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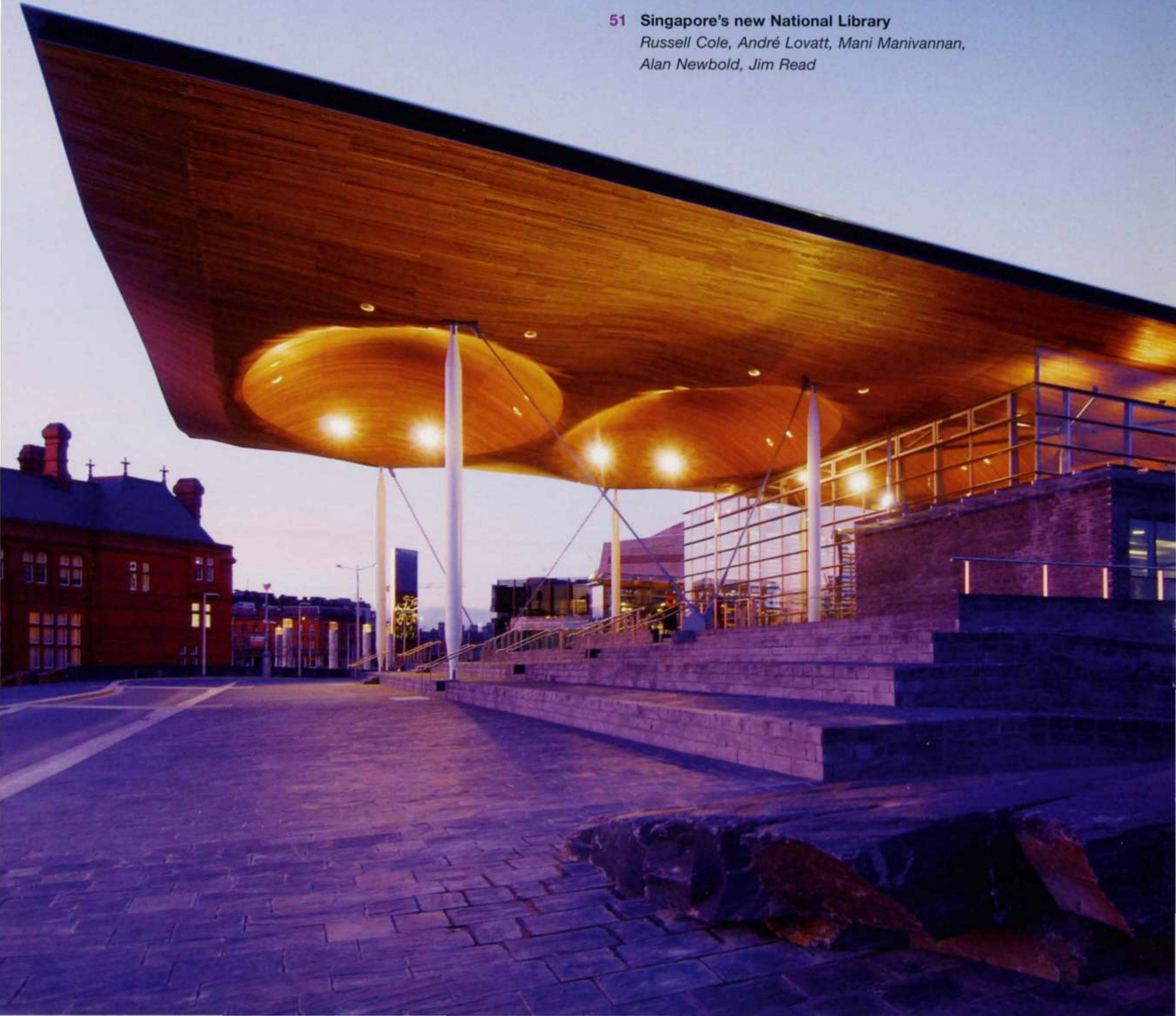
The Arup Journal

Contents



The National Assembly for Wales

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Introduction

The new National Assembly for Wales building in Cardiff Bay has been described as inspirational and an icon for Wales. Designed to be an open and inviting public space as well as providing accommodation and secure private areas for government ministers and Members, the building overlooks the Bay and Bristol Channel, an appropriate setting for the new parliament.

A powerful yet simple design concept embraces literally the desire for open and transparent government. Throughout, the primary driver for the design team was both to provide the new Assembly (Senedd) with a building of quality and dignity, and to draw in the Welsh people to view and participate in the operations of their government.

There are three levels, two of them open to the public, with a café and galleries overlooking three committee rooms and the concentric debating chamber for the 60 Assembly Members (Fig 1). Including offices, there is around 4000m^2 of accommodation. The most striking feature is the sculpted roof, inspired by the natural flow of forces within a folding plate structure. By refining its unique and complex geometry, it was fabricated and constructed simply without compromising its robust yet delicate form. It has already become a symbol for the Assembly and the Welsh people.

The building also had to exemplify sustainable design. Key to achieving this was the selection of durable finishes that would not need replacement during the 120-year design life. Arup worked closely with the contractor, Taylor Woodrow, and architect, Richard Rogers Partnership (RRP), to deliver innovative, pragmatic, and cost-effective solutions including single-glazed blast-resistant façades, an exposed in situ reinforced concrete frame, and slate walling and paving constructed from the plentiful by-product of the North Wales roof slate industry.

1. The debating chamber.

> **" The skill and imagination of those who've designed and constructed this remarkable example of modern architecture have given you a dramatic setting in which to work."**
>
> *-HM Queen Elizabeth II, in her opening speech*

History

Wales has not been politically independent since 1282, when Edward I defeated Llywelyn the Last. The country was annexed by the 1536 Act of Union and since then has largely shared a legal identity with England as the joint entity of England and Wales. By contrast, Scotland and Northern Ireland retain separate legal systems.

In 1955 Cardiff was established as capital in a formal step to re-establish a Welsh national identity. A referendum in 1979 rejected devolution by five to one, but in 1997, 559 419 people voted for an Assembly for Wales, with 552 698 against. Elections were held on 6 May 1999, and transfer of devolved powers and responsibilities from the Secretary of State for Wales to the Assembly took place on 1 July 1999.

After fierce debate, the Assembly's home was settled as Cardiff, and it occupied Crickhowell House in Cardiff Bay while an architectural competition for its new debating chamber building was held. The team led by Richard Rogers Partnership (RRP) and including Arup responded with a clear vision that dealt directly with the issues of transparency and openness, whilst anchoring the building to its dramatic site. It would embrace the Bay and have a rising ground plan formed by a slate plinth, drawing people into the main volume. A horizontal floating plane defined by the undulating roof form folds down and hovers in tension over the debating chamber. The roof and plinth are separated by transparent glazing, enhancing views over the Bay, whilst the centrepiece of the building, the chamber and its funnel, can be seen from all external points.

In 1998 the RRP team was announced winner and started the process of concept development and consultation. As with most significant national and public buildings, the requirements and brief continually developed. Over the ensuing months and years the accommodation, functions, and detail were increasingly defined, but the symbolism and initial concept remained pivotal and unchanging keystones of the design.

Initially a management contract was to be the procurement method, and enabling works and foundation packages were let and completed before the Assembly decided to retender what remained under a different procurement route for greater cost certainty. The original design team retendered with Taylor Woodrow as principal contractor under a design-and-build contract, ultimately delivering the building to budget and programme.

The Arup team

The design team comprised RRP, Arup and BDSP, with Arup's services including structural, civil, transportation, façade, geotechnical, wind and lift consultancy. The concept and scheme design was undertaken from London, enabling Arup to develop the design closely with RRP. During these phases, however, close collaboration with teams in the Cardiff office and specialists throughout Arup was key to delivering the project successfully.

Arup's local knowledge and understanding of local statutory requirements and procedures were invaluable in the preliminary development phases. Staff exchanges during early and later detailed design and construction phases were common and helped to maintain a consistent and efficient approach. This suited all concerned, particularly RRP from the outset, later Taylor Woodrow, and of course the Assembly and client body, of whom many were well aware of Arup and trusted in the firm's recommendations and advice.

The site

The site was originally part of the Bristol Channel foreshore, some 200m south of a bank that prevents tidal flooding of the Cardiff Moors saltmarshes. These were drained by a system of orthogonal drainage reens before Cardiff's first dock, the Bute Ship Canal (later known as Bute West Dock) and its tidal oval basin were opened in 1839.

In 1851 agreement was reached with the South Wales Railway Company for engineers Sir John Rennie and John Plews to draw up designs for an east dock. After criticism for inadequate provision of quayage and draw it was widened and, on the advice of Robert Stephenson, the cill level was fixed at 3ft lower than that of Bute West Dock.

Bute East Dock was built in three sections from January 1852, and the first 300m or so, including the sea lock, basin, and the main dock itself, opened in 1855. By then, the future Assembly site had been raised roughly to its present level as part of the docklands construction, but remained largely undeveloped subsequently apart from a swing bridge between the East Dock basin entrance lock and the basin itself (Fig 2). The East Dock basin and sea lock were gradually infilled during the 1970s and early 1980s, and the Dock Engineer's offices demolished in the early 1990s to make way for the NCM building south-east of the site.

2. The pierhead in 1923.

3. The new building in context.

Geology

The superficial deposits comprise estuarine alluvium - very soft to soft clay with subordinate silts, sands and gravels, and local peat beds. These are underlain by fluvioglacial outwash deposits - typically dense to very dense silty or sandy gravels. The site was covered with a varying thickness of clayey alluvial fill from the dock excavations, overlain by a layer of predominantly granular fill that formed the docks' development platform. The solid geology comprises Triassic strata of the Mercia Mudstone group, formerly known as Keuper marl. Here this is typically a very weak, increasing to moderately weak to moderately strong, red brown mudstone. The weathering and strength profile typically varies considerably with depth.

Groundwater and contamination

The fluvioglacial gravels and the upper, weathered parts of the Mercia Mudstone bedrock form the main water-bearing strata, the water being confined here by the overlying alluvium and alluvial fill. A perched water table in the granular made ground overlying the alluvium/alluvial fill is also usually present. At the start of construction, boreholes showed the piezometric levels in the fluvioglacial deposits be stable at +3.6mOD. Although a small risk of soil or groundwater contamination was suspected, no elevated levels were revealed by the contamination investigation, which was broadly in line with desk study assessment. Also, no elevated concentrations of soil gases or borehole flow rates were recorded.

Dock structures and other obstructions

Part of the East Dock basin and its associated sea lock are buried under the site. These have been infilled but their walls, foundations, and the lock floor remain. Drawings of the basin and sea lock walls were found in archive sources during the geotechnical desk study. In addition, previous investigations for adjacent developments had shown the basin infilling to be some 15m deep, with no indication of a structural floor, and that the south-east basin walls were founded on the dense fluvioglacial deposits at some 15m depth. The walls were about 5.5m wide at the base, tapering to 3m at coping level, and found to be built of masonry with sandstone ashlar facings, and indications of counterforts. The new project's ground investigations confirmed the previous findings on the structure, dimensions, and foundations of the basin walls and lock floor.

Foundations

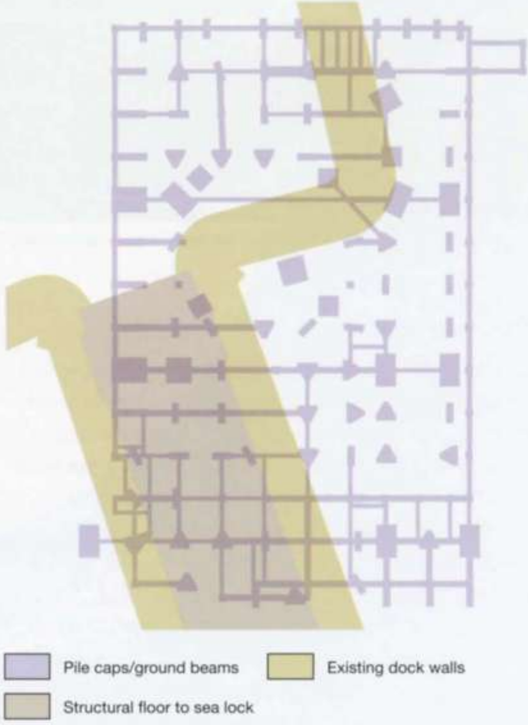
The column loads and spacing and ground floor loads were such that conventional spread foundations in the made ground and alluvium were not feasible, due to unacceptable total and differential settlements, and so the foundations were piled.

Several techniques were suitable including driven precast and cast in situ bored piles (continuous flight auger - cfa), but the former were likely to cause unacceptable noise and vibration to nearby commercial developments and the existing National Assembly building. Cfa bored piles were therefore used - a cost-effective solution with minimum noise and vibration.

The basin walls and lock floor could be avoided, removed, or utilized, with or without strengthening. Due to the different orientations of the building grid and the dock structures, a combination of avoidance and removal was adopted.

Wherever possible, the new piling avoids, and ground beams span across the dock structures. A few column positions were located over the sea lock structures (dock walls and structural floor) where avoidance was impossible. Here the dock walls/floor were drilled out in advance by conventional boring to form an oversized bore clear of obstructions. This was then backfilled with sand and a cfa pile constructed through the sand backfill on which the structural loads were carried.

Strict performance criteria were specified for the piled foundations, including requirements for vertical and horizontal movements, the latter to avoid loss of prestress in the inclined cable ties stabilizing the roof structure.



4. Plan of building with former dock walls superimposed.

5. Canyon and public entrance under construction.

6. Underside of funnel, showing ring beams and cantilevers.

Concrete structure

The transparent enclosure springs from the plinth, whose slate cladding, quarried at Penrhyn in North Wales, wraps around a reinforced concrete box designed to resist blast loads. The plinth sides have very few openings, daylight being admitted via rooflights and two "canyons" that separate the central public areas and debating chamber from the flanking offices and committee rooms (Fig 5, 7).

As well as transferring wind and blast loads from the superstructure to the foundations, shear walls within the box provide anchorages for the roof's raking ties. Each tie baseplate is secured into the wall below by four 32mm diameter, 2.5m long, stainless steel *Dywidag* bars, with an ultimate tensile strength of 1030N/mm^2. The dead weight of the plinth partly resists their uplift, the net force being taken by tension piles. The horizontal component of the tie load is transferred by shear keys recessed in the concrete structure, resolving the force across the building between each pair of opposing ties.

Inside, the concrete columns and soffits of the floors they support are exposed to view. Apart from its aesthetic place in the Senedd's distinctive palette of materials, exposed concrete contributes to the low energy environmental strategy by radiating "coolth" on warm days, and provides a very durable finish. It should need no maintenance other than occasional cleaning during the 120-year design life, and beyond.

Typically, the building has a 6m x 6m column grid. Rather than flat slabs, two-way spanning slabs on downstand beams were adopted, as even with the best workmanship, the variability of a flat slab soffit would be visually unacceptable in such a building. The downstand beams break up and provide order in the soffits and, together with the columns, act as visual frames to the openings on each side of the canyons.

In the centre of the building, the debating chamber punches 15.3m diameter holes in the first and second floor slabs, framed with ring beams supported mainly by four deep, diagonal cantilevering beams on circular columns set back from the debating chamber to allow space for future expansion (Fig 6).

It is notoriously difficult to communicate architectural aspirations for visual quality in exposed concrete to contractors. The engineer who drafts the concrete specification has an essential role as interpreter, but also should stand back and not hinder direct dialogue between the architect and contractor on such subjective issues. The successful outcome here can partly be attributed to the close communication that the design-and-build relationship generated. Equally important, the work was undertaken by a very skilled subcontractor team, and the architect was pragmatic about what could and could not reasonably be achieved.

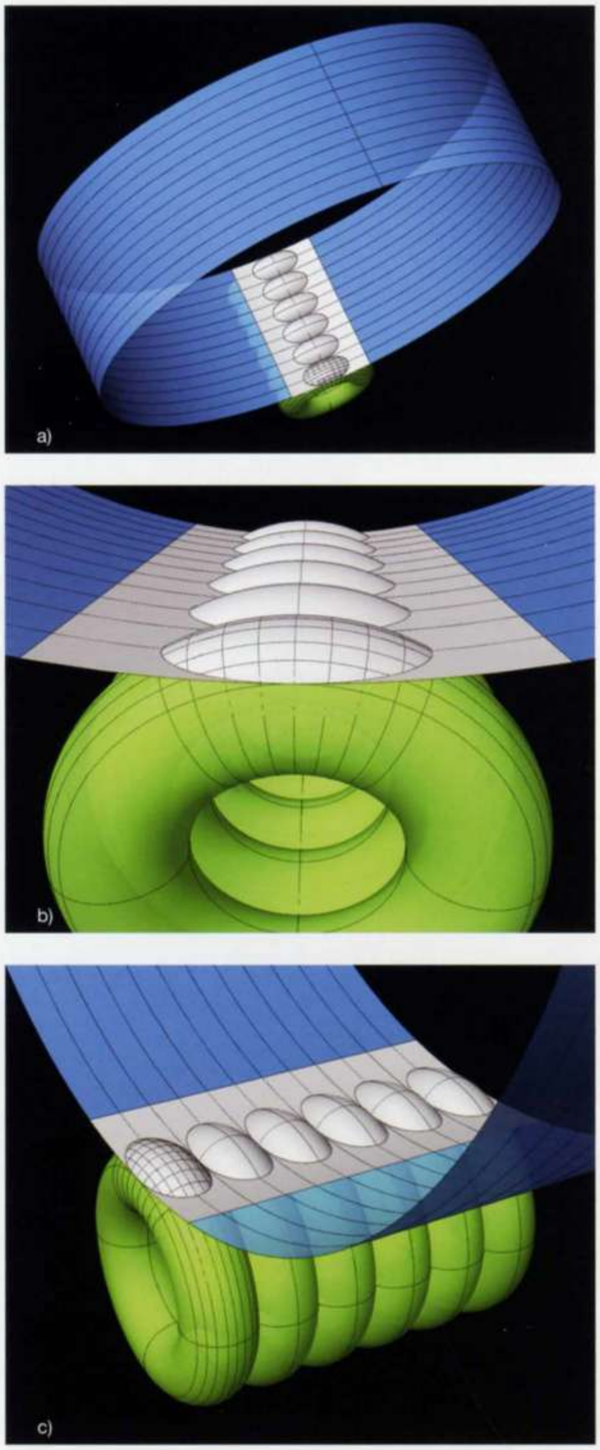
On the one hand, precise requirements were stipulated for forming recesses and other features, and in locating construction joints, tie bolts, and joints between sheets of plywood falsework. On the other, however, the architect considered and accepted the colour of the standard locally-available concrete aggregate. The ready-mixed concrete supplier could have imported a different aggregate specifically for the project, but the contractor regarded it as essential to have an alternative plant available, and so use of readily-available local material was critical. Before any visual concrete was cast in the building, the contractor built a trial structure that included samples of the proposed columns, walls, beams, and slabs. This enabled the architects to refine the final design of features like recesses and joints, and established a benchmark for the standard of finish. Being realistic about exposed concrete, RRP had no objection to minor blemishes such as small blowholes inevitable in even the most carefully cast concrete. Formwork tie bolt holes were not filled flush but left recessed. In the event, little making good was required and most exposed surfaces were simply rubbed down.

Close contractor-designer collaboration and dialogue benefited the project in many other ways. Before reinforcement detailing began, the steel-fixers were consulted about their preferred prefabrication methods to ensure that lapping details would suit them. The contractor asked Arup to minimize the need for preparing (by scabbling or safer means) construction joints, and by locating them in low shear areas it was possible to omit most of it.

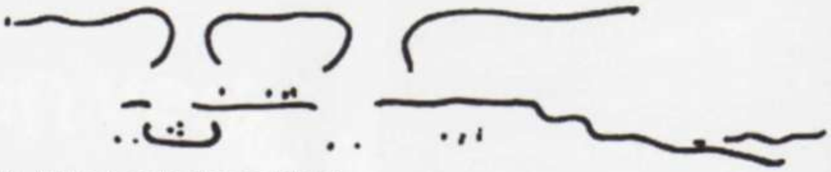
One consequence of exposing slab soffits to view is that services must be carefully co-ordinated and clutter avoided. Most services are in an undercroft that also contains plena for the natural ventilation supply air. Originally, the floor above the undercroft was to have precast beams and slabs craned into place after services installation, but once the contractor developed his preferred sequence of works, alternative systems were investigated to avoid the need for craneage. Finally, in situ concrete was pumped into place on permanent metal decking supported mostly on short-span steel T-beams and posts, most of them erected before the services installation.

7. Canyon.

8. Public level overlooking the debating chamber.



9. Definition of surface geometry.



10. Architect's sectional concept sketch.

The roof

Aspiration

Horizontal planes define and embody the concepts behind the Senedd. The slate plinth anchors and engages the public realm and waterfront, inviting and drawing people in, whilst over this powerful base is juxtaposed the undulating roof plane. This frames and articulates the extent of the building, and also folds and turns in on itself, holding in tension the funnel-like form that marks the building's centrepiece, the debating chamber (Fig 10).

Development of the roof form

From its inception the roof structure was developed to flow over a series of slender point supports spanning some 26m and cantilevering beyond the supports a further 8m. The structure was conceived as an undulating plate that developed inherent out-of-plane stiffness through folding. Initially, the plate was folded in a simple sinusoidal form, developing stiffness by offsetting the upper and lower chords to the perimeter of each module.

The simplest non-beam span was an arching shell between the columns, extended beyond the support lines to form the cantilevers. Tying the springing points of an arch is fundamental to its stability and efficiency, but introducing ties through this space would have been intrusive, creating a disjointed form. Offsetting the ties to the perimeter of the 12m wide module and within the roof plate both restrained and equilibrated the forces within it (Fig 13).

With the structural diagram established, the roof surface was defined by combinations of mathematically accurate three-dimensional forms: intersecting toroids and cylinders (Fig 9). By using such a rationale, the roof surface is defined by a series of repeating singly-curved elements, thus standardizing the elemental structure and subsequently simplifying fabrication, connections, and erection.

Defining the roof profile thus also showed subcontractors how the external cladding could be profiled and fixed. Similarly, the internal timber soffit lining was also developed within the guiding surface parameters that define the structural form. The roof form was sculpted using the program *Rhinoceros* (*Rhino*), and its profile was increasingly refined with regard to structural performance, repetition, buildability, and visual impact. The final geometry had to ensure the robust yet delicate form was preserved while its elemental framework was easily fabricated, transported, and erected.

Base parameters

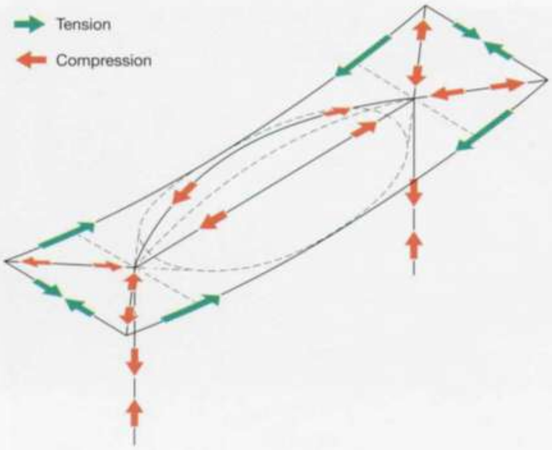
Of the six roof modules, five are typical and one supports the funnel and lantern structures. Each module is a closed self-balanced system, typically 12m wide x 41.5m long, with the end modules extending a further 2.5m on their long edge. The total plan area of the roof is approximately 3200m^2. It has a western red cedar timber soffit and a standing seam *Calzip* external finish, with associated guttering and insulation. The timber soffit profile generally follows the structural form but has been softened along the structural fold lines.

The roof plate is supported by six pairs of slender steel columns, each pair central to its 12m wide roof module and 26m apart. Beyond the column support line, the roof projects a further 8m, providing essential shading to the glass façades.

11. Front entrance.

12. Wind cowl and lantern.

13. Structural isometric force diagram.



Above the funnel, the lantern structure supports the lantern glazing and the wind cowl (Fig 12). The glazing draws light into the debating chamber via an inverted conical mirror directly above the debating chamber in the lantern centre (Fig 20). The wind cowl rotates like a weather vane with the wind direction and the negative leeward pressures draw out the warm air from the chamber.

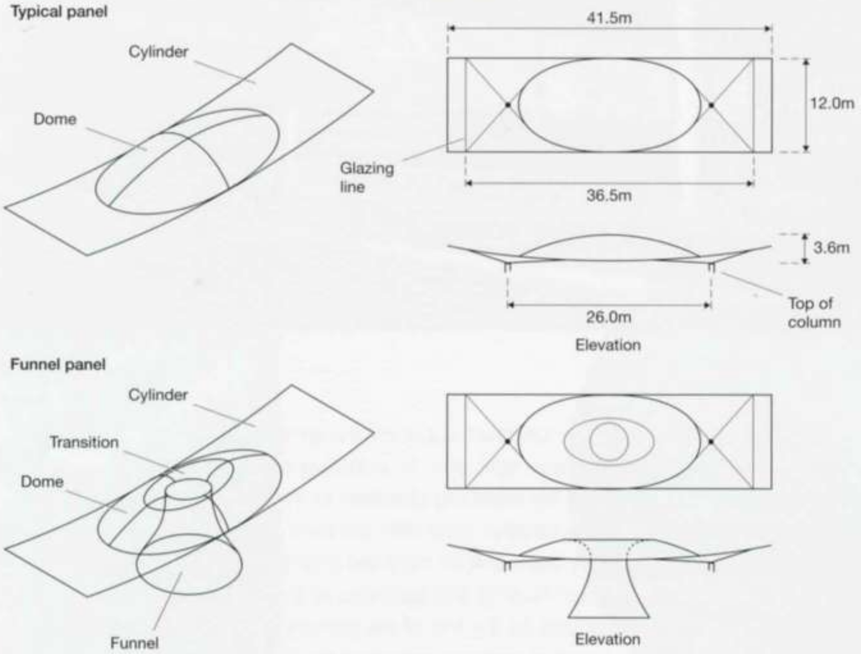
To punctuate the sense of floating and lightness of the roof structure, the façade mullions stop at the same level as the top of the primary columns, and are connected to a header beam or transom spanning 4m between horizontal props which project in plan diagonally from the top of the column. On the gable ends, the header beam is supplemented by a planar horizontal truss spanning 26m between primary columns. The façade between the top of the mullions and the roof soffit simply comprises a glass panel with the roof connection absorbing any differential vertical roof movements.

Structural principles

The roof form responds to the natural and efficient flow of forces within the folded plate and considers the bending behaviour of a simple beam with cantilevers at either end. Asymmetrical loads create bending effects that necessitate a minimum structural depth along the length of the roof plate. Primary uniform loads are resisted by arching action between the columns and beam action in the cantilevers. A minimum structural depth is maintained by offsetting the arch springing points from the cantilever beams at the column position. This results in a resisting couple being generated over each column location.

