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The Arup Journal

Contents

1.

Arup engineered one of the largest roofs in the world to create column-free spaces for the platforms at Beijing South station.

Beijing South railway station

Location
Beijing, China

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Introduction

Beijing is one of the world's oldest cities. It was planned as a hierarchy, with the Emperor's Forbidden City at the hub, and progressive outer concentric "rings" based on the cardinal points. Intersecting roads lead to a fairly rigid north-south/east-west planning grid.

Beijing South, one of the capital's six major rail stations (the others are Beijing Main, Beijing North, Beijing West, Hepingu, and Guang'ammen), lies between the second and third ring roads in Fengtai district (Fig 2), some 0.5km from the old station that it supersedes. The new station is contained within one of these "square" grids on 94ha of gazetted railway land, occupied by existing tracks on a diagonal south-west/north-east axis, some 6km south of the Forbidden City.

Beijing South station (BSS) also lies roughly 3km south-west of the Temple of Heaven complex, the proximity of which was to have a bearing on the visual appearance of the main canopy roofs.

Awards
Royal Institute of British Architects (RIBA) International Award 2009

American Institute of Architects (AIA) Hong Kong Chapter Merit Award for Architecture 2009

British Construction Industry Award (BCIA) International Finalist 2009

World Architecture News (WAN) Urban Design Awards Finalist 2009.

BSS is immense, one of China's (and Asia's) largest railway stations, with a total gross floor area of 144 190m². It caters for suburban trains within greater Beijing, regular-speed trains to numerous mainland cities, two underground mass transit lines (4 and 14), and high-speed trains to other cities as far south as Guangzhou and thence to Hong Kong*. Accommodating 450m high-speed and 550m suburban trains, the roof covers some 125 000m² – Beijing National Stadium[1] would be easily contained within the footprint (Fig 3).

An elevated road encloses the central check-in and departure hall (which can accommodate a peak of 6500 passengers) and serves as the arrivals and drop-off route for road transport. Beneath, at street level, are 11 island and two side platforms giving 24 platform edges, designed for a passenger throughput reaching almost 105M per year by 2030, equating to daily flows of 286 500 and peak hourly flows of 33 280 passengers. Flexibility in the overall planning allows for increased peak flows at festivals such as Chinese New Year and Golden Week.

Beneath the platform zone at the first basement level is the interchange hall, catering for some 87 000 people per day transferring to other transport modes such as taxis, buses and private cars. There are 52 taxi pick-up and drop-off bays with 138 queuing spaces, 38 bus bays with 48 queuing spaces, and a 909-space car park.

Below again are the two mass transit lines, each with a 120m long island platform arrangement skewed to the at-grade railway lines.

1 (Previous page). Beijing South station complete, June 2009.

2. Location of Beijing South station within the city's planning grid.

3. Overall station plan, with Beijing National Stadium for comparison.

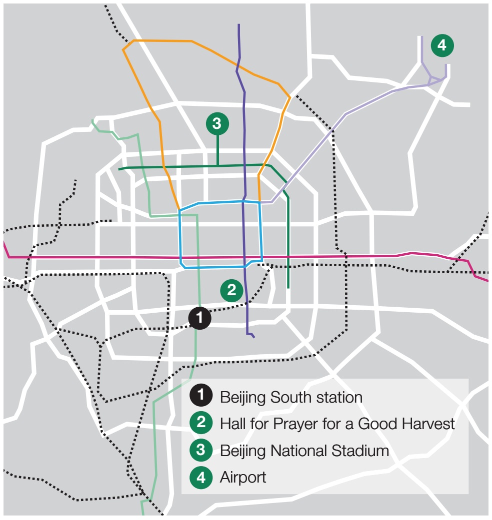
4. The "Hall for Prayer for Good Harvest" at the Temple of Heaven complex.

Background/competition

To provide a multi-modal transport service in time for the 2008 Beijing Olympics, in October 2003 the Chinese Government's Ministry of Railways (MoR) announced an international competition to redevelop the site, an initiative aimed at bringing a modern flavour to this very important addition to the capital's railway infrastructure. Terry Farrell & Partners, now TFP Farrells (TFP), was invited by the Third Survey Design Institute (TSDI) from Tianjin to collaborate for a three-month competition period. TSDI/TFP's station layout resolved the conflict of the square/diagonal axis by covering the platforms with a large low-rise domed roof some 400m in diameter.

In March 2004, the TSDI/TFP team was placed first out of five international design firms and then short-listed with two other design teams to advance to a second stage competition. This commenced in May 2004 and TSDI/TFP's roof was revised to an overall elliptical shape, split into two halves by a 100m wide glazed central section. Submitted in July 2004, this scheme won first prize but received comments and suggested design refinements from the MoR, requiring TSDI/TFP to incorporate further traditional Chinese architectural motifs, expressed in a contemporary manner.

The resulting roof silhouette was inspired by the tiered roofs of the "Hall for Prayer for a Good Harvest" in the Temple of Heaven complex (Fig 4), built during the reign of Emperor Zhengtong (1436-1449). Elevated on three white marble circular terraces, the temple has a triple set of conical roofs over a round building – a form unique in Chinese architecture. This new roof shape for BSS gained MoR approval, and TSDI/TFP set about the challenging task of preparing the overall station design for rapid completion in time for the 2008 Olympics.



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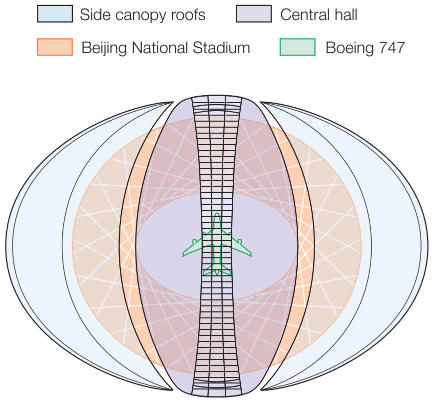

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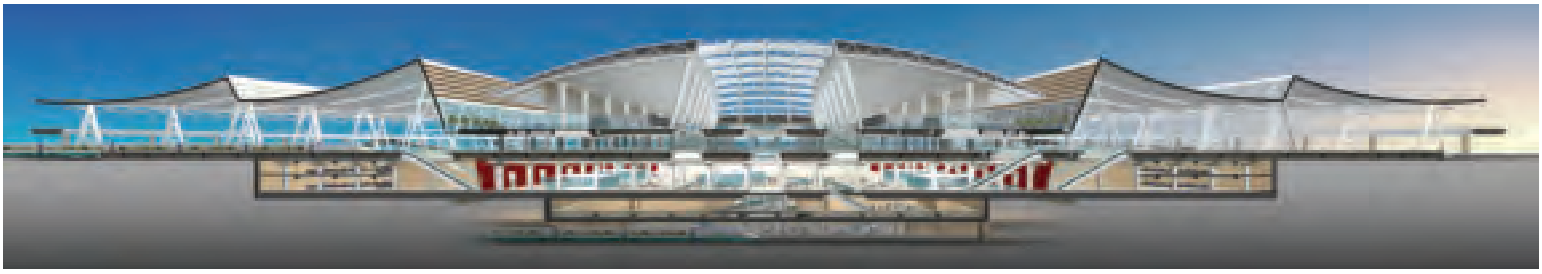
*The Hong Kong section known as the XRL (Express Rail Link) is a Hong Kong government-funded 26km wholly underground twin-tunnel project, currently under construction with a planned completion date of 2015. Arup has been involved from the beginning, completing the feasibility study in 2007 with further commissions won in 2008 and 2009 for the preliminary and detailed design of the tunnels and stabling depot.



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Arup's involvement

In early 2005 TFP and Arup had initial discussions about collaborating on aspects of the Beijing South station structure and internal environment. Arup's catalogue of large-span complex roofs, particularly for sports venues, stretches back for decades, but extremely long spans over rail stations are relatively rare in the firm's portfolio. The opportunity to collaborate on this project, particularly the roof, was quickly taken up, while commercial negotiations took place between TFP, TSDI, and Arup.

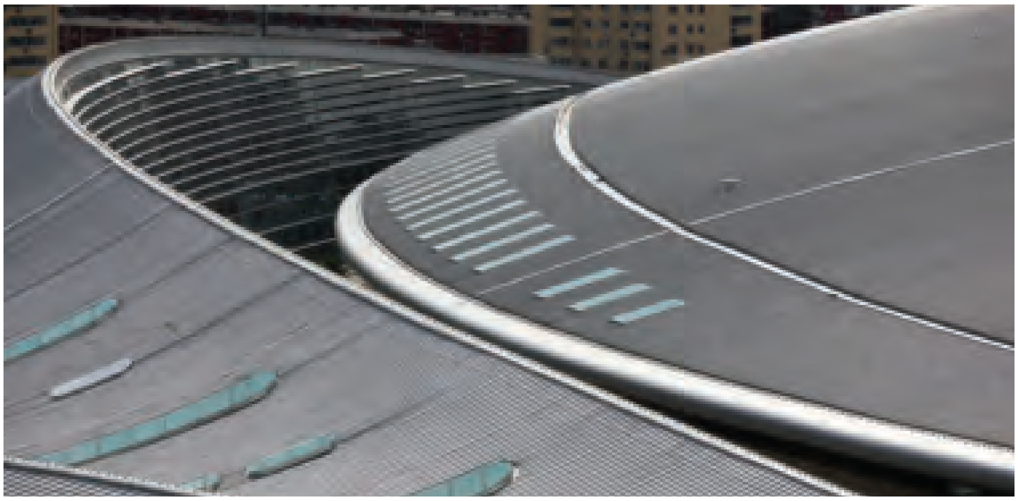
Initially, Arup's remit was for the structural, mechanical, electrical, and public health (SMEP) engineering design of specific areas (track level, concourse, and roof) up to the preliminary design stage, with a design review and checking role during construction.

This scope of work developed to include other disciplines and involvement on building physics, fire, and wind engineering, and Arup formed a multidisciplinary team of engineers from its railway, fire, building physics, and MEP groups in Hong Kong.

After three months' intensive design co-ordination, the international design team produced the initial scheme report, detailing the consolidated architectural concept supported with sound engineering ideas and details for the specific constraints identified for this project.

In January 2006, with TSDI as the lead consultant, Arup was formally commissioned for:

- preliminary and detailed design of the structure for the canopy roofs
- performance-based fire engineering
- special studies for various building physics topics.



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The firm's Sydney and Beijing offices were then involved in refining respectively the structural scheme and the detailed design workload for the follow-on work period. The preliminary design was approved in April 2006 and the detailed design deliverables for the canopy roofs were issued in September 2006.

Acoustic design for large-volume major railway transport hubs has been a challenge in China, as local designers are not familiar with it, and standards have not been fully developed to cover large volume buildings such as BSS. As a result, Arup was further commissioned by TSDI in October 2006 for acoustic design input.

MoR's design and construction programme was very aggressive, with 12 months for the total design, site start in mid-2005, and anticipated completion originally in early 2008.

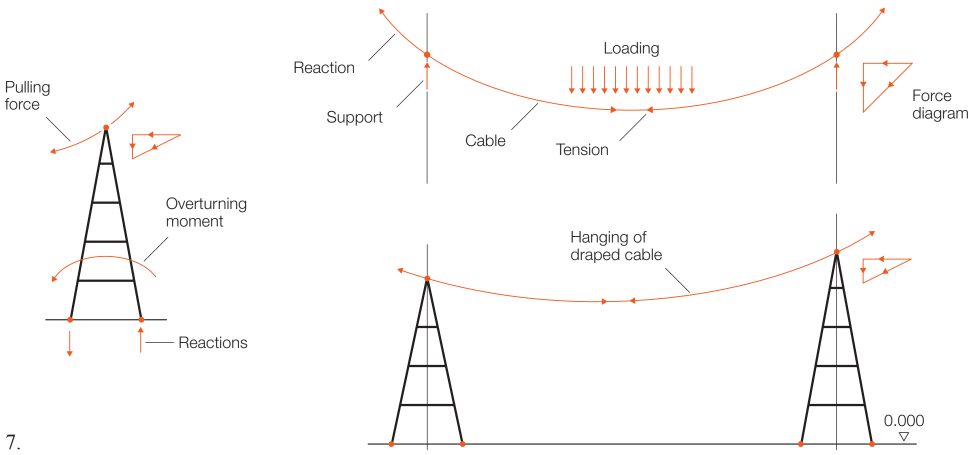
The groundbreaking ceremony was held on 8 July 2005 with piling commencing immediately, and after only three years' site work, BSS was formally opened on 1 August 2008.

5. Architectural cross-section of the station design, August 2006.

6. With a metallic ribbed cladding, this shape and surface was intended to reflect the design of the roofs of the "Hall for Prayer for a Good Harvest".

The challenge of the roofs

When Arup was first introduced to the project, TSDI/TFP had conceptualised the roof to follow the "Temple of Heaven" motif. This kept the overall oval shape, split into two halves by the separate large-span flat-topped roof over the central departure hall area, with each half reflecting the Temple of Heaven silhouette by being made up of three long-span separate roofs with tilted planes. With a metallic ribbed cladding, this shape and surface was intended to reflect the blue glazed tiled conical roofs of the "Hall for Prayer for a Good Harvest".



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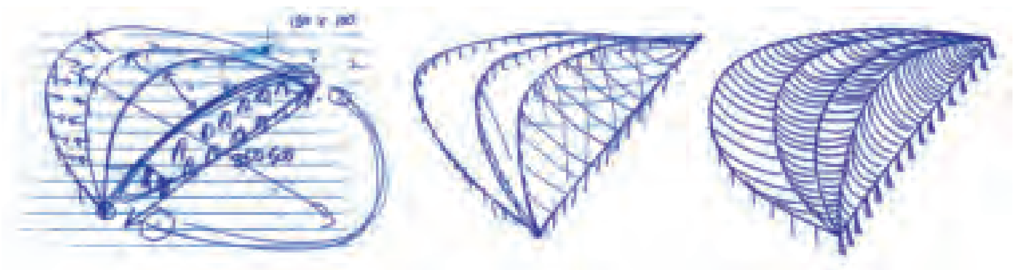


a)

b)

c)

8.

