technologies feature strongly, but the strategy was to strive for simplicity by adopting passive techniques. Energy reduction focused on an airtight, thermally efficient envelope, with heat demand minimised by recovering it where it was not required and using it in other areas. Free cooling was maximised, the implication being that the building could be cooled without using chillers when outside temperatures were favourable. Standard chillers for cooling were adopted when required, and no borehole or ground source heat pump systems were used as they were found to be unattractive technically. This low energy ethos enabled the building to achieve a 32.7% improvement over Building Regulations part L requirements 2006[4].

Mechanical systems

Ventilation and cooling systems are conventional. Ground source cooling and combined heat and power (CHP) were investigated and rejected. Ground source did not give a meaningful contribution due to the small footprint, while CHP didn't suit the building; such fundamental energy efficiency, giving a low base load, negated the benefits of this strategy.

22. Interior of main entrance.

The base building heating/cooling systems were designed to allow independent occupant thermal control in all separate rooms/areas. The metering strategy allowed for monitoring different energy demands throughout, and sub-metering is provided for each office floor.

On-site renewable energy

The Greater London Authority's "London Plan"[5] requires the metropolis to become a world leader in developing a low-carbon city, with the office sector contributing to this strategy. Site constraints for City buildings often preclude orientation to optimise energy performance, and do not provide much scope, due to site cover and massing, to install meaningful renewable energy sources.

At the time of design, the on-site renewable sources were to offset the building's CO_2 emissions by 10%, a metric conditioned in the Planning Consent. In the event, Ropemaker Place uses a combination of biomass boilers, $75m^2$ of solar hot water, and $75m^2$ of solar photovoltaics: this range of on-site renewables supplies 15-20% of the building's energy demand.

Site ecology

Initial assessment showed that the cleared site was of very low ecological value and sterile, with a low flood risk and no risk of damage to any species during construction. The inclusion of the series of substantial usable green roof terraces spiralling up the building predated the changes introduced into the London Plan whereby large developments in the capital are expected to incorporate some form of accessible green roof where practical.

Although this is not yet a legal obligation, many London boroughs have implemented this through their planning approvals process. The ecological value of the site was consequently enhanced by providing $1850m^2$ of new green roof area and introducing over 30 species of plant life, including trees, shrubs and seasonal herbaceous planting, suitable both for biodiversity and occupier amenity.

Water

Climate change is making water increasingly difficult to manage, as often excessive rainfall in one period is followed by lack in another, and supplying the increasing demand for water is becoming ever more difficult and expensive.

Ropemaker Place's strategy for water management included provision for storage and dealing with stormwater run-off while conserving through the design of plumbing systems. A $90m^3$ rainwater harvesting tank allowed attenuation of 80% of the run-off from hard roof areas and 30% of run-off from the green areas, the green roof attenuating up to 70% of the rainwater that falls on it. Harvested rainwater is used to flush WCs in addition to waste cooling tower blow-down water. Water to showers is limited to between 9-12 litres/min and faucets are low-flow or aerated. Water meters have a pulsed output connected to the BMS, which facilitates remote monitoring of water consumption.

The building incorporates a system to detect major water leaks both within and between it and the site boundary. A water supply shut-off system was specified for each toilet area, and these are linked to infrared movement detectors.

Green travel

Green travel considerations influenced the design of the ground floor and basement levels.

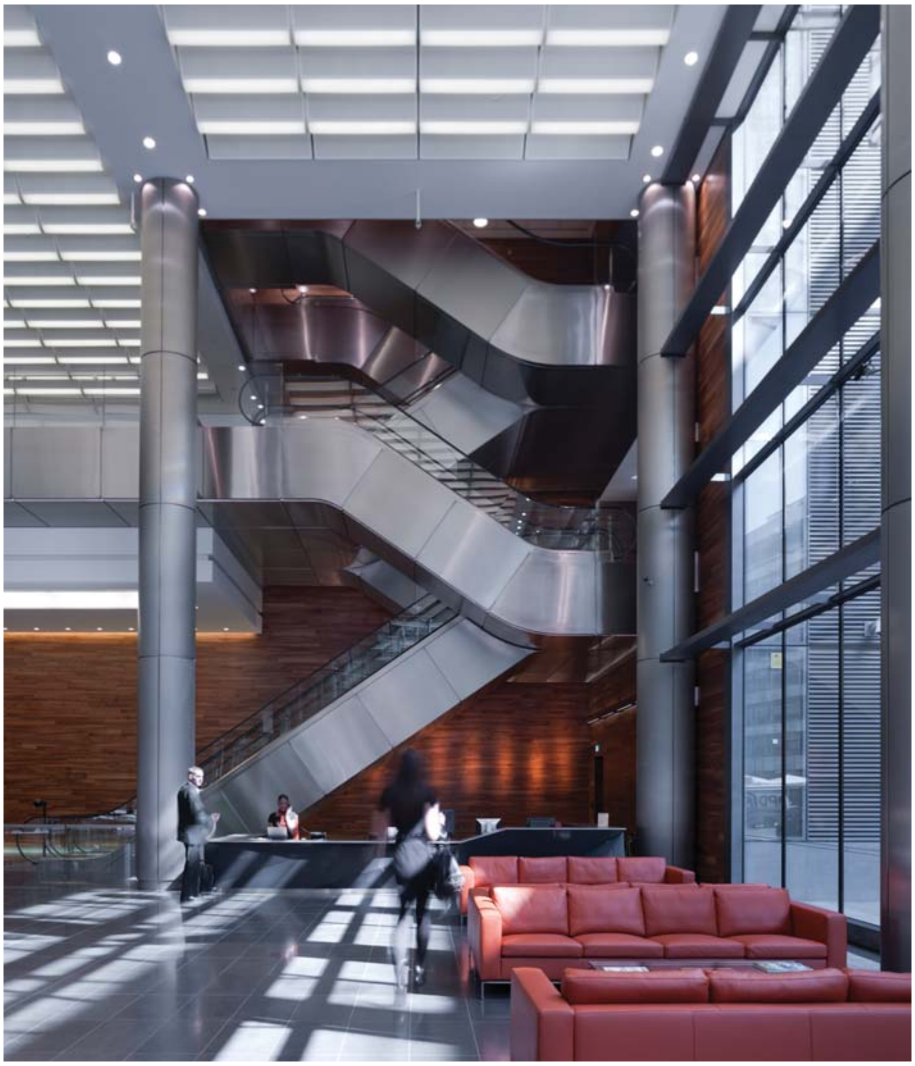
The development provided a limited number (23) of car parking spaces and 73 motorcycle parking spaces in the upper basement including four for disabled occupiers. The development exceeded BREEAM requirements by providing 270 secure cycle storage spaces, 15 showers with changing rooms, and 235 lockers.