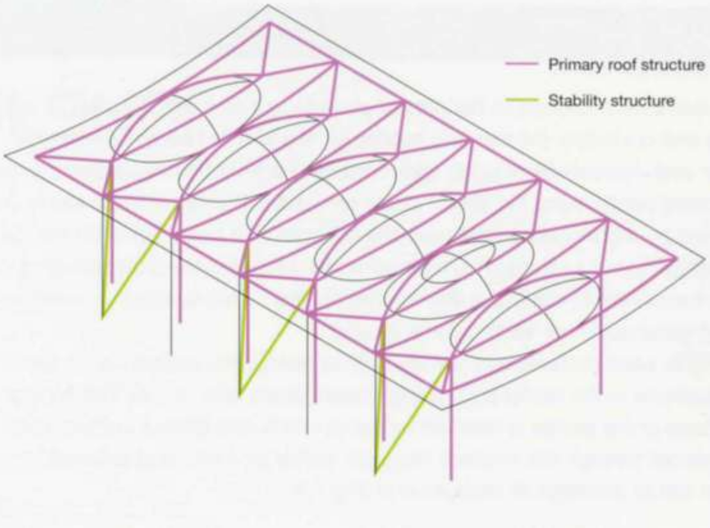
Within each module, two primary arches span 26m, inclined at about 45° to suit the aperture in the funnel bay, giving a span/depth ratio of 1:8. The vertical thrust at the base of the arches is resisted by the columns and the horizontal thrust transferred through the in-plane diagonal cantilever struts and balanced by the offset ties at the edge of each module (Fig 13).

14. Public areas around the funnel.



15. Geometry of typical panel and funnel panel.

16. Principal structural elements.



The roof perimeter cantilevers up to 12m diagonally at the corners, and the beams that support it are tapered and precambered to reduce dead load effects. The longitudinal roof members that form the undulating roof profile simply span between arches and ties. All other longitudinal members are straight, simply-supported beams except for the primary continuous element between each column location.

The funnel is hung in tension from the arching shell structure, without vertical support from the reinforced concrete structure below but with its base horizontally and torsionally restrained by horizontal diagonal ties which connect back to the concrete ring beams.

The funnel geometry was generated by taking a horizontal and approximately elliptical cut through the top of the arching shell. Following the plan of the debating chamber, the funnel base is circular, and this resulted in the lower portion of the funnel being defined by horizontal concentric circles and its upper portion having a transitional length that develops a circular profile to that of the elliptical profile (Fig 15).

The roof is stabilized laterally by pairs of inclined prestressed rods. Lateral loads on the roof are transferred to the stability ties by in-plane bracing, and hence the roof plate is designed to act as a stiff diaphragm (Fig 16).

17. Roof column head.

18. Ground anchorage of inclined roof tie.

Roof analysis and design

Wind tunnel testing initially modelled the environmental wind around the entrance to the building and tested alternative mitigation measures to reduce it to acceptable levels. However, further testing was undertaken to model the overall distribution of forces through the structure and pressure testing with taps strategically located to best model the façade pressures. The façade wind loading applied to the structural analysis model was derived from the wind tunnel testing pressure readings.

The results confirmed the distribution of wind-induced actions through the structure to be accurately modelled in the structural analysis.

As well as typical transient loads, the structural analysis included dead and superimposed dead loads from the standing seam roof finish and the underslung timber soffit, snow loading including drifting, thermal loads which accounted for the effects of external and internal steelwork temperatures; blast loading as a static equivalent load, and finally prestressing of stability ties.

The *Rhino* model of the roof and funnel was developed to generate the roof surface profiles and the element geometry. A spaceframe analysis model was derived directly from the *Rhino* model and GSA used as the primary analysis tool. Furthermore, a *GSRelax* non-linear analysis, which accounted for the second order effects of the deflecting structure, was undertaken to ascertain prevalence to buckling.

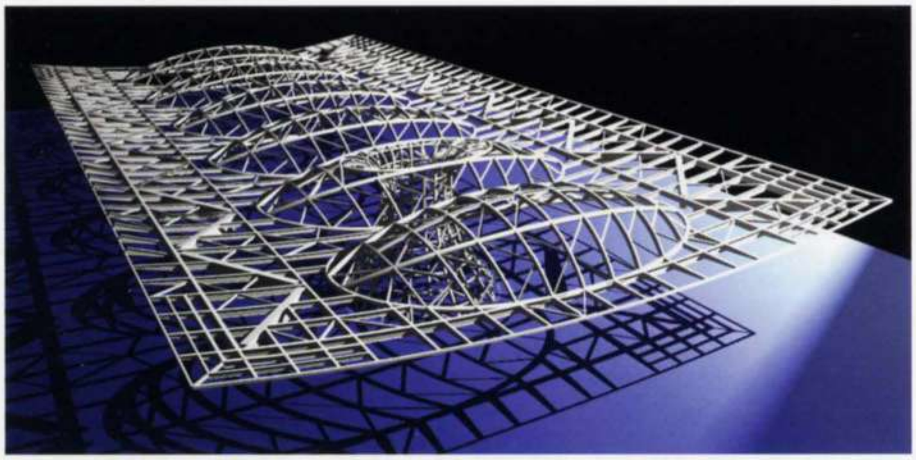
All roof members are standard universal beams and circular hollow sections, apart from the primary cantilevering beams and the "crease" members (where the domes intersect the cylinder), which are tapered I-sections and compounded T-sections.

Fabrication and erection

Due to the complex geometry, Arup developed each connection to suit load transfers, fabrication techniques, and erection sequencing. Using standard and conventional fabrication techniques on highly complex connections gave the steelwork fabricators great insight into the hierarchy of the member actions and their resolution.

An *X-Steel* model (Fig 19) was also produced from the *Rhino* geometry as the basis for all structural steelwork drawings and connections. Further developed once the steelwork contractor was selected, the model included each nut, bolt, splice plate, end plate and stiffener, ultimately being used directly to fabricate all the structural components. A full-scale trial shop floor erection of the entire module ensured ease of erection on site. This was enabled by confirming accuracy of fabrication and adequacy of tolerances. Subsequently, this proved invaluable on site whereby the roof erection proceeded unhindered and at great speed (Fig 20).

19. *X-Steel* model isometric view.



20. The roof under construction.

21. Underside of mirror cone in lantern.

Environmental design

The Senedd's environmental credentials establish a new standard for public buildings in Britain. To create a low-energy building with a minimum life of 100 years, additional capital was invested in elements that reduce energy on a life cycle model. Each system was analyzed in terms of initial, replacement, and life cycle costs so as to calculate long-term return on investment. These systems are projected to reduce running costs by 30-50%.

Natural ventilation is the default mode. Cooling and heating are supplied by earth heat exchangers, with heat pumps and 27 boreholes drilled 100m into the ground. A wood-chip boiler supplies additional heating, fed perhaps by some of the 500 tonnes or so of timber carried down the rivers each year into Cardiff Bay. The rotating wind cowl ventilates the debating chamber via the funnel hung from the roof. Natural lighting is provided, even to the chamber: glazing beneath the cowl (Fig 20) admits daylight which is reflected down by an inverted conical mirror. Rainwater is stored in a basement tank for recycling.

The exposed concrete frame moderates the environment and eliminates applied finishes, and other materials used for the construction and furnishing were chosen for their low environmental impact. The timber is from managed sources and the fixed furniture is in Welsh oak. Durable Welsh slate was selected for most of the flooring, inside and out. As independent confirmation of its environmental credentials, the building gained an "Excellent" BREEAM (Building Research Establishment Environmental Assessment Method) certification (the highest achievable).

22. The glazed façade: side view at night.

Façades

Arup's façade engineers worked closely with the architects to develop the concept and details for the glass walls that met the architectural aspiration, within the stringent performance requirements such as natural ventilation, interfacing to the roof structure and, most importantly, blast resistance.

The initial desire was to use glass fins for maximum transparency, and options including suspending the wall from the roof and cantilevering it from the floor were considered before settling on a ground-based wall restrained from the roof. The requirement for blast resistance led to steel vertical fins being used for the necessary flexibility and ductility.

The glazing was procured by developing design intent drawings and performance specifications from which the specialist glazing contractor completed the detailed design in close collaboration with the design team. To maintain the quality and intent of the glazing details, the information produced for the glazing contractor was highly detailed and prescriptive.

The main façade (Fig 22) is single-glazed, with numerous openings for natural ventilation. The steel fins, 6-9m tall and spaced 3m apart, form the primary glazing support, their heads restrained by horizontal transoms supported horizontally from a series of diagonal props that project directly back to the tops of the roof columns. The roof plate is thus divorced structurally and visually from the glazing structure, allowing independent movements between the roof and façade interface.

A unitized aluminium glazing frame, 3m wide and the full height of the building, is restrained by the vertical steel fins and further stiffened by T-section transoms, external to the glazing, between the fins. A torsion connection was developed through the glazing from the transoms to the fins to restrain them, allowing the fins to be as slender as possible to maximize sightlines from the building.

The glass panels for the main façades are formed from two leaves of low-iron glass laminated together. Low-iron glass was used throughout the project; it lacks the green hue of float glass, thus increasing transparency.

As with most seats of government and significant public buildings, post-9/11 security measures increased the requirement for the glazing to be blast-resistant. Most fatalities and injuries in a blast event are caused by flying debris rather than the explosion itself. Brittle glass is potentially a dangerous and significant component of such flying debris.

Arup used experience gained on Portcullis House, Westminster, London, and the Scottish Parliament Building[1], Edinburgh, to provide the level of blast resistance performance required by the Government's specialist advisors whilst meeting the architectural aspirations and natural ventilation requirements. Arup's blast-resistant glazing details were approved by the security advisors without resorting to an off-site blast test that would have had significant cost and programme implications.

Surroundings and infrastructure

Background

Achieving the high-quality, natural stone finish, public open space around the building presented significant design challenges, including the road and paved areas, drainage, utilities diversions and co-ordination, ground conditions, topography, and the impact of adjacent and concurrent works. All this required innovative and carefully co-ordinated responses.

Sculptures

Among the Senedd artworks, two external sculptures required Arup input. The first is "Assembly Field 2006" (Fig 23), artist Danny Lane, a thicket of glass blades that sits on a plinth at the building's west corner. It also shelters visitors from the strong south-westerly winds that sweep across Cardiff Bay, a need identified in a series of pedestrian comfort studies undertaken by Arup as the design developed. The blades, and the stainless steel shoes that secure them to the concrete slab beneath the slate paving, are designed to resist blast pressures.

The second sculpture is "The Meeting Place" (Fig 24), a two-tier stepped arc of slate blocks weighing up to two tonnes, designed by Richard Harris. Apart from ensuring the stability of the cantilevering blocks under a hypothetical load of two rugby players, Arup's role was to translate the sculptor's sketches and a foundation survey into a 3-D computer model. The process was iterative, with Richard Harris sitting at the CAD technician's side to agree design refinements. A dimensioned drawing was produced for each of the 39 slate blocks so that they could be cut to shape at the Cwt-y-Bugail quarry in North Wales before shipping for assembly, using a setting-out drawing with co-ordinates and levels for the corners of each block.

23. "Assembly Field 2006": artist Danny Lane.

24. "The Meeting Place": artist Richard Harris.

Drainage and utilities

Before it was acquired by the Assembly, the site had been prepared for commercial development within the Capital Waterside estate masterplan. A new road, Harbour Drive, was built around the plot, accommodating all major trunk services for this part of the estate. This road also followed the line of a deep, large-diameter concrete storm drain designed for storage during storms coinciding with high tides in Cardiff Bay.

The new building footprint required Harbour Drive to be re-aligned and all utilities serving this part of the estate to be diverted, including the storm storage drain. Deep chambers and tidal flap valves had to be reconfigured to accommodate the front entrance steps and new raised road position.

All services were diverted in a single combined trench, running approximately along the line of the lower front steps; this was done during the original management contract. The corridor between the debating chamber and the adjacent Wales Millennium Centre (WMC) along Pierhead Street required particular attention to detail to co-ordinate existing and proposed services, including the WMC, the new street furniture and trees, and the proposed new road line.

The new building's foul drainage system outfalls into existing deep sewers along the route of this service road, together with the outfall from a "drainage blanket" under the building, which incorporates a network of porous pipes that intercept any rising groundwater and vent any potential ground gases via pipes within the building envelope.

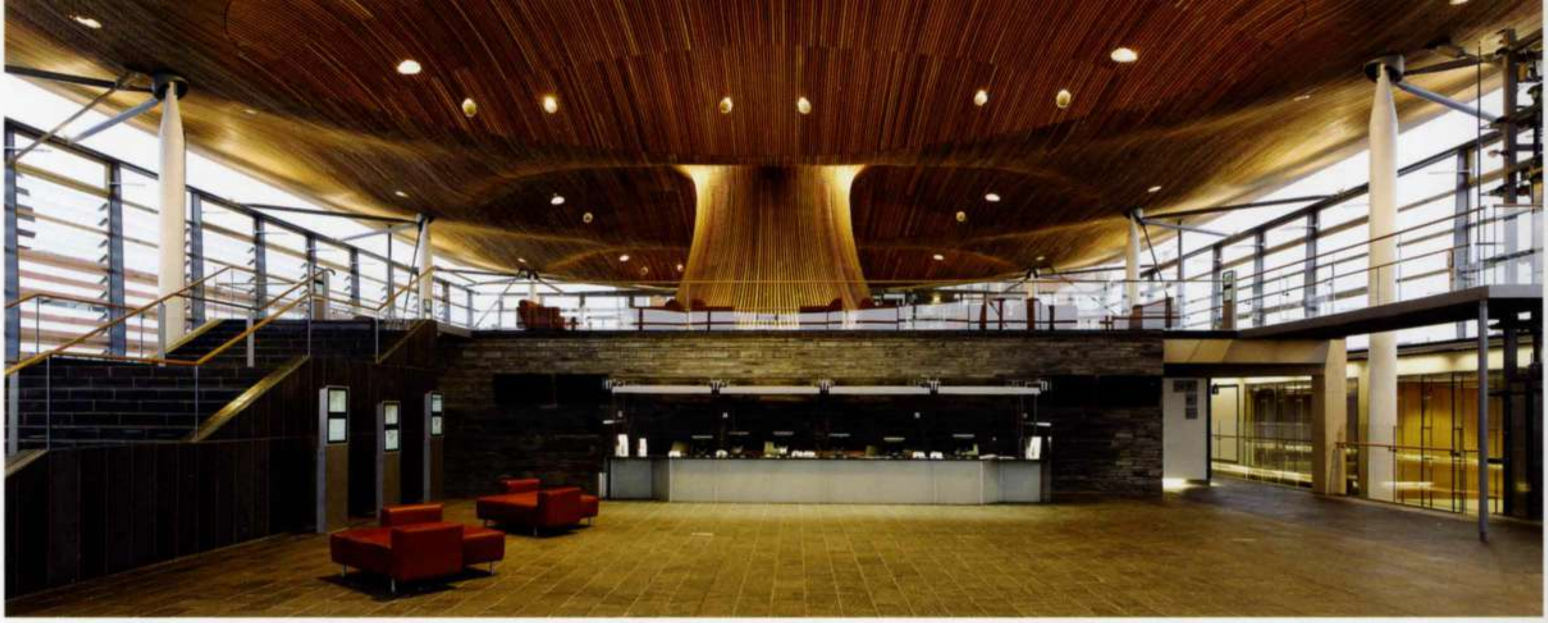
Roads and hard landscaping

The rising slate plinth necessitated a natural stone road and adjacent hard landscaping, raised above the existing (essentially flat) site levels. The one-way road's horizontal alignment fitted the building footprint and its relationship to required vehicle movements, both around it and to adjacent buildings. The vertical alignment, however, was significantly constrained by the need to:

- tie the new building floor level with the surrounding topography, via the steps and ramps for disabled access
- tie the perimeter levels to the existing dock walls, roads, and adjacent buildings, to which specific vehicular access had to be maintained
- ensure disabled access around all perimeter areas
- achieve adequate drainage throughout, constrained by generally very flat gradients.

The final alignment was achieved iteratively, taking into account the phased construction and interim pedestrian routes. The design required existing levels along the building front to be raised by up to 1.5m, leading to concerns over future settlement and damage to the high quality finishes. The slate and granite around the Assembly would be particularly sensitive to such movements, which could seriously affect the structural performance of the paved areas.
This was overcome by seeking a "net zero increase" in ground loadings, with lightweight fill beneath the road and existing material removed and replaced with less dense material along the front of the building. The upper front steps sit on suspended structure, but the ramped steps to the side are on existing ground. To avoid the risk of settlement here, there is a "voided" structure on lightweight fill.

The pavements in both trafficked and pedestrian areas were designed to "Natural stone surfacing: good practice guide" published by the Society of Chief Officers of Transportation in Scotland[2], which contained the most up-to-date research and guidance in the field.



25. Public areas between the front of the building and the funnel.

The stone is generally founded on either a reinforced concrete or cement-bound sub-base. Site categories only allow the use of surface elements 150-250mm wide and 200-500mm long for the road. Natural stone within this range is defined as a "block" and required a nominal depth of 180mm at this particular application. The depth, strength and width of joints are the primary factors controlling resistance to loading for rigid pavements. Natural stone must conform to various material characteristics (eg strength and durability) and manufactured blocks must conform to defined size, shape, and texture.

The loading and site categories adopted for the paving design precluded the use of a flexible pavement and a rigid construction was adopted, in view of the heavy loadings from vehicles such as three-axle buses and delivery lorries. Size of stone elements, jointing arrangements, mortars, surface texture, and workmanship all significantly affect structural performance, and the specification was prepared with great care. Manual handling also impacted the choice of sizes, though the contractor still had to use specialist hydraulic lifting equipment for some sections. Granite paves the road and vehicle-running surfaces, to ensure appropriate durability, skid-resistance, and general mechanical properties. Elsewhere, slate was used to enhance the effect of the original design aspiration.

Conclusion

On 1 March 2006 – symbolically and appropriately St David's Day - the Senedd building was officially opened by HM Queen Elizabeth II. In its original competition brief the Assembly stated that the building "should not be openly adversarial in shape or argument..." and "...in due course we [the Assembly] would dare to hope it will become a visible symbol, recognised and respected throughout the world, wherever the name of Wales is used." It is hoped that the design team's response has delivered this vision, and that it will contribute to the Assembly's future success.

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(1) HADDEN, D *et al.* The Scottish Parliament Building, Edinburgh. *The Arup Journal*, *40*(2), pp10-20, 2/2005.

(2) SOCIETY OF CHIEF OFFICERS OF TRANSPORTATION IN SCOTLAND. Natural stone surfacing: good practice guide. First edition, The Society, 2000.

Awards

- 2006 Royal Institute of British Architects (RIBA) Award - Wales
- 2006 Structural Steel Design Award Winner
- 2006 Building Exchange BEX Awards: Sustainable Regeneration Award - Winner; Innovative Regeneration Award - Runner-up

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Gabriel Hyde is an Associate of Arup in the Cardiff office of the Wales group.

Gavin Kerr is a senior engineer with Arup in the Facades London group.

Ray Lake is an Associate of Arup in the Cardiff office of the Wales group.

Ed Newman-Sanders is an Associate of Arup in the Building London 5 group.

Matthew Skuse is an Associate of Arup in the Cardiff office of the Wales group.

Credits

Client: National Assembly for Wales (2003-) **Architect:** The Richard Rogers Partnership **Structural, civil, geotechnical, façade, lifts, wind, and transportation engineer:** Arup – Andrew Allsop, Nick Ashby, Hannah Babor, Malcolm Barrie, Jenny Baster, Matthew Blackburn, Stuart Bull, Phil Coomer, Greg Cooper, Joseph Correnza, Gary Davies, Jon Davies, John Jo Hammill, Richard Henderson, Roger Howkins, Gabriel Hyde, Hywel James, Chris Jofeh, Kevin Jones, Sarah Jones, Gavin Kerr, Ray Lake, John Lange, Tom Linder, John Lovell, Bruno Miglio, Paul Morgan, Luis Navarro, Ed Newman-Sanders, David Palmer, Fabio Parenti, Bernie Pemberton, Matthew Skuse, Antony Smith, Ryan Sukhram, Keisuke Tanikawa, Calvin Tsang, Ellis Walker **Services engineer:** Bode Duncombe Stanisovic & Perry (BDSP Partnership) **Quantity surveyor:** Northcroft **Design-and-build contractor:** Taylor Woodrow Construction Ltd **Subcontractors:** ***External slate:*** Allard et Fils ***Building slate:*** CB Watson ***Timber soffit:*** Barrett Ceilings ***Roof steelwork:*** SH Structures ***Ancillary steelwork:*** Rowecord ***Reinforced concrete:*** Whelan and Grant **Client adviser:** Schal **Client technical adviser and blast consultant:** TPS Consult **Illustrations:** 1, 8, 14, 22, 25: Arup/Redshift Photography 2: Amgueddfa Cymru - National Museum Wales 3: Arup/Andrew Hazard Photography & Design 4, 13, 15, 16 Arup/Nigel Whale 5, 12, 17, 18: Arup/Andrew Holt Photography 6, 7, 9, 19, 20: Arup 10: Richard Rogers Partnership 11: Arup/Mitchell Duncan 21 Paul Burnett/Welsh Assembly Government 23 Peter Wood 24 Richard Harris.

Hudson River Park:

Urban waterfront renewal for New York City

Cliff McMillan John Urquhart

The Hudson River Park is New York City's most significant park development in decades. Including water area, when completed it will be Manhattan's second largest, 150 years after Central Park.

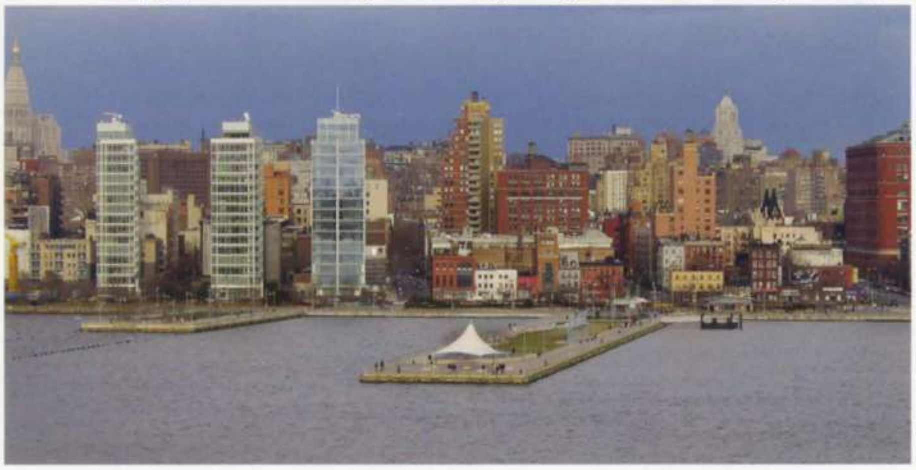
1. Manhattan Island.

Introduction

The Hudson River waterfront once embodied the spirit and culture of New York. Before the first European contact, the river sustained human settlements. Afterwards, it became the focus of commerce and a vital link to the world beyond. By 1913, before federal income tax, duties collected from the Port of New York accounted for most of the US government's income. Closely tied to the lives of people living in the adjoining neighbourhoods, the Hudson River and its edge reflected the diversity of the city as a whole. The west side waterfront was used by everyone.

And then, gradually, it wasn't. The once-grand gateway to New York was abandoned when changing modes of transportation made the Manhattan port obsolete. Generations of industrial and warehouse use and a long slide into dereliction followed. From 1927 to 1948 the elevated West Side Highway was built close to the waterfront, but in subsequent decades it deteriorated until its progressive demolition between 1977 and 1989. Fences prevented all but the most adventurous from enjoying one of the nation's most spectacular riverfronts.

2. Piers 45 (right) and 46 in HRP's Segment 4, looking east against its Greenwich Village backdrop.

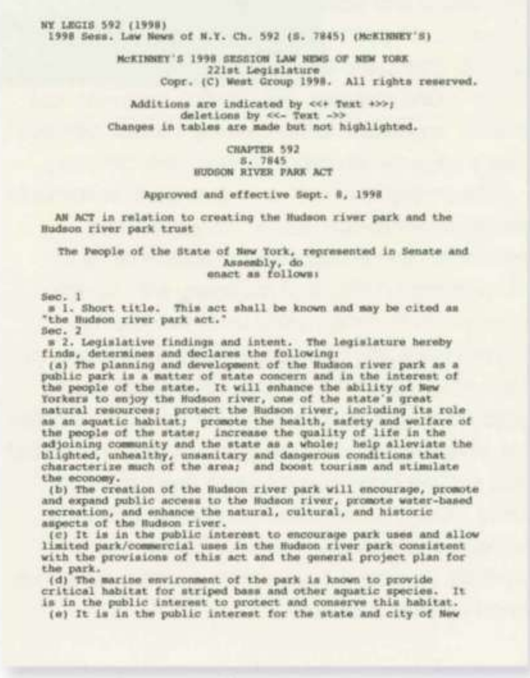


Creation and mandate of Hudson River Park Trust

When the controversial Westway plan to bury the West Side Highway south of 40th Street and build a park on its roof was withdrawn due to public protest in 1985, it took seven years to achieve consensus on what should replace it. Various initiatives led to the creation of the Hudson River Park Conservancy in 1992, which undertook a very extensive public and community consultancy programme. In 1998 the State of New York passed the Hudson River Park Act (Fig 2), establishing both the park itself and the Hudson River Park Trust as a partnership between state and city to design, construct, own, and operate it.

In response to the over-commercialization associated with Westway, severe restrictions on commercial use govern the development, which is guided by the memorandum of agreement embodied in the Trust's mandate and by the Design Guidelines Master Plan prepared in 1997. Development of the in-water portions is regulated by the Army Corps of Engineers and the New York State Department of Environmental Conservation permit, which governs such factors as habitat, coverage, and marine disturbance. The Army Corps of Engineers Permit that covers all the marine work generally requires the new piers to be built over the same area as the old and, in the interests of fish habitat, limits changes in pile density to within 10% of the old pile density.

3. The first page of the Hudson River Park Act, 1998.



NY LEGIS 592 (1998)
1998 Sess. Law News of N.Y. Ch. 592 (S. 7845) (McKINNEY'S)

McKINNEY'S 1998 SESSION LAW NEWS OF NEW YORK
221st Legislature
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Additions are indicated by <<+ Text +>>;
deletions by <<- Text ->>
Changes in tables are made but not highlighted.