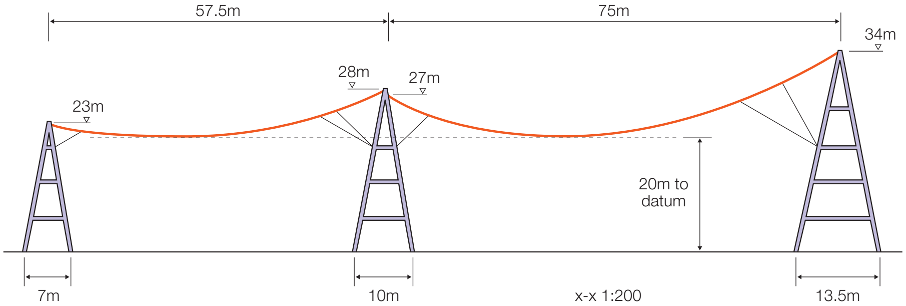
Canopy roofs either side of the central hall

Development of the original concept
Structurally, TSDI initially conceived these canopy roofs, which have a combined area of 71 000m^2, as using long-span tapered triangular trusses tilted to gain the roof cant. However, with long spans up to 85m and the need for a tapering profile, this form was structurally inefficient unless additional columns were introduced to reduce the spans. This was difficult due to the juxtaposition of platforms and tracks with the roof truss orientations.

The TFP and Arup teams met in Hong Kong in April 2005 to scheme ideas for the roof. These ranged from more rigid and regular smaller-span gridded options through to more free-form larger-span ideas using support trees and fabric. None proved particularly satisfying and neither were they capable of realising the "Temple of Heaven" motif as envisaged by TFP.

Extending and extrapolating the ideas of others is nothing new in the fields of medicine, science, industry, engineering, architecture, even art, and so it was with the canopy roof. A chance reference at a TFP/Arup design meeting resulted in further investigation of ideas developed by others for an exhibition hall at Hannover Fair completed in 1996 – a series of draped roofs above a space measuring some 220m by 110m. While the Hannover project was much smaller and covered a purely rectangular space, the concept was immediately applicable here, as the draped roof could be varied in span to cope with the oval shape and the potentially irregular column support grid (Fig 7).

Scheming proceeded along these lines with designs developed through spring and summer 2005 (Fig 8). An initial scheme comprised spans up to 75m parallel to the platforms, using the concept of steel "flats" at some 3m-3.5m spacing, acting as the equivalent of draped cables spanning between collector trusses in the same plane as the roof. The collector trusses carried the "cable" forces onto tall braced steel A-frames at 20.6m centres across the station



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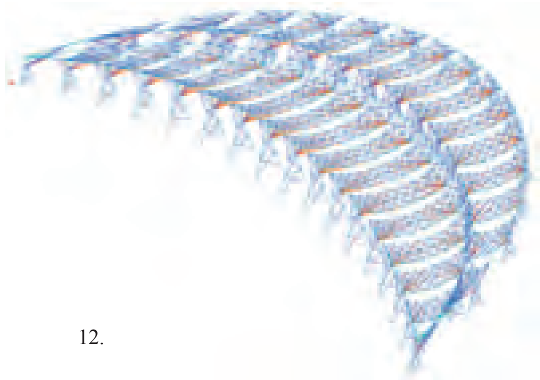

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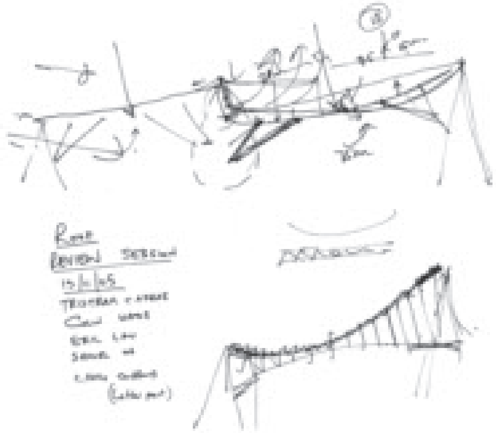

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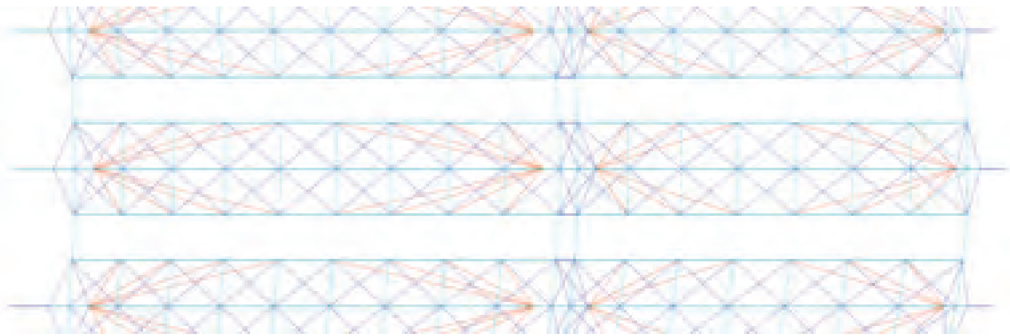

11.

between the rail tracks, with stability from deep trusses spanning between each A-frame, forming a continuous portal frame structure. The A-frames comprised box section legs fabricated from steel plate. The A-frame geometry varied depending on the height and span each was supporting: initially the largest was 34m tall and 14m wide at its base, the smallest a "mere" 23m tall and 8m at its base (Fig 9).

Structural system

The initial concept described above for the roof span was similar to a stressed ribbon structure. Such a simple and elegant geometry is very effective at resisting downward loading, with the load being resisted by tension in the catenary. However, the single curvature of the roof means that a different philosophy is required to resist uplift and pattern loads.

Due to the lightweight nature of such a concept, under upward loading the dead load tension in the catenary member is usually overcome and the catenery is no longer effective in resisting the loads. On other projects such a problem has been overcome by adding mass to the roof so that an overall uplift on it is never generated, ie adding superimposed dead load so that the dead load is greater than any wind uplift loading. However, in this situation the catenary member then has to be "over-designed" to take this additional loading, leading to a heavier solution. Also in such a system the resulting cable forces are larger and hence have a corresponding knock-on effect to the collector trusses, A-frames, and foundations.

To resist such uplift and pattern loads on the BSS roof, an innovative scheme was developed whereby the draped steel plates were replaced with draped I-beams. These have flexural stiffness and consequently are able to act as an arch and resist the upward loading in compression. During this process, spans were optimised and refined within the elliptical roof outline to a maximum of 65m at the centre, reducing to as little as 22m between the perimeter A-frames.

7. Simple structural model of roof concept.

8. Initial scheme development: a) & b) TFP sketches, March 2005; c) Arup sketch April 2005.

9. Arup scheme design, summer 2005.

10. Sketch by Tristram Carfrae of Arup from the November 2005 design review. The use of "weight" to counteract uplift due to wind on the draped roof shape is avoided, resulting in a draped roof system comprising a series of parallel I-section beams braced by inclined rods from the A-frames.

11. Part plan showing bracing in the roof plane.

12. Structural model of half the canopy roof.

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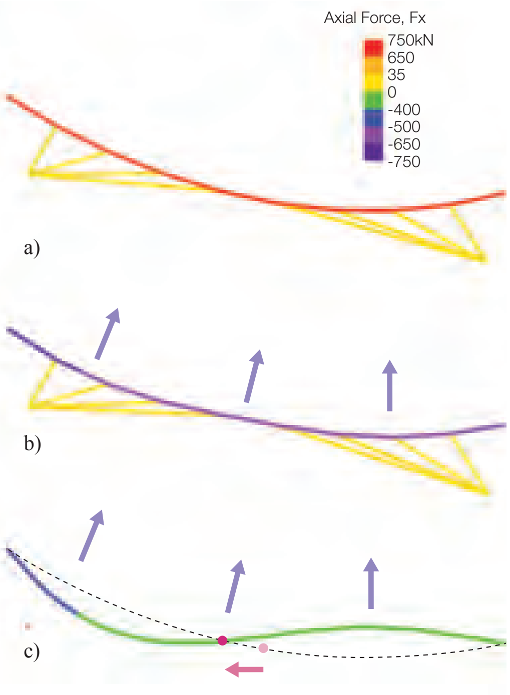

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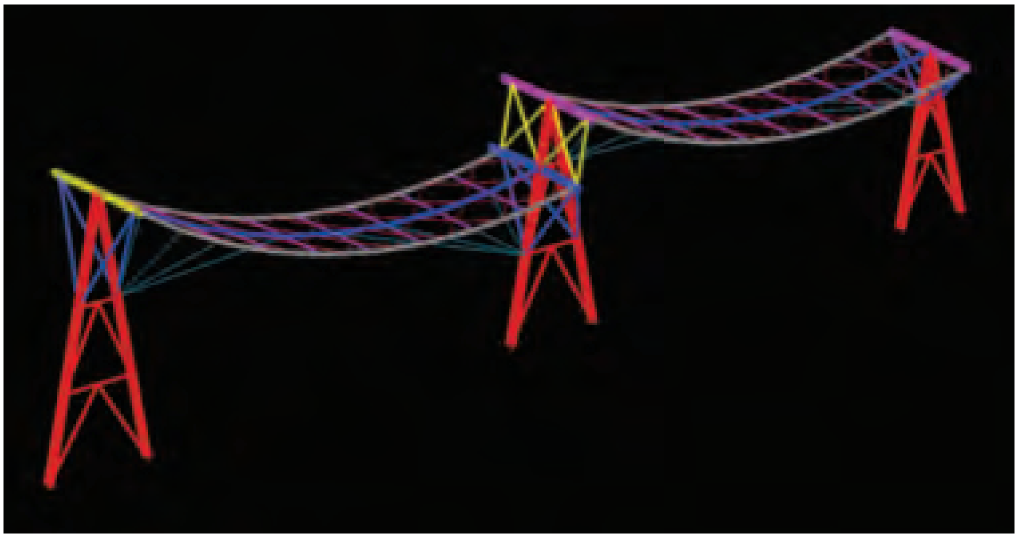
13. Completed roof over platforms.

14. Typical section of the canopy roof, showing stabilising splaying cables.

15. Member forces and deflection of catenary with: a) 1kPa downward roof loading, b) 1kPa upward roof loading. c) I-beam catenary without cable stays, starting to sway buckle at a lower compression load (approximately 0.5kPa upward roof loading). As indicated, the pink dot on the arch moves laterally as the arch buckles. The cables prevent this lateral movement, increasing the arch's compression capacity.



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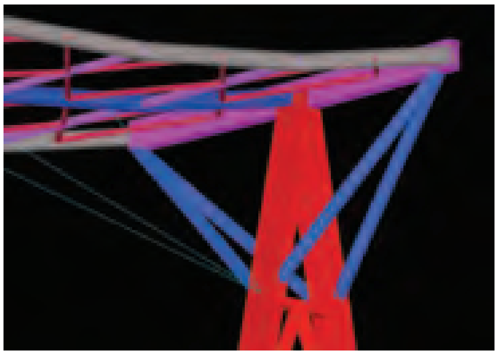

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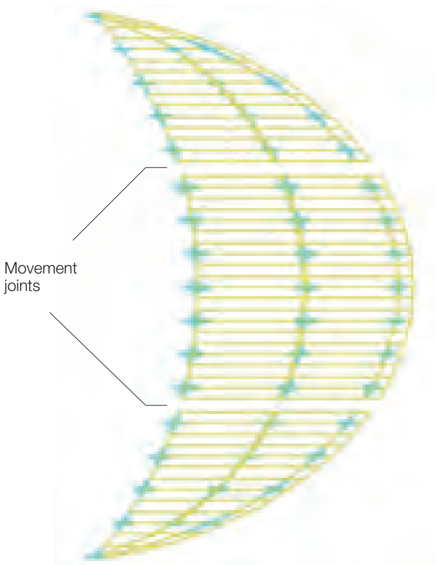

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16. Perspective of a typical section of the canopy roof.

17. Outrigger at A-frame.

18. Plan view of half the canopy roof, indicating location of movement joints.

The roof is formed mainly from 600mm deep x 350mm wide I-beams with a 1:10 drape (Fig 13). Over a 65m span, the flexural stiffness of such an I-beam is very small, and so under downward loading the member acts just like a catenary cable, using its axial stiffness to resist the vertical load. However, the flexural stiffness does allow the catenary to act like an arch under upward loading. The arching behaviour is maximised, with the minimum flexural stiffness of the member, by the in-plane and out-of-plane bracing.

The in-plane bracing of the I-beam arch is provided by splaying cables from the A-frames to the underside of the roof (Fig 14). They are **not** cable stays and do not directly resist the upward load, but simply provide increased stability for the arch. When an arch starts to buckle, it wants to move sideways, but such cables prevent the sideways movement and prevent the arch from buckling (Fig 15a-c). As these cables are not being used as "tie down" cables, their diameter can be reduced to 22mm, minimising the visual impact and not affecting the architectural aspiration to have a clear line of ceiling/space.

Diamond-shaped elements in the plane of the roof provide out-of-plane bracing to the I-beam arch. This diamond-shaped bracing is set out so that the minor axis buckling and major axis buckling occur at the same load. Three I-beams are braced together (Fig 16), leaving every third bay clear of bracing for skylights. Purlins supporting the roof sheeting and members supporting the skylight material running across the catenary beams further brace the I-beams and ensure that the roof acts as a whole under lateral loads, thereby adding redundancy to the system.

The structure was analysed at scheme stage using Arup's GSA non-linear *GsRelax* program so that the catenary shape and behaviour were modelled accurately, resisting the loads efficiently. The roof was investigated under preliminary wind loads, uniform and patterned, as well as possible patterned snow loads, and it was found that the lightweight draped I-beams effectively resisted the various applied loads.