Materials and recycling

Wherever possible, *Green Guide*[6] "A"-rated and responsibly sourced materials were supplied during construction; concrete floors and roof achieved "A+" *Green Guide* rating, and frame, foundation, floors, roofs, and timber finishes were responsibly sourced. Design measures to reduce waste included the *Technik*[7] flooring solution. This reduced waste by over 50% compared to traditional screed, and prefabricated toilet construction also lowered waste on site significantly. 30% of new steelwork was manufactured from scrap, and the existing buttress foundations on the site perimeter from the previous building were reused, totalling 20% of the site footprint. The construction managers used WRAP's *NetWaste* tool, which showed the new building to include 24% recycled content overall.

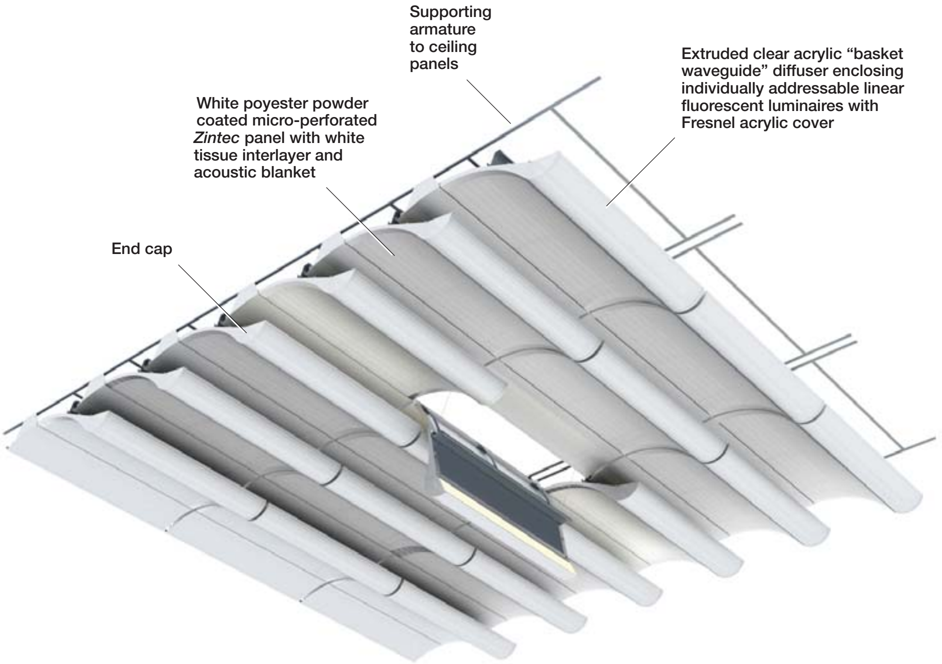
Sustainability summary

- BREEAM score of 72.7% with an "Excellent" rating
- LEED core and shell pre-certification "Platinum" level: the first office building in London to achieve this
- 32.7% better then *Building Regulations Part L2A: 2006*
- building carbon emission rating (BER) of 24.6 $kgCO_2/m^2$ annually
- air leakage rate of $5m^3/hour/m^2$ of façade at a pressure of 50Pa.



23. Main entrance interior.

24. Close-up of wave-form ceiling.



An exercise in product design: The wave-form ceiling at Ropemaker Place

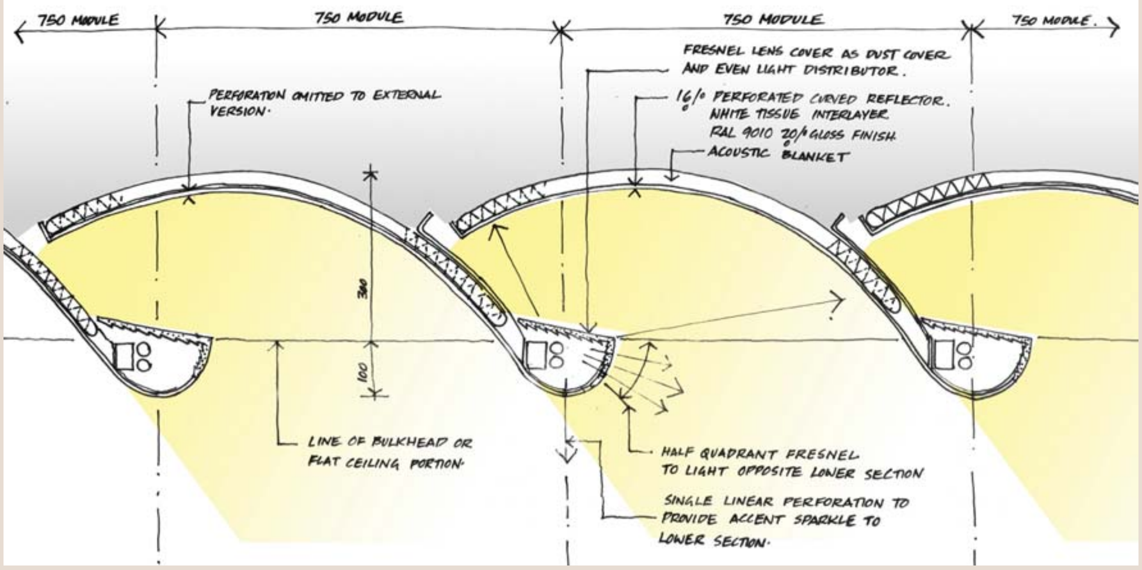
25. Wave-form ceiling in the main entrance.