CHAPTER 592
S. 7845
HUDSON RIVER PARK ACT

Approved and effective Sept. 8, 1998

AN ACT in relation to creating the Hudson river park and the Hudson river park trust

The People of the State of New York, represented in Senate and Assembly, do
enact as follows:

Sec. 1
§ 1. Short title. This act shall be known and may be cited as "the Hudson river park act."
Sec. 2
§ 2. Legislative findings and intent. The legislature hereby finds, determines and declares the following:
(a) The planning and development of the Hudson river park as a public park is a matter of state concern and in the interest of the people of the state. It will enhance the ability of New Yorkers to enjoy the Hudson river, one of the state's great natural resources; protect the Hudson river, including its role as an aquatic habitat; promote the health, safety and welfare of the people of the state; increase the quality of life in the adjoining community and the state as a whole; help alleviate the blighted, unhealthy, unsanitary and dangerous conditions that characterize much of the area; and boost tourism and stimulate the economy.
(b) The creation of the Hudson river park will encourage, promote and expand public access to the Hudson river, promote water-based recreation, and enhance the natural, cultural, and historic aspects of the Hudson river.
(c) It is in the public interest to encourage park uses and allow limited park/commercial uses in the Hudson river park consistent with the provisions of this act and the general project plan for the park.
(d) The marine environment of the park is known to provide critical habitat for striped bass and other aquatic species. It is in the public interest to protect and conserve this habitat.
(e) It is in the public interest for the state and city of New

4. Piers 45 (left) and 46 in Segment 4, looking west to New Jersey across the mouth of the Hudson.

Scope of the park

The 550 acre (220ha) park stretches five miles (8km) south to north from Battery Park to 59th Street, and west from the continuous bikeway and walkway along West Side Highway to the pier head line, giving public access to the Hudson from a waterfront esplanade with landscape planting. Recreational activities embrace the history, ecology, and culture of the river and its surrounding areas, with 13 existing or former piers being reconstructed for passive and active public use as venues for concerts, art performances, and other public events. Boat piers and water taxi stops encourage water-based activities, with floating platforms, get-downs, and beach areas allowing contact with the river's edge for recreation, sailing, and canoeing.

The project encompasses a range of sustainable development design issues, including social, economic, and environmental. Goals include a 50-year design life for all materials, with durable, sustainable materials being used to foster low maintenance and operational costs, and conserve resources. As for the ecology, regulations are in place to ensure minimal effect on the river's aquatic life, and selected piers will be isolated from the land and planted to provide a human-free habitat for birds. During construction, no pile installation or removal is allowed between November 1 and April 30, to protect over-wintering fishery resources and migratory waterfowl.

Incorporating the historic past

Hudson River Park embodies over 100 years of Manhattan's rich maritime and industrial history. Here waves of immigrants took their first steps onto American soil, the point of arrival and departure for travel between Europe and America, and the centre of the meat and import industries. The *Lusitania* departed on her last voyage from Pier 54 on 1 May 1915, the same pier that had welcomed the survivors of the *Titanic* three years earlier. This stretch of the Hudson River became the country's principal interface with the world, as an almost constant stream of dignitaries arrived and departed on the great ocean liners that docked there.

Now the park incorporates this history through a programme that includes:

- existing historical artifacts within the project area, such as the Baltimore & Ohio Railroad Float Transfer Bridge (Pier 66A) and the remnants of adjacent rail tracks
- information on historical sites and events, so that visitors can learn about the richness of the Hudson's past – its ferries, the Newgate Prison, the historic rail transfer pier, the old Cunard cruise ship loading piers, the cattle pass under Twelfth Avenue at 36th Street, and longshoremen's activities
- several special areas strongly moored to history: the Float Bridge, Pier 54, and the last remnant of 13th Avenue on the Gansevoort Peninsula.

Also, artists have been commissioned to consider specific historical sites and events as the inspiration for their creations.

Within the park nearly five miles of bulkhead extend in an almost unbroken line, embodying a history of this form of construction by the NYC Department of Docks over the 65 years from 1871 to 1936. It was then the city's costliest and most important waterfront improvement, initiated in response to its deterioration, congestion, and silt-filled condition, which threatened both public health and commerce. Quarry-faced ashlar granite blocks form the visible face along most of the frontage, supported by 12 types of foundation system, some quite intricate.

Various bulkhead repairs have been made over the years, often without any attempt to recreate a uniform appearance, the most common being replacement of the top layer (or capstone) with concrete. A major task in the design has been to survey and rehabilitate the miles of old stone bulkhead founded on wooden piles and grillage, some of which has settled and become misaligned.

Arup supervised four sub-consultants to survey the bulkhead over most of the park length, and inspect the front face above and below the waterline and the timber platforms and piles, to check for any deterioration. These surveys were then used by the design teams to propose bulkhead rehabilitation to provide the required 50-year design life.

To preserve this heritage, all designs for repair and treatments are being co-ordinated with the New York State Historical Preservation Office. The bulkhead is now eligible for listing on the National Register of Historic Places.

Design and project management

For its detailed design, the park was divided into segments along its length, and four separate design teams are responsible for executing the design and producing construction documents. The HRPT appointed Arup and Bovis Lend Lease to provide park-wide project management and design co-ordination services to assist the Trust's internal resources with implementation. Arup's work, which has included employing 19 sub-consultants covering a wide range of disciplines, commenced in 2000 and will continue at least through 2006.

The scope of the Arup team includes:

- establishing overall design guidelines for all aspects of the park for use by the designers of each segment
- ensuring that the Trust's goals are consistently met and controlling consistency and standards park-wide
- designing park-wide elements such as the railings and light poles. The five miles of railing (bulkhead plus piers) gave Arup several challenges, particularly in the use of cast and rolled stainless steel and in maintaining the required high-quality finish in the harsh corrosive environment adjacent to the Hudson. Grade 316L stainless steel was chosen, but it proved necessary to coat this with protective covering manufactured by Adsil Inc to prevent fairly rapid tea-staining from occurring.
- advising on park-wide issues such as historic interpretative material and pedestrian and vehicle movements
- co-ordinating with the segment design teams and managing the stage-by-stage review of their design documents
- reviewing estimates and schedules
- controlling documents, including establishment of a historic reference documents library
- implementing *Constructware*, a web-based project management system, for all project communication during design and construction
- co-ordinating permitting through NY State and city agencies.

Hudson River Park

Segment 7: Clinton (44th Street to 59th Street)

This is the northernmost section, and the first to be developed on the city-owned portion of the project. It includes a large grassy area, "Clinton Cove", which features a boathouse and kayak launch at Pier 96, a get-down at Pier 95 for sitting near and enjoying the river, and eventually Pier 97, which will be primarily for active recreation and historic ships. Construction here cannot commence until Department of Sanitation trucks currently at that pier are relocated.

Segment 6: Chelsea North to Clinton South (26th Street to 44th Street)

This begins just north of Chelsea at 26th Street and continues to Pier 84. It will include a large ecological habitat area, two boathouses, a rocky beach, and a major civic plaza with fountain near 42nd Street. As well as the developments around Pier 84 and Pier 66 at 26th Street, Segment 6 also includes several continuing water-dependent uses, including Circle Line and World Yacht. A new ferry terminal at Pier 79 will bring commuters and other visitors to West Midtown.

Segment 5: Chelsea (Horatio Street to 25th Street)

Extending from the Gansevoort Peninsula to West 26th Street, Segment 5 will feature two expansive spaces for active and passive recreation, including a rocky shoreline, beach, a small boating facility and ballfields on the southern end, and a great sweeping lawn at the north. In addition, four public piers, including one (Pier 54) devoted to historic ships, will be reconstructed for public recreation. The Chelsea Piers Sports and Entertainment Complex will continue its operations on Piers 59, 60 and 61.

Segment 4: Greenwich Village (Clarkson Street to Horatio Street)

The Greenwich Village section features a large lawn on Pier 45, a recreation field on Pier 46 and a playground on Pier 51. The piers are linked to the rest of the park by a wide landscaped area, display fountain, garden area, food concession, dog run, and tree bosques.

Segment 3: Tribeca (Chambers Street to Clarkson Street)

To be funded by Lower Manhattan Development Corporation, construction on its two public piers, 25 and 26, begins in 2006. Pier 25 will be HRP's longest. Segment 3 is about the environment, and active recreation, as well as focusing on the Hudson itself through inclusion of the "estuarium" near Pier 26 and an ecological pier at Pier 32. Public facilities will include a boathouse, restaurant, children's playground, volleyball courts, an open lawn, mooring area, a mini golf course, and a skate park, all be linked by pathways and planted areas.

Segment 2 (Battery Place to Chambers Street)

Unlike the rest of the project, Segment 2 does not border the Hudson but instead runs along the eastern side of Battery Park City. Detailed design will not begin until final plans for reconstructing West Street in the World Trade centre area have been determined.

5. The division into Segments 2-7 ("Segment 1" does not exist).

6. The new green open space on Pier 45 for passive recreation.

Phasing and construction

The park development is multi-phased over many years. This is partly for logistical and funding reasons, but also because the park is interrupted by many other uses on various piers and along its length, some with long-term leases. The bike path, railing and esplanade form the nearly continuous link over the five miles.

A feature of the contract packaging and management challenge is therefore the many contracts required - ultimately over 100. This is because of the staged nature of the construction, the severe constraints for access and lay-down areas, the need to separate marine from upland from building work to get the best work and most favourable prices (normally from smaller, more specialized contractors), and the application of "Wicks Law", the New York State provision requiring separate contracts for building electrical, mechanical and plumbing work, to benefit smaller contractors.

A significant amount is already constructed and there is much more development to come. Segment 4 (north of Pier 40 and near Greenwich Village) includes three public piers and related upland areas and was opened in spring 2003, while Clinton Cove Park between 54th and 57th Street (part of Segment 7, the park's northernmost section) was constructed from 2003 and opened in May 2005.

Construction at Segment 6 is currently under way near 44th Street, with the entire Pier 84, one of the park's largest and located just south of the Intrepid Sea, Air and Space Museum, planned to open in 2006. This pier is 900ft (274m) long and 140ft (43m) wide and provides a boathouse, play area, sports facilities, a large paved area and gently sloped lawn for passive recreation and the public to gather, and a get-down extension at the western end. Just east of the pier in the upland park is a concession building and large multi-nozzle paved fountain. Construction has also started on Pier 66 which includes a boathouse and floating marina.

The first major activity planned in Segment 5 is the reconstruction of Pier 64, where demolition work began in fall 2005. Pier 64 is another example of a large existing timber-piled pier being demolished and replaced.

There is contamination, such as abandoned underground oil storage tanks, at various locations along the site because of the historic industrial use.

The existing Pier 64 was covered by a two-storey shed superstructure. Prior to demolition, inspection of this revealed asbestos-containing materials (ACM). Besides the usual wiring/pipe insulation and window caulking ACM, the entire 40 000ft^2 (3700m^2) of roof sheeting was found to contain ACM. This has had a significant impact on the demolition method for this work, which was completed by spring 2006.

Marine sanctuary

The water area of the park constitutes a 400 acre (162ha) marine sanctuary extending its full length and from the bulkhead to the pier head line. A separate and complementary sanctuary plan governs the management of this resource. Primary goals of the park plan are to recognize that the living resources have important ecological, recreational, and commercial functions, and to increase and enhance both physical and visual access to the river while disturbing the habitat as little as possible.

Measures to respect the integrity of the existing aquatic environment include:

- maintaining habitats, and prohibiting landfill to avoid adverse effects on the many fish species
- providing new public access within the original pier or bulkhead footprints, while prohibiting new piling or pier decking outside these footprints
- using appropriate plant materials in landscaping (species and varieties that predominated before European settlement, supplemented, where necessary, by selected naturalized species)
- the creation of an ecological learning centre or "estuarium" on Pier 26.

7. Pier 64 in Segment 5 cleared of its old shed.

8. Pier 95 at Clinton Cove Park, Segment 7.

Events, maintenance, and operation

Hudson River Park is a fully operational park, with resources to undertake operations, maintenance, and events planning. The bikeway/walkway is in constant use, and thousands of people attend events throughout the summer, including the annual Hudson River Park Day in June, the weekly "Moondances" near Pier 25 in Segment 3, the open-air Riverflicks free film shows, and other park programming events.

Along its length are major tourist attractions such as the Circle Line, the Intrepid Air and Space Museum near 42nd Street, the Chelsea Piers complex, and the Chelsea Waterside and 14th Street Parks - all functioning amenities while the rest of the park is being developed. Other activities such as the passenger ship terminals which lie outside the park will continue to operate. The Trust's on-going educational outreach programme involves students in classes and activities related to the river and the history of the waterfront.

The interaction between the design and construction and the future operation and maintenance of the park is a critical influence throughout the design. Experience has shown the importance of creating a nearly "zero maintenance" park as an overarching goal. The design addresses this in the selection of materials: Grade 316L stainless steel with a protective coating for the park-wide railing, which will never require painting; long-lasting Ipe, a farmed and sustainable tropical hardwood, for rails and benches; granite and blue stone for the esplanade paving; and *FieldTurf* artificial grass for active recreation and picnic areas on the piers. This material features long polyethylene blades planted into a base of sand and a deep layer of granulated rubber. The surface is soft and pliable, resists compaction, and drains extremely well.

The piers are built on prestressed precast concrete piles threaded among the timber remains of their predecessors. This reduces the overall long-term maintenance of the park's marine structures to maintaining the volume of existing deteriorating timber, which supports a thriving population of fish, wildfowl, and aquatic organisms.

9. Pier 45 illuminated at night.

10. The Arup-designed coated stainless steel railings.

11. The two-storey shed on Pier 64 before it was cleared.

12. New hybrid precast prestressed piling for Pier 84, Segment 6, threaded amongst the remains of the old timber piles.

13. Precast pile caps at Pier 84, November 2004.

14. Pier 84 in September 2005, with the Intrepid Sea, Air and Space Museum in the background.

The piers and marine structures

Unique to Hudson River Park are the public piers that represent a major component of the area and amenity. In general, they contain more active areas towards the land side, and more passive, contemplative areas towards the pier ends. Some feature educational, historical, ecological and sports activities, while others simply offer sweeping views of the river and skyline and a place to relax. The serenity at the ends of the piers, away from the noise of the city and out over the water, is one of the great attractions.

The longest were originally designed to be 900ft (274m) long, to accommodate the ships of the day. Even this proved insufficient, so in two places "bow notches" were cut into the bulkhead to accommodate the prow of the longest ships.

The existing old pier timber piles are exposed to tidal action and have been subject to marine borer damage, so that many have collapsed completely. These are the most significant factors affecting the strength and future life of the existing timber piers, but other factors such as the normal aging of untreated wood, and physical damage from vessels, storms, debris, and ice have also affected the existing pier condition. The result is that most existing piers are severely deteriorated and 13 are being replaced with new precast concrete piers with the same coverage area as the old.

The 13 new piers represent a major design challenge and their optimal design was key because they will consume much of the park's capital cost. Geologically, the silts and clays under the river are not ideal for founding, and depths to rock vary from 50ft near the bulkhead to over 300ft (15m-90m) at the pier head. To allow for the finishes, soil, and planting trees, as well as possible future uses, the piers have been typically designed for a superimposed dead plus live load of 350lb/ft^2 (1710kg/m^2). The piers must also resist substantial horizontal loads from marine effects and the seismic forces prescribed in the codes. These factors led to long, driven, end-bearing piles founded on or near the rock being selected, some as deep as 300ft (90m). To provide the 50-year design life and minimize corrosion and maintenance, high quality precast prestressed concrete driven piles have been selected after careful evaluation of options, including steel tube piles.

A hybrid type end-bearing pile was developed with input from Arup and the design teams as a cost-effective solution for the deeper piles. The top 80ft (24.4m) of the pile is prestressed concrete providing the stiffness, bending moment capacity, and corrosion resistance where they are most needed, but the lower portion is a steel HP pile section capable of resisting the axial loads that predominate at depth. Using steel below about 80ft (24.4m) achieved a cost saving over a full-length concrete pile, and also substantially reduced the pile's self-weight, facilitating lifting and splicing. Notably, the weight of the piles caused them to fall through the soft material with minimal driving until just above rock level.

The buildings

Many small new buildings ranging from 1000ft^2 to 8000ft^2 (93m^2-740m^2) are being built along the park, including food concession areas; maintenance, operation and storage facilities; boathouses on four of the piers; a carousel on Pier 62; and a combined restaurant and boathouse complex on Pier 26. The "estuarium" already noted is currently being developed to be sited near the head of Pier 26. Generally the design of the buildings has been governed by considerations of functionality, sustainability, and ease of operation and maintenance.

One of the more important Arup functions has been to help the client with the contract packaging for each building, including identification and co-ordination of the scope of work for the "Wicks Law" contract packages, and the co-ordination between these, the new pier structures, and the upland area contract packages.

The Upland areas

The Upland work refers to the landscaped and paved areas being created both on the piers and along the full length of the park. This includes the narrow strip of new Upland park, typically 100ft (30.5m) in width, being bounded on the eastern side by the bikeway and on the western side by the existing bulkhead line. This limited width creates problems in providing the numerous utilities needed to serve points along the whole park, including storm, sanitary, electricity, gas, telecommunications, water, and irrigation. Added to this are several major combined sewer outfalls (CSOs) that cut across this zone in various positions, and that required extensive survey and in some cases repair. Arup's role as a design reviewer has helped the design teams to co-ordinate the utilities to minimize the possibility of clashes.

Conclusion

After more than six years' work, much of the waterfront has become a vibrant environment. Dynamic new connections have been forged with adjacent neighbourhoods, providing access to and enjoyment of the majestic river itself. Already Hudson River Park is a recreational resource for all New Yorkers and visitors, respecting both the ecology and natural environment of the Hudson and the culture and history of adjacent neighbourhoods, and generating revenue to support the park's maintenance and operations.

15. Clinton Cove Park, with Malcolm Cochran's public art piece "Private Passage". The 29ft (8.8m) wine bottle contains a recreation of a cabin from the original *Queen Mary*.

16. Clinton Cove Park, looking north.

Cliff McMillan is a Principal of Arup, based in New York City.

John Urquhart is a Professional Engineer with Arup in New York City, and currently Arup's project manager for Hudson River Park.

Credits

Client: Hudson River Park Trust **Project management and design co-ordination services:** Bovis Lend Lease and Arup - Jin Fan, David Farnsworth, Guadalupe Frattini, Graham Gedge, John Giamundo, Ken Goldup, Helga Gregory-Chmielowski, Robert Hoffmann, Tom Kennedy, Hillary Lobo, Haiyan Lu, Brian Logue, Haruko Masutani, Cliff McMillan, Raymond Medina, Carl Mister, Nigel Nichols, Liam O'Hanlon, David Palmer, Albert Palumbo, Lynn Pang, Richard Prust, Thomas Puttman, Jose Rivera, Mark Roche, Ron Ronacher, Yet Sang, Anatoliy Shleyger, Liem Tran, John Urquhart
Segment design teams: 3 Concept to detailed design, led by Sasaki Associates / DMJM + Harris; Detailed design through construction, led by Matthews Nielson Landscape Architects; **4** Led by Abel Bainnson Butz; **5** Led by Michael Van Valkenburgh; **6/7** Led by Richard Dattner & Partners Architects / Miceli Kulik Williams & Associates
Specialist sub-consultants: Emphasis Design (parkwide signage), Deanna LaBianco Tessler (financial planning), ETM Associates (facilities planning), Fisher Marantz Stone (lighting design), Fox & Fowle Architects (building architecture), Li Saltzman Architects (historic preservation), Langan Engineering (geotechnic design), Macon Pace (consultant), Matthews Nielson (landscape architecture), Mclaren (marine design), RG Roesch & William B Kuhl (landscape architecture), Vollmer Associates (parkwide topographical survey), Northern Designs (irrigation design), Ray Searby (specification consultant), Han Padron Associates (marine design), Edaw Inc (landscape architecture), Ed Weinstein, Wendy Feuer Public Art & Urban Design (consultants)
Illustrations: 1 Nigel Whale; 2, 11 Arup/HRPT; 3, 7, 12-14 HRPT; 4, 6, 8, 15, 16 Luca Vignelli/HRPT; 5 Nigel Whale/HRPT; 9, 10 Chris Figueroa/HRPT

Reference

(1) BODDEWYN, M *and* McMILLAN, C. Planning, design and construction of Hudson River Park. *Port Technology International*, October 2003.

Acknowledgments: Marc Boddewyn, Vice President, Design and Construction, Hudson River Park Trust; Connie Fishman, President, Hudson River Park Trust.

Weblink: http://www.hudsonriverpark.org

1. The skyline of Perth, Australia: 21st century cities consume energy on a grand scale.

Energy as a driver of change

Simon Roberts

In the not-too-distant future, energy provision will shape many aspects of our lives. How we prepare for this future demands new ways of thinking.

Introduction

The human race, its activities, and the world it occupies are subject to a vast range of influences that contribute to change. These "drivers of change", as they have been dubbed by Arup's Foresight + Innovation + Incubation group[1], function and interact across five broad categories: social, technological, economic, environmental, and political (the STEEP framework). More than one driver of change has a foot in more than one of these camps, including energy as it is fundamental to all our needs.

For the second half of the 20th century, energy has been comparatively cheap and we have grown to take it for granted. The general perception is that, although it is not overly abundant and we have to pay those regular utility bills, there will be enough energy to meet our present and future needs. Thus we need not really worry about it too much because the scientists and engineers will sort out any hiccups in supply.

I would suggest that in recent times - only a couple of generations - we in the industrialized world have forgotten the profound role energy really does play in our everyday activities. In the not-too-distant future, it is likely to become the prime driver of change of many aspects of our lives. The way we prepare for this future demands new ways of thinking.

Global energy demand

Increased supply of energy has been essential for economic development, and developing countries have high aspirations to climb the wealth ladder. Traditionally, the demand for energy can be considered as a simple combination of three fundamental factors:

- the human population;
- the economic output and activity of that population;
- the energy intensity of that economic output and activity (ie the energy used per unit of output).

World population is rising by an average of +1.4% per year (projected to reach 8.1bn by 2020). World output per head has been growing at an average annual rate of +1.5% (to an average of US$4200 in 1990). The average energy intensity of output was -1.1% over 1985-90. On this basis, the global change in demand for energy is expected to be +1.8% per annum (purely according to predicted population expansion and historical trends).

Admittedly the last two average values conceal very great differences between countries and groups of countries. For energy intensity of output, the value varies widely: becoming more negative (and thus improving) where economic growth is strong, stagnating where growth is sluggish, and increasing where growth is negative. Unfortunately overall energy intensity, as a global average, is not falling fast enough through technological progress to compensate for the factors of population and economic growth, and so energy demand is rising[2] (Fig 2).

There is growing acceptance that climate change is anthropogenic (human-caused), with the finger pointed at energy use as the largest culprit. As the consequences of climate change become more apparent and detailed, concern is growing to "do something" about our means of energy supply. However, the solution is not simple, especially as population and economic growth are underlying drivers for global energy demand to continue its unremitting rise.

In exploring how to meet future demand for energy and its conflict with climate change, first let us examine the main fuels.

Fossil fuel supply - the mainstay

A definition of energy in this context would be "primary energy"[3] (Fig 3), corresponding to "raw materials" at the start of the production chain. Another definition would be that this is "traded energy" (bought from energy supply companies) together with the traditional biomass used in developing countries (mostly firewood and animal dung).

The vast majority of primary energy is from the fossil fuels: coal, oil, and natural gas. In considering energy as a driver of change that affects aspects of life, the question can be reduced to asking: "What will happen with the fossil fuels?"

Many commentators tend merely to extrapolate past consumption patterns, "predicting" with a straight line into the future. The predict-and-provide approach is deemed to ensure that supply will be there to meet demand, as it has in recent decades, so energy has not been a headline issue. However we need to examine if there are features of fossil fuel production and its use that might cause it to become a driver of change, quite a different situation from the predict-and-provide we are used to.

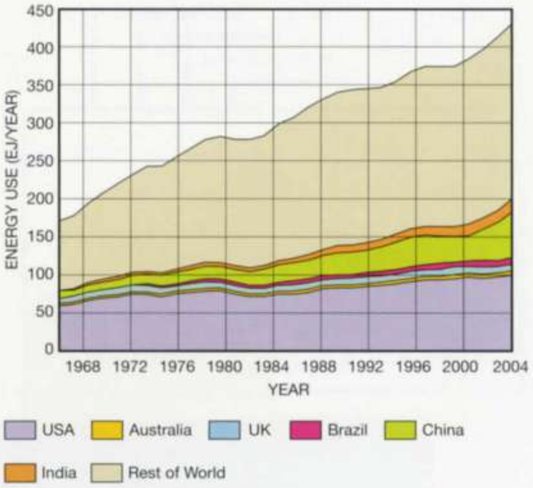
Oil

In the case of oil, the questions most often asked are: "How much is left?" and "How long until the last drop?"

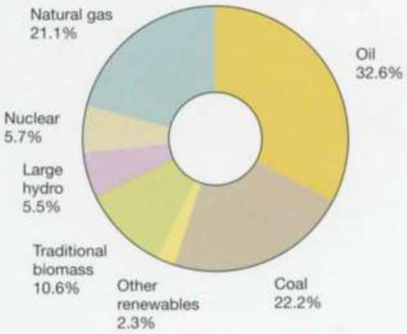
These can be answered using the ratio R/P: the estimated reserves remaining (R) divided by current annual production (P). Some major oil companies quote 40, ie 40 years to go at current rates of consumption. While P is known with certainty, R is an estimate, but rather than argue the relative merits of R estimates, there is another view of future oil production.

The R/P ratio gives the impression that oil extraction is like consumption of the fuel in a vehicle's fuel tank: freely flowing at a constant rate, then stopping abruptly when the tank is empty. However, a growing number of geologists from the petroleum industry are predicting that P will be constrained geologically so that global production reaches a peak, then transitions to decline. This view is certainly contested, but we should note some of its key arguments.

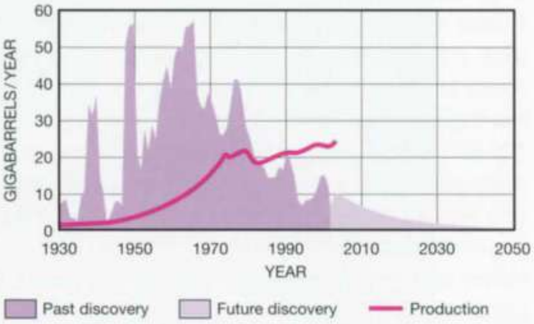
The first is that production can only follow discovery. The significance of this is seen in a graph on which discoveries are revised according to what is now known about their size. For instance, when a giant field is first encountered, the consequences of this discovery are not realized until the full extent of the field has been explored. This may take many years. Also there has been a tendency by oil companies initially to under-report the size of their discoveries as prudent reporting of their assets to shareholders. However a revised form of the graph[4] (Fig 4) is one in which the full size of a field, as now known, is attributed to the date when the first strike was made.



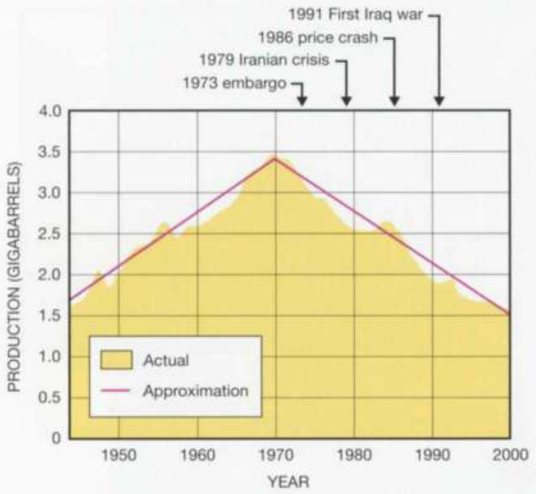
2. Global demand for energy including details for selected countries. Note the incessant rise in energy use, particularly the recent speed-up caused partly by China's "economic miracle".[2]



3. Global split of "primary energy" consumption in 2003[2,3]. (Note that all are compared in terms of thermal energy, so electrical output of nuclear, hydro and electrical renewables has been multiplied by 2.63 from a notional 38% plant efficiency.)