The weight of the roof structure in a traditional truss solution would be around 75kg/m², but with the braced catenary shape to resist the upward, downward and patterned loads, the draped I-beam solution is approximately 37kg/m² for the draped beams and roofing.

The catenary beams are connected back to the A-frames by outrigger arms (Fig 17). The deep, stiff A-frames resist the lateral and earthquake loading, while a portal frame formed by the A-frames, outriggers, and connecting horizontal beam is used to resist the lateral and earthquake load in the perpendicular direction, even though the load is in the weak direction of the A-frame.

Altogether 94 A-frames support the entire canopy roof. The tallest is 31.6m with a base width of 13.1m, while the shortest is 18.1m tall and 7.5m wide.

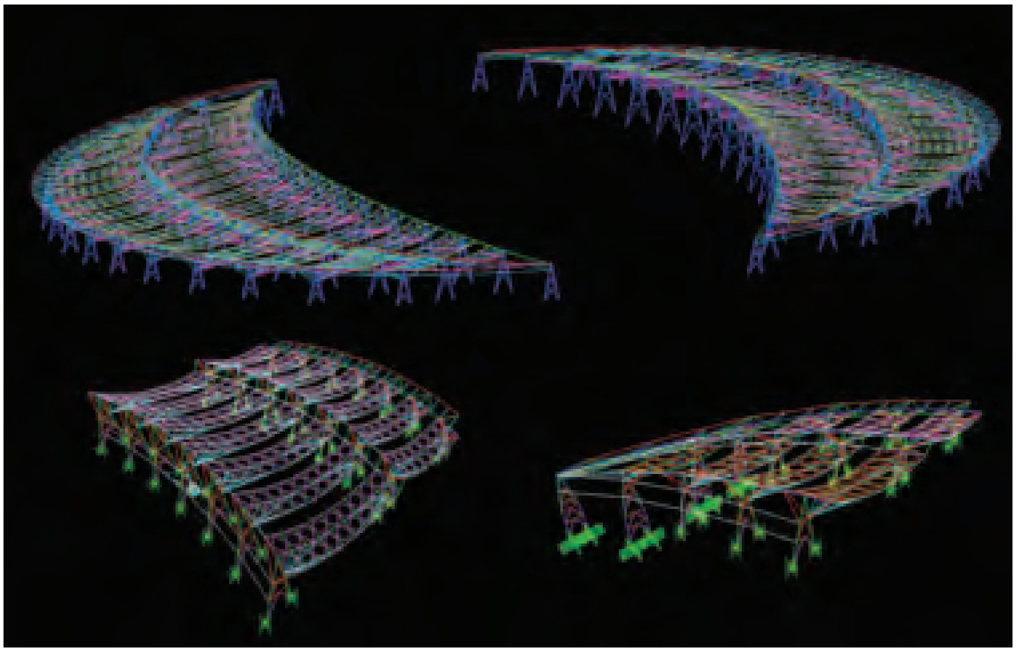
Because of the size and geometry of the roof, it was split into three separate structures. The breaks in the roof are in line with movement joints in the structure below ground level, allowing for independent thermal movements as well as seismic movements (Fig 18).

19. Wind tunnel test model.

20. 3-D analytical models.

21, 22. Stability systems for A-frames supporting three catenaries.

19.



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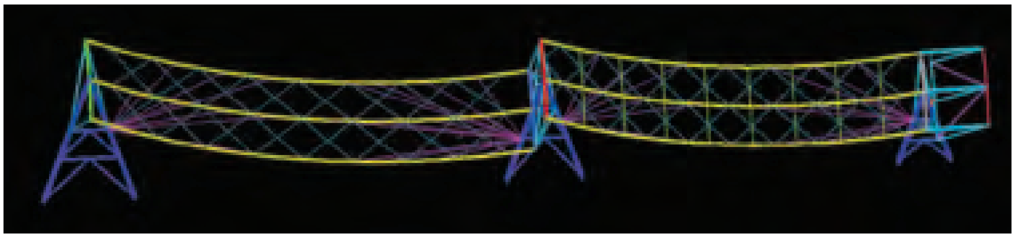

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Detailed design

Wind/snow engineering

During scheme design, approximate wind loads were estimated using other similar roof shapes covered in various international wind codes. However, due to the lightweight nature and unique geometry of this roof, a boundary layer wind tunnel study was carried out by Tongii University of China to assess the structural and cladding pressures. As wind tunnel test results are required for the formal Expert Panel Review approval process in China, Arup was asked to manage the liaison with a wind laboratory to carry out the wind tunnel test (Fig 19).

The cladding pressures over the roof were measured simultaneously on both the upper and lower surfaces, and were assessed as the peak differential pressures occurring there simultaneously. The highest peak pressures and suctions were used in the design. Roof wind loading was derived from wind tunnel measurements using load effect analysis to assess the structural wind loading relevant to the design of the roof structure.

Due to the unusual shape it is possible that snow could drift and build up at lower positions, so a combined boundary layer wind tunnel and numerical modelling study was also carried out to estimate the snow loading relevant to the roof design. This gave an assessment of design snow load distributions, accounting for balanced, unbalanced, drift and accumulated snow loads and sliding snow loads for the station roof.

Analysis

Dynamic loading and response of the roof were also investigated under the applied loads. Because the roof is relatively light in weight, the period of the structure is very sensitive to the mass on the roof. Two models were therefore built so as to capture the upper and lower bound values under seismic loading. The seismic mass of the first model was taken as the characteristic value of dead and superimposed dead load, and the second model was assumed to have dead and superimposed dead load plus 80% of the characteristic snow load. The vertical seismic effect of the roof and cantilever were taken as 10% of the standard gravity load value in accordance with code requirements. The design was also verified by considering vertical seismic spectrum analysis.

A 3-D model was built for the canopy roof superstructure, using *SAP2000* and *MIDAS* for cross-checking under all the standard Chinese code load requirements (Fig 20).

Beijing is located in a high seismicity zone, with PGA equalling 0.07, 0.2g and 0.4g for 50 years, 475 years, and 2475 years return period respectively. Because of the geometry, standard response spectrum analysis was applied to the elastic model. In addition, two sets of natural and one set of artificial tri-directional time history records were computed to validate the results of response spectrum analysis. As already described, this was applied to the two seismic dead load cases. Earthquake load in both cases was applied in 15° increments to review the structural performance and cover the worst case. The analysis results indicated that the structure is controlled by wind load.

The light and slender roof structure was susceptible to buckling, and so the global stability was checked, taking into consideration geometric non-linearity, to obtain the relationship between load factor and displacement as required by the Chinese technical specification for latticed shells[2]. Similarly, the stability of every A-frame supporting three catenaries was also checked (Fig 21).

As the main load-bearing members, the A-frames are carrying high compression loads. The catenary beams are also under compression when uplift windload acts on them. The stability of each member was checked and found to meet the Chinese code's requirement on the basis of the effective length obtained by both *GSA* and *NIDA* software.

Due to the importance of the project, as well as the unique structural system and complex shape of the building, the approval authority held separate expert panel review meetings at the preliminary design stage and the construction design stage. The Arup team successfully presented the scheme and obtained construction approval for this new structural system in China.

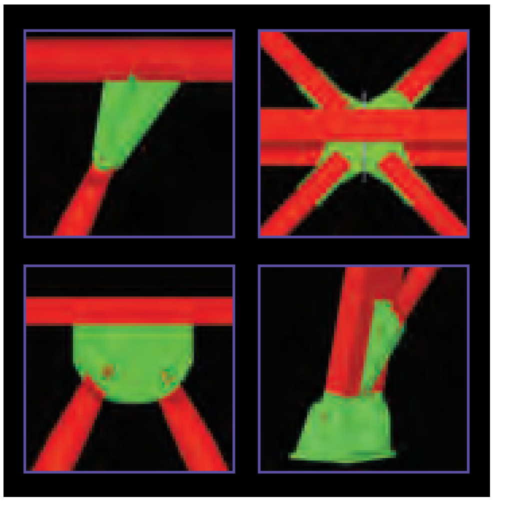
Detailing

An *X-Steel* model of the entire irregularly-shaped roof structure, including all the connection details, was also built, so as to:

(1) determine the impact and intersection lines of members running into each other

(2) check the connecting plates, stiffeners and welding, and

(3) satisfy the architectural design intent of all visual connection details (Fig 23).



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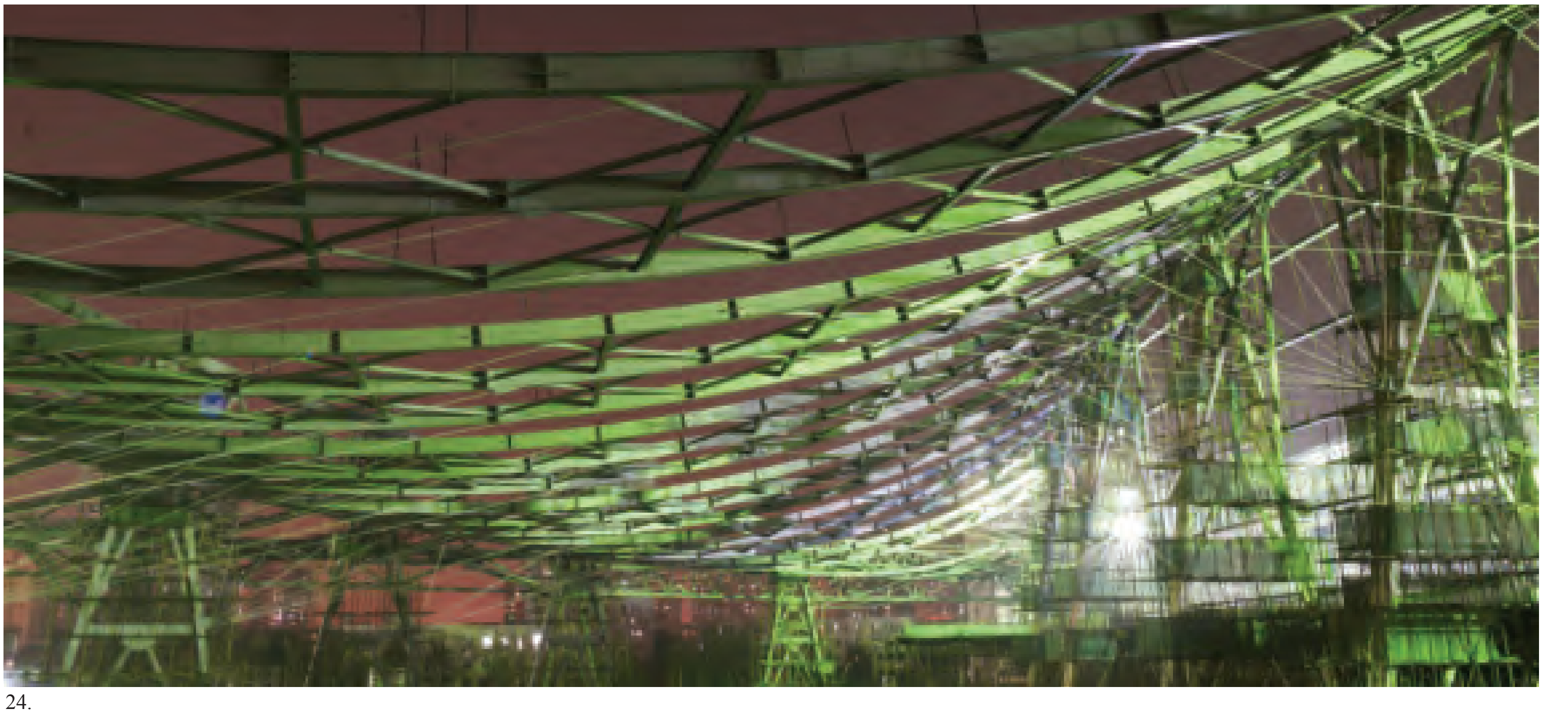
23. Connection details.

24. Roof over the platforms under construction.



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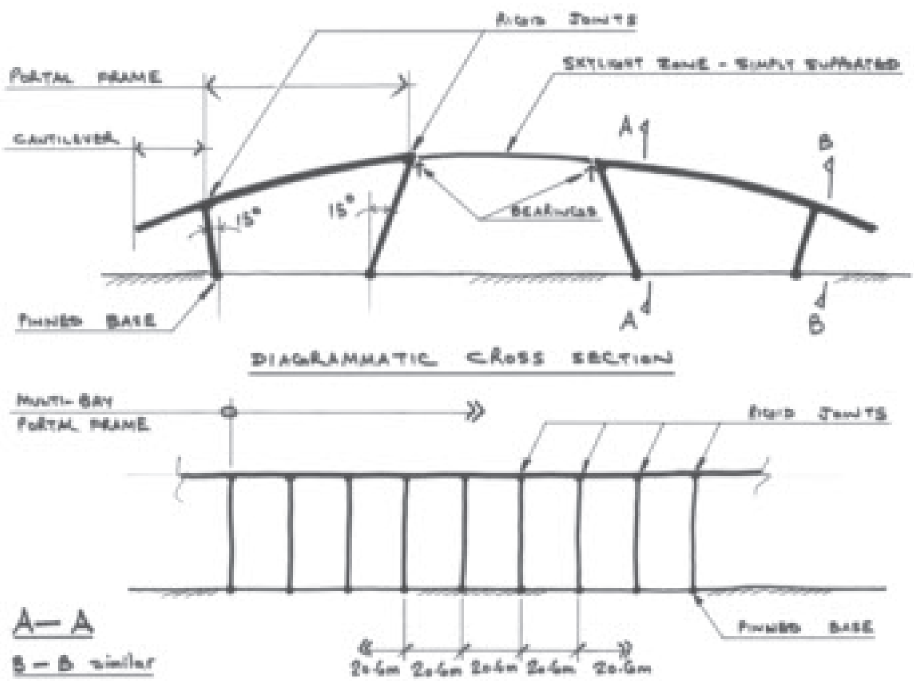


26.