The design of bespoke façades components, furniture, and fittings in Arup Associates' buildings has always been a natural aspect of the practice's multidisciplinary approach. Many items are specified in the normal course of a project, but situations can arise where a particular idea cannot be resolved with available materials and components, so there is an imperative to invent from first principles.

An obvious example of this is the façade cladding system (see pp41-42). Another is the waveform ceiling and lighting system developed for the main entrance and atrium ceilings in collaboration with Zumtobel Lighting, SAS international, and Stortford Interiors. It is a refinement of similar ceilings designed with Zumtobel in previous British Land projects in the City.

The purpose was to create an indirect/direct lighting source, with an acoustic performance, giving the 10.5m tall corner entrance foyer spatial impact and visual focus in the views from City Point Plaza and Ropemaker Street. A series of illuminated vaulted waves seem to flow into the interior, its volume perceptually expanded by the uplit waveform surfaces. This curvaceous profile provides a visual tour de force as well as a practical solution to the lighting and acoustic requirements.

The ceiling comprises curved, preformed, white polyester powder coat, micro-perforated steel sheeting with a white tissue interlayer and an acoustic blanket, together with a clear acrylic "basket" diffuser to contain the individually addressable linear fluorescent luminaires.



26. Concept sketch.

The basket diffuser is a bespoke linear extrusion designed using Zumtobel's patented waveguide technology, which refracts a proportion of the light flux onto the ceiling and the remainder into the interior volume.

The relationship between the diffused refracting light source and the reflective surfaces, together with the profile, were determined through extensive mock-ups that iteratively refined the design. Other crucial features – concealed fixing details, panel accessibility, and material finish – were also determined at this stage.

The ceiling system had to form both the main internal ceiling surface and also the external canopy surface, so as to give visual continuity between the interior and exterior systems. In practice, as both ceilings need to be fully accessible, the internal system uses a hook-on system for support, and the external system a more robust and secure suspension method. This involves a concealed but accessible cam lock and fixed hinge to support the panels and allow access to services in the void area above.

The individual ceiling cassettes were based on a 1500mm module (1475mm actual), designed both to exactly fit a standard linear fluorescent luminaire, and for ease of construction and replacement.

The entrance foyer, through its spacious volume, finishes, and lighting design, appears now as the main focus to the local urban context and provides a transformed backdrop to the street promenade and activities centred on City Point Plaza.

Building structure

Structural strategy

The structural design played a major role in enhancing the project's success through strategic decisions to bring buildability to the heart of the design, enabling the brief, the architecture, and the sustainability objectives to be delivered within the required timescale.

This involved establishing three principal phases of work, providing appropriate, efficient, and economic responses to each, and ensuring overlap between planning, design, and construction.

When the client purchased the site in April 2006 with planning consent for the previous developer design, the existing building had been demolished and an extensive combination of previous 1950s and overlaid 1980s concrete foundations left in place. This influenced the previous developer decision to limit to a single basement, leaving no other option than to use the entire roof for plant. The new proposal, with its ascending garden terraces, required most plant areas to be relocated to a much deeper basement, with the remainder out of view above the ultimate storey.

The project needed to overcome the difficulties of the existing foundations, as excavation of the major new basement had to start before the new design was fully known or the new planning consent could be gained. A basement design and overall construction strategy was therefore devised whereby a supplementary permission for the basement could be agreed within the existing consent, allowing significant enabling works to begin. This in turn allowed time for the new planning approval process, and the design and award of sequential substructure and superstructure works packages to maintain the required construction timescale.

The key to unlocking this in practical terms was the way the new building and stepped massing, integrated with structural framing, was overlaid to accommodate the site constraints. The most substantial existing perimeter foundations were re-used, with excavation for the new basement only within the clearer central zone, and the new building geometry, stepping, and loading were balanced between new and existing foundations by adapting the grid to suit: a predominant orthogonal central zone, with adjustable tapers at the edges.

This unique harmony of architecture formed from its urban setting, as well as its physical constraints and structural response, exemplifies Arup Associates' integrated approach to design.

The design strategy thus comprised the following key structural stages (Fig 27):

(1) *Enabling works:* demolition of existing substructure within retained perimeter buttresses, installation of secant pile retaining walls and temporary propping works, and bulk excavation as advanced works for proposed new basement substructure.

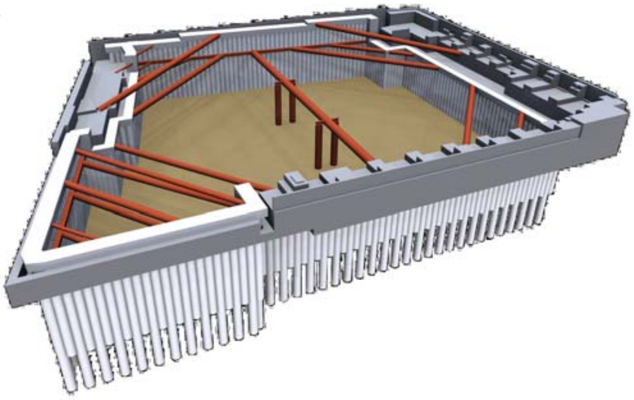
(2) *Concrete substructure:* construction of a reinforced concrete raft foundation and basement framing up to ground floor to complete a substructure "box". As the superstructure stability is provided by reinforced concrete walls at the primary core, this work was also included as an independent slip-form operation in advance of the steelwork.