4. The growing gap between oil discovery and production[4]. The discoveries use revisions backdated to the first discovery for each field.



5. Oil production from the lower 48 US States for 1945-2000[5].

6. USA oil consumption and price to 2004[2].

The largest known field in the world forms the peak in 1949. This is the Ghawar field in Saudi Arabia, which still accounts for half that country's output. Overall, the history of discoveries has a prominent peak in the 1960s with a declining trend ever since. About half of the world's output is currently from just 116 very large fields (delivering more than 100 000 barrels per day). The prediction for future discoveries is set to go even lower because we are only likely to discover ever-smaller fields, rather than any more giants. Fig 4 also shows the production history and now an increasing mismatch between production and discovery. The production curve must be similar to the discovery curve: a peak, just delayed in time.

The second key argument is that output from oilfields is geologically constrained. A good example of this is the history of USA domestic oil production[5] (Fig 5). This peaked in 1971, never to rise again despite several significant global events. As oilfields "age", oil can still be extracted, but with greater difficulty and at ever slower rates.

It is well known that each oilfield has its own peaking profile under commercial development, with a certain amount of time for development (before the peak) and then decline. Thus the overall behaviour of a region, such as the USA's lower 48 states, is merely the summation of these individual profiles. Global oil production comprises countries whose output is either increasing or decreasing. It has been increasing steadily since the mid-1980s but, at some point, the number of countries entering decline will cause the global summation to go into decline. According to BP's statistics on oil production by countries, at least 18 are now in decline.

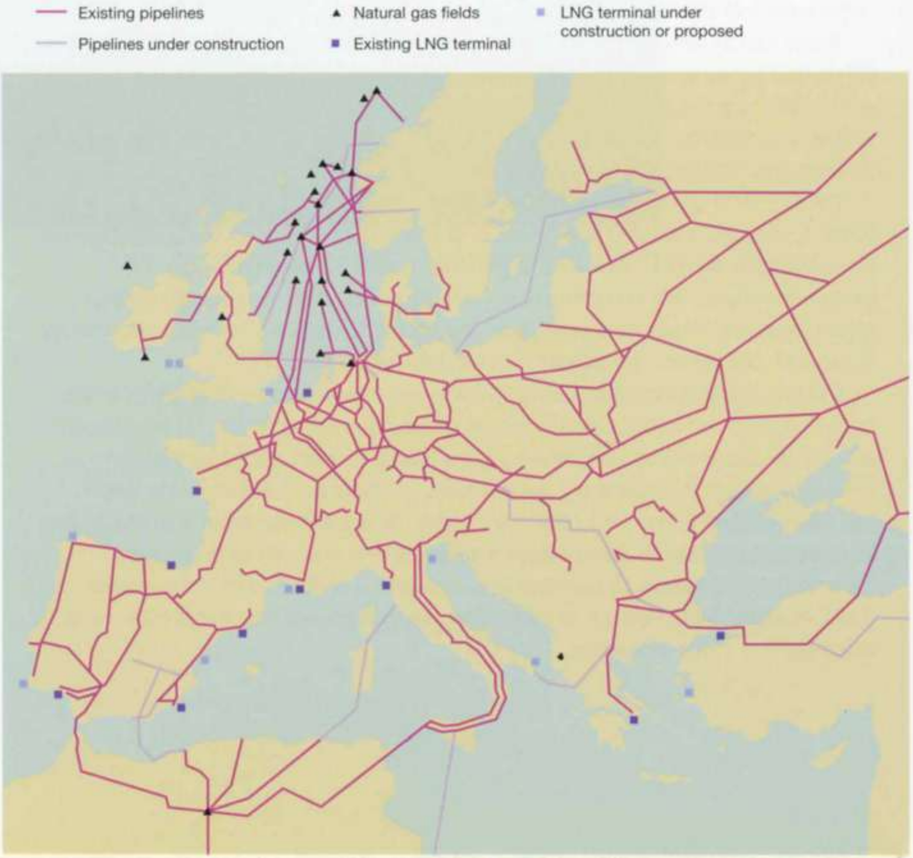
Thus one prognosis for oil is for it to reach a global peak and then settle into a steady decline. Though prices will certainly rise when there is a supply shortfall, geological constraints will mean that high price cannot automatically translate to technology and investment to get oil out quicker. Instead, higher prices will kill demand so that it matches supply, not the other way round. In the USA in 2004[2] (Fig 6), the price exceeded its highest level during the oil crisis of the 1980s, and has since gone much higher. Demand doesn't appear to be "killed" here, but as a global commodity, the high price pain is certainly being felt in developing countries who are now having to reduce their demand.

Natural gas

The production of natural gas has many similarities to oil and is often extracted from the same fields, but there are key differences. While oil as a liquid is easy to store in tanks and to transport by tanker, natural gas is more difficult to store and the predominant means of distribution is by pipeline. (In this respect it is similar to electricity, with production and demand being kept in close balance.)

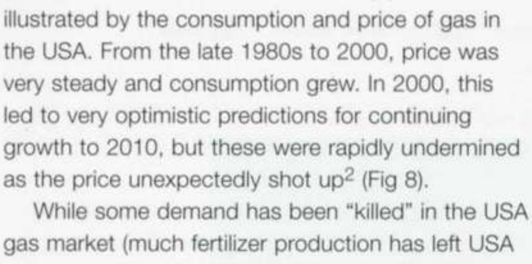
Globally, gas fields are divided between those sufficiently near to market for a piped connection and those that are remote, sometimes called "stranded". For instance, an extensive natural gas pipe network has developed across all of Europe[6] (Fig 7). This has not been sufficient to meet all demand so the network is supplemented by LNG (liquefied natural gas) receiving terminals, also shown on Fig 7.

7. Distribution of natural gas in Europe[6].

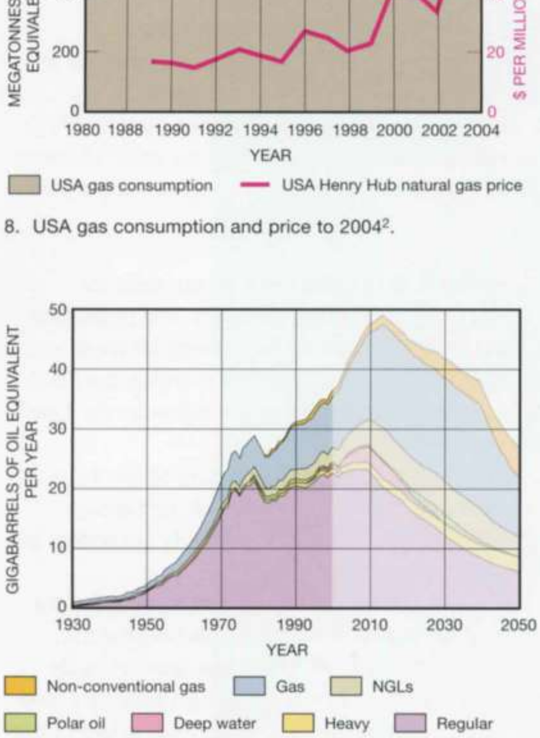


Another difference from oil is that natural gas is easier to extract from the ground. The extraction rate is generally fairly constant for most of the life of a reservoir, being set by the capacity (pipe diameter) of the infrastructure initially built. But whereas an oilfield tends to signal its halfway point in development as declining output sets in, the latter stages of a gasfield's life give less warning since production tends to be flat over many years. This is illustrated by the consumption and price of gas in the USA. From the late 1980s to 2000, price was very steady and consumption grew. In 2000, this led to very optimistic predictions for continuing growth to 2010, but these were rapidly undermined as the price unexpectedly shot up[2] (Fig 8).

While some demand has been "killed" in the USA gas market (much fertilizer production has left USA shores, and gas-fired electricity generation has switched to coal), there is rapid growth in LNG-receiving terminals attempting to make up the shortfall. A pipe network provides a degree of certainty through long-term price contracts that suit both suppliers and consumers. As the proportion of gas transported by cryogenic tankers starts to become significant, natural gas will become a global commodity as oil is, with tanker routes tending to follow the highest prices, leading to local price instability.



8. USA gas consumption and price to 2004[2].



9. Combined oil and natural gas production[7].

10. Coal: an underrated resource?

Coal

Coal, the third main fossil fuel, was the first to be exploited. Coal reserves are very widespread across the globe but coal is less convenient to work with, partly through being a solid rather than a liquid or gas. Though coal consumption in the UK has dropped by two-thirds in the last four decades, obviously influenced by North Sea oil and gas development, in most other countries it has increased, being a major contributor to generation of electricity.

In R/P terms, one quoted figure for coal is 200 years, certainly a long period by comparison to oil and gas. The main issues for coal are still the pollution from conventional coal-fired power stations (SO_x, NO_x and particulates) and high CO_2 intensity for the electricity it generates compared to gas-fired stations.

Components of the future

The story so far suggests problems in the short- to medium-term for oil and gas, whereas coal, the least popular fossil fuel, has large reserves.

One analysis[7], by Colin Campbell, a retired oil geologist, combines several resources for oil and gas together (Fig 9) in which the main resources up to the present have been "regular" oil, "NGLs" or natural gas liquids (propane and butane, known as LPG), and natural "gas". This analysis first shows oil peaking soon after 2010 while gas products show a steady output to about 2040 before they themselves then start their own steep decline.

Though this view is not necessarily typical - others may be more optimistic in not showing an overall peak as soon as 2012 - it is helpful in setting the lesser or unconventional sources in context. "Deep water" oil is set for expansion followed by development of "polar oil". The new candidates are "heavy" oil from shales and tar sands and "non-con gas" (non-conventional natural gas), such as coal bed methane. Though all these new developments are important and necessary, the annual production they can contribute is still very small compared to conventional oil and gas, as the graph emphasizes. If decline of conventional oil and gas really does happen in the way this analysis suggests, the unconventional sources will lessen the overall rate of decline but certainly not halt it.

Let's summarize the observations. Global energy demand rose steadily and continuously through the second half of last century and is set to continue so if unfettered. An overwhelming majority of this demand is met from fossil fuels. Campbell's analysis of prospects for oil and gas is that they are shortly expected to peak before starting an unremitting decline. Clearly the world is heading towards a new period when energy issues are going to be top of the agenda.

The next part of this article considers separately supply and demand.

Alternative technologies and EROEI

We hear a lot about the "clean" sustainable technologies, especially wind and solar (photovoltaics or PV). Once oil prices really start to go up in consequence of a major supply/demand mismatch, won't these alternative technologies waiting in the wings have their heyday?

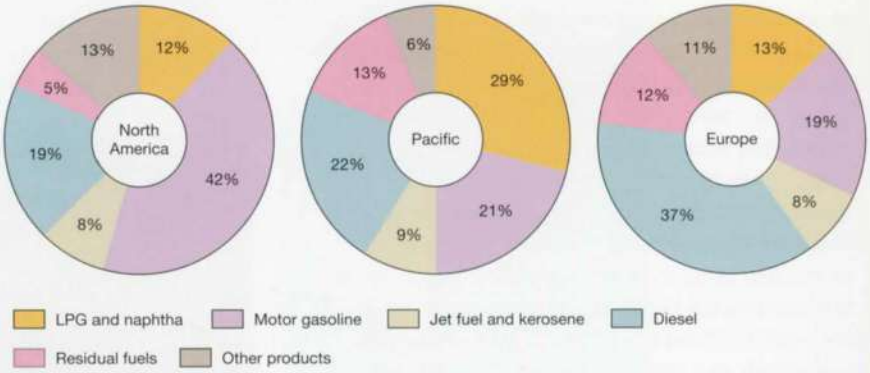
At first sight, they will certainly become more favourable than they have been. However caution must be exercised in considering differences between absolute prices alone. As prices for oil and gas rise, they will have knock-on effects across the whole economy. Costs of all goods will increase to varying degrees, including manufacture of wind turbines and PV cells.

The energy sector of the economy must obey one basic principle. While all sectors consume energy, the energy sector must produce more energy than it consumes. Compared to the familiar financial concept of return on investment (ROI), the energy equivalent for the energy sector is EROIE (energy return on energy investment), the energy profit ratio. The principle is that the EROEI must be greater than one and preferably a high number.

In the early days of oil production from self-pressurized fields, the EROEI was as much as 100. In 1916, the ratio was about 28:1 for the US oil industry, a very handsome return. For energy forms in general, data are not readily available and vary according to method of analysis. However, some indicative figures for guidance are listed in Table 1.

Table 1. EROEI values for a range of energy forms[8, 9]

Primary energy form		EROEI
Coal	at the mine electricity from power station	30 9
Oil	1970s From Alaska	23 11
Natural gas	Onshore Offshore	10 7
Hydro		11
Solar PV		1.7-10
Ethanol	From sugarcane From corn	0.8-1.7 1.3
Oil shale	Estonia	2



11. Current oil use by region showing over 75% for transport[11].

For alternative energy technologies to compete, they need to have comparable if not superior EROIE values. The fossil fuels have good values in the 10s and higher. They really are excellent energy sources, "easy" to extract (ie not requiring much energy to do so). Alternative energy technologies tend to have low EROIE values, so will remain poor competitors except in niche markets. Rather than price differentials, relative EROIE values should be compared as technologies develop. If the market for alternatives is distorted too much in favour of low EROEI technologies, we will find they need a lot of energy for their construction but produce comparatively little.

Coal and climate change

We have to pay close attention to coal. There are still large reserves and it has a good EROIE. Furthermore it can be processed into gaseous form (the old "town gas") and even into a liquid form for transport fuel. However coal has various environmental concerns, chief amongst these being the amount of CO_2 it puts into the atmosphere, thus contributing to climate change. Concerns for climate change have brought the carbon intensity of energy processes very much to the fore, with natural gas preferred over coal for electricity production.

There is talk of capturing the CO_2 and burying it underground (carbon sequestration), so that we get our cake (energy) and eat it (minimal impact on the climate). However, it should be noted that carbon sequestration comes at an energy cost, with a range of 20-40% being suggested. This means that the EROIE of "clean" coal, ie with carbon sequestration, will be low, unless the basic efficiency of the power station is also improved, such as by operating at higher temperature.

Demand

Some conclude that shifting to a service economy has reduced our need for energy, but this view is naive. Heating, cooling, lighting, transport, and production of goods all need energy, even if processed offshore so their energy bill does not appear in national accounts. Where there is genuine reduction in energy per GNP, this is largely technological change based on intensified use of *higher quality* fuels[8] with very little effect from a shift to service-orientation.

The 1970s' oil crises sensitized the world to its dependence on oil and tested its response systems. A lot of the low-hanging fruit of switching fuels and energy efficiency have been plucked. Very little oil is now used for electricity generation but oil products have not been substituted for transport[11] (Fig 11).

Furthermore, transport is ubiquitous, the key to economic activity enabling the "efficient market" of trans-global trade for goods. Natural gas has become the primary energy source of choice, especially in the UK. There has been a steady increase in its use for domestic heating, an abrupt increase in the 1990s for power generation, and a continuing key role in industry for products such as fertilizers and plastics[12] (Fig 12).

Views on the future

Optimism...

Many economists are optimistic: once the prices of oil and gas rise, market mechanisms will swing into action stimulating more exploration and energy alternatives. However, geologists say that basic geology will constrain the rate of extraction.

Another view is that concern for climate change will stimulate energy alternatives. But their EROIE should always be noted; low values would simply mean less energy delivered by the energy sector into the rest of the economy that produces food, goods and services. EROEI is fundamental. Prices, the mechanism of the market, will move to reflect poorer EROEI as increased energy costs propagate through all of manufacturing.

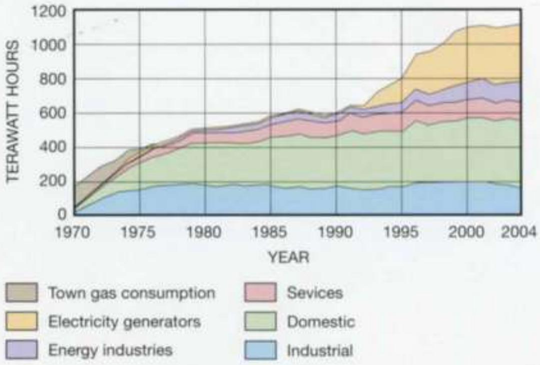
... or a shake-up?

A more profound view is that the abundance and excellent EROEI of fossil fuels has underpinned the astonishing growth in industry and general economic activity around the world over the last century. As fossil fuels decline, we are due for a radical shake-up. Energy efficiency will have to get a lot better while we curtail many uses of energy to which we have become accustomed. A very apt description of this peak in energy use is "the party's over", after the book by Richard Heinberg[13].

The nuclear option

Although nuclear power is only a small proportion of global electricity capacity, it is receiving much attention for diversity and security of supply as well as low CO_2 emissions. Much discussion revolves around cost estimates, but how should the nuclear option be considered in EROEI terms?

The EROEI for nuclear power station construction and provision of fuel is currently better than for gas-fired power stations. However there are two key points. First, reprocessing and containment of waste involves expenditure of energy in the future[14]. Unlike money, future energy can't be discounted; it must be "paid" in full by generation technologies at that time. If we are in a world of less energy than today, a significant proportion of that precious commodity will be "paying" the energy debt of nuclear legacy: this could include wind turbines that refine encapsulation materials and power excavation of geological repositories.



12. Natural gas usage in the UK to 2004[12].

13. Wind and especially solar will likely be major contributors to energy forms.

Second, poorer grades of uranium ore require ever higher amounts of energy per kg of uranium oxide extracted, with 0.01% as the energy-losing threshold[14]. If no further rich ores are discovered, this sets a very real limit on growth of the industry.

The very long term

In the very long term, there is general agreement that sustainable energy forms will be established, of which wind and especially solar will likely be major contributors. The problem is that they do need to grow extremely rapidly over the coming decades to offset decline in oil and gas. Starting from a comparatively low base today, they can only be a small part of the medium-term solution, much though they are encouraged.

Any energy system requires capital - infrastructure and materials - and capital requires both energy and time to produce. In planning the best options we must consider rate of growth and remaining resources. If a resource becomes depleted or even too energy-expensive to refine, its own particular capital needs become redundant, and thus a stranded asset. It is crucial to evaluate all capital creation options, going on to identify a portfolio that includes optimal energy returns throughout the transition to sustainable energy provision and use.

Conclusion

Our work has shown that energy, and access to energy, are key drivers of change. We may consider some of the impacts in terms of the STEEP framework:

Social

Energy prices are likely to rise, either through a shortfall of supply to demand or through market intervention to tip the balance to energy efficiency investment, etc. Whatever the trigger for price rises, can reconciliation of these drivers be left to simple market mechanisms of price? An important casualty would be the least well-off, also the least able to invest in energy-efficient alternatives. The way forward in social terms is not simple.

Technology

Improvements will focus on energy efficiency in both supply and demand and on developments that reduce the fossil fuel component. These will include LED

14. Arup Energy's ACE self-installing platform concept[15] operates as a movable offshore gas production unit, providing flexibility to develop scattered pockets of gas across 1600km^2 of the West Natuna Sea.

lighting, ultra-light vehicles with hybrid engines, bio-liquid fuels from cellulosic materials, information systems that manage demand for peak shaving and matching to intermittent supplies, passive techniques in buildings for heating and cooling, and CHP (combined heat and power, or co-generation).

Economic

If energy prices were to shoot up rapidly, the abrupt transition to much-reduced energy use might be painful. Local services have been lost as the urban landscape has evolved taking advantage of progressively lower cost of transport over the years. Once oil production flattens off and starts to decline, economically there is very likely to be some demand destruction and prices will stay high for users. Such changes will drive a radical change in our use of transport.

Environmental

Since coal is likely to dominate the energy mix in the near future, we must pursue the "clean" technologies that minimize coal pollution. Key amongst these is gasification with separation of pollutants before combustion, together with capture of CO_2 for sequestration.

Political

The mix of new built infrastructure must strike a balance between immediate needs and longevity. Crucially we must avoid stranded assets, for example a new gas-fired power station that then runs out of fuel.

Year-on-year investment in durable capital, probably necessitating some market intervention, is necessary, be it in generation (eg more wind turbines), efficient use (eg fitting more double-glazing in buildings, as imposed by retrospective Building Regulations), or reduction of use (eg relocating homes and workplaces to achieve shorter trips).

Finally, political leadership that transcends the political cycle is essential in order to let the longer-term investments be made and, it must be hoped, pay off.

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Credits
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Project PAMELA

Andrew Harrison Kheng-Lin Khoo
Florence Lam John Lyle Sam Wise

University College, London, commissioned Arup to design the world's first installation that simulates paving layouts for research into how pedestrians, both able-bodied and handicapped, react to different configurations and aural and visual environments.

Introduction

The Accessibility Research Group at University College, London, needed a facility to evaluate pedestrian movements across a range of paving layouts, and early in 2004 commissioned Arup for its design and delivery.

The result is PAMELA (Pedestrian Accessibility Movement Environmental Laboratory), the main component of which is an adjustable platform that can be configured in a range of slopes and features to provide a controlled environment for researching street layouts, lighting, and paved surface types.

This facility, the first of its type in the world, had to be safe and reliable. Unlike most test rigs at UCL, it was to be used by members of the general public, both able-bodied and disabled, and so this aspect needed to be considered carefully from the start.

Since the facility was financed by the Engineering and Physical Sciences Research Council (EPSRC), the anticipated cost meant that procurement was subject to European Union bidding and procurement rules. This created a complication, as meaningful tendering could only really be achieved if the platform was clearly defined. Arup undertook a concept study to help define and refine the tender information.

Arup's service included project management, planning supervision, and procurement management; concept design of the platform (structure, mechanisms, control systems); specification and preparation of tender documents; formal checks of the structure and mechanisms; facility modifications; lighting design; acoustic engineering advice and sound system design; and supervision of rig manufacture.

Background

Accessibility research is a relatively new science that examines all aspects of accessibility in the built environment. It works towards eliminating barriers to access, especially for those who experience physical, sensory, or cognitive hindrance to their involvement in society. The UCL group, based at the Centre for Transport Studies in Bloomsbury, London, has a wide-ranging brief: what is accessibility, why is it important, what barriers to it exist, how can these be eliminated or reduced, and who do they affect?

Central to UCL's research is the shifting of demographic in the UK and elsewhere towards larger handicapped and aging populations, and the need to understand their difficulties and investigate appropriate solutions. The UK Disability Discrimination Act 1995, phased in from 1996 to 2004, has started to give disabled people a right of access to goods, facilities, services, and premises. These apply to pedestrian facilities and services, and in transport-related infrastructure: bus stations and stops, airports, and rail stations. PAMELA is a key tool for improving understanding of pavement layout and pedestrian facilities, and influencing policy.

From the outset, UCL wanted a world-class facility in terms of flexibility and range. In such an environment, where pedestrian movements can be evaluated under controlled conditions, research into surface type, layout, topography, and barriers such as vertical and horizontal gaps and obstacles, as well as ambient lighting and noise, can be carried out. The facility also needed to house a range of data acquisition systems to capture robust experimental data for analysis.

As well as pedestrians, in particular the disabled and the elderly, the facility can benefit:

- designers, who will have an improved database of pedestrian characteristics and a flexible simulation tool to support accessibility audits of existing and proposed designs

- government and agencies, who will have better data on which to base policy that affects pedestrian activities
- owners and managers of pedestrian facilities (including public buildings) for whom the simulation tool will help make strategic decisions about pedestrian routes (including escape routes) and the location of unavoidable obstacles and facilities such as seats and other resting places
- academics and consultants, to support further research in designing and implementing more inclusive pedestrian infrastructure
- medical researchers, who will be able to examine in a controlled environment medical conditions that impact the senses and physical movement, supporting diagnosis and review of how proposed treatments perform.

Development of the scheme requirements

UCL's initial brief set out its requirements for platform size, range of movement and other capabilities. From the outset PAMELA clearly needed a flexible, modular design that allowed platform sections and their surfaces to be interchanged, so as to replicate different street scenarios.

As well as functionality, usability and safety issues had to be addressed. The client wanted a facility that could be used safely by subjects recruited from the general public to generate test data. There were no obvious guidelines and standards for such a unique structure, and so those for movable footbridges based on *BS5400*[1] were used to form the basis of the loading requirements in the performance specification. The need for the platform to change form introduced design elements that would be at odds with creating a dynamically stable platform. To find this fine balance between flexibility and enough stiffness and design tolerance to create an impression of walking on solid ground or paved surface, the team developed a series of tests as part of the performance specifications.

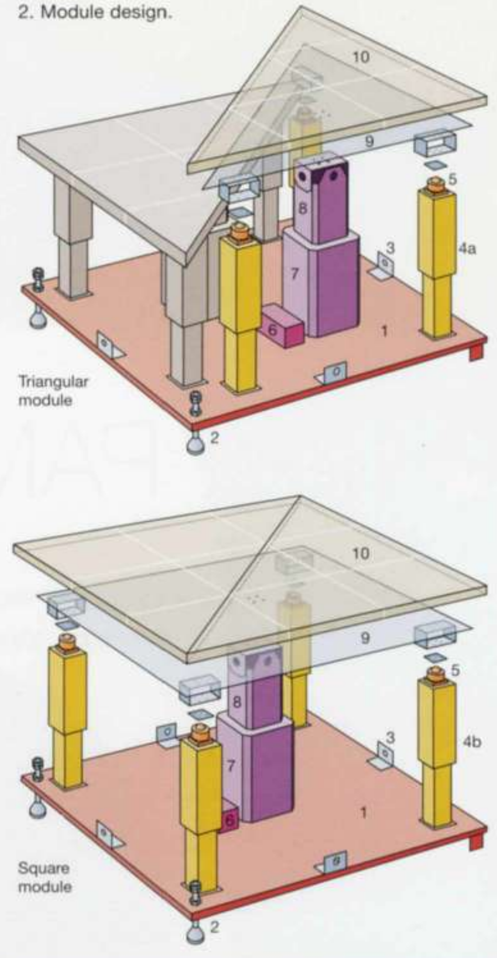
Apart from the platform itself, performance specification requirements were also developed for the control system and ancillary components, ie the parapet, stair, and lift design. The parapet system also had to be modular, and stackable to minimize storage space. A European CE mark, in accordance with current machinery design legislation, also had to be obtained for the platform.

Several concepts were considered initially. For maximum flexibility in surface movement, a six-axis flight simulator design would be ideal. However, for a modular system this would mean a multiplicity of components that would exceed the budget of a publicly-funded project. To reduce the number, Arup proposed two module types with different levels of flexibility that would still provide the required overall platform functionality. The resulting scheme requirements, as discussed below, were developed after the initial study.