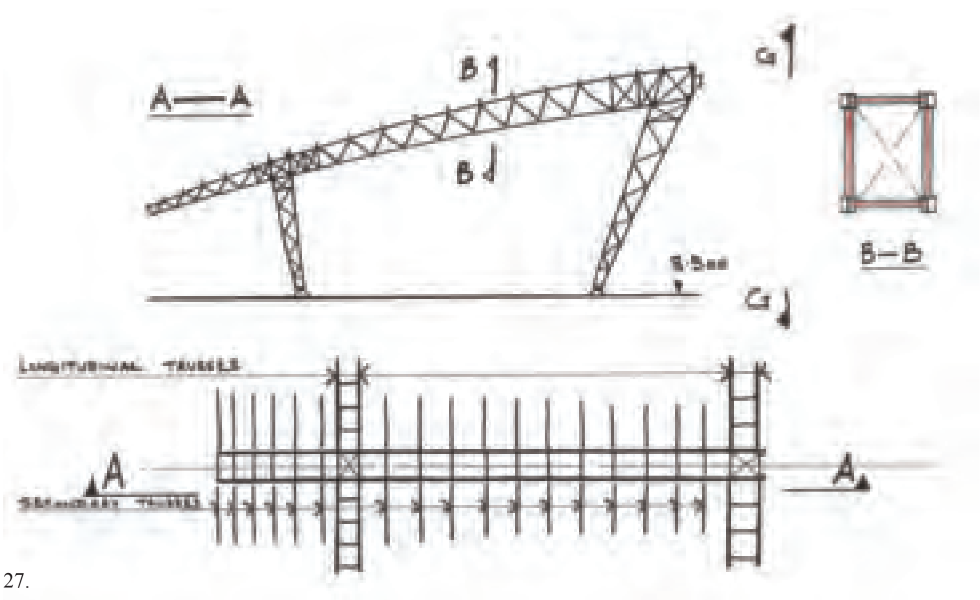
Central hall roof

Statistics

This roof is on a grand scale both in plan and height. It covers a total area of around 54 000m², including the entire 50 000m² departure hall, is some 350m long perpendicular to the platforms and a maximum of 190m wide, and overhangs the hall's perimeter wall. A central glazed skylight extends the whole length and over some 25% of the total area. The roof rises as a shallow dome in both directions from a height of 20m above the departure hall edge to 40m at the centre.

Design development

As with the canopy roofs, this central zone underwent design development with TFP during summer 2005. Initial schemes ranged from sloping regular Warren trussed options through to bowstring arches with combinations of four or five rows of supports, some with tree-like column arms.



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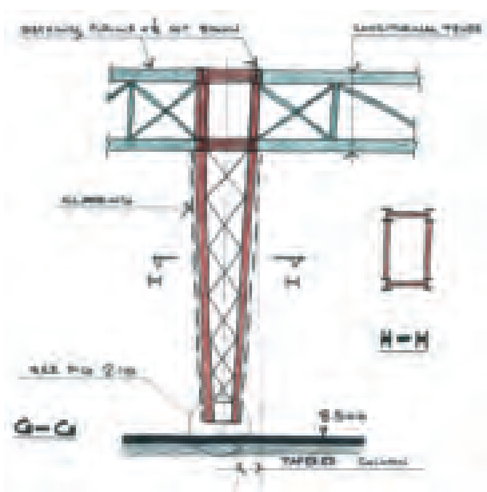


28.

As a foil to the draped roof of the side canopies, a curved roof naturally suggested itself, as opposed to the flat roof solution proposed at the early competition stage. To reflect the grand scale, it was felt that there should be minimal columns, resulting in a 20.6m grid across the station as for the A-frames of the canopy roof, with four rows of columns in the direction of the platforms.

Both TSDI and TFP felt, however, that these columns should reflect the A-frame motif, so instead of being simple vertical members they were initially all given an inwards rake of up to 15° to the vertical. A total of 60 columns support the roof.

Structural model

With a central width of 190m a large-span structure was inevitable, but it had to be as light as possible to avoid overloading the substructure for which piling was already under way. Column locations were dictated by the substructure grid, and this led to rows of four columns initially with feet on a variable grid parallel to the platforms, giving spans of some 40.5m, 67.5m, and 40.5m. The remaining edge zone is the large overhang (almost 21m) which partly covers the surrounding perimeter road and drop-off laybys.

The plan layout of the roof structure ties in with the overall movement joint layout of the main building substructure. In each of the orthogonal directions, two movement joints were introduced to split the building into nine smaller floor plates so as to deal with the temperature expansion and compression of the structural members on the departure hall floor plate.

Achieving these spans economically was only possible with the use of steel, and so they were conceived as sets of central skylight beams spanning simply supported between slightly extended tips of shaped portal frames formed with a gently curved sloping roof and inclined columns (Fig 27).

Structural form

The initial architectural concept was to form the main skylight beams as members tapered in section and elevation, but as this would be difficult with normal rolled steel sections, Arup's preferred solution was trussed members using simple straight rolled sections that could be clad to form the tapered shapes.

The side portals were similarly conceived, using box trusses for the roof beams and tapered trusses for the inclined columns (Figs 27, 28). Again, these were assumed to be clad. A possible exposed pinned foot detail was sketched as an idea to accentuate the station's engineered nature – again as a foil to the canopy A-frames, which adopt visible connections (Fig 29).

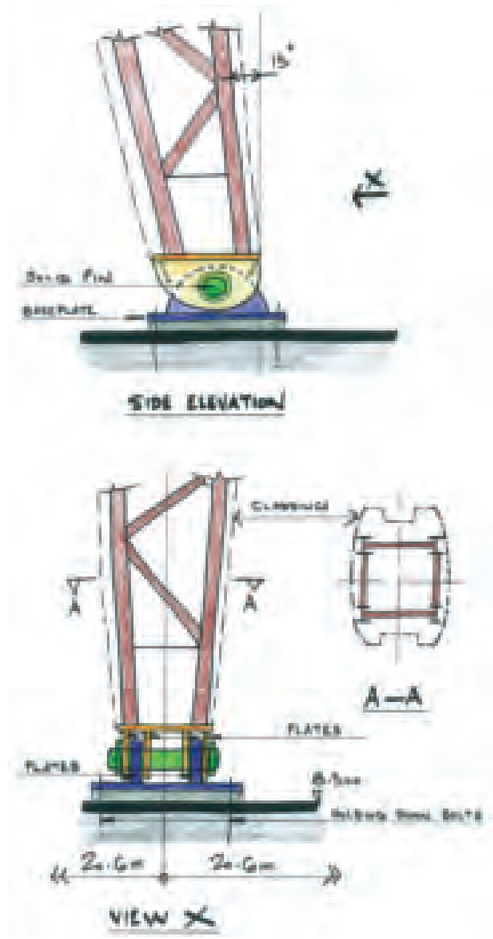
25. The complete central hall roof.

26. Initial structural concept for central hall roof.

27. Elevation and plan at roof level.

28. Arup-proposed structure for the side portals.

29. Arup-proposed pinned footing for the side portals.



29.

The built form

Arup's ideas were not initially accepted by TSDI, and some of the design development went though several iterations without further input. However, after some cost analysis, Arup's trussed member concept was adopted for the main side portals (Fig 30).

Some adjustment in setting-out resulted in only the inner columns having the 15° rake, with the outer ones being vertical. With up to 6m cantilevers beyond the raking columns, the central skylight beams span some 40m.

The featured pinned feet detail for the portal frames was covered by cladding (Fig 31), but the 21m edge cantilever has remained and forms a dramatic overhang to the perimeter access road around the departure hall.

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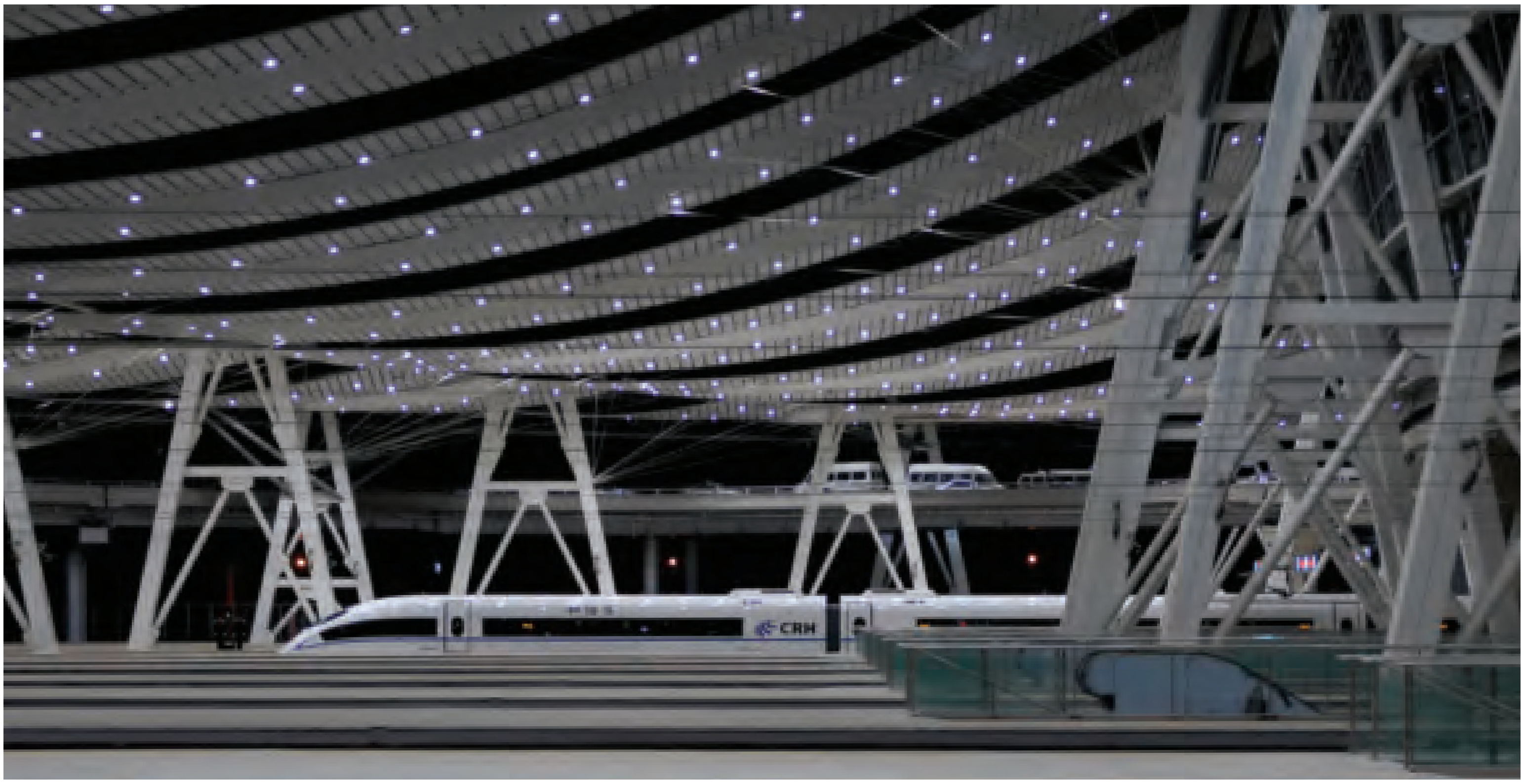
31.



32.

30. Inclined, tapered truss for side portal, before cladding, April 2008.

31. Pinned foot for side portal, before cladding, April 2008.

32. The platform roof dwarfs a train beneath.

33 (overleaf). Inner portion of platform canopy roof, adjacent to the elevated perimeter road around the central departure hall.

Construction stage

Superstructure construction began in mid-2006, and during this Arup also provided a design liaison service to:

- carry out site walks and make sure the design intent was fully understood and properly implemented by the contractor
- answer major queries from the contractor on design intent
- revise and develop typical connection details as required when the steelwork contractor developed his shop drawings
- resolve interface issues with other designers and contractors when the contractor's shop drawings were developed, and the design of other packages such as the curtain walling and the roofing were developed during construction.

Arup designers from Hong Kong, together with local engineers from the mainland China offices, visited the site regularly to help answer queries in the initial construction stage. After a few months, it became possible for minor queries to be answered quickly face-to-face or by phone calls. Generally, construction ran very smoothly within the extremely tight timeframe. The entire superstructure construction took approximately two years before the opening of the Olympic Games.

Substructure

On the same building footprint, and beneath much of the canopy roofs and departure hall, is a large basement containing plant, car parking, back-of-house, and ancillary areas. Basement 1 level is a transfer concourse for passengers between the long-distance trains at ground level and the metro lines M4 and M14 at basement levels 2 and 3 respectively.

The basement structure is a waterproof concrete box on a concrete raft foundation. In some places where concentrated column loads or substantial uplift loads due to wind would be expected, cast in situ bored piles were used.

Arup was responsible for the detailed design of the canopy roof structures, which, from top to bottom, include the roof catenary structure, A-frames above ground level, in situ concrete wall panels directly supporting the A-frames within the basement levels, and their piled foundations. This design demarcation was to ensure that the canopy roof design between superstructure and substructure was fully compatible, though there were design interface issues horizontally between the in situ concrete wall panels and other elements in the basement designed by TSDI. These interface issues were carefully checked and co-ordinated in the design liaison process during construction, as already discussed.

Arup's collaboration with TSDI also included advice on train loads and load patterns for the platform/track level support structure, and trackway issues.

Train loading
Design loads were derived from normal platform loads as well as from the rolling stock, using data supplied by TSDI.
The structural framework at track level is a two-way grid of reinforced concrete main framing beams supported on reinforced concrete columns. A set of load patterns was derived for various train configurations across the structure (ie at right angles to the platforms) with different load factors, so as to arrive at maximum bending moments, shears, and axial column loads.