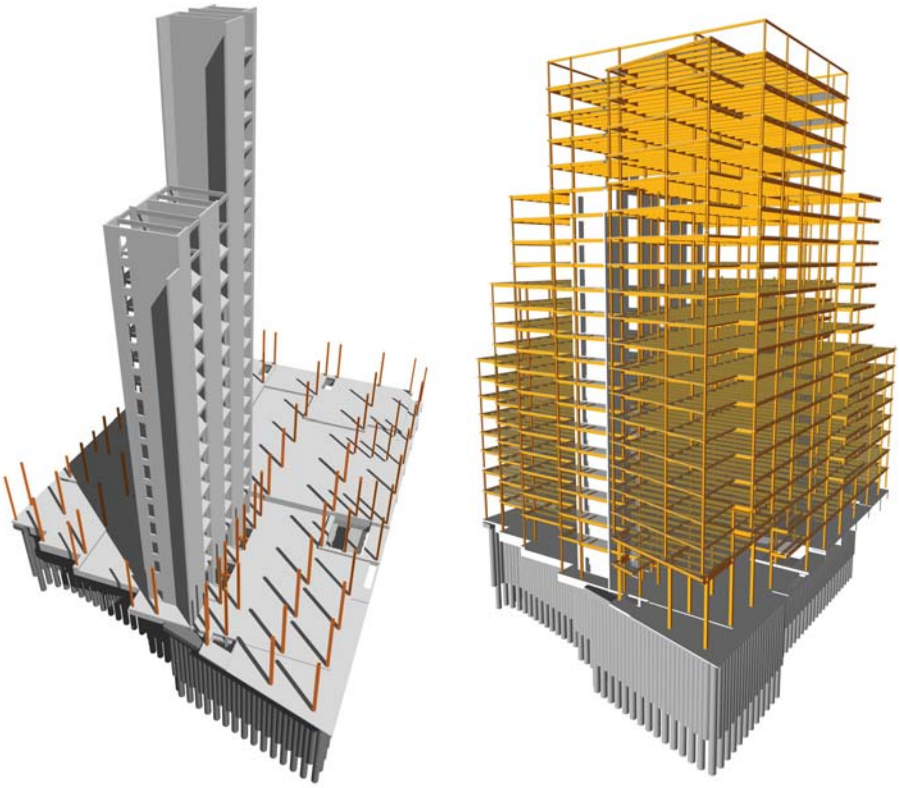
(3) *Steel superstructure:* Construction of multi-storey steel framing, metal decking, and normal weight concrete slabs to form the superstructure floor plates.

Design considerations behind this strategy are described on the following pages.

27. The design strategy comprised the following key structural phases of work:

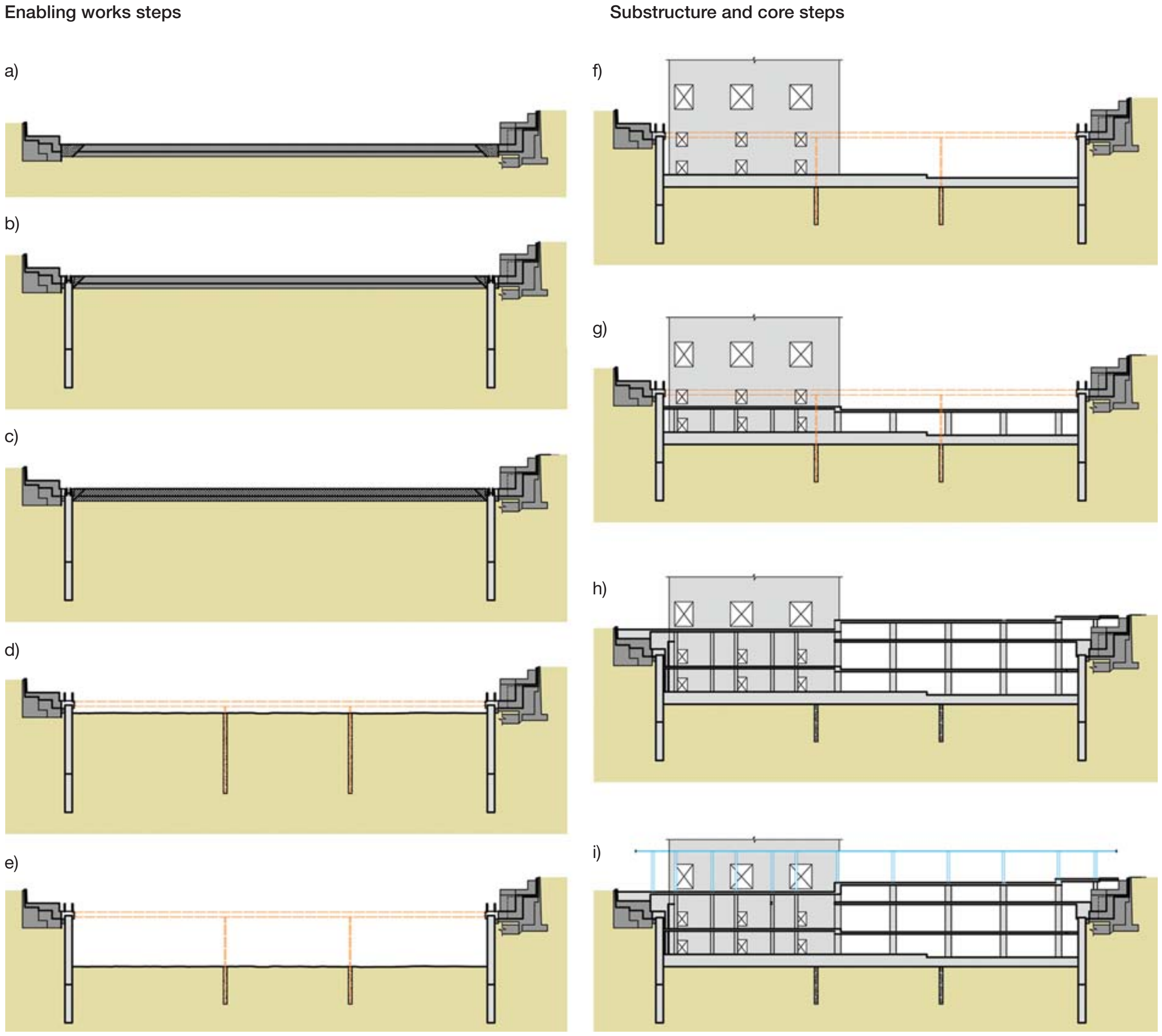
a) Enabling works, to give time for a new building planning application.