The platform comprises 36 modules, each 1.2m square, with interchangeable surfaces. Each module can slope in any direction up to a maximum of 20%. Street furniture (obstacles and amenities) can be arranged on the platform with specifically designed lighting to simulate conditions from daylight to darkness. Surround sound also allows noises to be included, eg trains passing through stations, announcements, etc. This enables UCL to test combinations of defined street environments and the range of capabilities of pedestrians and wheelchair and scooter users. From these data existing pedestrian microscopic simulation models can be verified and extended, for checking existing and proposed street layouts.

The platform's ability to change its shape and surface is computer-controlled, so that slopes, gaps, etc, can be stored and recalled for study of the effects of changes in the surface (including surface type); layouts can also include obstacles like street furniture to examine wheelchair or scooter accessibility. The 50m^2 surface area can change from a square of about 7m per side to a rectangle of some 2.5m x 20m, and may be wetted if desired. Currently the surface used simulates a pedestrian footway (concrete pavers) but this can be changed if wanted. As well as slopes of up to 20% (over a short distance) in different directions, step heights of up to 250mm can be created. With bespoke steps, larger inclines are possible.

2. Module design.



How the module works

1 Base plate carries components with clearance beneath to allow stacker truck's forks to slide under to lift
2 Adjustable feet compensate for uneven floors
3 Mechanical interconnect – modules are bolted together via these holes
4a Actuators – three bolted to base plate beneath the triangle top plate corners; actuator heights independently controlled to change top plate height and slope.
4b Actuators – four bolted to corners of base plate; heights of three independently controlled, fourth acts as slave
5 Rollerball joints bolted to top of each actuator, enabling the top plate to slide over and pivot about the tops of the actuators
6 Control unit on base plate controlling actuator heights from commands sent by users through control system; unit also records actuator positions in flash memory and feeds back information to control system
7 Central column - close tolerance telescopic box section bolted at bottom to base plate and to a universal joint at the top
8 Close tolerance universal joint bolted to top plate, allowing rotation in two axes but not about the vertical axis
9 Steel top plate, bolted to universal joint at its centroid; the paving tray assembly's feet are bolted to top plate
10 Steel paving tray assembly, with box section feet to provide clearance for pallet truck's forks to lift trays. Paving slabs are glued to the steel trays, interchangeable between modules for flexibility to use different paving slab types on different modules.

Assembling the cost plan was a challenge, given the platform's bespoke nature and the limited knowledge base in the industry of such installations; risk and contingency also needed to be carefully assessed as there was no opportunity to obtain more funding during the development.

The delivered solution

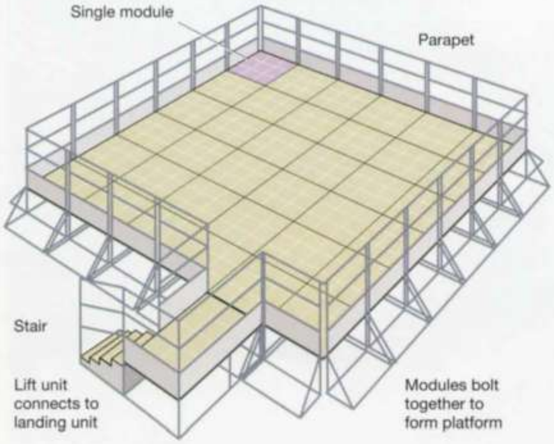
The main contractor chosen was Weir, Strachan & Henshaw (WS&H), following a prequalification and tender process under EU bidding and procurement rules, managed by Arup. WS&H's final design consisted of square and triangle modules (Fig 2).

The latter comprise two triangular plates, each independently controlled by three vertical actuators (mostly carrying the vertical loads) and a central vertical sliding column (carrying the lateral and torsional loads). The square module's plate sits on four vertical actuators and a central vertical sliding column. By varying the heights of the actuators, the surface's height and slope can be changed. The paving trays on top of the plates can be changed by pallet trucks and the modules transported around by stacker trucks.
The modules are bolted together at the base to form a platform with the required layout.

In addition to the modules forming the platform itself, WS&H also developed a parapet and stair design and procured a lift unit. The parapet units form an enclosure around the platform perimeter, and the stair/lift access unit is attached to the side (Fig 3).

A control system and a user graphic interface program to drive the actuators were also developed. In response to the performance specification requirement to address potential clashing between module surfaces, WS&H developed within the control system a way to flag up potential clash problems when configuring the assembly.

3. Fully assembled platform (modules in square layout with parapets and stairs connected).



4. PAMELA in use.

Throughout development of the final design, Arup carried out the formal Category III checks and tests required because of the team's adoption of guides and standards for bridges, to ensure that the modules, parapets, and stair design satisfied the specification requirements prior to fabrication.

In parallel to the platform development, separate works were undertaken to upgrade a medium-sized warehouse in North London for use as the laboratory. This included minor modifications for support systems and access, and the development and installation of specialist lighting rigs to simulate varying lighting conditions for roadways, stations, etc. Arup also procured and supervised these works.

Platform testing

Once platform fabrication was completed, a series of tests at WS&H's Bristol workshops verified that it satisfied the performance specification requirements. These included demonstrating the movement of the surfaces, gap size between surfaces, ease of transport, loading tests (also on the stairs and parapet), and walking and modal tests to confirm the platform "felt" like a pavement. Control and electrical tests demonstrated the range of movement of the 176 actuators, positional accuracy, effectiveness of the clash prevention software, and the usability of the user's graphic interface program.

Full assembly tests at both WS&H's workshops and UCL's PAMELA laboratory (Fig 4) involved setting up four different layouts to demonstrate (a) that the design can be assembled within a reasonable time frame, (b) the positional accuracy of the mechanical components and the control system, (c) that the gap sizes in the platform will not create trip hazards, and (d) the accessibility of the platform to users.

Acoustics

Wherever pedestrians walk, the ambient acoustic environment may distract or disturb their ability to do so safely, either by drawing their attention, or by startling or frightening them. But while these effects are well known, there has been little detailed study of the subject.

The goal was to create a three-dimensional ambient acoustic environment over the whole platform area, whatever its set-up. It was also desirable to include "spot effects" like the arrival of a bus, a baby crying next to the pedestrian under test, or a gunshot. The system had to be able to deliver, for example, the sound experienced in a car park beneath the flight path at Heathrow Airport.

The PAMELA warehouse had had no acoustical treatment and possessed significant reverberation and acoustic character of its own. It was necessary to suppress this, and to superimpose a simulation of the sort of space the pedestrians were to experience, ranging from streetside (nearly acoustically dry) to a cathedral interior (very reverberant).

Initial work led to two options:

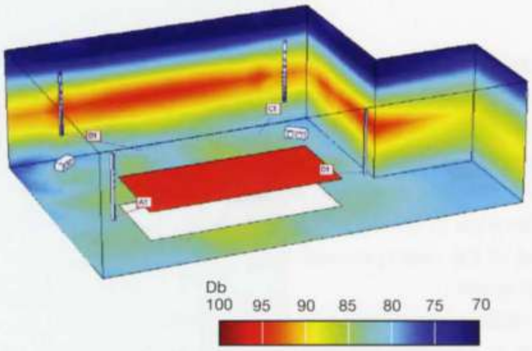
(1) Treat the space with acoustic absorption and then mount a set of loudspeakers, spaced fairly closely, on the walls and ceilings. This would mean substantial expenditure on installations, some of which would remain in the building (the lease is short and PAMELA's expected success is likely to lead to a move to larger premises relatively soon). Also, the adjustments in platform shape and height complicated initial sound system set-up for each arrangement.

(2) Use specialized loudspeakers, from Duran Audio, that produce a "plate" of sound that can be electronically adjusted to put a nearly constant level of sound across any platform shape, just skimming through the pedestrian's range of listening heights. This suppresses the room character by exciting less of its reverberation without the need for any surface treatment.

An initial evaluation in Arup Acoustics' Soundlab demonstrated what could be achieved using only four loudspeaker systems, together with ambisonic recording and sound processing, to give a realistic 3-D effect. Recordings of streetside and aircraft flyover noise were made for this evaluation. On its successful conclusion, Duran Audio brought four of the loudspeakers to the PAMELA site and these proved the concept in the real room. The loudspeakers are large fixed-format column arrays, each supported on a heavy-duty, wheeled, adjustable height stand. Duran *Intellivox* control software puts the platform layout, listener height, and loudspeakers into a computer model, then automatically computes the algorithms to control each loudspeaker driver (16 in each of the four systems) to give the desired coverage over the PAMELA platform. In addition, two high-powered sub-woofers provide the low frequencies, and four small portable loudspeakers can be placed anywhere on the platform for spot effects – triggered either randomly or by pedestrian presence (Fig 5).

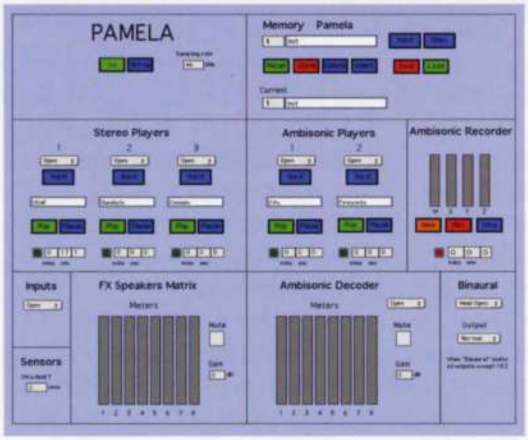
The final elements are the sound production and playback systems. Recordings can be made using a Soundfield microphone that captures full 3-D sound information within one physical microphone and a shoulder-worn digital four-track recorder. This can then be transferred to a computer and mixed with other sounds using audio recording software, in this case *Cubase SX3*. The final playback, comprising both the four-channel ambient 3-D sound environment plus spot effects, is controlled via a custom interface running on a PC under Max/MSP (Fig 6).

Pedestrian-triggered actuation of spot effects has been demonstrated using pressure pads and infra-red proximity detectors. Since PAMELA includes a 3-D tracking system, it is hoped that the final implementation can be linked to that.



5. The audio system produces a "plate" of sound, the position and intensity of which are computer-controlled to suit the different scenarios.

6. Audio control panel.



Lighting

Street lighting fulfils several purposes. It assists mobility during the hours of darkness for pedestrians, cyclists, and vehicles, it reduces the risk of road accidents, and it improves the sense of communal safety.

To fulfil the objective in the PAMELA project of accurately simulating various real-life scenarios, the lighting installation design was a key element. It had to accommodate a wide and appropriate range of light levels and light spectra for a variety of road scenarios and urban settings, eg single carriageway, street corner, pedestrian crossing, railway footpath, and shopping centre access way (Figs 7-9). It is thought that variations in colour properties among different light sources have significant implications for how pedestrian accessibility and movement environments are perceived and reacted to.

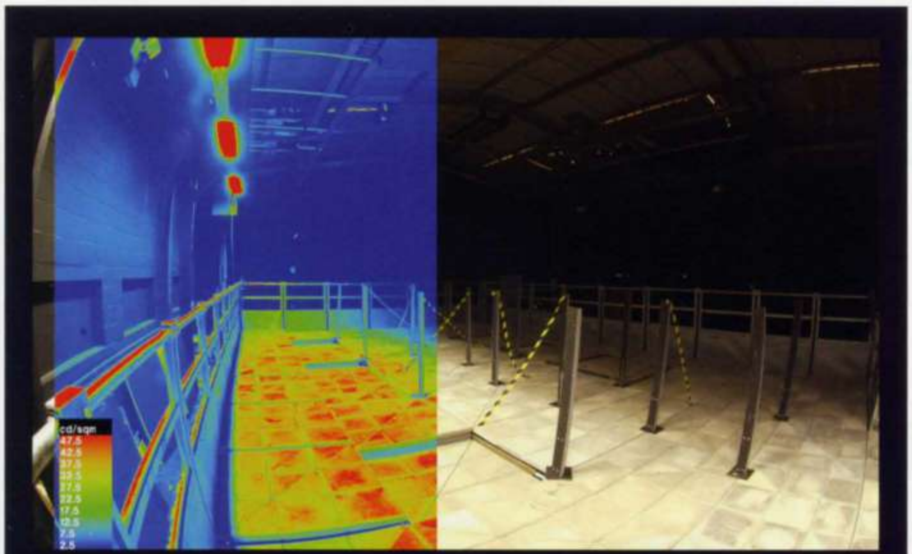
In ideal circumstances the required scenarios would represent a wide range of solutions, but the room limitations (4m height clearance only) and cost constraints reduced the number of light sources and fittings to the minimum needed to simulate reasonably well a real environment. Compromise was needed, with the use where possible of the same photometry for different tasks.

Such a flexible lighting solution involves:

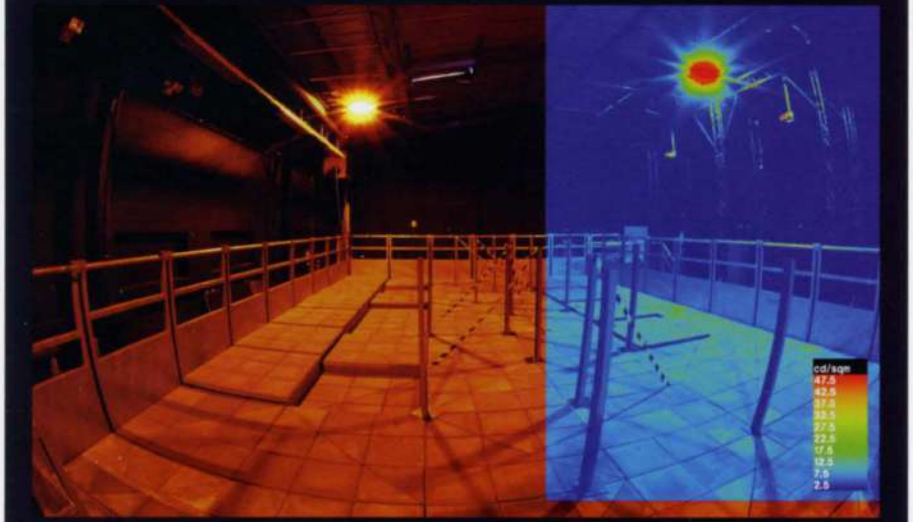
- selection of multiple light sources (low pressure sodium, high pressure sodium, ceramic metal halide, and fluorescent lamps)
- adjustable lighting levels to match European standards for various types of road and pedestrian access ways
- the ability to change test rig configurations (tilt, spacing, etc).

The final design has light fixtures on a steel truss frame high along the primary perimeter wall, as well as on a movable floor-standing structure to allow easy access to luminaires for maintenance and aiming. Road lighting fixtures of various lamp types, asymmetric projectors for façade lighting, and linear asymmetric fluorescent fixtures to simulate railway platform lighting are also employed, as well as additional spot projectors to create light effects that simulate a bus stop, shopping centre façade, etc.

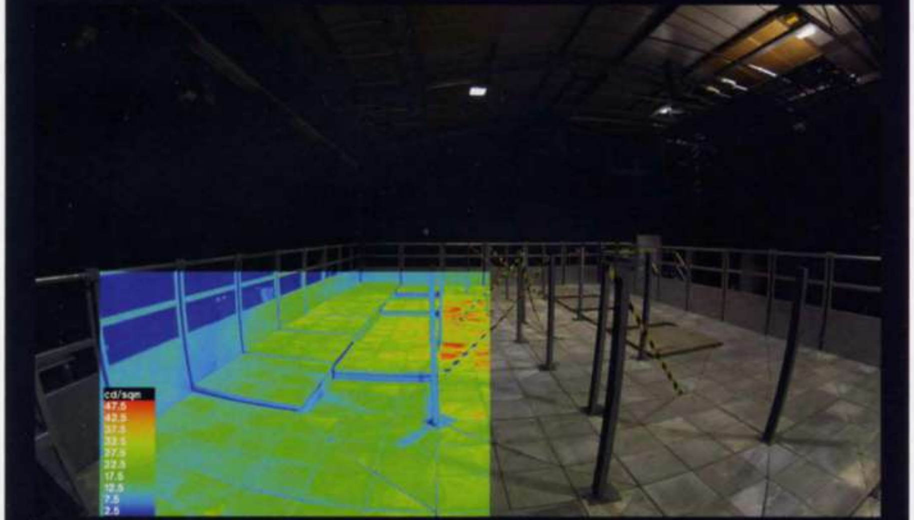
A *Sceneset* lighting control system configures the system for various test scenes. To adjust the light level settings, high-pressure sodium, fluorescent, and metal halide lamps are dimmed via main signalling, while for the non-dimmable low-pressure sodium lamps this is done by temporary gel filters.



7. Fluorescent lighting for railway footpath scenario.



8. Low pressure sodium lighting for residential street scenario.



9. Metal halide lighting for shopping centre accessway scenario.

The falsecolour plot indicates the luminance (cd/m^2) map over the photographed area. The exposure setting is the same for all three photographs for ease of direct comparison of brightness.

Conclusion

The rig has been in use since April 2005 (initially using subjects recruited from UCL) to verify pedestrian simulation models, examine the physical environment in which pedestrian activities can be tested and develop capability profiles for a wide range of people under several different physical and sensory conditions.

Current research involves transportation engineers working alongside ophthalmologists and orthopaedics specialists. UCL has been very pleased with the amount of cross-departmental research the rig is generating, and has also received interest in using the facility for external research from organizations including other universities, national/local government bodies, transport operators, and medical science research groups.

PAMELA shows the value that combined specialist and multidisciplinary skills can bring to a client wanting to develop unusual and significant research facilities. The project was ultimately delivered below cost plan, which was quite an achievement, and at the official opening in June 2006, the procurement process used by Arup and UCL was commended by EPSRC.

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Kheng-Lin Khoo is an Engineer with Arup in the Advanced Technology & Research London Group.

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Credits

Client: University College London **Lead consultant (Project management, SME, control systems, and lighting design):** Arup – Giulio Antonutto, Chris Cole, Leslie Dep, Ben Glover, Andrew Harrison, Trevor Hodgson, John Hunt, Kheng-Lin Khoo, Florence Lam, Ben Lawler, John Lyle, Vahadi Minah, Simon Rainsbury, Rob Smith, Roland Trim, Michael Underhay, Sam Wise **Platform detailed design and manufacture:** Weir Strachan & Henshaw **Sound system programmer:** Dave Hunt Audio **Loudspeakers:** Duran Audio **Illustrations:** 1 Dutchy/iStockphoto; 2 Weir Strachan & Henshaw/Arup/Nigel Whale; 3 Arup/Nigel Whale; 4 Simon Rainsbury; 5 Duran Audio; 6 Arup/Dave Hunt; 7-9 Giulio Antonutto.

Reference

(1) BRITISH STANDARDS INSTITUTION. *BS5400*. Steel, concrete and composite bridges. BSI, various dates.

Weblink: http://www.cts.ucl.ac.uk/arg/pamela2/index.asp

The Technik floor system:

Materials consulting and product design

Darren Anderson Bruno Miglio Rebecca Minnitt

Background

Arup has been involved with research and development for nearly half a century, and a major strand of that involvement has been to do with the properties and potential of materials. Usually this has been an integral part of Arup's service to clients for major building and infrastructure projects, but more recently materials consulting for its own client base has been a growing activity within the firm.

One long-standing and strong relationship for the materials consulting group in London has been with the building developer Stanhope plc, for which it provides a consultancy service on many stone projects in the London area.

Finding a difference

Stone floors for most projects typically involve the stone being laid on a cementitious screed. While screeds have a successful track record there are also numerous examples of failure if they are not properly designed and their long drying times are not incorporated into a project programme. They are also heavily dependent on site workmanship.

Laying screed floors is a wet process, with the usual thickness for a floor screed being between 40mm and 75mm. Drying time for a typical screed is usually considered to be around one day for each mm of screed. Laying and drying a concrete screed floor thus takes a substantial part of a building's construction time, and the other services are unable to work around the floor during this period.

Stanhope began discussions with Arup's materials consulting group and one of its main stone contractors (Grants of Shoreditch Ltd) to see if it could eliminate floor screeds from its projects. Grants had previously worked with several raised access floor suppliers, where the floor is laid as individual stone composite panels on pedestals with a void between the concrete floor slab and the stone panel. None of these products produced a homogeneous stone finish typical of a traditional stone and screed floor.

The Arup specialists and Grants saw the requirement for a prefabricated, panellized stone flooring system that behaves as a single-surface layer. For assistance they engaged with Lindner plc, which has a long history of designing and supplying bare boards to the construction industry - boards made from 95% recycled paper, with structural, acoustic, and insulation properties exceeding those of the usual MDF board. One of Lindner's products was a panel with tongue-and-groove joints so that, when laid adjacent to the next panel, the special jointing enables the boards to behave as one. This idea forms the basis of the Technik floor.

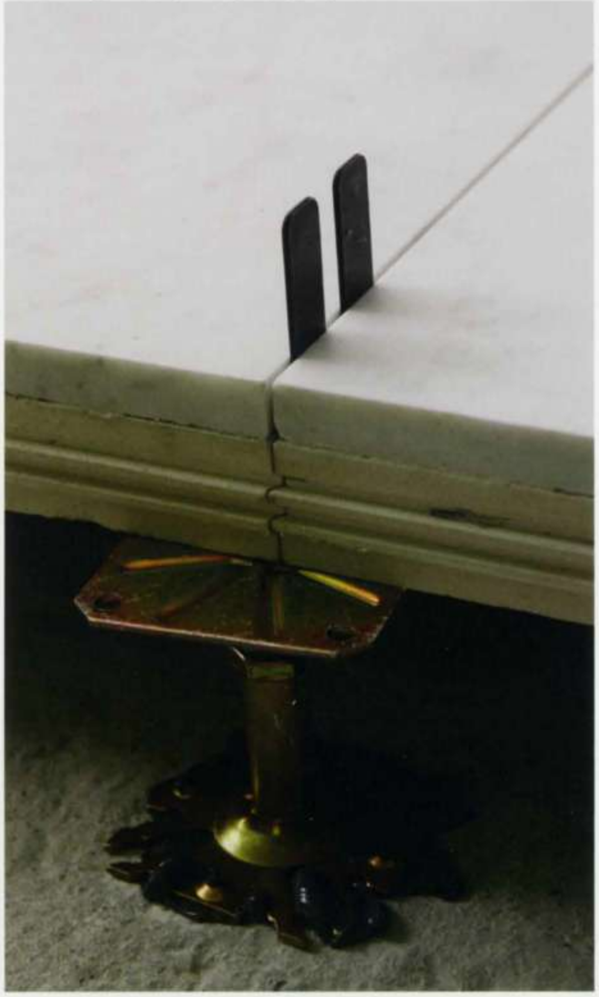
The Technik floor

The system is a partially accessible raised floor comprising tile modules placed on height-adjustable steel pedestals. Each tile is made from a panel comprising 95% recycled paper with the stone (or ceramic layer) factory bonded on top. The tiles are joined together via the tongue-and-groove joint, resulting in a monolithic support layer. Compared with other systems on the market, the Technik floor has clear advantages. It convincingly offers the closest possible adherence to deadlines together with shorter construction times. The system is cost-neutral vis-á-vis wet cement floor systems where stone or ceramic layers are applied at the building site, but adding factors such as shorter construction times, weight savings, and lower stone thickness, clearly tilts the cost balance in favour of the Technik floor. On top of the cost advantages, the recycled paper board substrate to which the stone is laminated has strong sustainability characteristics.

The types of project for which Technik floors are ideal include airport concourses, shopping centres, galleries, and large, open office lobbies. In addition, the system is not only appropriate for such modern construction projects but also for an increasing volume of restoration work. At present it is unique in the marketplace, and Grants has repeatedly experienced a 15% saving over traditional concrete screed for the same quality.

Having met Stanhope's challenge the Technik floor is now to be specified on many of their stone flooring projects, initially at its new office development at 51 Lime Street, London EC3.

1. Tongue and groove jointing of panels.



Making the difference

Having seen the immense value in the system, all three parties involved saw the need to put into contract a working relationship by which everyone would benefit. Each realised the mutual value in being part of a three-way relationship to take to market the Technik floor. Arup's materials consulting group joined forces with its product design group, which has expert knowledge in outlining contracts between global external parties, to help broker the deal. Most recently the product design group signed a contract between an Australian seating manufacturer/distributor, a Chinese extrusion plant, and Arup to take to market a new terminal seating system.

Deciding the value that each party brings to the Technik floor, the amount of investment needed, and relative gains, is key to assigning the rights to the intellectual property of the floor, and therefore the levels of reimbursement for each company. The value, in this instance, comprises the following:

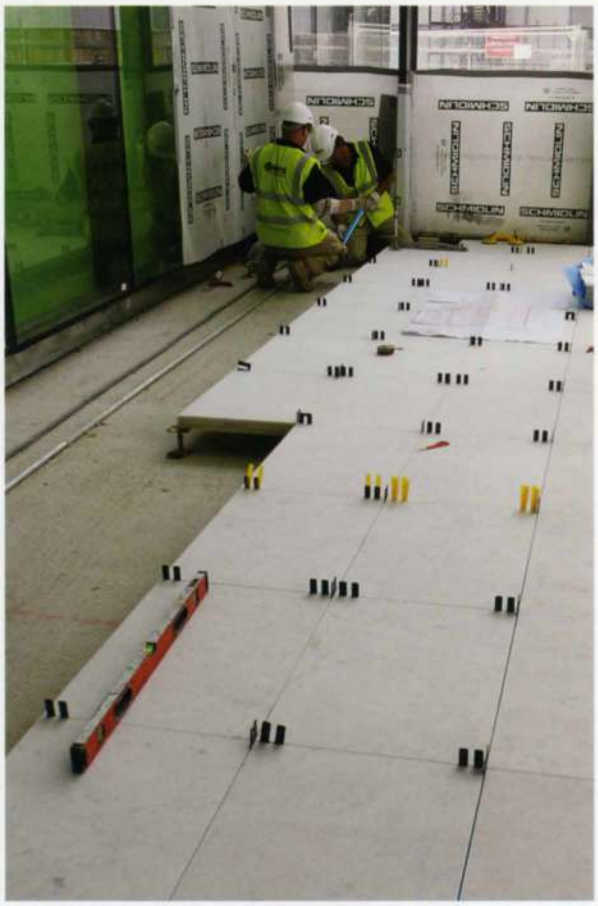
- the inventiveness of the idea
- the uniqueness of the product
- the individual company brands
- the networking opportunities for new projects that a company can bring
- the assets of each company that enable the project to come to fruition
- the technical expertise needed to ensure the flooring system is right for individual client needs.

Each company assigned a value it thought it could bring to the three-way relationship, and the deal was debated before a reimbursement value (in this case a percentage of the contractual value) was decided upon for Arup.

The key to this highly beneficial arrangement is, as always, the nature of a particular long-standing relationship based on trust, in this instance built up over many projects between Arup's materials specialists, Grants, and Lindner. Without the materials group's foresight and understanding of what could make a good commercial project, supported by the product design team, Arup would not be in its present position, receiving good income without substantial man-hours being spent on the Technik floor.

This is one of several joint ventures in which Arup's product design group (which works from the London, Melbourne, and Hong Kong offices) is contractually involved. The income from these ventures is completely non time-dependent and can potentially run for many years (in the case of the Technik floor the predicted product life is 10 years, to be continued until superseded).