Longitudinally (ie in the direction of the platforms), generic enveloped loads were indicated to represent rolling loads of a typical train set. Part of the issue here was to advise whether it was necessary to carry out 2-D or even 3-D analysis to arrive at maximum values. The team concluded that, given the scale of the basement structure and the effective restraint from the surrounding soil, an overall 3-D analysis – which would have been very cumbersome and time-consuming – was unnecessary. Even an overall 2-D analysis was felt to be too unwieldy, and Arup's recommendation to carry out only local 2-D modelling was included in the technical report to TSDI.

Trackway issues
Advising on the practical considerations of trackway drainage, waterproofing, vibration, and temperature variation (ie cold bridging effects) was an interesting exercise. To minimise drainage penetrations into areas under the trackways, it was suggested to contain the drainage above the structure, transfer it to catchpits, and then drain beneath accessible areas under the platforms.

Waterproofing was conceived as a membrane with a concrete protection mat under the track support, while structure-borne vibration effects were solved by adopting the floating track slab design commonly used in suspended railways in Hong Kong, particularly where an air-rights development is supported by the railway structure.

As the platforms are effectively in the open air, there is a tendency in Beijing's extremely cold winter months for the cold-bridge effect to be an issue, as the basement areas below the trackway will be much warmer. Placing an insulation layer directly above the support structure was seen to be of most benefit, either by using an insulating material or introducing a void of still air within a double slab structural system.

All these issues were discussed and illustrated with generic solutions in a technical report, and used by TSDI in its final detailed design.

MEP/building physics

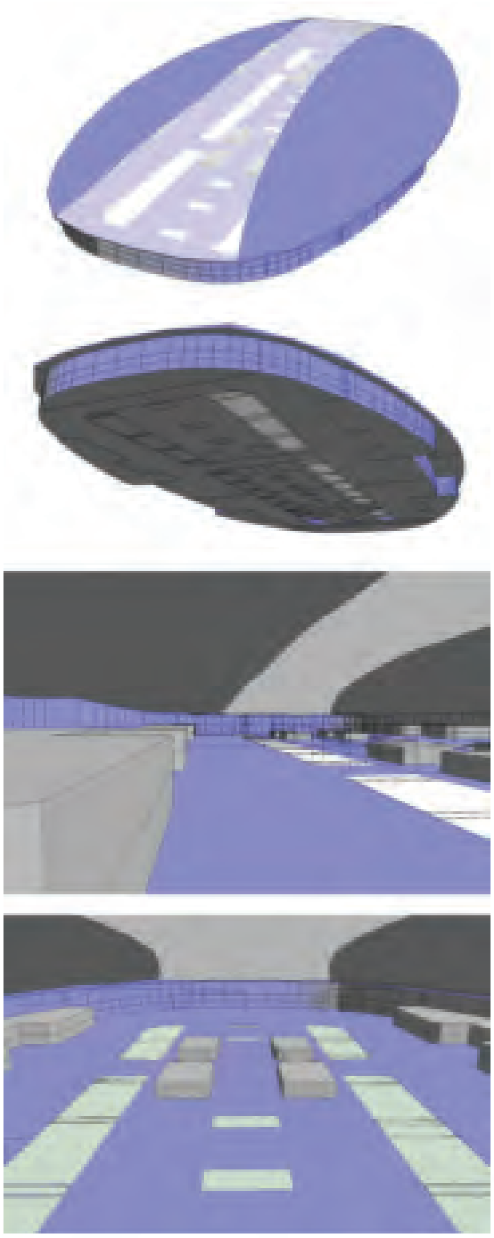
Sustainable station design
Arup's Hong Kong building physics group conducted a series of specialist studies for a sustainable design, including dynamic thermal simulation; annual energy analysis; CFD simulation and analysis of the departure hall for air-conditioning design; design of a combined heat and power (CHP) system; financial analysis of the CHP system, district heating and cooling system; outdoor air quality analysis of the elevated perimeter road underneath the central roof; and a photovoltaic (PV) system.

In addition, the energy efficiency of the HVAC system, and economic and environmental protection issues, were taken into consideration in the specialist study and design. The result achieved improved effectiveness in the HVAC system performance, energy cost savings, and green power generation.

Energy simulation and analysis of heating and air-conditioning demand
The building envelope of the roof structure comprises composite aluminum sheets coupled with insulation, a high-intensity, tough, and decorative material chosen for both sustainable and aesthetic reasons. The design considerations for the building envelope, such as solar heat gain, shading, and thermal comfort of passengers in the departure hall, were established by integrated environmental simulation (IES) analysis (Fig 34).

This was done in order to review the overall thermal performance and mandatory Chinese design code compliance in accordance with the mainland design standard for energy efficiency of public buildings[3].

Operation and control strategy for HVAC system
The thermal environment, ie temperature and humidity for the entire BSS, was predicted through dynamic thermal simulation modelling. Energy-efficient operation and control of the HVAC system was developed and annual energy simulation and analysis determined in various operation modes (summer, winter and transition seasons) for the detailed design review on annual energy consumption and its operational and maintenance cost.



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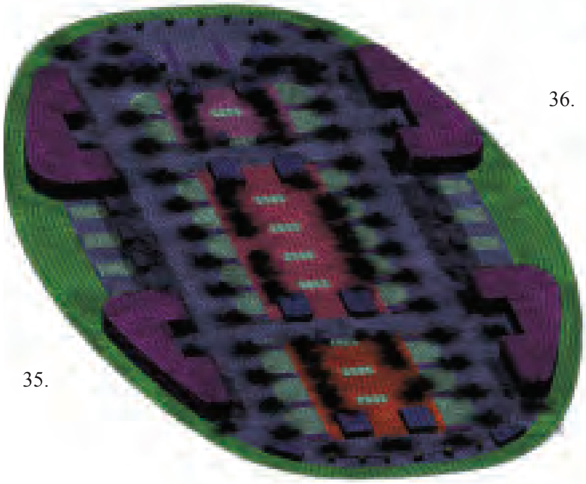

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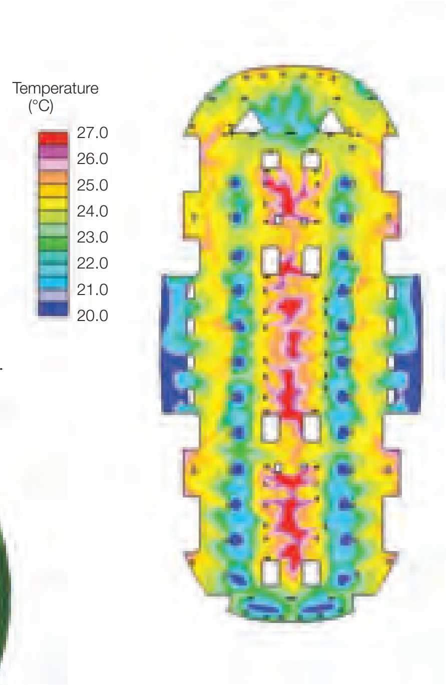
CFD simulation and analysis of the departure hall for the air-conditioning design
The architectural design intent for the departure hall was to give users a spacious and pleasant indoor environment, sheltered from intense heat, wind and rain. To achieve energy conservation, a stratification methodology for the air-conditioning supply system was used, simulated and validated with CFD analysis to maintain acceptable indoor environmental conditions.

Successful implementation of this stratification methodology requires careful planning planning for the indoor air distribution by the air-conditioning system. Its performance is also subject to passenger flows in the departure hall, local climate conditions, and the design parameters of the building envelope in terms of the overall thermal performance of the station. Comprehensive data on the resultant thermal environment and prediction of user perception of the space were also required for detailed study and analysis. The aim was to predict, using computer simulation, the likely summer environmental conditions in the large departure hall space, taking into consideration local heat gains, including solar and non-solar sources and the surrounding environment (Figs 35, 36).



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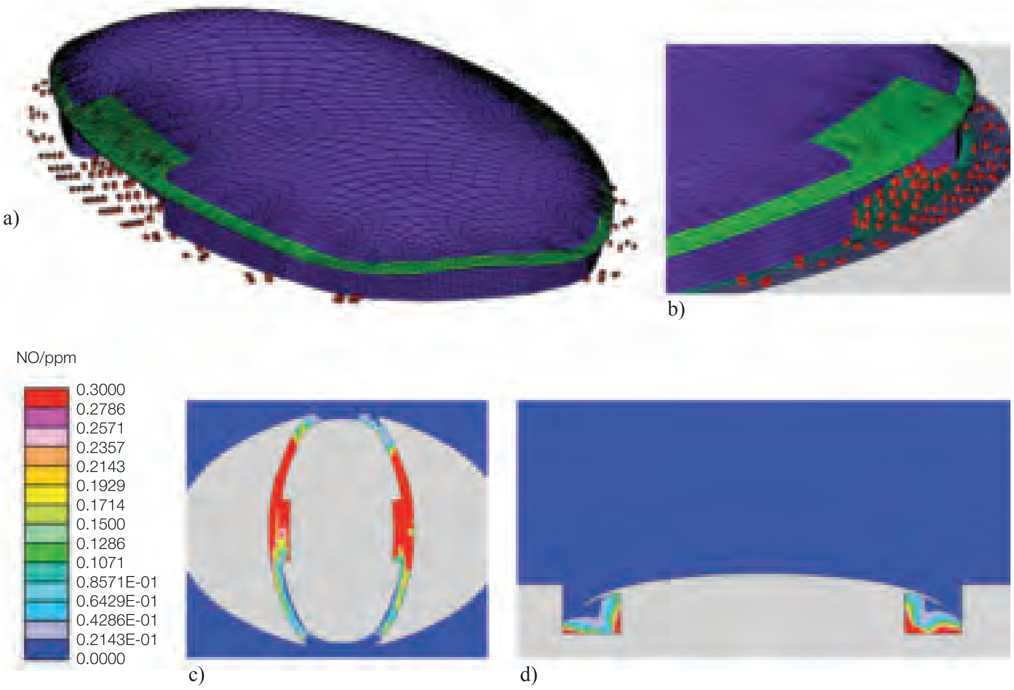
Arup's building physics team conducted a series of precise and comprehensive analyses of materials selection, enhancement of indoor environment, resources, and energy. Based on this, a cost-effective solution was developed for the overall system design of BSS to provide a sustainable green building: a pleasant indoor environment for railway operations, with energy conservation, but without sacrificing user comfort.

Perimeter road air quality
Considerable traffic is anticipated on the elevated perimeter road around the departure hall and it was considered essential to examine the outdoor air quality through analysing relevant emission of vehicle exhaust pollutants.

To achieve a sustainable air quality solution, traffic information was gathered for the ultimate design year for various vehicle traffic flows, vehicle types, and vehicle emissions, noting the ratio of petrol and diesel vehicles. The building physics team then reviewed the estimated pollutant levels from vehicle exhausts at both short and long-term peak-hour traffic flows. CFD was used (Fig 37) to simulate the exhaust pollutants, with the aim of achieving Chinese design code compliance for ambient air quality standards with acceptable concentration levels of nitrogen dioxide and carbon monoxide.

Sustainable energy: the CHP system
Combined heat and power (CHP), also known as co-generation, is the name applied to processes which, from a single fuel supply, simultaneously generate heat and electrical power. CHP uses either a gas turbine or gas-fired engine to drive an electrical generator and makes practical use of the heat that is an inevitable by-product. This waste heat can be used for making process steam and for cooling through absorption chillers.

The overall efficiency of CHP systems can be above 80% – far better than conventional power stations – leading to considerable reductions in emissions of CO_2, nitrogen oxides and sulphur dioxide. Thus CHP systems not only increase the security of energy supply, but also aid environmental protection. The station's system (Fig 39, overleaf) is a pioneering CHP design project to provide a sustainable energy solution.



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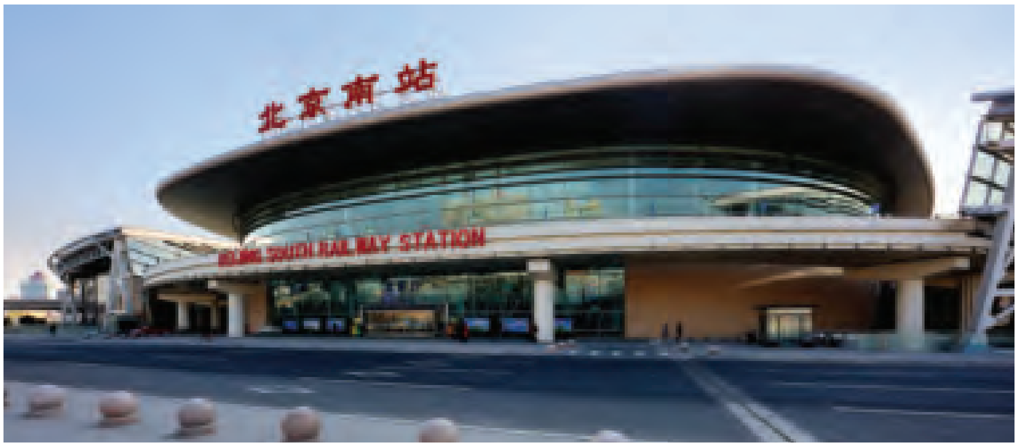


38.

34. Integrated environmental simulation model.

35. CFD model of elevated departure hall and arrangement of air-conditioning poles associated with supply air nozzles.

36. Indoor temperature distribution of elevated departure hall.

37. CFD model of station showing (a-b) arrangement of vehicles on perimeter road; (c-d) outdoor air quality of the perimeter road.