b) Concrete substructure, to give time for the new superstructure design and procurement.

c) Steel superstructure, for fast construction of critical path façades and following trades.



a) First stage demolition/pile probing through existing reinforced concrete raft, inside the line of existing perimeter buttress retaining walls, to form trench for new secant wall.
b) Secant pile wall installation, with access at existing basement reinforced concrete raft.
c) Second stage demolition/clearance to central area of existing reinforced concrete raft.
d) Secant pile trim, capping beam, and temporary propping installation (supported on temporary piles at centre).
e) Bulk excavation to new lower basement formation level.
f) Lower basement reinforced concrete raft and slipform core commencement.
g) Middle basement slab, beneath propping level, and removal of props from above.
h) Completion of upper basement and ground floor slab construction, plus ongoing core construction.
(i) Steel superstructure commencement, accessed by mobile craneage directly off ground floor slab. Superstructure supported by new lower basement raft, and by existing upper basement buttresses at the perimeter.

28. Sequence of enabling works and substructure construction.

Enabling works

The site was an open, former single-storey basement, with existing foundations that included a reinforced concrete raft foundation and mass concrete fill from the 1980s, overlaying 1950s reinforced concrete pad foundations over part of the site, together with 6m thick perimeter buttress retaining walls.

These buttresses were known to have supported loads of a building up to 12 storeys since the 1980s. Original design information was available, and sample cores were drilled on site to prove the founding on London Clay. Since these buttresses would have presented a significant difficulty to remove, advantage was taken of their re-use as perimeter foundations for the new building, as well as their retaining wall capabilities, to limit the extent of demolition and required new retaining wall construction. In total, 20% of the footprint of the new building is supported on existing foundations, enhancing the sustainable design credentials.

Significant existing raft slab demolition and deeper excavation work were still required. The mass of the existing foundations was exploited for use as perimeter buttress retaining walls, within which the central area foundations could be demolished and new deep excavation formed within a temporary works-supported secant pile wall. This was deliberately positioned off grid, so that forming the basement “hole” was effectively “off-line” of the as-yet-unknown final building design.

This work was let as a separate enabling works package, which commenced within six months of the client’s site purchase.

Substructure design

The substructure was committed to a bottom-up construction, as a site start had to be made, and the piled foundation design that would have permitted top-down could not yet be defined.

A raft foundation at the central lower level was thus the most pragmatic choice to form a compatible system with the re-used existing perimeter upper level buttresses, as well as with the bottom-up construction sequence.

The design was optimised by calibrating normal software analysis and structural design techniques with more sophisticated soil/structure modelling, to more definitively assess and confirm the adequacy of overall and differential settlement characteristics. This enabled economies in raft thickness and excavation depth. The technique has since been applied to other Arup projects.

29. Site view to the south, showing slipform platform prepared for launch from the lower basement raft slab, between propped secant pile and existing buttress retaining walls.

30. View from the south-east corner of slip-form core construction progressed to level 15 of 21, with the first four-storey bay of steelwork commenced.

The remainder of the basement substructure was naturally in reinforced concrete, due to the short lead-in required and robust means of permanently supporting the retaining walls. As the superstructure needed to be in more lightweight steel-framed construction to satisfy the maximum foundation capacities of both the retained existing perimeter foundations and the new raft, it was practical to separate the substructure as a separate concrete works package. This offered a longer lead-in for the following steel superstructure package. Concrete works started on the first anniversary of the client's site purchase.

The sequence of enabling works and substructure construction was thus dovetailed to transfer basement stability from the temporary propping to permanent slab support systems (Figs 28, 29).

Stability core design

The overlap between sub and superstructure works was further enhanced by including the main slip-formed concrete stability core within the substructure package, and launching it directly off the raft foundation slab.

The core essentially comprised the three connected cells of low-, mid-, and high-rise lifts, stopping off at levels 8, 15, and 21 respectively. Services risers were kept outside the core walls to maintain cell simplicity and avoid complex penetrations. The risers were instead within their own "ring" of column supports, which in turn avoided long-span floor beam reactions on the core walls, and the subsequent need for heavy connection plates cast into the core walls, further simplifying and speeding core construction.

Lobby slabs were cast in situ on permanent metal deck formwork as the core progressed, with spliced coupler joints to subsequently connect stiff "arms" to bypass the services zone and maintain diaphragm integrity with the main floor plate.

The concrete substructure and core to Level 21 were completed 18 months after site purchase (Fig 30).