2. Tile modules making up the flooring system.



3. Laying the Technik floor system.

Darren Anderson is a senior geologist with Arup in the Materials Consulting London Group.

Bruno Miglio is a Director of Arup in the Materials Consulting London Group.

Rebecca Minnitt is a designer with Arup in the Façades London Group.

Credits

Client: Stanhope plc **Joint venture partners:** Grants of Shoreditch Ltd (UK only)/Lindner plc/Arup – Darren Anderson, Andrew Hall, Bruno Miglio, Rebecca Minnitt **Illustrations:** 1-3 Arup.

1. The main terminal building, summer 2005.

Terminal 5, London Heathrow:

The main terminal building envelope

Steve McKechnie

Introduction

When Heathrow Airport opened in 1946, a group of tents and some phone boxes formed the first passenger terminal. Facilities at the airport have moved on immeasurably since then, but there is always room for improvement and so, at the end of the 1980s, BAA started to plan a fifth terminal.

The process of deciding what to build and getting planning approval was long and complex, but by early 2000, the project team had started work in earnest on the design of the new terminal.

T5 was to handle 30M passengers per annum and had to make a significant statement on the world travel scene. BAA wanted "the world's most refreshing interchange" and so, when the structural engineer suggested that the main terminal building could have a single-span roof that vaulted over all its disparate activities to enclose them in one space, the architects and BAA took up the idea with enthusiasm.

BAA set up the project team under a partnering contract and made Arup responsible for structural engineering of the buildings above ground level. The firm worked alongside the other "first tier suppliers" in a partnership where architect, contractor, engineer, and client took joint responsibility for the project's successful completion. The whole team worked in one place, on site, at Heathrow.

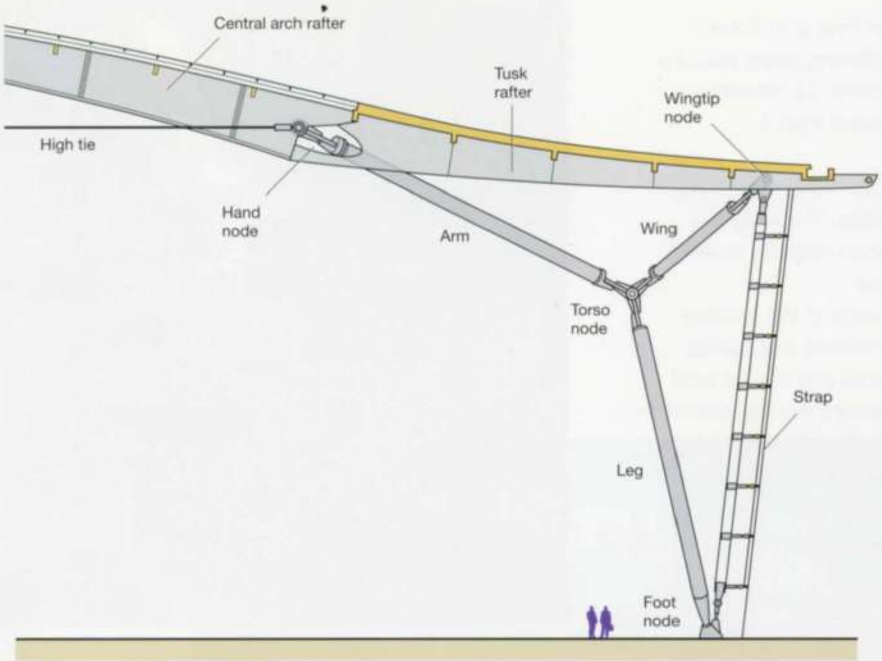
There is a lot to say about T5. The innovative computer-aided design tools have already been discussed[1]. This article covers solely the design and construction of the roof and façades of the main terminal building (Fig 1). Further aspects of the complex will be dealt with in future *Arup Journal* articles.

2. Dramatic full-height circulation space.

Main terminal building roof

The roof has a span of 156m, and is 396m long. It is supported by 22 pairs of 914mm diameter steel legs that reach down to apron level in dramatic full-height spaces just inside the façades (Fig 2). These spaces also form the main routes for passenger vertical circulation to and from the gates.

The span is formed from steel box girders at 18m centres: 800mm wide and up to 3.8m deep. These are tied at high level by pairs of 115mm diameter prestressed steel cables. 914mm diameter steel arms reach up from the tops of the legs to support the rafters, and solid steel tie-down straps from the rafter ends complete the 3D hybrid portal frame structure (Fig 3).



3. Main structural elements of the roof.

5. Minimal intrusion of façade vertical structure.

Single span

The three-storey superstructure of the terminal is completely separate from the roof and façades (Fig 4). BAA chose this bold structural arrangement because it gave several important benefits. The roof acts as a visually unifying element for the building. It is intended to give travellers a sense of place in the world as well as an intuitive feel for where they are within the terminal. The lines of the structure and roofing are deliberately simple and clean to impart a feeling of calm and purpose to the space.

BAA strives always to provide value for money by constantly fine-tuning the retail and passenger service offered within its terminals. This can lead to a lot of building work and inconvenience caused to terminal operations, but in T5's main building all this work will be internal, on the upper levels, and non-structural, so disruption to BAA's business will be minimized.

4. Structural separation of envelope and content.

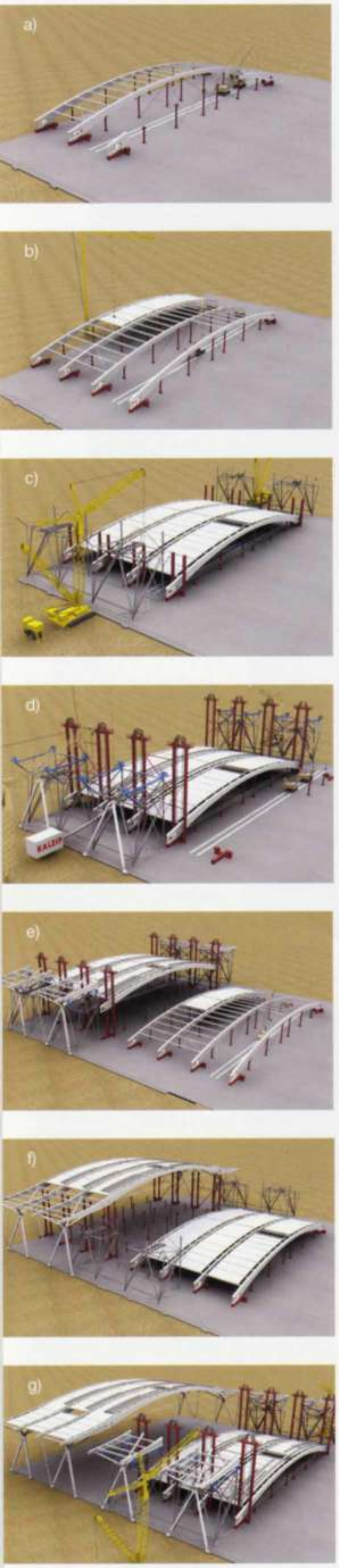
The construction critical path went straight from completion of basement slab to roofing and façades, which led to an early date to achieve watertightness. Moreover, the internal structure was constructed in a semi-indoors environment, improving build quality and reducing programme delay from bad weather.

Perhaps the most significant benefit has been the fact that design and construction of the roof and façades was free to go ahead completely unimpeded by any decision-making about the function or layout of the internal spaces. For instance, in 2003 BAA made huge changes to the internal layout of the building so that British Airways could move its whole operation into the terminal in one go, but that did not affect the roof team at all. The site programme continued to march forward, without even pausing in mid-stride.

Façades

A key part of the passenger experience in this building will be the ability to look out at the airfield and aircraft and get a taste of the excitement of air travel. The façades are thus fully glazed, and the design team strove to minimize the intrusion of vertical structural elements into oblique views through them (Fig 5).

The team decided to use the roof tie-down straps to support the façade wind loads. The straps are part of the roof structure: they run vertically and carry tensions from the roof of up to 9000kN. When the wind blows on the façade the straps will deflect,



6. Roof assembly sequence.

but as they deflect the tension tries to pull them straight again. This tension stiffening effect reduces bending moments and deflections, so the straps can be slimmer and less obtrusive than a conventional façade support.

Elliptical hollow sections span horizontally 18m between the roof tie-down straps. The weight of glass and steel is carried to apron level by a series of 139mm diameter steel props.

The façades on the gable ends of the building each consist of a simple grid of steel that carries gravity loads down to apron level and resists wind loads by spanning vertically up to the underside of the roof. There is a joint at the head of the gable façade that allows vertical and in-plane horizontal movement between the façade and the roof while still carrying wind load in the out-of-plane direction (Fig 7).

All the façade panels are 2m x 3m double-glazed and toughened with aluminium framing. *Brises-soleils* are used to reduce building cooling loads and consequent carbon emissions. On the "land side" of the building the glass is laminated, and the robustness of the framing, the fixing of the glass, the frame, and the steel connections are enhanced to resist blast loading from terrorist attack.

Erection method

Arup strives for quality of a building in its widest sense rather than merely achieving the "best" design in each individual discipline. This, of course, includes its construction as well as its systems, aesthetics, usefulness, and sustainability. Here the construction was a major consideration, and so the Arup team was delighted to work with the steel supplier Watson, the architects Richard Rogers Partnership, the heavy lifting specialists Rolton, and the rest of the construction and design team to tailor the frame design to suit a safe and efficient construction method. They, in their turn, were also keen to tailor the construction method to suit the design -so much so that it is now hard to say where the "design" ended and the "construction method" began. This was made much easier by the partnering contract that BAA set up for the T5 project and by the co-location of all concerned in dedicated offices at Heathrow.

The roof was assembled in five phases of 54m and one of 18m. The central arched section of each phase was assembled, clad and prestressed at ground level, and temporary works frames used to position the abutment steel for each phase accurately (Figs 6a-b). The centre section was then jacked 30m vertically into position and bolted to the abutment steel (Figs 6c-e). Once each phase was complete the temporary works frames were rolled north by 54m ready for the next phase (Figs 6f-g).

7. Joint at head of south façade.

8. Rafter section arriving on site.

Transport factors

The dimensions of this structure are such that almost every design decision included some reference to how the steel would be transported to site. There was no space for storage and so every load had to be planned so that it could arrive on site and be unloaded directly onto the work face.

The largest sections of rafter weighed around 50 tonnes and were up to 3.8m high. Other rafter sections were 27m long. They were fabricated in Finland and brought to the UK by ship, where they took to the road (Fig 8). The torso nodes were slightly lighter at 38 tonnes, but they did require purpose-made transport frames so that they were in the correct orientation for assembly as soon as they arrived on site.

9. Roofing material in place prior to erection.

10. Jacking of roof elements.

The low-level assembly of the central arch sections was a key decision, and had three main benefits:

- It reduced the risks of working at height for both the steel erectors and the roofing installers. All the cladding for the central arch sections and the aluminium roofing material for the whole width of the roof was placed on the central sections before they were lifted into place.
- It minimized the height of the props needed to assemble the arch.
- It allowed the whole operation to be carried out by cranes whose tops were below the airport radar ceiling.

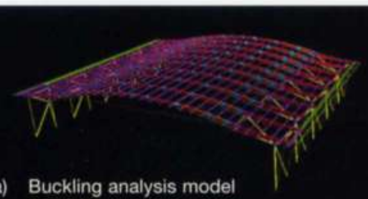
The construction team planned the whole process meticulously at the start, and refined its plans as the job progressed. Arup members of the design team observed the prestressing and jacking processes and so were able to take an active part in the construction process and in problem-solving on site. Overall, the construction went very well and it was a pleasure to have such close involvement in it (Figs 9-11).

11. Central section clad and prestressed, May 2004.

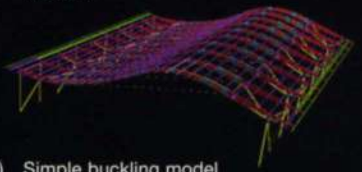
Modal buckling analysis

The T5A roof is a massive arch and carries huge compression forces. It is essential to prevent buckling both of its individual parts, and of the structure as a whole. In the past, engineers typically used rules of thumb, simple calculations, and educated guesswork to design against buckling, but here, the team carried out a modal buckling analysis (Fig 12) to predict the most critical possible buckling modes, and then processed the mode shape data to give sets of design forces. Designing for these forces ensured that there is a consistent reserve of strength against buckling, without wasting money on providing strength where it is not needed.

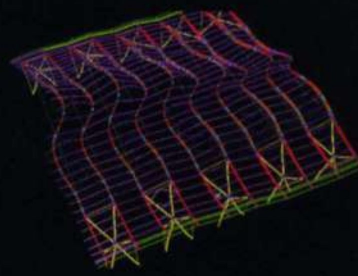
This method gives safer and more realistic results than the use of traditional notional restraint forces for the rafters in their minor axis, and enabled slimmer leg and arm sections because of the partial fixity provided at main nodes. Moreover, it allowed Arup to quantify the effective length of the major axis buckling mode of the main rafters rather than just taking an educated guess.



a) Buckling analysis model in GSA.



b) Simple buckling model predicted by the analysis.



c) Complex buckling mode predicted by the analysis.

12. Modal Buckling analysis.

13. Bracing in roof plane and abutments.

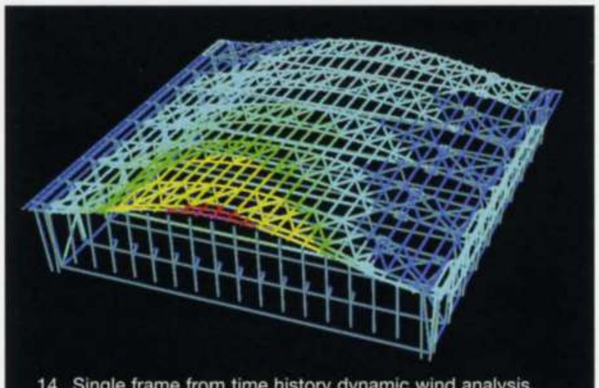
Structural action

The structural action of this roof lies somewhere between the stone vaults of a cathedral and the portal frame steelwork of a retail warehouse. As in a cathedral roof vault, the self-weight of the roof and the steelwork generates compression in the rafters and legs, and the feet push outwards and downwards on the apron level slab. This outwards force is resisted by steel beams in the apron level structure. This "arch action" in the rafters massively reduces the bending moments they would otherwise have to resist.

Wind loads or other asymmetrically applied loads in the east-west (lateral) direction are resisted by portal frame bending action in the rafters. In the north-south (longitudinal) direction, wind loads are carried to the abutments by lines of bracing between adjacent pairs of rafters. At the abutment, the wind loads are transferred to ground level through X-brace action in the legs and arms (Fig 13). The bracing in the roof plane also restrains the rafters against minor axis buckling.

The high-level prestressed steel cable ties have a similar action to the apron level tie. The tension in the ties creates upward bending moments in the rafters that almost exactly balance the downward moments from the self-weight of the rafters and roofing materials. During the jacking process, the central section of the roof becomes a perfect arch spanning the 107m between lifting towers.

The east and west façades have movement joints at 36m centres to co-ordinate with joints in the aluminium framing system. The roof also has movement joints at 36m centres, starting at the eaves and cutting into the roof plane by around 30m. These dramatically reduce the forces that are induced in the abutment steelwork by differential thermal expansion of the roof and the substructure. The joints provide flexibility to the roof plane but do not divide it into sections, and so the whole frame can be mobilized to resist north-south loading.



14. Single frame from time history dynamic wind analysis.

Dynamic time history wind analysis

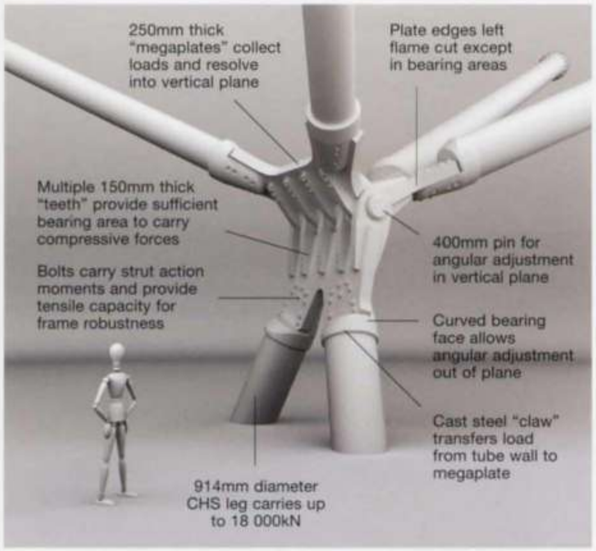
This structural form moves most under asymmetrical or uneven wind loading. The team had to protect the façade and roofing from damage by excessive movements, but it would have been uneconomical to make highly pessimistic assumptions about how wind pressures might be distributed.

Data acquisition and processing technology have advanced enormously in recent years, and it is now possible to record how wind pressures vary from second to second across an array of pressure taps on a wind tunnel test model. Arup's Advanced Technology Group took this data and built a computer model (Fig 14) of how the roof would move from moment to moment, taking into account the varying wind pressures, its structural behaviour, and its inertia. This new technique gave a more accurate estimate of deflections in service than was ever possible before. As a result, the team saved 800 tonnes of steel by reducing the rafter flange thickness from 85mm to 70mm.

Design for manufacture and assembly

The way the building design was chosen to optimize construction has already been touched upon. This fundamental aspect of the partnering contract was carried through the entire design almost to the last nut and bolt. The paragraphs below give examples of how this "design for manufacture and assembly" led to reduced site programme time, risks, and cost.

Having said this, one might expect to find that visual quality or usability had been compromised because the design team was focusing on construction issues. On the contrary, the architects used this focus as an opportunity to express the building's engineering visually. The structure and its connections and details became sculptural objects in themselves. The language of exposed welds, as-cast steel surfaces, and visible bolts gives a feeling of scale and a grain to the building, and speaks of the human hands that have brought this huge structure into being.

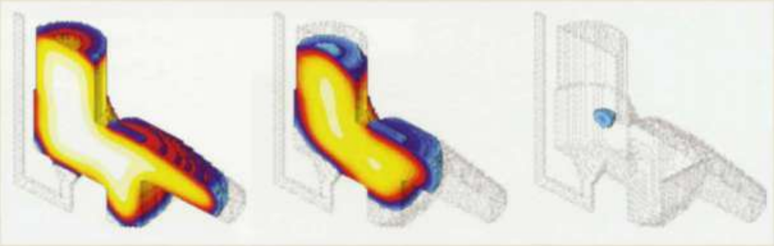


15. The torso node.

16. Connection of arm to torso.

17. Casting removed from sand mould.

18. Cutting of timber patterns.



19. Computer modelling of casting solidification.

Casting structural steel

The success of a structural steel casting depends on its shape because the steel shrinks as it solidifies, and it is essential to allow new molten steel to flow in to make up for the lost volume. The ideal would be a carrot shape with molten steel flowing in from a header at the thick end. The shapes of all the cast components were developed in consultation with the foundry (William Cook); the design team developed 3-D computer models and Cook then used its numerically controlled five-axis cutter to cut timber patterns directly from the computer files.

The torso node

The geometry of the abutment steel generated its own engineering challenge: how to connect the 914mm diameter circular hollow sections so that they could carry compressive loads of up to 18 000kN but still be easy to assemble on site into the required geometry.

The team looked at past solutions to this type of problem. Oil rigs, with similar geometries and steel sizes, generally use fully-welded structures and very large steel castings for the more complex nodes. Site welding was to be avoided, however, because it can be dangerous and prone to error, and is relatively slow. The team wanted to maximize work at the factory to streamline the site process and, where possible, avoid any welding of steel over 50mm thick - even at the factory - because of the complex welding procedures required and the risk that repair of any significant flaws could delay the project. A different solution had to be found.

The abutment steels carry loads that are (almost) always compressive, so direct bearing of steel on steel is an efficient way of transferring forces. However, any tiny error in the angle of machining a bearing face could throw the far end of a 22m long member seriously out of position. We had to find a node design that would allow the angle of each of the arms and legs to be adjusted independently on site.

The final node design (Fig 15) took inspiration from those old-fashioned wooden puzzles that you might find in your Christmas stocking. The nodes are made from pieces of steel plate that are flame cut to shape and slotted together. The bolts provide robustness but do not carry the primary forces (Fig 16).

20. Connection of arm to torso.

21. Adjustable connections.

22. Conjunction of rafter with top of abutment frame.

The geometry and fit of the parts were optimized with Corus Process Engineering, the supplier, to make the best use of its production facilities and the manufacturing process run as smoothly as possible. For instance, the teeth are 150mm thick but the Arup team set them out at 154mm centres because plates from steel suppliers are never exactly 150mm thick. The nominal 4mm gap allows for this tolerance. This removes the need for the plates to be machined to the correct dimension and saves time and money in the workshop. The partnering contract allows gains like this to be passed on to the client.

Design for assembly

The most obvious example was the way all stages of the construction sequence were analyzed and designed for at the same time as the final state analysis was carried out. In addition, all the site connections (Figs 20-22) were designed by the original design team at the same time as the overall frame.

The connections had to fulfil three requirements:

- The piece size had to be chosen to suit cranage and space available at the works, as well as transport restrictions and the limits imposed by cranage on site.
- The steel had to slot together on site in a positive way with a minimum of direct human intervention. This would reduce the risks of injury and falls for the steel erectors and speed the site process.
- The connections had to be well proportioned and elegant, because they are potentially the most visible part of the structure.

In the case of the rafter splices in the central arched section the splice is almost completely invisible but is very quick and easy to build (see panel below). Watson was able to off-hire two crawler cranes when it discovered how quickly the units went together. This alone saved the client a six-figure sum over the duration of the contract.

23. Close-up of shear key.

24. Rafter assembly.

Rafter splices

One of the more subtle advantages of the prestressed high ties is that the splices in the central arched section of the rafters always carry significant net compression. Therefore, they can transfer forces from section to section in bearing, rather like the joints between the stones of a gothic cathedral. No welding is required. 120mm diameter "male" and "female" shear connectors interconnect during erection so that the whole rafter fits together like giant Lego bricks (Figs 23, 24). Some bolts are required for extreme wind load cases but these can be accessed from inside the rafter section after assembly and off the critical path.

25. The main terminal building in summer 2005.

Tolerances

When components are manufactured, the dimensions of the finished piece are always slightly different from those on the drawings. The team knew that when all the pieces of the roof went together, their dimensional deviations would add up and could throw the frame out of position. Under a traditional contract, this often leads to recriminations and remedial works and, very often, delays to the rest of the project.

Because the project team had decided on an erection sequence, such problems could be designed out by providing adjustable connections in the frame. Arup carried out a statistical analysis of the probable combined effect of all the individual dimensional deviations of the elements, and designed a set of connections with packing plates, threaded rods, and friction grip bolts in slotted holes that would allow the frame to be adjusted back into an acceptable geometry.

Conclusion

Roof construction started on site in December 2003 and the building was watertight by November 2005, beating the programme milestone by three months and coming in on budget. This was a testament to the hard work, professionalism and, above all, team spirit of all involved. Everyone on that team was focused on designing and constructing a great building and doing it in the best, safest, and most efficient way they knew.

Reference

(1) BEARDWELL, G, *et al*. Terminal 5, London Heathrow: 3-D and 4-D design in a single model environment. *The Arup Journal*, *41*(1), pp3-8, 1/2006.

Credits

Client: BAA **Architect:** Richard Rogers Partnership Assistant architect: HOK **Multidisciplinary engineer:** Arup - Graham Aldwinkle, Andrew Allsop, Jolyon Antill, Trevor Baker, Mike Banfi, Kathy Beadle, Dan Birch, David Bloomfield, Isobel Byrne-Hill, Simon Cardwell, Mark Collier, Andrew Cunningham, Lee Cunningham, Pat Dallard, Tony Fitzpatrick, Brian Forster, Damien Friel, Ian Gale, Clare Gardiner, Florence Gautron, Kathy Gibbs, Chris Godson, Lee-Zane Greyling, Ray Ingles, Barney Jordan, Tarsem Kainth, Vince Keating, Richard Kent, Steven Luke, Steve McKechnie, Ian McRobbie, David McShane, Pablo Marsh, Astrid Meunzinger, Dervilla Mitchell, Phillip Moneypenny, Gareth Mooney, Chris Murgatroyd, Paul Nuttall, Deirdre O'Neill, Gabriele Presot, Steve Roberts, Joe Spatola, David Storer, Martin Tarnowski, Gursharan Thind, John Thornton, David Trelease, Rebecca Wright **Cost management:** EC Harris/Turner and Townsend **Steel supplier:** Watson Structural Steelwork Ltd **Heavy lift consultant:** Rolton **Team management and programming:** Laing O'Rourke **Steel foundry (castings):** William Cook **Machining and heavy assembly (nodes):** Corus Process Engineering **High tie supply and stressing:** Bridon **Wind tunnel testing:** RWDI **Checking engineer:** Flint and Neill **Roofing:** Hathaway **Strand jacking:** PSC Fagiolet **Building control:** BAA Building Control **Images:** 1, 2, 4-7, 9-11, 13, 24, 25 BAA; 3 Nigel Whale; 8, 17, 18, 20 Richard Rogers Partnership; 12, 14, 16, 21-23 Arup; 15 Arup/Richard Rogers Partnership; 19 William Cook.

1.

Khalifa Stadium, Doha, Qatar

This signature stadium upgrade is both a showcase for engineering expertise and a sign of Qatar's resolve to be a leading venue for world sporting events, as host to the 2006 Asian Games.

Tristram Carfrae Jane Nixon
Peter Macdonald

2. The stadium before upgrading.

Introduction

Khalifa International Stadium, the first in the United Arab Emirates state of Qatar, was built in 1976 and hosted several international and national events, such as the GCC football tournaments. As Qatar was to stage the Asian Games on 1-15 December 2006, however, the stadium had to be enlarged and refurbished to 21st century standards. Located within the Khalifa Sports City complex, this 20 000-seater with only a small canopy on one side was converted to 50 000 seats, with a roof and a signature lighting arch over the western and eastern sides respectively.

Design and construction formed a truly global collaboration. A Belgian developer client and main contractor acted on behalf of the Khalifa Sports City Development Committee, and Australian architects, engineers and project managers worked with an Indian steel contractor, a British steel manufacturer, a Malaysian steel shop draughter, a Canadian cable manufacturer, an American fabric supplier, and a German cable erector to deliver this complex and demanding project.

The Development Committee wanted a world-class facility, unique in design and instantly recognizable as an emblem of Qatar. From late 2002 a team from Arup's Sydney office worked with Cox Richardson Architects & Planners to develop the scheme for the complete stadium expansion, including seating extension, foundations, roof, and private box for the Crown Prince of Qatar. Following the award in August 2003 of the design and construction tender to Midmac/Sixco, Arup was asked to undertake the detailed design of the structurally complex roof and lighting arch.

Programme was of the utmost importance to the Development Committee. The design, documentation, and erection of the roof and lighting arch had to be completed in a little over 12 months. Practical completion was issued and dated on 28 February 2005, and the stadium hosted its first event (a soccer match) in June 2005.