38. The elevated perimeter road around the departure hall.

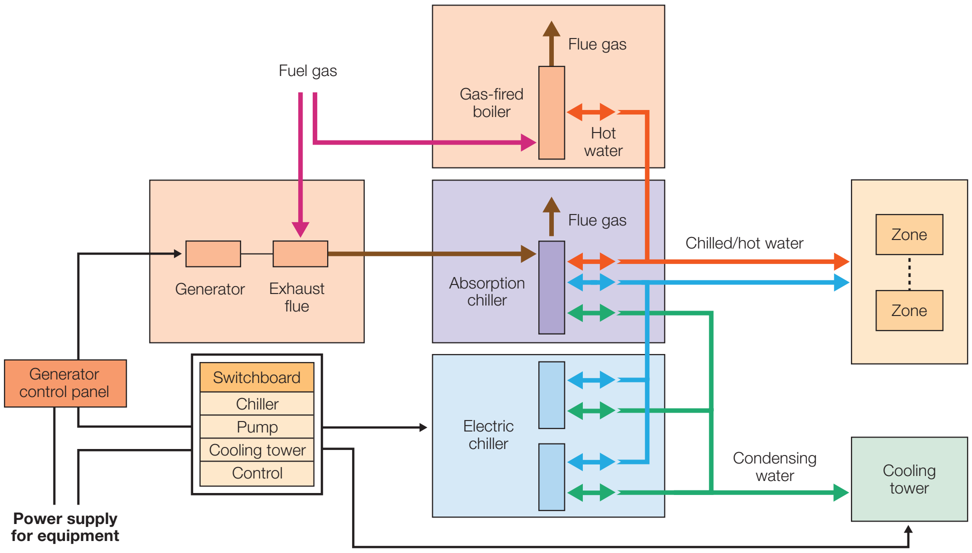
District heating and cooling system

The CHP system provides electricity, cooling in summer, and heating in winter to the station and its ancillary buildings, as well as developing the heating and chilled water piping network for a district heating and cooling system as an integrated energy service.

Natural gas-fired internal combustion engines have been adopted for power generation with the flue gas used for heating and air-conditioning.

This energy-saving technology can cater for over 45% of the overall electricity demand of the station and its ancillary buildings, and the energy efficiency can exceed 80% with less transmission loss in the surrounding district.

The Beijing Municipal Commission of Development and the Reform and Construction Committee have supported applying the CHP system in the development of a pilot project for future station developments.



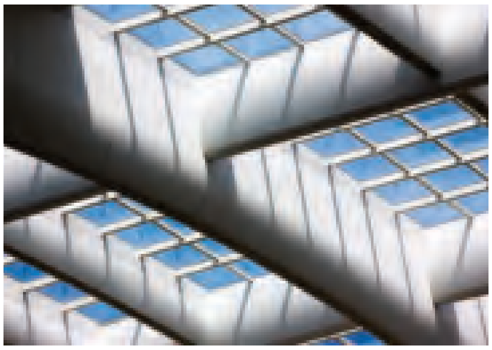
39.

30. Schematic of the CHP system.

40. PV panels are integrated with the skylight area.

41. Numerous stairs and escalators connect the large open spaces.

42. Bracing stays at the perimeter of the platform roof.



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Performance and material specifications review for PV panels

The large roof size and the height of the departure hall make it very suitable for a solar power generation system, and integrated PV panels have been installed with the transparent glazing material of the large skylight area.

They were carefully integrated into the design early on in the process so as to maintain the aesthetics of the roof design. These solar panel systems are costly, but they may exemplify renewable energy technology in the design development of future railway stations; it is hoped that the BSS design will highlight environmental protection and energy-saving concepts.

The departure hall roof integrated with the central portion of skylight and PV panels provides 350kW total power. During daytime operation, the solar power generation system will be the station's auxiliary plant to cope with any supply fluctuations from the local grid.

Fire engineering

The structural and fire safety design of buildings in China used to be based on national codes, but the national economy's rapid expansion has led to more and more large and complex buildings, notably airports and railway stations.

Current building codes can thus no longer cover the whole range of design, especially for fire safety. Arup confronted many challenges in the structural and fire safety design of BSS, which exemplifies performance-based fire safety design in a representative piece of large-scale infrastructure.

Overview
Tall, open canopy roofs at both ends of platforms are connected to the departure hall area above by numerous stairs and escalators. The departure hall is surrounded by the open elevated road and is designed with natural-ventilation openings on the floor on the two sides of its central axis. Beneath the platform zone is the interchange for buses, two MTR lines and cars, as well as underground car parks. The whole station can be functionally characterised as spacious, well-connected, with high fire loads for specific locations, and densely populated.

Fire safety
Beijing South station is a special case, with great challenges in trying to apply current codes to the fire compartmentation, control of fire and smoke spread, evacuation, and active fire prevention and fire-fighting facilities. Fortunately, the latter can be optimised and adjusted based on performance analysis of actual fire risk. Generally speaking, a fire breaking out in a railway station is rare, although consequences may be disastrous if it does happen, with interruption of normal operations, heavy economic loss, and severe social impact.

A performance-based fire safety design brings into consideration all the hidden issues that may not be covered by the current fire codes. On the one hand it ensures the safety of both occupants and structure; on the other, it avoids conflict with the architectural design concept.


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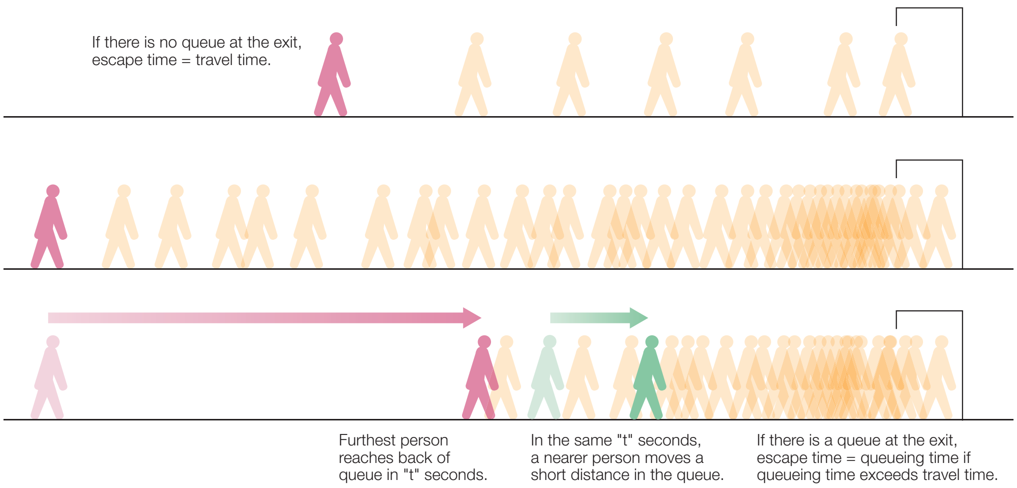


43.

The performance-based fire safety design concept

The "cabin"

A fire "cabin" is formed by a fire-rated roof that oversails high fire load areas with automatic fire sprinklers and smoke exhaust and fire alarm systems under the roof. The cabin can help extinguish fires at an early stage and prevent smoke from entering the adjacent large space. There are two forms of cabin, open and enclosed.

For the open type, fire-proof walls are not required around the cabin that holds smoke; an enclosed cabin can be totally or partially closed, so long as any open part can be automatically closed in the event of fire (as by a fire shutter). An enclosed cabin can be implemented in the fire safety design of critical areas in a large space, such as locations with a large area and a high fire load, or where functional operation may be affected by a fire.

With the integration of fire prevention and fire-fighting methods such as mechanical venting, automatic fire spray and fire partition in the cabin, fire can be localised in a large space. There is thus no need for partitions for limiting fire and smoke spread in the large space, ensuring the free mobility of people and continuity of station operations.

The "island"

When fuels burn in a large space, the smoke and around two-thirds of the combustion heat are convected to the upper ceiling layer; fire radiation is the major effect of heat transfer between fuels.

The effective ignition radius can be computed based on the fire heat release rate and the minimum heat flux required to ignite the target fuel. The heat radiation of fire descends sharply with increase in distance, so if fuels are kept far enough apart, fire spread will not happen even without sprinkler protection. Thus "islands" are formed, and the spaces between are called fire separation zones. The fire loads of the islands have to be controlled by prohibiting the introduction of hazardous materials.

Phased evacuation

Major transport buildings are characterised by their large spaces and different functional layers. Emergencies such as fires do not have a direct and urgent threat to occupants outside the immediate incident area, so there is no need to evacuate the whole station simultaneously.

Sending out an evacuation alarm and giving priority to the evacuation of areas that have fire events does not mean limiting the evacuation of the areas outside the threatened areas. Yet these areas should be secured with proper evacuation routes and safety exits so that the whole station can be quickly evacuated in the event of extreme out-of-control events. The process of evacuating the emergency area first (and only the whole area simultaneously in extreme events) is called phased evacuation.

Evacuation distance and exit width

The functional requirements of the structure of a large transport facility may lead to improper placement of stairs and exits, or overlong evacuation distances, but are usually compensated by open and clear spaces and obvious evacuation routes and signs. In this type of building, evacuation distance is much longer than in normal commercial buildings.

Evidence shows, however, that in densely populated public places it takes a much shorter time for individuals to get to exits than for all the occupants to pass through, so lengthening does not have a significant influence on evacuation safety (Fig 43).

The exit width should match the requirement of relevant codes as much as possible, otherwise a performance-based method should be applied to analyse its evacuation safety by comparing the ASET (available safe evacuation time) and RSET (required safe evacuation time) and thus determining the appropriateness of the exit width. When predicting RSET, the building's occupancy should be properly estimated, and a simulation should be carried out, while determining the ASET in a fire can be based on quantitative and qualitative methods.

The performance-based fire safety scheme

Departure hall

The departure hall has localised two-storey zones at the four corners for ticketing, business, baggage handling, and customer service, while around its central axis are extensive holes providing daylight to the central platform zone below. Overall, however, most of the departure hall area is used for public circulation, with no fixed fire load except for passengers' hand luggage.

This means that the fire risk here is low, as is also true for the central waiting area where the passengers seats are mainly made of non-combustible metal. In the premium coach waiting room, the soft furnishings are combustible, resulting in a high fire load. The two-storey corner zones, open to the large space area through ticket windows and doors, have a high load of combustibles, so the fire risk here is also high.

The other functional room areas are much smaller, protected by sprinklers and solidly partitioned from the large space, so the fire risk here is again low.

By this analysis, the two-storey functional rooms in the four corners of the hall are partitioned as fire cabins; there are no fire partitions for the other areas of the hall. The four high-fuel-loaded premium coach waiting rooms are also protected as fire cabins, utilising fire detection, sprinklers, a mechanical exhaust system, and fire-resistant structural materials. The luggage consignments at the entrance of the hall are protected as islands and the surrounding wide fire separation zone helps prevent fire spread. This is unlikely to occur in the ordinary seat waiting and enquiries area, due to the low or sparse fuel loading and the partition effect of the public passages.

Smoke control

Fire size is an important parameter in performance design. The design fire sizes of different locations in the departure hall, determined through quantitative fire scenario analysis, are listed in Table 1.

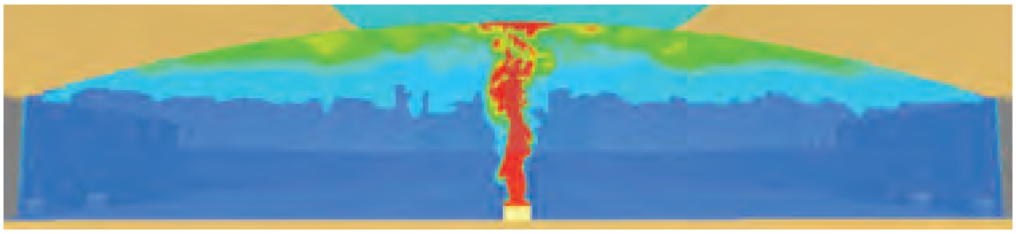
Mechanical smoke exhaust systems are installed in the four soft coach waiting rooms, the ticketing area in the four two-storey auxiliary functional rooms designed as fire cabins, and the business and service centre, with smoke exhaust volume fluxes of at least $7.1m^3/s$ and $10.2m^3/s$ respectively, according to the fire size and required clear smoke layer height.

43. Relationship between time of walking to the exit and waiting time at the exit in public places.

44. The departure hall has localised two-storey zones.

44

Table 1. Design fires.				
Location	Fire scenario	Design fire	Fire type	Fire size
Departure hall	Premium coach waiting room	Fast	Sprinkler controlled	1.7MW
	Business centre	Fast	Sprinkler controlled	2.4MW
	Public passage	Fast	No sprinklers	1.2MW
	Luggage consignment	Fast	Sprinkler controlled	1.7MW
Platform	Train fire	-	-	16.0MW



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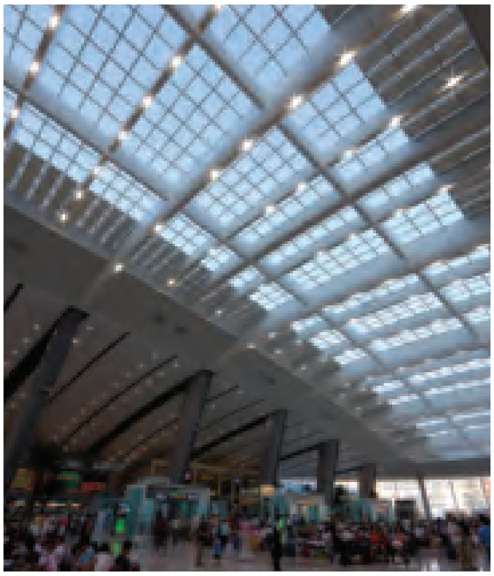

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Table 2. Evacuation analysis result of departure hall.	
Total number of people to be evacuated	9142
Total width of evacuation exit	119m
Required safe evacuation time (RSET)	586 secs
Acquired safe evacuation time (ASET)	7660 secs
Determination of safe evacuation	ASET > RSET

45. CFD simulation results of the 10MW departure hall fire (10 mins).

46, 47. Structural elements of the roof are designed to meet required fire safety levels.

48. Acoustic design areas, approaches used, and key acoustic issues.

The large open space of the departure hall forms natural smoke vents with an effective venting area not less than 263m^2, and the HVAC system on the roof as an auxiliary venting instrument. The natural smoke vents are opened during a fire, after which clearing of the cooled smoke is accelerated by the HVAC system.