Steel superstructure design

Various studies were made to evaluate the preferred planning grid for the office floor plate. Essentially all were based on steel frame with composite lightweight concrete metal decks, as opposed to concrete frame alternatives, in the interests of lightweight construction to remain within the viable capacity of the combined raft and re-used existing perimeter foundations. Long spans, 15m and above, were generally ruled out due to the corresponding high column loads. Long spans were also not appropriate to the stepped building massing and floor plate arrangement, as they would have generated significant transfer structure.

The orthogonal building geometry and core anatomy was thus developed with a base, repetitive, 9m x 13.5m structural grid of cellular steel beams, offering deep clear floor plates, set back at grid lines to mitigate transfer structure, with a variable perimeter grid to adjust the otherwise simple orthogonal plan to suit the trapezoidal site footprint and foundation constraints (Fig 31).

The cellular beams do not occupy the full depth of the structure/services zone, but have a reduced depth to allow fan coil condensate drains to run in a 300mm clear zone beneath, while ductwork runs through the beams. This option also allows the tenants the alternative of fitting a chilled ceiling.

Secondary beam spacing selected was 3m. The merits were studied of a 4.5m spacing to further reduce steel piece count and potentially enhance programme, but this was found to increase steel weight, overall building weight, performed less well dynamically, and the nominal programme advantage for steel erection did not in principle follow through to speed up the following cladding to improve end date.

A study of footfall vibration effects showed the advantage of using normal weight concrete over lightweight, and so the former was adopted, to also make use of preferred site placing and finishing characteristics.

The steel frame is fully fire-engineered, with fire assessment first mitigating the required fire resistance periods and thickness of any protection required, and then fire analysis defining where protection was not required. Generally, fire protection is provided to all beams that connect directly to columns, but all other secondary beams are left unprotected. Where fire protection was required, it was provided as an off-site applied intumescent coating to minimise site activity. The result saved not only the material cost of coatings, but also time and handling logistics.

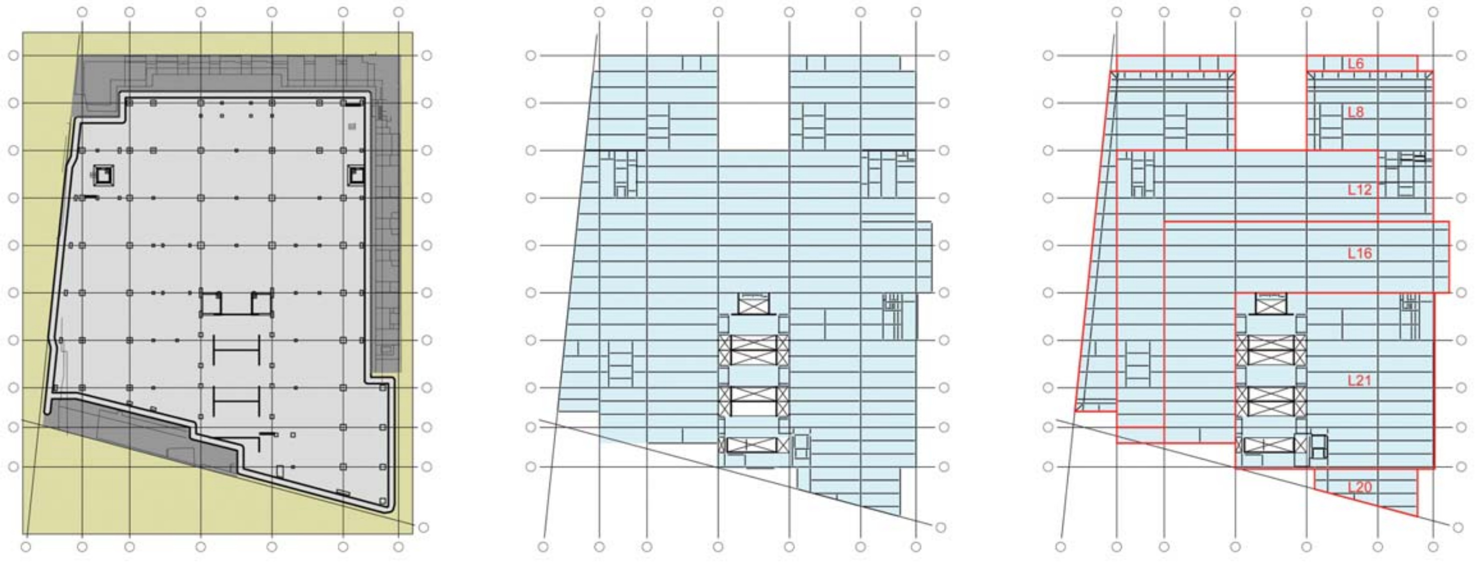
32. Steel frame nearing completion, and façade commenced.

Due to the eccentricity on plan of the primary concrete stability core at the south of the site, additional stability bracing was added at the secondary stair cores towards the north of the site to mitigate dynamic lateral torsional effects.

Collaboration with the construction manager and steel contractor enabled all construction logistics, temporary loadings, crane openings, and tolerance allowances to be directly incorporated into the design documentation, which was delivered in a sequence to suit the procurement and construction.

Steel frame 3-D model transfer, and general fabrication drawings approval were also directly managed, with the fabricator's modellers working alongside in the design office.