Structural summary

The main roof is in lightweight PTFE-coated membrane totalling some 15 000m². It spans approximately 220m along the length of the stadium, and is up to 50m wide. The roof membrane is supported on a cable net structure tensioned against two arches at the rear of the seating and tied down at the north and south ends of the stadium by two relatively small concrete buttress foundations 265m apart. The main arch, raised 26° from the horizontal, reaches 67m above the ground at its highest point, while the "horizontal" arch – actually 11° above horizontal – reaches 32m at its apex.

The lighting arch is slender and cable-stiffened, again spanning 265m from the same buttresses, and 75m high. It leans away from the roof arches at 24° from the vertical, thus forming a right angle with the upper roof arch. It has been designed to support sports lights, loudspeakers, and fireworks during the opening ceremony of the Asian Games.

Loading

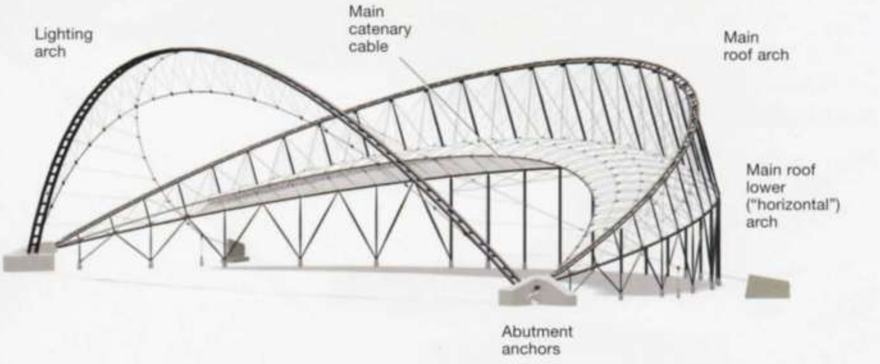
A desert environment generates extremes in loading and the structural design had to cope with these. The steelwork and the cables were designed to handle a temperature range of 5°-85°C, while the fabric roof was designed to withstand not only wind but the weight of heaped sand from sandstorms.

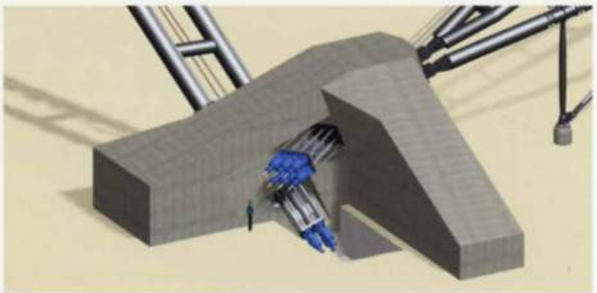
The surrounding flat terrain creates significant wind loading. Arup worked with the wind tunnel laboratory, BMT Fluid Mechanics Ltd in the UK, to discover the worst possible that could impact the roof; a total of 12 combinations of upward and downward loadings were determined as producing the most severe structural actions. These were measured via groups of pressure taps connected to give pressures over portions of the roof. This method produced an instantaneous distribution of wind loads, ensuring loading was not conservative.

Structural system

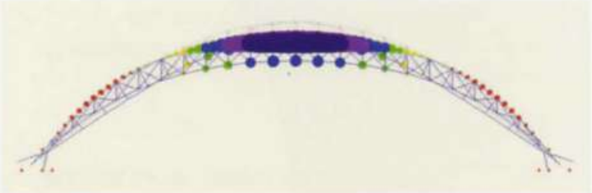
The main roof and lighting arch are independent structures , meeting only at the buttress supports (Figs 3, 4). To create such dramatic yet delicate structures with no obviously visible means of support, the team developed and analyzed cable systems in GSA using GSS *Relax* software. Form-finding was carried out on both structures to find the most efficient geometry and prestress field to ensure that they were stiff and able to resist the applied loads.

3. Stadium arches structure.

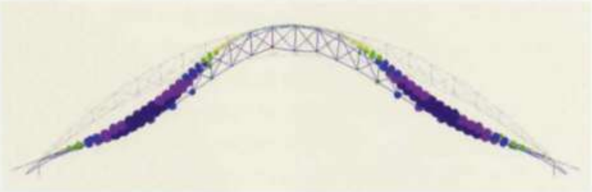




4. North concrete abutment and anchorage.



5. Lighting arch - Uniform compression buckling.



6. Lighting arch - push/pull buckling.

The major arches on both structures comprise pairs of circular hollow sections (CHS): 1.1m diameter and 3m apart on the lighting arch; 800mm diameter and 2.4m apart on the main roof arch, battened together with tubular cross-members to form vierendeel trusses. The "horizontal" roof arch is a single 900mm CHS.

The arches are not subject to uniform compression and have flexible restraint systems, so the appropriate effective length for design, in line with the codified axial capacity of compressive members, was not obvious. As both the lighting arch and main roof involve cable systems, linear elastic buckling could not be used. Using the GSS *Relax* solver, the buckling behaviour of the arches was investigated by increasing compression until instability ensued. Although the concept was simple, care was necessary to ensure that the stiffness of the restraint system remained unaltered and only the destabilizing force in each arch increased until buckling occurred.

A uniform compression (the severest axial force distribution) was used to establish the buckling capacity of each arch (Fig 5). A push-pull buckling, analogous to the flexural torsional buckling moment of a vierendeel arch, was also investigated and accounted for when making design checks (Fig 6).

Lighting arch

As its name indicates, the lighting arch supports an array of sports lighting, as well as a loudspeaker array. Lateral stability against the significant wind loading on the leaning arch is provided through a wing and flying cable system, which also serves to enhance the out-of-plane buckling behaviour. An underslung bowstring cable arrangement controls the in-plane buckling behaviour. Careful form-finding ensured that the cables would support the arch under dead and gravity loads, but then not overstress it and cause instability from prestressing forces (Fig 7).

Main roof

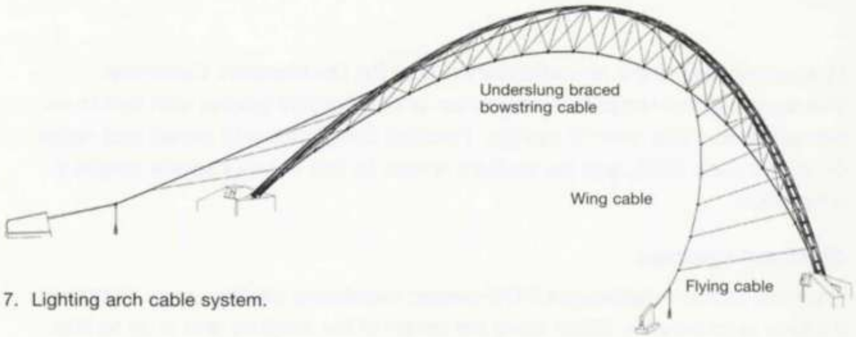
A series of radial cable stay/trusses, at 9m spacing, are secured on one side by the main catenary and on the other side by the main and "horizontal" arches. The geometry of the cables and main catenary was determined so that the stressing of the main catenary, to a final force of 18 500kN, pulls and secures these radial trusses into the roof shape, producing prestress forces and geometry so that the roof as a whole is stiff and able to resist variations in wind loads.

Variations in upward and downward wind loads are accommodated by redistribution of forces between the two arches, with minor change in cable forces and geometry (Fig 8).

As the main catenary and the arches meet at the same points, so the arch compression and opposing tension forces in the catenary could be balanced with no major loading on the foundation caused by eccentricity.

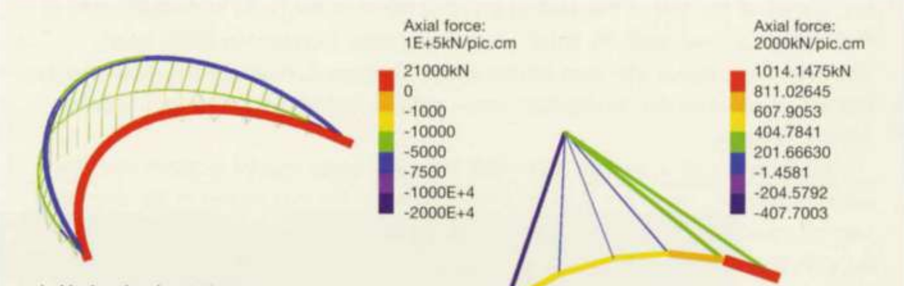
The arches are supported by a series of tapered struts, with X-shaped *Macalloy* bar bracing between them to add to the stability of the arches and roof. The use of tapered, cigar-shaped columns adds to the appearance of the roof floating above the seating with no visible means of support (Fig 9).

The tapered columns were initially sized in line with *BS5950*[1], where the capacity of such a member of varying cross-section is based on the properties of the member's minimum cross-section. However, an alternate method, originally developed in Arup, was also used to take advantage of the tapered shape of the column in determining its capacity, and ensuring an efficient design. A 15% reduction in tonnage of the tapered columns between tender and construction was achieved following this analysis/design process.

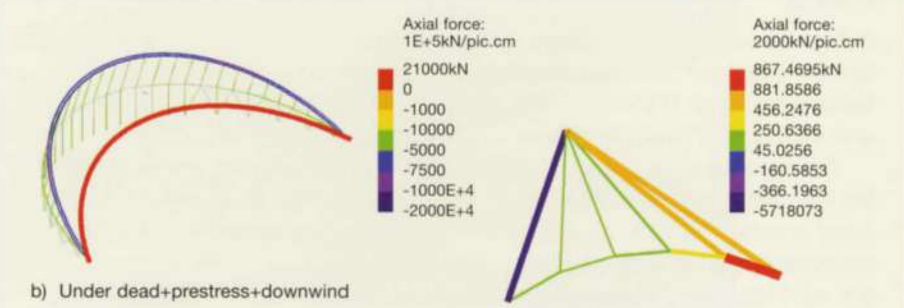


7. Lighting arch cable system.

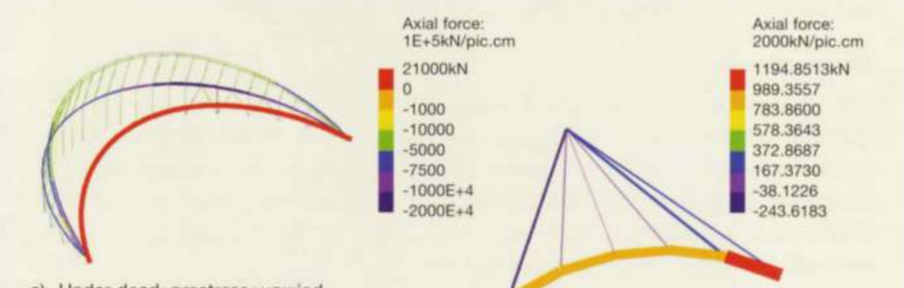
8. Main roof forces.



a) Under dead+prestress.

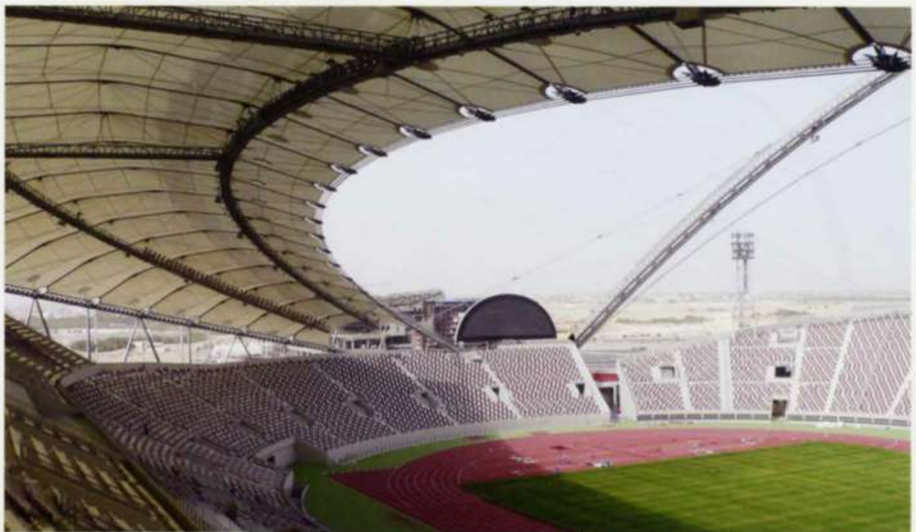


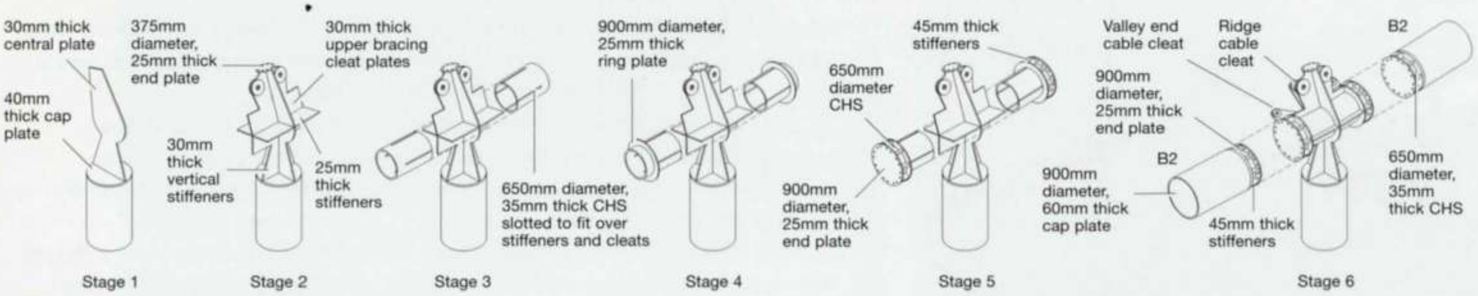
b) Under dead+prestress+downwind



c) Under dead+prestress+upwind.

9. Detail of PTFE fabric membrane roof.





10. Built-up construction produced from 3-D model.

Details

The architect specified that structural connections be attractive and striking in appearance, adding to the stadium's overall visual impact. Arup therefore worked with the architect to develop connections that were both efficient and matched the stadium's architecture, initially designing them with the aid of 3-D CAD and reviewing them with the architect. This process also allowed the main contractor - part of the client body - to understand the details and method of construction.

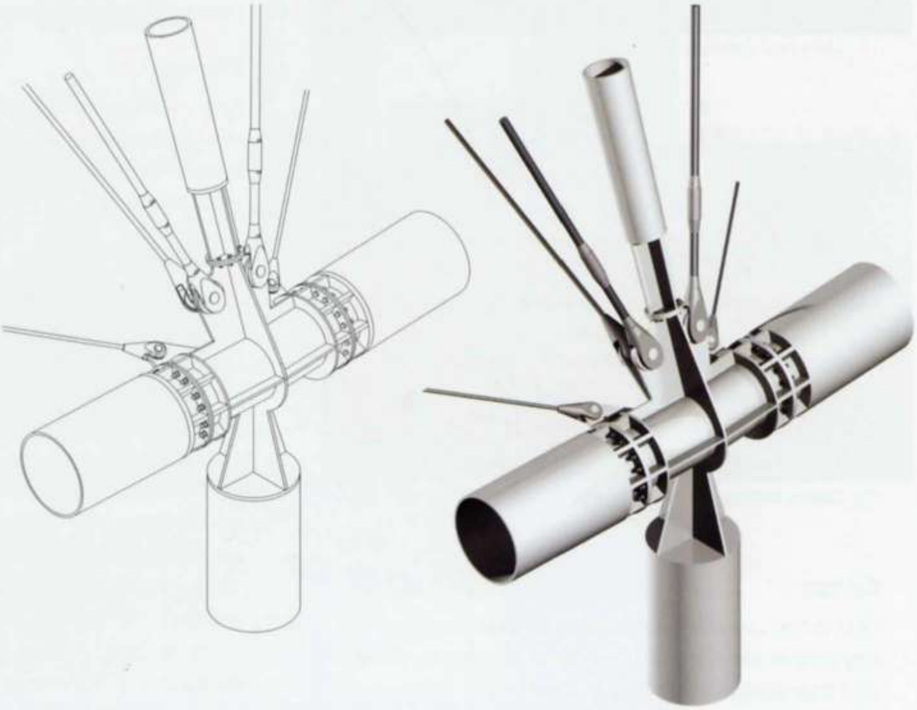
3-D drafting

Both the main roof and lighting arch were modelled using the Bentley *Structural* program, providing information during detailed design, fabrication and construction. It was an excellent means of communication of key details and structural logic to the client and project team. Due to the structure's geometry and the physical size of the members being connected, it was not enough to think of the structure in terms of a centreline model only.

Arup undertook extensive 3-D modelling of the structure to ensure connections were designed for the appropriate forces, looked good, and were buildable. The 3-D modelling allowed isometric views of the fabrication sequence to be generated, clearly showing the "build-up" of connections (Figs 10, 11).

With this accurate and realistic detail drafting, Arup could help the workshop with both connection details and the structure as a whole in preparing the fabrication drawings for this complicated geometry-dependent structure.

To check that the shop detailers understood the complex geometry, their *Xsteel* model was overlaid with Arup's 3-D CAD model, allowing any instances where the model and the geometry had been misinterpreted to be corrected; fabrication had to take into account both the initial and the final geometry after stressing. By confirming the validity of the shop detailers' model, more reliance could be placed on the shop drawings, ensuring fabrication matched design intent and any issues were resolved before fabrication and erection.



11. The erected detail.

12. Main roof catenary and ridge clamps.

13. Clamp testing.

Clamps

Due to the use of cables and their geometry, the key connections in this structure were the clamps and their design. Such clamp connection details are uncommon, and when used are often inserted to create a change in angle, acting as saddles rather than transferring a significant lateral load in the structure. Here however, in the main roof, it is the clamps that transfer the tension force from the inclined hangers to the ridge cables forming the roof, linking the main catenary to the roof's main compression arch. Some ridge cable clamps needed a total clamping length of 2.0m to be able to transfer the load from the hanger to the ridge cable (Fig 12).

The design used guidelines from both American[2] and European[3] cable codes as well as information from Arup Associates, derived from design of the City of Manchester Stadium[4]. Many factors affected the design and performance of the clamp details, strength/stress criteria needing to be met as well as those for set-out and geometry.

A key aspect of the design was the clamping force. This is critical to the behaviour/capacity of the clamp to resist lateral loading; if the clamp force is too low, the clamp will slip and be unable to resist the applied load; if too high the cable can be damaged. Aluminium cushions were used between the clamp and cable to allow a higher clamping force - and hence shorter clamping length - without damaging the cable.

Due to the variability and sensitivity of clamp behaviour, in particular the clamping force, to its design, full-scale testing was carried out by the cable manufacture on a typical lighting arch wing cable clamp to verify the design and clamping procedure (Fig 13).

At the completion of the project, Arup's Sydney office team was able to discuss differences encountered and additional issues, contributing to a technical note[5] produced from experiences on the Manchester and Khalifa stadia and others.

Erection

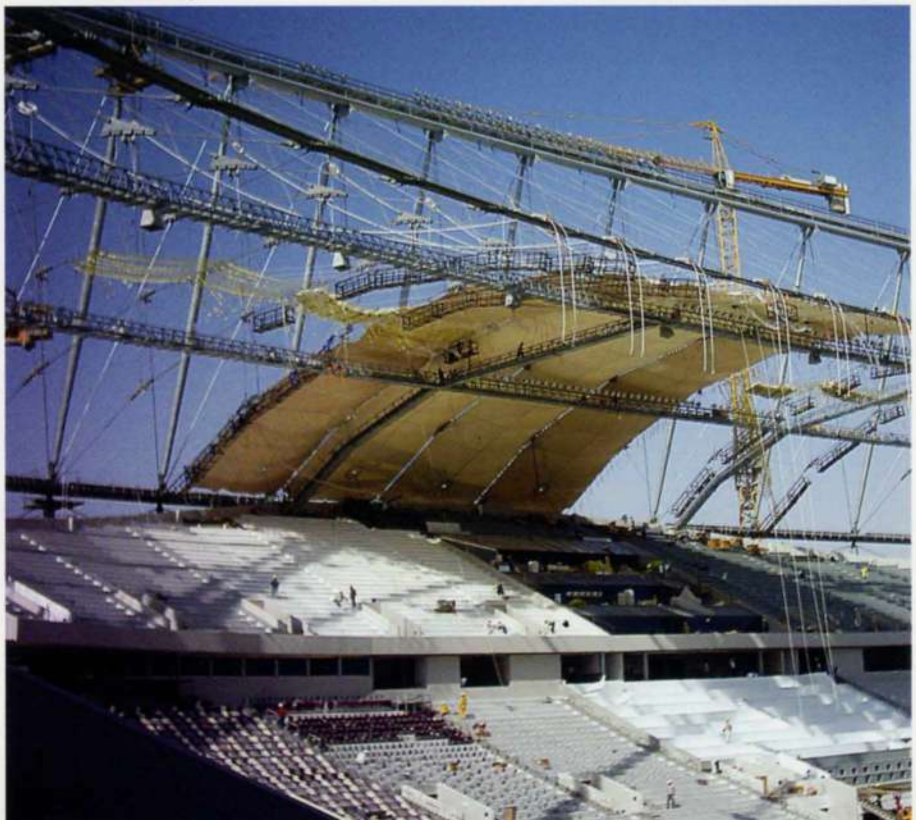
Arup produced an erection and stressing procedure for both the main roof and the lighting arch early on in the works, showing the contractor and client that such a structure could be built systematically whether they then chose to use that method or not.

Main roof

For such a complicated structure, the set-up of the main roof allowed for a relatively simple erection procedure. First the steel arches and tapered columns were erected, supported by temporary towers. Once the arches were complete the temporary structure could be removed, leaving the arch/column assembly as a stable structure. The cables were laid out and connected on the ground, allowing a trial assembly of the cable net to check its set-out before it was lifted and hung from the supporting steelwork. The roof was then simply pulled into shape by stressing the main catenary simultaneously at the two abutments. There was no adjustment on individual cables; the predetermined length of the cables and the roof geometry were such that when the correct force was achieved in the main catenary, the final geometry and prestresses were generated in the roof as a whole.

Once the roof cable grid was stressed, the fabric could be easily rolled out, stressed and connected to the supporting network of ridge and valley cables, completing the roof (Fig 14).

14. The roof being erected.



15. Erection: cables prior to stressing wing cable on the lighting arch.

16. The lighting arch supports an array of sports lighting, as well as a loudspeaker array.

Lighting arch

Arup skills were especially useful in erecting the lighting arch. Its stability depends on stressed cables and their geometry, in particular the bowstring catenary in the plane of the arch, and so before completion of stressing, the arch was very unstable and dependent on the temporary structure for its stability and flexibility (Fig 15).

Arup was not responsible for temporary works and erection. However, due to the structure's complicated non-linear behaviour, the team worked with the contractor to analyze and establish an erection sequence that would ensure that the structure was not undermined during erection and that the temporary supports could accommodate movements of the arch during stressing.

Once the steel arch was erected and the cables hung, a staged stressing of the wing catenary and bowstring catenary from the respective abutments was carried out following Arup's analysis and discussions with the steel erector.

A procedure was developed whereby successive steps in stressing were made, such that the arch just lifted from the supporting structure while still maintaining its stability. No jacking or depropping were required on the temporary towers.

Firstly the bowstring was stressed to a nominal force to ensure the arch was locked in and had some stability. The wing catenary was then incrementally stressed to its full force, taking the weight of the arch and lifting it from the supports.

Because the bowstring was only at a nominal force, the arch was held down on the central three temporary towers to provide arch stability at this intermediate stage. This also ensured that lateral movements of the arch were not excessive and could be accommodated in the temporary support system. Force was then jacked into the bowstring and the arch allowed to lift off the central towers. Once clear of the supporting structure, the bowstring continued to be incrementally stressed to its final force.

As well as the movements of the arch caused by stressing, the large temperature range in such a desert environment was also important in determining the movement and behaviour of the arch. As well as analyzing the structure and determining structural movements at each erection stage, its behaviour and movements at temperature extremes were also investigated at each stage. Such movements under temperature change were then used to further aid in removing the supporting structure. For example the wing catenary was

17. The official opening on 4 June 2005 with a celebratory soccer match.

stressed so that the final force was achieved near the middle of the day, at high temperature. This then increased the amount of upward movement of the arch, allowing the immediate temporary supports under it to be removed more easily. Stressing created horizontal and vertical movements up to 250mm, while temperature contributed movements of 200mm horizontally and 120mm vertically.

In the end the stressing procedure took place smoothly and the structure behaved as had been predicted, making the procedure and the work done by Arup prior to it a success.

Opening

The stadium was officially opened on 4 June 2005 with a celebratory soccer match - which Qatar won (Fig 17). Since then it has been used for soccer, but for the international setting of the 2006 Asian Games it will function as a world-class Olympic-standard stadium. For its contribution to the design of the Khalifa Stadium, Arup was awarded the 2005 Association of Consulting Engineers Australia Award for Excellence, Gold Award of Merit, in the category of International/Export Projects.

Tristram Carfrae is a Main Board member of Arup and a Principal in the Sydney office of Arup's Australasia region. He was project director for Arup of the Khalifa Stadium.

Peter Macdonald is a Senior Associate in Arup's Sydney office. He is head of the Structures Group in Sydney and was project manager of the Khalifa Stadium.

Jane Nixon is a structural engineer in Arup's Sydney office, specializing in lightweight structures and their defining geometry.

Credits

Client: International House General Trading in association with Midmac Contracting and Six Construct (main contractor) on behalf of Khalifa Sports City Development Committee **Architect:** Cox/PTW in association with GHD Qatar **Structural engineer:** Arup – Tristram Carfrae, Jianha Ding, Stuart Jones, Steven Lindsay, Peter Macdonald, Daryl McClure, Simon Morley, Bill Newton, Jane Nixon, Steve Pennell **Project manager, acoustic and lighting designer:** GHD **Steel contractor:** Eversendai **Steel shop drawings:** Seacad **Steel manufacturer:** Cleveland bridge **Cable manufacturer:** Wire Rope Industries **Fabric specialist:** Birdair Corp **Cable erector:** Pfiefer **Illustrations:** 1 Midmac/Sxco; 2 BMT; 3, 4, 7, 10 Arup 3-D drafting; 5, 6, 8 Arup GSA analysis; 9, 12, 16 Peter Macdonald; 11, 13- 15 Jane Nixon; 17 GHD

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Singapore's new National Library

Russell Cole Andre Lovatt Mani Manivannan Alan Newbold Jim Read

Singapore's National Library embraces innovations in information and communications technology, building physics, fire, and façade engineering to create a knowledge hub for the 21st century.