The departure hall's great volume enables it to store smoke and heat during a fire, allowing time for evacuation and fire-fighting. This capability to store smoke and heat was shown by CFD simulation (Fig 45) on a disadvantageous scenario that assumed a fast-developing 10MW fire, no smoke exhaust system, and a disabled sprinkler system.

These results showed that 11 minutes into the fire scenario, the smoke layer height was 10m above the floor with a visibility of more than 15m, implying that it was still safe at this time, with an ASET far greater than 11 minutes.

Evacuation

People in the departure hall can evacuate to the passenger platforms, or to the perimeter road. Once on the platforms they can scatter to the open areas beneath the canopy roof. All gates will be kept open in a fire emergency, and there will be enough exits of sufficient width in the low walls in the waiting area (Table 2).

Fireproofing for large space steel structure

Chinese codes require a minimum fireproof period of 2 hours for the columns on the platform, 0.5 hours for the structural components of the canopy roof, 2.5 hours for the departure hall columns, and 1.5 hours for the structural components of the departure hall roof.

To meet the required safety level, the actual temperature profiles of the critical components were analysed by a performance-based method. The common acceptance criteria are:

(1) The load a component or structure can resist under normal conditions is not less than the combined effect of all forces in the prescribed fire endurance time.

(2) The fireproof time of the structure or components under a real fire and various loadings is not less than the required limit.

(3) The highest temperatures of structures or components in a real fire do not exceed their critical temperatures in the prescribed time limit. Critical temperature is defined as the cross-section temperature of a component or structure when it reaches its stress limit under loadings and a uniform temperature rise longitudinally and laterally.

Criterion (3) is taken as the control parameter. The temperature of the trusses near the skylight zone of the departure hall below 3.2m was found to exceed the critical level, with a safety factor of 1.5, meaning that the parts below 5m need two-hour protection based on the fuel's combustion time. Fire protection is not required for the trusses above the departure hall, as the analysis indicated its maximum temperature to be lower than critical after 1.5 hours. The steel components in the canopy roof also do not need fire protection because they too meet the safety requirement.

For the tall A-shaped canopy columns, fire protection was suggested for the sections below 19m to improve their safety. Considering the fire size and development of a train fire, it was found that flash-over through the train windows will not occur at the initial stage. As a train carriage typically burns for around 80 minutes, Arup proposed a two-hour fireproof protection for the A-shaped columns.

Conclusion

The fire safety design introduced several important performance-based design concepts, emphasising the rationality and safety of the departure hall smoke control strategy, evacuation, and fire protection of steel structures. Detailed analysis of the fire protection of the large steel space structures showed extra fire retardant coating for the roof steel structures to be unnecessary. The existing design was adequate for safety and for appearance, and at lower cost.

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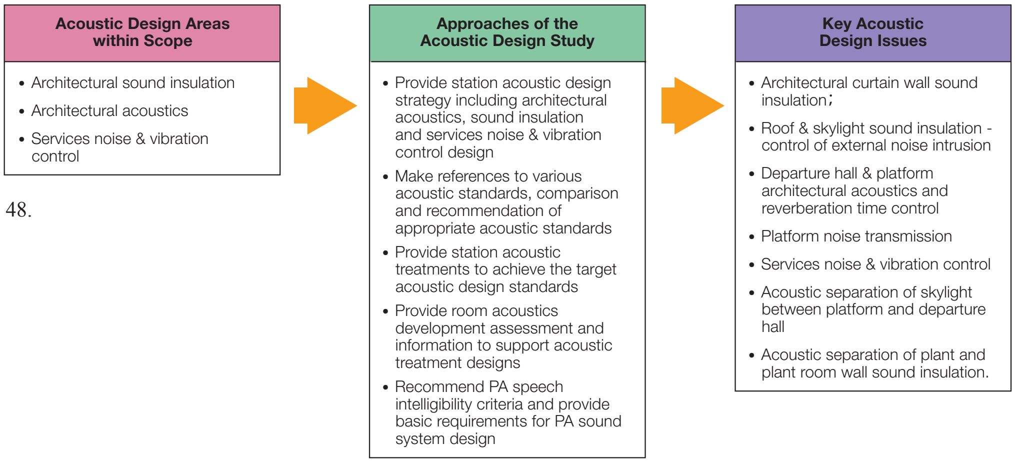

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Table 3. Summary of target acoustic criteria.

Floor	Area	Services noise standard (i)	Breakout noise limits from plantrooms (ii)	Intrusive noise limits through glass curtain wall (iii)	Reverberation time at 500Hz/sec (iv)
B1	Transfer area	NR50	NR50–10dB	NR50 + 5dB	1.6sec
	Entrance area	NR50	NR50–10dB	NR50 + 5dB	1.6sec
	Plant room	NR70*	-	-	-
	Office room	NR40	NR40–10dB	NR40 + 5dB	0.7sec
	Car park	NR60	NR60–10dB	-	-
Platform	Platform	NR50	NR50–10dB	NR50 + 5dB	1.5sec
	Entrance area	NR50	NR50–10dB	NR50 + 5dB	1.5sec
	VIP	NR35	NR35–10dB	NR35 + 5dB	0.5sec
	Plant room	NR70*	-	-	-
	Office room	NR40	NR40–10dB	NR40 + 5dB	0.7sec
	Canopy space	NR50	-	70dB(A) **	<2sec
Departure hall	Entrance and waiting area	NR50	NR50–10dB	NR50 + 5dB	<4sec
	Lounge	NR45	NR45–10dB	NR45 + 5dB	1sec
	Shops	NR45	NR45–10dB	NR45 + 5dB	-
	Office rooms	NR40	NR40–10dB	NR40 + 5dB	0.7sec
	Plantroom	NR70*	-	-	-

Notes

* Maximum level

(i) Include suspended services equipment at platform and B1 floor

** Canopy space is of semi-open design without glass wall.

(ii) NR = noise rating in accordance with ISO

(iii) dB(A) = A-weighted noise level

(iv) Reverberation time also helps to minimise echoes and improve room acoustics.

Acoustic design

Special acoustic design considerations and approaches were developed, playing an important role in the station design because of passenger safety in relation to public address emergency broadcasts. Acoustic design helps to provide a comfortable aural environment, enhances intelligibility of PA announcements, ensures that M&E services noise does not affect the surrounding environment, and that noise impact from the environment around BSS is minimised (Fig 48).

Acoustic criteria

The acoustic design took into account the relevant guidance in Chinese and other international standards, and combined these with local requirements to establish the acoustic design criteria for achieving a comfortable acoustic environment (Table 3). These were developed to reduce reverberation time and background noise (eg railway, road traffic, services equipment, activities noise, etc) important in enhancing PA intelligibility.

Several special considerations were also taken into account in developing the acoustic criteria, including:

- design heights for reverberation times at platform and B1 level
- tolerability above the indoor ambient noise levels of slightly higher intermittent intrusive noise via the glass curtain wall from external visible noise sources
- environmental noise levels according to the PRC standard[4] in the semi-open space under the canopy roof under the "no train" condition
- train noise levels at platforms with high-speed trains entering and leaving without platform screen doors
- reverberation times for very large room volume at departure hall level
- the relatively tall height of the platform area under the canopy roof in a semi-open space.

Glass curtain wall/roof sound insulation
In designing curtain wall/roof sound insulation, intrusive noise is controlled to within the established noise limits.

The main noise sources outside BSS are the railway track "fan" areas and surrounding roadways. As the existing background noise levels were not appropriate to use due to very low road traffic, the sound insulation design of the curtain wall is primarily based on analysis of traffic noise results and estimation of the representative noise of activities at ground level.

Traffic data from the station's own road traffic assessment were used to assess the external noise levels. Noise surveys from locations such as the Olympics Exhibition Centre and Dongzhimen Transportation Interchange were used to establish the typical environmental noise spectrum for reference analysis. Railway noise mainly depends on the entering/leaving speed of trains through the fan areas and was determined based on US methodology[5].

The combined external noise levels from road traffic and railway were then used to determine the minimum sound insulation requirements for the external façade to achieve the indoor noise criteria. Sound insulating glass in the curtain wall specification delivered this.

Airborne sound insulation requirements for the metal roof and skylight were similarly determined and analysed, as well as rain impact noise.

Based on statistical data over the past 30 years from the Beijing Observatory, the average annual rainfall was determined. The thunderstorms and heavy rain common in July and August provided the basis to determine the maximum sound from rainfall onto the metal roof and skylight. This must not exceed the allowable noise limit for the departure hall, and the metal roof and skylight design provides adequate sound insulation.

The roof mainly comprises double skin aluminium panels with glass wool insulation and a double-layer glass design for the skylight areas. The waterproof layer also provides damping to insulate against rain impact noise.

49.

The entrance doors in the departure hall can also be sources of traffic noise intrusion. Here, two pairs of automatic doors in parallel for each entrance create a vestibule to minimise external noise intrusion.

Architectural acoustic design
To cater for the huge volume of the departure hall, *Odeon* acoustic modelling was adopted for acoustic and reverberation time analysis. Elsewhere (eg platform, B1 floor), reverberation time was calculated by the more usual *Sabine* program.

One acoustic design challenge was large skylight and glass walls in the departure hall. Here the acoustic treatment took the form of suspended acoustic ceilings under the roof, with additional treatment behind the aluminum tube ceiling fixed by metal mesh and on parts of the beams under the skylight. Sound absorbent material is also provided in column louvre locations and on top of the four two-storey corner zones.

At the B1 floor level, a suspended aluminium metal acoustic ceiling was designed to achieve the reverberation time criteria. Close co-ordination with the architects was needed to achieve the acoustic and aesthetic requirements, and an acoustic model was created to verify the analysis (Fig 51).

Curved surface acoustic analysis
The departure hall roof is elliptical and concave. Generally, a concave surface introduces sound focusing – an undesirable acoustic effect.

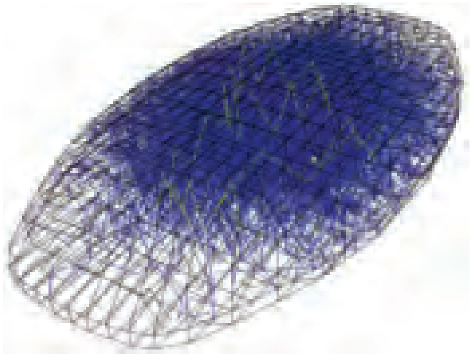
Acoustic focusing analysis shows that sound sources (loudspeakers) and receiver locations (the listening zone about 1.5m above floor level) should be as far as possible from the focusing zones to minimise the detrimental acoustic influence. Acoustic treatment on the suspended acoustic ceilings below the roof and the frames under the skylight also helps to reduce acoustic reflection.

In addition, the curtain wall is inclined slightly upwards, reflecting sound to the roof where it is absorbed, again improving the acoustics.

Canopy space acoustics
The canopy is convex, and sound directed towards it is reflected and diffused to other areas. Due to the semi-open design in the space under the canopy, sound partly escapes through the high-level louvre windows, and is partly reflected/diffused, escaping out through the open sides to avoid acoustic focusing or echo. An acoustic model was also constructed for the canopy area to verify the acoustic analysis (Fig 52).

50.

51.



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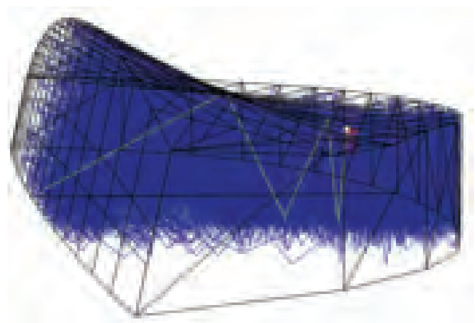

53.

49. Acoustic treatment to the suspended ceiling.

50. Acoustic treatment on the suspended acoustic ceilings below the roof and the frames under the skylight also helps to reduce acoustic reflection.

51. Aluminium perforated panels control reverberation above the platforms.

52. *Odeon* acoustic model ray tracing diagram: departure hall.

53. *Odeon* acoustic model ray tracing diagram: inner canopy space.

54 (overleaf). The complete Beijing South station and its fans of rail tracks to the east and west.

Table 4. High speed railway reference noise source terms.

Speed (km/h)	Source level dB(A)	Track condition	Reference location	Correction
300	89.5	Straight, continuous rail, 60kg/m rail track, concrete sleeper, ballasted, track in good condition	At 25m from track centreline, 3.5m above railway track	For non-ballasted track, apply 3dBA; for non-ballasted track on viaduct apply 6dBA.
200	82.5			

Platform acoustic design treatment

Major noise sources here include rolling stock during train arrival/departure, air-conditioning noise from condenser units, the PA system, and passengers themselves. As trains are the major noise source, acoustic analysis was based on the established train noise data (Table 4).

Even when trains pass non-stop through BSS, their speed does not exceed 55kph, so controlling reverberation time is also important. Acoustic treatment for the suspended ceilings in the platform passenger area is in the form of perforated aluminum panels or tubeline ceiling.

Noise separation between platform and departure hall and B1 floor

The ceiling space in the platform is designed for sound absorption, helping to minimise and reduce the impact of noise transmission from platform to departure hall. Sound insulation requirements of the skylight were determined based on the source-path-receiver analysis. Double-glazing and laminated glass was designed for the skylight to achieve the noise criteria. Between the central portion of the platform and departure hall, there are a number of stair and escalator openings through which noise can travel. Glass enclosures were designed for these openings to provide the screening effect during train arrivals and departures.

Plantroom sound insulation design

Breakout noise from the plantrooms is controlled primarily by acoustic walls and doors, rated STC (Sound Transmission Class) 40-55. STC rating depends on the acoustic sensitivity of the adjacent rooms. At locations near noise sensitive areas, the sound insulation requirements are higher. Three types of acoustic walls were developed for the project to achieve the requirements: Type 1: STC55; Type 2: STC45-50; and Type 3: STC40.