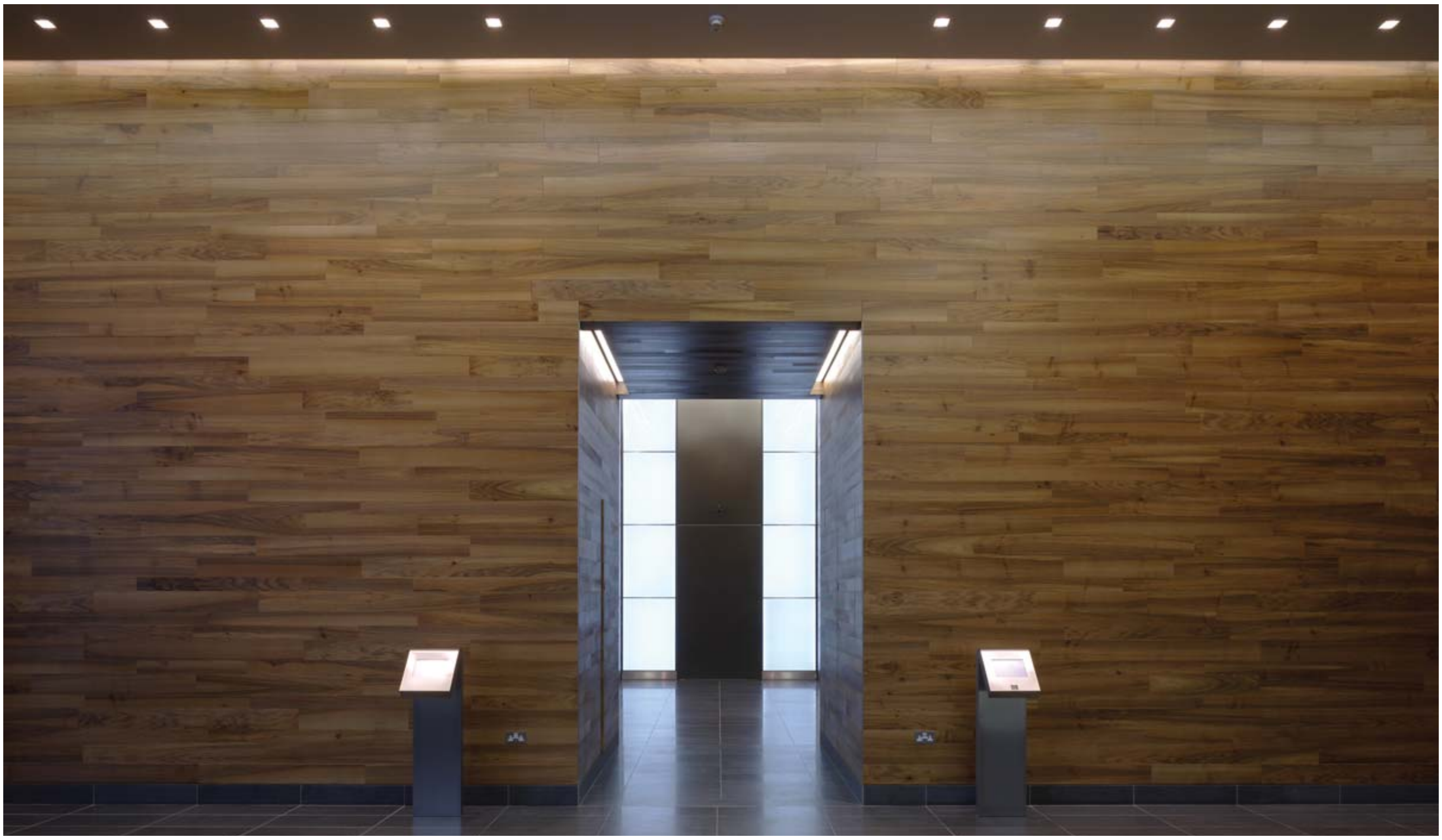
31. The building structure was formed with a base orthogonal, repetitive, 9m x 13.5m grid, and with a variable perimeter grid, to provide harmony between the substructure and superstructure forms and the roof terracing.



a) Substructure: to adjust the otherwise simple plan to suit the trapezoidal site footprint, avoid obstructions, and re-use existing perimeter foundations.

b) Typical superstructure floors: large open floor plates, though moderated spans to balance loading between new raft and existing buttress foundations.

c) Roof terraces: structure set back at grid lines to mitigate transfer structure.



33. View from the main reception area into the lift core through the European walnut panelled wall.

Completion

Completion of the entire building was achieved three years after the initial site purchase, and within the original budget. This achievement justifies the client's preference for an integrated design and construction team approach, and reflects well on the collaborative and "can do" spirit of all those involved.

Ropemaker Place is the only UK office building to have been shortlisted for an Award in the "offices" category at the World Architecture Festival, to be held in Barcelona in November 2010.

Credits

Client: British Land plc **Architect and multidisciplinary engineering designer:** Arup Associates – Ann Marie Aguilar, Andrew Allsop, Gert Andresen, Simon Anson, Jake Armitage, Jenny Austin, Michael Beaven, Mick Brundle, Chris Bryant, Alan Burge, Gary Burnap, Melissa Burton, Jonathan Chew, Kenny Chong, Carl Collins, Peter Connell, Sarah Crabtree, Sho Das-Munshi, Philip De Neumann, James Devine, Tarun Devlia, Paul Dickenson, Philip Dixon, Rory Donald, John Edgar, Mike Edwards, Shu-Lei Fan, Geoff Farnham, Martin Finch, Pietro Franconiero, Holly Galbraith, Andrew Gardiner, Marjan Gholamalipour, Sarah Glover, Maureen Godbold, Wendy Grant, Tony Greenstock, Andy Harrison, Neil Hitchen, Tony Hoban, Tom Honeyman, Lee Hosking, Richard Hughes, Sarah Hunt, Wieslaw Kaleta, John Lacey, Andy Lambert, Leonora Lang, David Lee, Bee Choo Lloyd, Martina McManus, Mei-Yee Man, Paul Matthews, John Miles, Marek Monczakowski, John Napier, Sotirios Nikologiannis, Declan O'Carroll, Dinesh Patel, Rebecca Pearce, Nicola Perandin, Anton Pillai, Esad Porovic, Barrie Porter, Carlos Prada, Robert Pugh, Graham Redman, Connie Ridout, Darlene Rini, Brendan Scarborough, Elizabeth Shaw, Annalisa Simonella, Mark Skinner, Adam Smith, Nikolaos Socratous, Kenny Sorensen, Lexy Stevens, Callum Stewart, Eric Sturel, Peter Sullivan, Vaughan Sutton, Simon Swietochowski, Mark Thomas, Gareth Thyer, Jason Trenchfield, Eduard Van Zyl, James Ward, Gary Webb, Darren Wright, Andrew Yeoh, Hitoshi Yonamine **Project manager, construction manager, and cost consultant:** Mace **Landscape architect:** Townshend Landscape Architects **Colour consultant for façades:** Antoni Malinowski **Illustrations:** 1-2, 8-10, 17-18, 22-23, 34 Peter Cook; 3 ©Cityscape; 4-7, 11, 13, 15, 19-20, 24, 26-28, 31 Arup Associates; 12, 14, 16, 21, 25, 33 Christian Richters; 29-30, 32 Mace.