1. The new National Library building in Singapore.

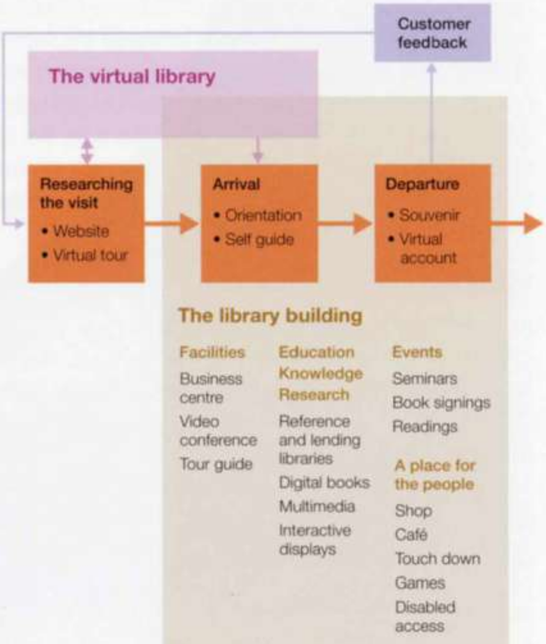
Introduction

Singapore's National Library Board (NLB) is a statutory government organization globally respected for achievements in modernizing its public libraries. It operates 24 libraries across the island including the National Library, formerly housed in a much-loved but small brick building close to Fort Canning. In the late 1990s the NLB determined on building a new National Library to meet Singapore's aspiration as a centre for knowledge, learning, and technology - a state-of-the-art facility that combined a building for the tropics with the latest information technology.

The Singapore government, keen to lay the foundations for a 21st century knowledge-based economy, initiated the "*Library 2000* vision" in the mid-1990s, as a part of structural changes that would safeguard the future competitiveness of Singapore's economy. During the project's concept stage the then NLB Chief Executive, Dr Christopher Chia (holding a PhD in information technology), was tasked with achieving the vision and objectives set out in the *Library 2000* document. He promoted a new landmark National Library building as the key facility for realising those objectives.

Whilst an architectural statement was needed to connect with the citizens of Singapore, the contribution of technology to the success of the transformation project was given very high prominence. This focused on improving services to all types of library users – young and old, students and professionals - by giving access to patrons through both virtual and physical media, and at the same time reducing operational costs (Fig 2).

2. The visitor journey.



Traditionally, libraries are thought of as learned, academic, and rather stuffy environments. The vision here was to redefine the services offered and change the way they are delivered, and the NLB believed the solution lay in adopting innovative technology to bring a new learning experience to Singapore's citizens.

Named after Dr Lee Kong Chian, in honour of the Lee Foundation's S$60M donation, the reference library aims to be the premier research and academic resource on Singapore and the region, occupying Levels 7-13 at the NLB building, with a floor area of 14 265m^2. By July 2005, when the new building opened, the collection exceeded 530 000 print and non-print materials. The library's full range of services includes reading/meeting rooms, wireless access to the internet, access to electronic databases, document delivery, microfilm, reprography, and audiovisual resources.

The new facility is not only an impressive reference (and lending) library but also seeks to be a focus for national events and social activities, with a 615-seat concert-grade auditorium, 14 sky gardens, and a roof-top observation pod (Fig 3).

Arup involvement

A consultant consortium led by the Malaysian-based architectural practice TR Hamzah & Yeang (now Llewelyn Davies Yeang) won the design commission early in 1999, and Arup's involvement dates from the same year. In December the communications group, based in London, was appointed by the NLB of Singapore as information and communications technology (ICT) consultant. The façade design involvement that stemmed from the consortium's competition win became, in 2001, a direct commission for Arup's façade engineering team in Singapore itself.

For the communications group this was a milestone win - the first assignment where it could offer a fixed-price tender for a long-term project without its staff being locally resident. Planning the bid response, collating relevant content and working up a financial model that factored effort, risk, and expenses over a period of four years (in the end six years) was a challenging task. After award of contract, the client praised the quality of the bid response, the range of skills and experience, the reference projects, and the understanding of the NLB's functional requirements in the context of a large construction project. Though Arup did not bid the lowest price, the team was determined to add significant value in the NLB's quest to lead in technology-based service delivery at the new library, interpreting the client's vision with creative yet practical ideas. Of particular value was Arup's international experience in procuring and deploying business-centric ICT solutions.

As for the façade design commission, during the development stage Arup worked closely with TR Hamzah & Yeang to develop the design and find solutions that maintained the design intent, achieved the technical performance requirements, and were practical. This last aspect was a particular challenge because of the envisaged ambitious form of the building. Arup was responsible for preparing outline designs and specifications for the tender package for the develop and construct main contract, and was a major participant in the client's tender review panel that eventually selected the main contractor Nishimatsu Lum Chang Joint Venture (NLCJV).

The ICT design

An early challenge facing the communications team as it joined the project at scheme stage was to add innovation and value to the design proposals for technology systems. The team was asked to create and test concepts for several systems integration and intelligent building opportunities that would improve staff and visitor experiences.

In meeting this challenge, the Arup team was able to draw on extensive experience of both architectural and construction-facing aspects of ICT design, procurement, and delivery in offering its advice.

RFID and interface between CCTV and IP network

One of the first major ICT projects that the NLB implemented, and in which it currently leads the way globally, was RFID (radio frequency identification) tagging. All NLB books in Singapore have a discrete passive RFID device to enhance four key library processes. This:

- eliminates the need for staff to be present for a patron to borrow or return a book (Fig 4)
- minimizes the time between a book's return and it being back on the shelf for others to borrow
- eliminates the need for a patron to return a book to the same library it was borrowed from
- improves security of the books - the NLB's most valuable asset.

A big problem with Singaporean libraries is their very popularity. To enable patrons to see the build-up of queues and the number of people in the library from its website, and without installing additional cameras, 32 analogue security cameras feeds that would not impact the integrity of the security system were selected and fed into multiple axis digitizers and then output through the IP network to the web portal.

3. The roof top observation pod.

4. The new automated borrowing stations.

5. The nGuide PDA in use.

6. The virtual tour.

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Venue : Lee Kong Chian Reference Library - Level 5 - Possibility
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Admission : Free admission

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7. Researcher portal.

Customer experience enhancers

Another challenge tackled by Arup was the NLB's requirement for its patrons' library experience to be enhanced. Arup's research & development group was commissioned to come up with some innovative ideas. These included concepts for capturing and visualizing, through devices like infrared motion sensors and computerized virtual networks, the movement of people and the patterns of their usage of the library's various services, and for personalized interfaces for users with the library. From these concepts came four major work streams aimed at providing IT solutions to meet the following NLB requirements:

nGuide: To enable NLB staff to give organized Library tours to visitors and VIPs, an "eControl" application was developed for remotely controlling all plasma displays individually via personal digital assistants (PDAs) connected to the WLAN (Fig 5). This enables tour guides to toggle content between dynamic signage, corporate presentation, video, and digital audio to match their verbal commentary as they follow the tour route. It can also identify immediately when additional stops are available on the tour whilst giving the latest commentary to the guides to update them on changes as they occur in real time.

Virtual tour: One of the hardest challenges was to make as much content as possible available via the internet, giving as many users as possible access to the Library's unique collections. Unfortunately copyright legislation has meant that this project is still ongoing. However, to give internet users some experience of the Library, a virtual tour at http://virtualtour.nlb.gov.sg/ provides a snapshot of the building's unique architecture and describes some of its facilities (Fig 6).

Researcher portal: One principal focus of the Library is the 500-1000 world researchers that come to the Library every year as part of an international research project. To facilitate access to the information they need, NLB required some specific portlets to be created. These give researchers a toolbox of resources, including access to premium databases and knowledge repositories as well as limited virtual storage for internet search results and other electronic data. In turn this led to redevelopment of the LKCRL and NLB websites at http://www.nlb.gov.sg (Fig 7).

iSouvenir: This kiosk (Fig 8) was designed for patrons to take something away with them as a souvenir of their visit. This included being able to print off bookmarks and send e-postcards or photographs to their friends. On opening day this proved to be one of the most successful additions to the library - the printer ran out of paper within an hour!

8. The iSouvenir kiosk.

9. The main server room.

10. In the large triple-height spaces of the library, the mobility afforded by wireless devices is important.

Next generation infrastructure

MPLS LAN: To support these applications, plus the other essential databases and NLB enterprise applications, all information is routed across a single NLB-owned IP infrastructure. Before the library opened, all the NLB central servers and core equipment was at the Network Operations Centre (NOC) in east Singapore, but having considered the implications for disaster recovery, security and risk of this set-up, Arup proposed to use the new Library's main server room (MSR) as a resilient hub for the NLB central servers and core equipment (Fig 9). Today, all the other 22 libraries are connected into the MSR and NOC through a diverse MPLS IP carrier grade network. Each server is also set up for full resilience should either the NOC or MSR fail. During commissioning of the IT infrastructure, a full power shut-down of the building was performed to make sure that the failover to the NOC would work under real fault conditions.

In addition to the MPLS core, the NLB had an extensive Cisco gigabit Ethernet network installed, able to provide fixed connections to the users at up to 1Gb/sec. This IP network has resilient connections to Singapore ISPs from opposite sides of the building.

Wireless LAN: One of the newest infrastructure elements to be installed is the extensive NLB-owned wireless LAN. This provides connections at up to 54MB/sec for NLB staff to their corporate services from anywhere in the library, and free internet access for users from any public area. About 100 hidden dual-standard access points in the ceiling connect into two resilient connected wireless LAN controllers supplied by Aruba Networks. This infrastructure is also used for additional services to NLB staff and the public, eg the nGuide application described earlier.

Cabling infrastructure

Due to the unique requirements to serve not only the NLB but the Drama Centre and other tenants' different ICT services, and the important regulatory restrictions in place for a Singapore government statutory body, three different cabling infrastructures were required. To provide connectivity to the various end devices about 6500 Category 6 ICT outlets were installed in various locations:

- in ceilings, for initial and future wireless LAN connectivity
- a "grid and grommet" solution on all library floors to give flexibility to change the floor layout, redo the ICT cabling, and eliminate intrusive and easily damaged floorboxes
- on all public-facing desks to enable patrons to access the free intranet services and the internet
- additional ICT outlets and wireless connectivity in all conference facilities and meeting rooms
- specific outlets to service the PA and RFID systems, and provide connectivity to the multimedia stations, kiosks, borrowing stations, and electronic catalogue search stations.

As well as the Category 6 cabling system, a supplementary Category 3 system was installed, terminating in different risers and a different central copper exchange for provision of a Centrex telephony service to NLB itself, and external connectivity from public telecommunications operators to other tenants of the building.

Finally, a coaxial-based distribution system was installed for the master antenna television system to distribute free to air and subscription television services to NLB and the tenants within the building from the television providers in Singapore.

11. Information counter: an essential and easily accessible resource for using the reference library.

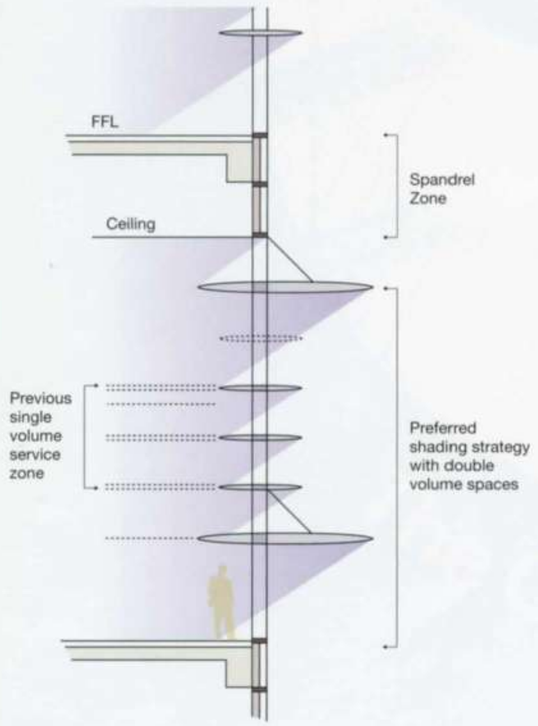
The façades design

After award of the façades contract, Arup's role was to review the designs, fabrication, and installation. This involved working closely with the specialist sub-contractor on its designs, assisting with co-ordination issues, and working through the proposed details.

With the key need to support the architectural design intent, Arup reviewed the proposed materials and resolved the various interface and co-ordination issues with other elements and trades. For its part the contractor's team had to meet the demands of the performance specification. A large full-size mock-up of the façade was assembled to finalize the position of joints and selection of materials - the glass in particular.

Design for tropical conditions

The library has a commanding presence in the Bugis–Bras Basah district of central Singapore, with its predominately white structure and surrounding shades. This is partly because the parameters set for the design team ultimately inspired and drove the architectural outcomes. The building had to be able to respond to the tropical climate. Solar heat, humidity, and light could potentially make it very uncomfortable for its occupants and threaten the important collection. The façade design was crucial in both respects.



12. Cross-section through sunshades.

13. Exterior sunshades in place.

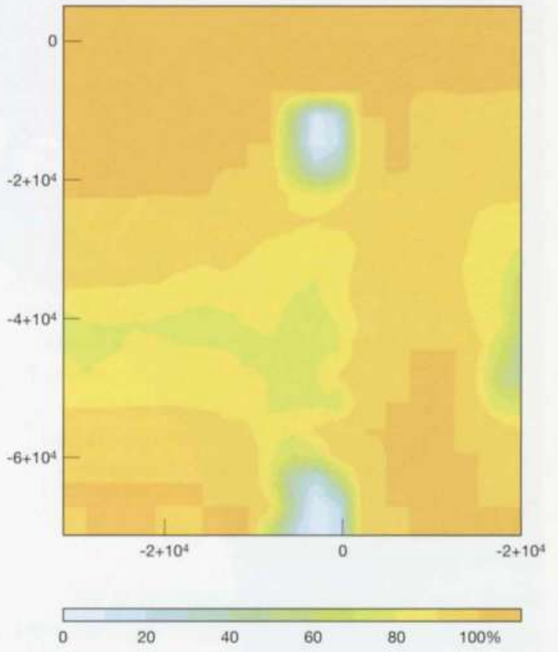
The building had to be heavily shaded to reduce solar heat gain through the façade, and so a 30° solar cut-off was adopted, ie there should be no direct sunlight visible in the building when the sun was 30° and more above the horizon. This gave the design team an unusual challenge: though almost no direct sunlight should enter the building between 10am and 4pm, as much useful daylight as possible still had to penetrate so as to allow artificial light to be reduced.

In response, the team designed what are probably some of the world's biggest sunshades on a curtain wall, projecting up to 1.8m from the face of the glass (Figs 12-14). These wrap around the building and control solar radiation and glare, yet maximize daylight. To speed installation and to avoid the difficulty of fixing in mid-air, they were attached to the curtain wall before erection. The need to support the sunshades and the 5.4m storey height led to the curtain wall mullion being 250mm deep - the maximum available for most aluminium extrusions.

It was accepted that part of the shades could be located inside the building as these would also cut the sunlight, but any energy in the radiation that had passed through the solar selective glazing would still enter the building. Several studies of window height and shade spacing were conducted to determine the best option. Eventually, a general vertical module of 1.1m was adopted with a 2.2m module closest to the floor. This generated shades up to 2.4m wide, with a 1.2m shade inside.

For the typical curtain wall panels, these shades were supported by deep steel plates projecting out of the aluminium mullions, in combination with tie rods. These were added at site, allowing the panels to be transported flat. Each shade had the same basic construction but the form was modified to create the intended sweeping lines. Clear double-glazing completes the façade, coated to cut down on energy transfer from solar radiation and ambient temperature. A visible light transmission that avoided glare problems was selected.

14. Interior sunshades in triple-height space.



15. Daylight autonomy map showing probability of daylight exceeding 250 lux.

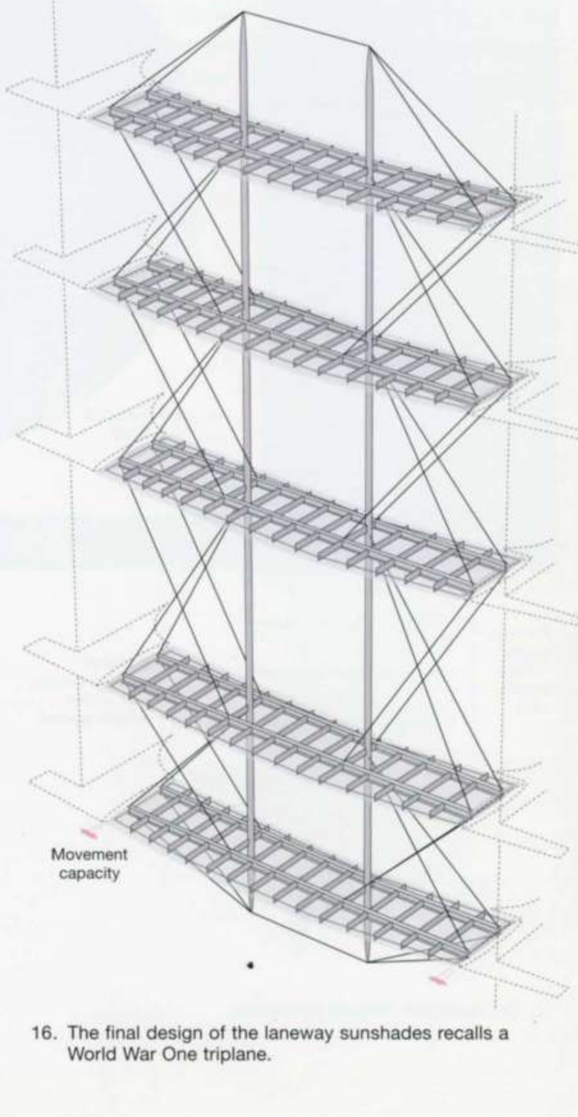
Some areas of the building have automated drop-down blinds that engage when the sun is too low for the sunshades to be effective; a daylight autonomy map (Fig 15) predicts that these will be needed for at least 2% of the year. (Daylight autonomy is the percentage of occupied times per year when the minimum illuminance level can be maintained by daylight alone.)

Laneway sunshades

The pattern of shades continues around the building. Between the two main blocks, they span up to 6m wide and 14m long, but only 400mm deep. Together with natural breezes, the shades here create a dramatic enclosed environment which, though in a humid tropical climate, remains comfortable.

From the start, the architect conceived these shades as being tied together by pairs of vertical tubes that do not reach the ground; and, as the shades are a continuation of the main shades for the curtain wall, they need to be as thin as possible. The structural concept developed into a floating framework of steel frames supported on bearings on the main blocks each side of the laneway. Diagonal ties were added, and the final arrangement is reminiscent of the wings on a World War One triplane (Figs 16, 17).

A complex arrangement of bearings restrains the suspended shades laterally and supports them vertically, but lets them articulate on plan and not tie the bundings together. To minimize the size of these articulated joint to account for building movement, one was to be put at each end of the sunshades, but during development of the final detail by the specialist subcontractor, the joint locations were studied further and it was decided to fix one end of the shade and let the other float. Nonetheless, the thin overall sections were maintained, resulting in a dramatic structure to enclose the laneway space.



16. The final design of the laneway sunshades recalls a World War One triplane.

The beauty of glass versus the challenge of light

The entire façade is glass. Considering the local environment, and the goals the design team was determined to meet, its selection and properties were critical to the building's success. The main contractor undertook a comprehensive study in which the visual light transmission of the glass in combination with the position of the shades was checked using a complete three-dimensional model of the building. Arup analyzed the process and its results in detail. The design intention was to use clear double-glazing, and the study verified that visible light transmission would be acceptable, but that some small adjustments to the shading arrangement, duly implemented, could produce even better results.

Thermal flows through the aluminium sections and the acoustic performance of the façade were also assessed in detail - leading to further refinements - but the biggest impact on the final shape of the extrusion came from incorporating conduit paths to the external lighting in the sunshades.

Testing the design

With the design finalized and custom aluminium extrusions in production, performance prototype testing on the curtain wall system ensued.

The test specimen was 10 full panels in two rows and a strip of half height panels. Assembling a full section of the curtain wall also allowed the architect to fine tune the design, and the contractor to trial production and installation methods. This demonstrated that the contractor's design met all the various strength, waterproofing, and air infiltration requirements. After the main test, panels were used to resolve a design issue as described below.

The library needs to be a quiet place, so the curtain wall was also subjected to acoustic testing, both for transmission of sound into the library spaces and to review the noise from rain falling on the aluminium sunshades.

17. Sunshades in position in the laneway.

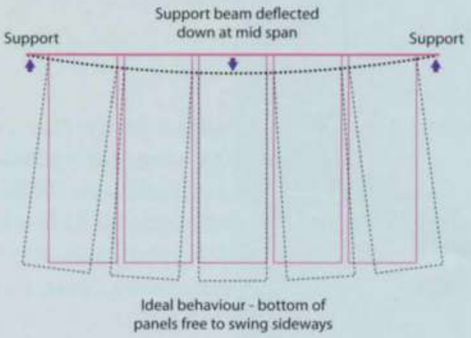
The curtain wall - straight lines or stress-free deflections?

During design development, the sub-contractor suggested a restraint to the bottom of the curtain wall panels, and so a clip was proposed in the cavity of the interlocking sill at the bottom of the prefabricated panels.

Although this would make aligning the panels easier, there was concern that it would prevent free movement and create stresses in them, leading to tears in the sealant or structural failures. Five panels from the prototype test were, therefore, suspended from a steel beam (representing the floor slab), and after a survey of their position and the joints, the beam was deflected and the panels' new position found.

They were expected to fan out, remaining square, with the slope of the top edge following the relative height of the brackets at each side (Fig 18). The restraint in the joint affected the panels, which now rotated, tipping the fixed bottom corner. The result was that the critical seal between panels was distorted increasing potential for leakage.

The joint was thus detailed to allow free movement and the panels' alignment achieved with care during erection.



18. Panel behaviour.

As production got under way, Arup team members visited the subcontractor's fabrication plant to review his progress and crosscheck his QA/QC procedures. Finally, the panel installation was inspected, including defect monitoring to ensure quality throughout the process.

Maintaining an icon for the long term

Given the building's unusual form, a full range of access equipment was needed. The main building maintenance unit is a gondola suspended from a monorail running around the underside of the roof level shading. To clean the glass between the shades, the gondola incorporates a pantograph system with counterbalances that positions the operators 500mm from the glass face. There is also capacity to carry the glass panels not accessible from the inside. Elsewhere on the building, access is provided to walkways with safety lines to allow cleaning and maintenance.

19. Opening celebrations, November 2005.

Conclusion

The Singapore public's enthusiasm for the new library was demonstrated at the "Soft Launch" on 22 July 2005 when many people queued for hours before the 10am opening. On the first day there were 40 000 visitors, with 14 000 of them visiting the lending library and borrowing 12 000 books! Four months of consolidation followed, as staff, contractors, and consultants completed the final fit-out works ready for the official opening ceremony on 12 November in the presence of the President of Singapore (Fig 19).

In the same year The National Library won the platinum Green Mark Award, the Building Construction Authority of Singapore's highest honour for environmentally-friendly buildings. Buildings which have achieved the Green Mark Award are recognized for their sterling efforts and commitment towards environmental sustainability. In general, Green Mark buildings have adopted energy-efficient features and water conservation measures which set them apart from other buildings. They have also made substantial use of greenery in their projects and taken care in ensuring a good indoor environment quality for their users.

The National Library obtained the Green Mark Award for:

- initial design studies including computer stimulation and modelling to optimize the building orientation to protect from direct solar radiation and to maximize the use of daylighting and natural ventilation
- sunshading providing an additional shield against solar heat gain
- energy-efficient features including lighting, motion sensors, and equipment; daylight sensor used together with automatic blinds at the building façades
- extensive landscaping, sky terraces, and roof gardens to lower local ambient temperatures and the adoption of automatic irrigation system for rooftop gardens to conserve water
- automatic integrated daylighting zoning and control using daylight sensors.

Fire engineering design

Arup's fire engineering group was engaged by NLCJV to assist with its bid for the main contract, and Arup's proposal to eliminate large proportions of the fire protection allowed NLCJV to submit the significantly lower price that helped it win the project. As a result, the National Library is one of the first buildings in Singapore to have performance-based design of its structural steel fire safety.

Traditionally, structural steel beams are coated with sprays, boards, or paints for fire protection. This can be expensive, and requires maintenance throughout the building's lifetime. Arup's design allowed for most of the steel floor beams to be either unprotected or to have reduced applied fire protection, while maintaining the building's structural stability in a fire. This enabled the bare steel structure to be expressed and enabled cost-effective construction of the building.

The performance-based solution also allowed the two blocks to face each other with no additional fixed fire protection systems. The authorities were initially concerned that a fire in one block could spread to the other, but Arup demonstrated this would not occur and eliminated the need to install additional fire protection measures.

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Jim Read is an Associate Director of Arup in the Communications London Group

Credits

Client: National Library Board of Singapore
Architect of design: TR Hamzah & Yeang Sdn Bhd
Engineer of design: Buro Happold Singapore Pte Ltd
Communications and IT services, façade, and fire engineering designers: Arup - David Barber, Michael Chin, Russell Cole, Ben Coulson, Daniel Davis, Ran Fan, Liew Kim Hoe, Rajan Janakiraman, Peter Johnson, Richard Johnson, Aditya Kapoor, Ken Kilfedder, Ada Law, André Lovatt, Chris Luebkeman, Mani Manivannan, Tom Mason, Robert Morgan, Graham Naylor-Smith, Alan Newbold, Pecksuan Ng, Jonathan Peats, Stephen Phillips, David Proe, Kash Qadeer, Mohan Raman, Jim Read, John Ryder, Sam Shemie, David Smith, Justin Trevan, Duncan Wilson, Ruth Wong, Joanne Woo **Project manager and quantity surveyor:** Rider Hunt Levett & Bailey **Design and build contractor:** Nishimatsu-Lum Chang JV **Project architect:** DP Architects Pte Ltd **Project civil/ structural engineer:** Maunsell Consultants (Singapore) Pte Ltd **Project M& E engineer:** Beca Carter Hollings & Ferner (SE Asia) Pte Ltd **Specialist façades subcontractor:** Permasteelisa Group
Illustrations: 1, 3, 20 Arup/KL Ng Photography; 2, 12, 15, 16, 18 Nigel Whale; 4, 9 Alan Newbold; 5 Teik Tian Seah; 6, 10 Jeffrey Ng; 7, 8 Singapore National Library; 11, 19 Jim Read; 13, 14, 17 Russell Cole.

20. The Singapore National Library at night.

ARUP

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Arup is a global organization of designers, founded in 1946. It has a constantly evolving skills base, and works for local and international clients throughout the world.

To celebrate its 60th anniversary, Arup is partnering with the international charity WaterAid in a new initiative, The Arup Cause, which focuses Arup's mission to "shape a better world" on the provision of safe domestic water, sanitation, and hygiene education to the world's poorest people.


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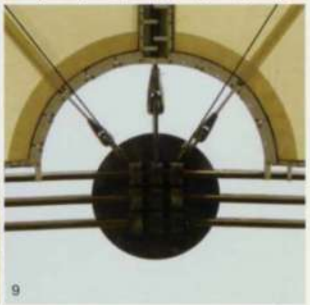
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Front cover: Hudson River Park is New York City's most significant park development in decades: Luca Vignelli/HRPT

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thearupcause
celebrating 60 years of shaping a better world