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Robert Pugh is an Associate Director of Arup Associates in London and leads structural engineering in Arup Associates. He was lead structural director for Ropemaker Place.

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Founded in 1946 by Sir Ove Arup (1895-1988), the firm is now owned by Trusts. This ownership structure, together with the core values set down by the founder, fosters a distinctive culture and an intellectual independence that encourages collaborative working.

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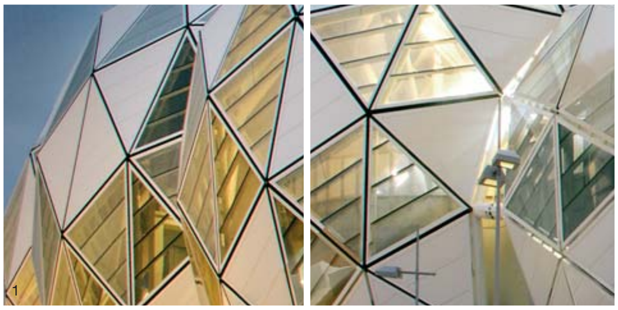

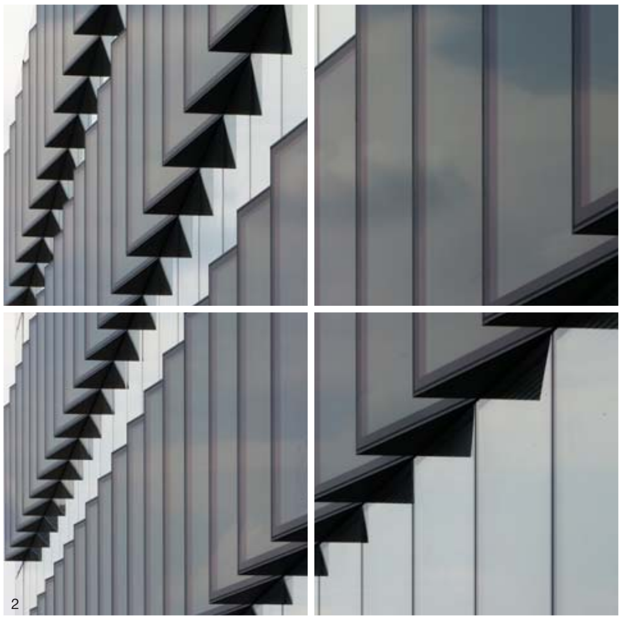

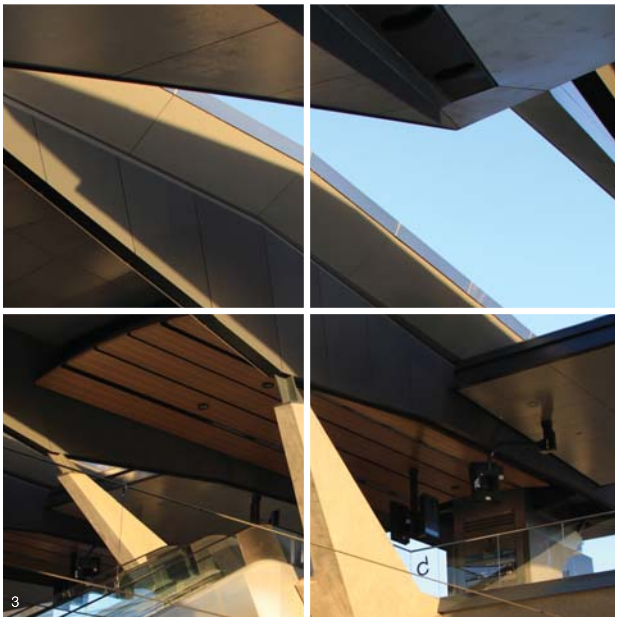

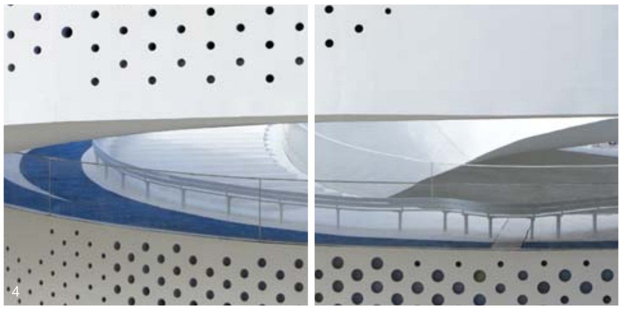

1. Geodesic shell roof at AAMI Park, Melbourne: John Gollings; 2. Windows on the façade of Ropemaker Place, London, angled to reduce incident solar radiation: Peter Cook; 3. Precast arms supporting the concourse roof at the refurbished North Melbourne station: Peter Hyatt; 4. Perforated steel façade to the Denmark Pavilion, Expo 2010 Shanghai: ©Arup/Hufton+Crow.

Front cover: Ropemaker Place, London EC2: James Ward, Arup Associates.

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