Services noise and vibration control

Services in the building include air-handling units, ventilation shafts and fans, water pumps, the air-conditioning system, escalators, generators, etc, all of which generate noise. Major structure-borne noise emanates from water pumps, lift machine rooms, etc. Acoustic analysis, based on guidelines in *BS EN 12354-4:2000*[7] and the US ASHRAE Handbook[8], was conducted to determine the attenuation requirements for compliance with the indoor acoustic criteria. Analysis was based on source sound power level, reverberation time, distance attenuation, and acoustic reflection.

54.

Project co-ordination

Apart from the technical challenges faced by the designers, project co-ordination was one the most complicated and difficult tasks, heightened by combinations of the following factors:

- The international design team of TFP and Arup was involved in the project alongside the TSDI designers, and time-consuming effort was needed to achieve mutual understanding.
- Cultural backgrounds were different – some common construction practices in Hong Kong are not applicable in mainland China, and vice versa.
- Some designers in the international design team could not speak Putonghua and most local engineers in the LDI could not speak English.
- The international design team was mainly resident in Hong Kong while the LDI was in both Tianjin and Beijing.

Measures to mitigate and solve these challenges included:

- extensive use of electronic communication including e-mail, teleconference and ftp (file transfer protocol)
- all correspondence from the international team in both English and Chinese
- frequent flights by designers from Hong Kong or elsewhere to Tianjin or Beijing for face-to-face meetings as and when required
- in the critical stages, some key designers resident in Tainjin or Beijing for longer, eg three months, to make sure issues were dealt with in a timely manner
- key designers retained through the entire design period
- involvement of bi-lingual project co-ordinators throughout
- meetings and workshops as necessary to align all objectives.

Conclusion

Completing this project from a design competition finally won in autumn 2004 to opening in August 2008 was a tremendous achievement for all concerned. The principal design firms – TSDI, TFP, and Arup – collaborated with the common aim to design one of the best railway stations in the world. Arup staff in offices from Beijing, Hong Kong, Shanghai, and Sydney worked closely together to achieve the multidisciplinary engineering of this hugely ambitious station design. In addition the contractors faced and overcame the daunting task of completing the entire building in 37 months from ground breaking to railway operations.

Beijing South station has been included in a TV documentary entitled “Manmade Marvels China –World’s Fastest Railway”, which describes the development and construction of China’s newest high-speed line from Beijiing to Shanghai. Zhou Tie Zheng, chief architect of TSDI, Stefan Krummeck, director of TFP Farrells, and Goman Ho of Arup were interviewed on a visit to the station.

As well as receiving various architectural awards, the station topped a “Beijing Contemporary Top Ten Architecture” poll, attracting almost 3.5m votes from the Beijing public.

Authors

Tristram Carfrae is an Arup Fellow, a Principal of the Australian Practice and a member of the Arup Group Board. He led and developed the refined scheme of the canopy roofs.

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Mingchun Luo is a Director of Arup China and has overall responsibility for the Hong Kong fire engineering group. He acted as team leader for all aspects of the fire engineering design.

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Colin Wade is an Associate Director of Arup in the Hong Kong railway infrastructure group.
In collaboration with TFP Farrells, he conceived and carried out the concept design of the roofs and the trackwork support substructure.

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Project credits

Promoter: *Ministry of Railways, Government of the People's Republic of China* Client/Architect: *TFP Farrells in collaboration with The Third Railway Survey and Design Institute GroupCorporation* Roof structure and specialist structural input, MEP, building physics, fire, wind engineering, and acoustic engineering designer: *Arup – Stuart Bull, Tristram Carfrae, Hei-Yuet Chan, Henry Chan, Vincent Cheng, GY Cui, Stella Fung, Da-Gang Guo, Jun-Ping Guo, Sophy He, Goman Ho, Kenneth Ho, Cai-Xia Hong, Cheng-Gang Ji, Li Kang, Eric Kwong, Barry Lau, Eric Lau, Ching-Kong Lee, Ryan Lee, Fu-Gui Li, Xing-Xing Li, Qu-Ying Ling, Di Liu, Tarry Liu, ZZ Liu, Li-Hua Long, Mingchun Luo, Lily Ma, Tin-Chi Ngai, Jane Nixon, Samuel Oh, Bi-Bo Shi, Hai-Ying Shi, Timothy Suen, Alex To, Isaac Tsang, Colin Wade, Bai-Qian Wan, Yi-Hua Wang, Frederick Wong, Sui-Hang Yan, Raymond Yau, Rachel Yin, Rumin Yin, Anna Zhang, Meng-Jun Zhang, Zhi-Qin Zhang, Juddy Zhao, Yue-Ci Zhao, Wayne Zhou* Pedestrian/traffic engineer: *Atkins China Ltd* Main contractor: *China Railway Construction Engineering Group* Steelwork contractor: *Jiangsu Huning Steel Mechanism Co Ltd.*

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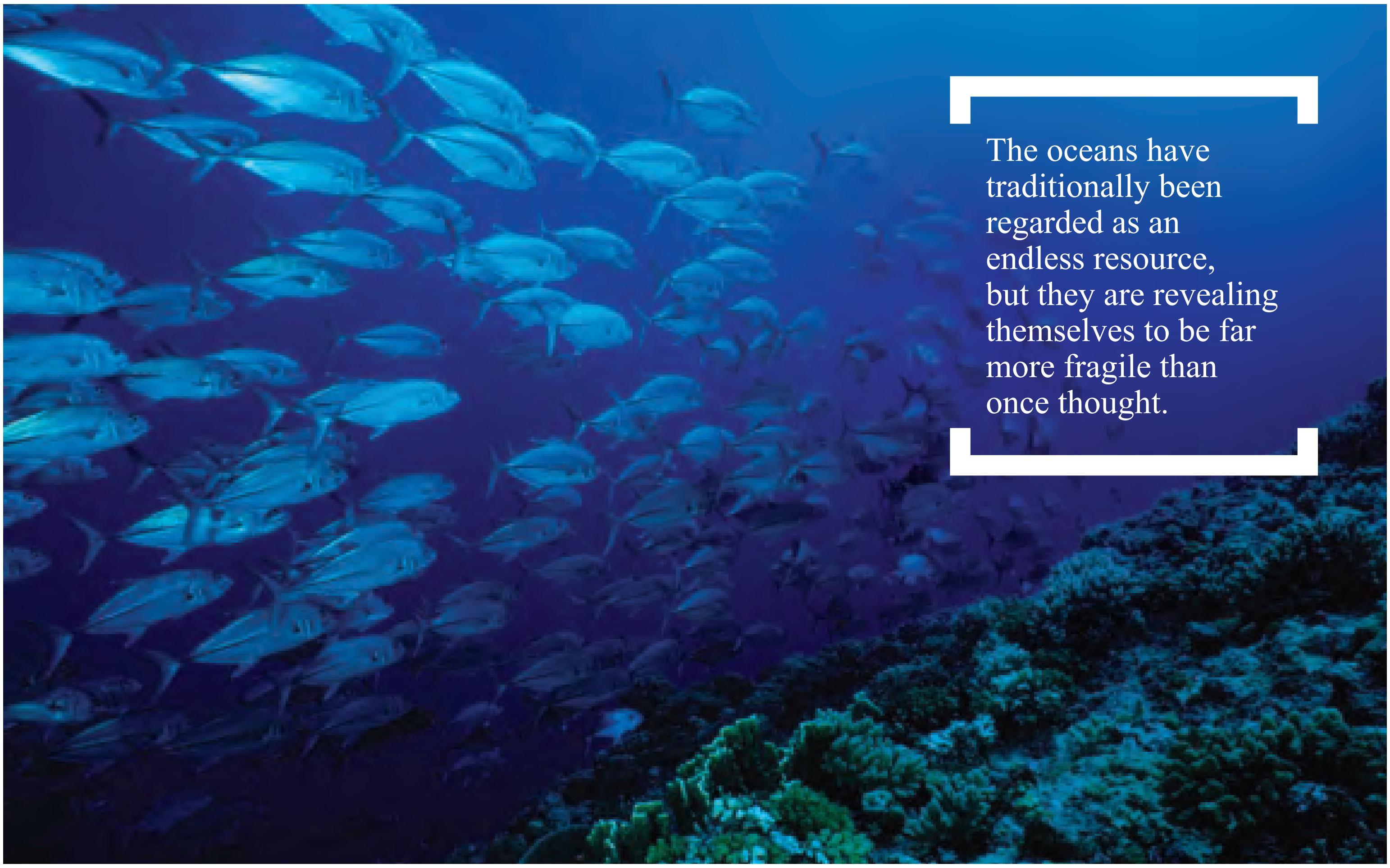
The oceans as a driver of change

Author
Elizabeth Jackson



1.

Introduction

Life as we know it would not be possible without the global oceans, though as is often stated, we know more about the external universe than we do about our oceans, as 95% of them remain unexplored[1]. The ocean systems are a complex series of physical and chemical interactions between land, sea, and atmosphere; they drive global weather patterns and the carbon (CO_2/O_2 exchange) and hydrological cycles, which provide the foundation for much that humans depend upon.

The oceans have traditionally been regarded as not just vast, but effectively an endless resource, capable of absorbing any and all natural and human impacts. There has long been a degree of cognitive dissonance between what humans put into the oceans and subsequent impacts over time. It is now clear that as the human population has increased exponentially, impacts have compounded, and the oceans are revealing themselves to be more fragile than once thought. As impacts compound, the effects are potentially and systemically irreversible; systems-wide tipping points are more likely to become a tangible reality. The available data should be considered carefully, and serve as a wake-up call to all of us, since numerous small and seemingly unrelated impacts are being shown to have enormous cumulative effects that are playing out on a global scale.

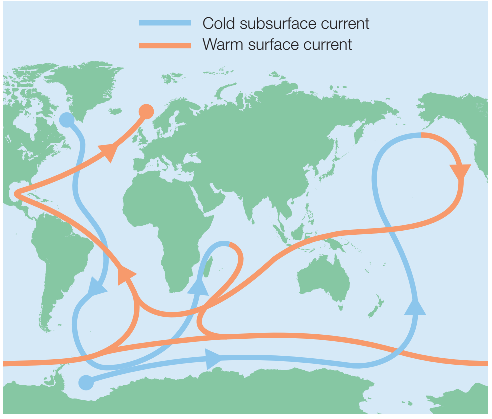
The oceans are thus neither entirely invincible system nor endless resource. As a system, they exist in a delicate balance between global surface temperature, chemistry, and physical systems – and human impact on land and sea is changing that balance. Fortunately, evidence shows that the oceans can heal and rebound if anthropogenic impacts are reduced or eliminated and if ecosystems are given sufficient time to recover. However, this resiliency is more evident and possible in species restoration. Physical and chemical systems are slower to respond, as they operate on a longer timescale, which is why the oceans as buffer systems remain a significant concern.

Deep time

Life on Earth began in the sea, and developed there before the first terrestrial creatures emerged on the land surface. Some 3bn years ago all life comprised single-celled organisms, and aeons passed before more complex forms evolved. Ancient marine fossils are found today both on land and under the sea; clearly, life on land would not have been possible without the oceans[2]. Today 32 of the 33 different animal phyla occur in the sea, only insects being exclusively terrestrial, while 15 phyla remain exclusive to the marine environment. The links between phyla in the animal kingdom further reinforce the relationship between life and the oceans[3].

Cultural history and the oceans

Many historical accounts represent the oceans as the great unknown, places to fear and respect that have inspired awe and appreciation around the world. Horizons appeared to be vast and infinite, journeys could take weeks, or even years. Tales of mermaids, shipwrecks, pirates, drowning, and fierce storms permeate global mythology and historic lore. In Western cultural history, books like "Moby Dick" (1852) and paintings like Géricault's "The Raft of the Medusa" (1818-19) represent and perpetuate fear of the sea and its living systems. Such representations are often based on a lack of understanding that continues to be perpetuated by and sensationalised in films like "Jaws" and the contemporary media. Cetaceans (whales, dolphins, etc) hold places of great cultural significance in coastal indigenous populations like the Arctic Inuit and the Pacific Islanders. Whales figure in the myths of Paikea from the New Zealand Maori, and on the totem poles of the Haida, Tlingit, and other coastal peoples. The Coast Salish people in Northwest Washington and British Columbia referred to themselves as the Salmon People, indicating a crucial link between perception, cultural identity and the sea[4]. The tribal relationship between the people of the land and the people of the sea is honoured and revered to this day.



2.

Oceanic engines

The oceans play a crucial role in global life support systems. This includes the thermohaline circulation, the macro-currents that facilitate the exchange of heat, oxygen, minerals, and other essential nutrients in the global marine environment. These currents function as flushing and cleansing mechanisms for continental shelf and coastal areas, helping to cycle nutrients from the deep oceans to the surface waters. This circulation is crucial to maintaining clean and healthy ecosystems, coastal water quality, and the deep-water areas of over 75% of global fishing grounds[5].

The current transit time from the Southern Ocean to the mid-level of the North Pacific Ocean is between 500 and 1000 years[6]. Cold subsurface waters and warmer surface currents mix via upwelling at a few key places globally – notably in the Northern Atlantic Ocean. The warmth of the Gulf Stream current is one of the reasons why Western Europe is more temperate than it would be otherwise (Fig 2).

The timing of natural upwelling cycles is changing in response to increasing global surface temperature and additional cold fresh water on the surface of the oceans. A decrease in salinity (due to melting sea-ice and glaciers) affects upwelling patterns, as the saltier ocean water is denser and heavier[8]. As ocean surface waters get warmer and become more static, less oxygen is exchanged between the surface and the deep ocean[9]. An increase in freshwater in the North Atlantic Ocean is affecting full-depth convection mixing, most likely due to the increased melting of the Arctic ice sheet. The models developed by climate scientists predict that the potential stalling of the current will affect the climate on land, disrupting local weather patterns and resulting in areas of increased drought as well as increased moisture. The 2010 floods in Pakistan and the fires of Northern Russia are excellent examples of changes on land.

1. 32 of the 33 different animal phyla occur in the oceans.

2. Oceanic engines[7].

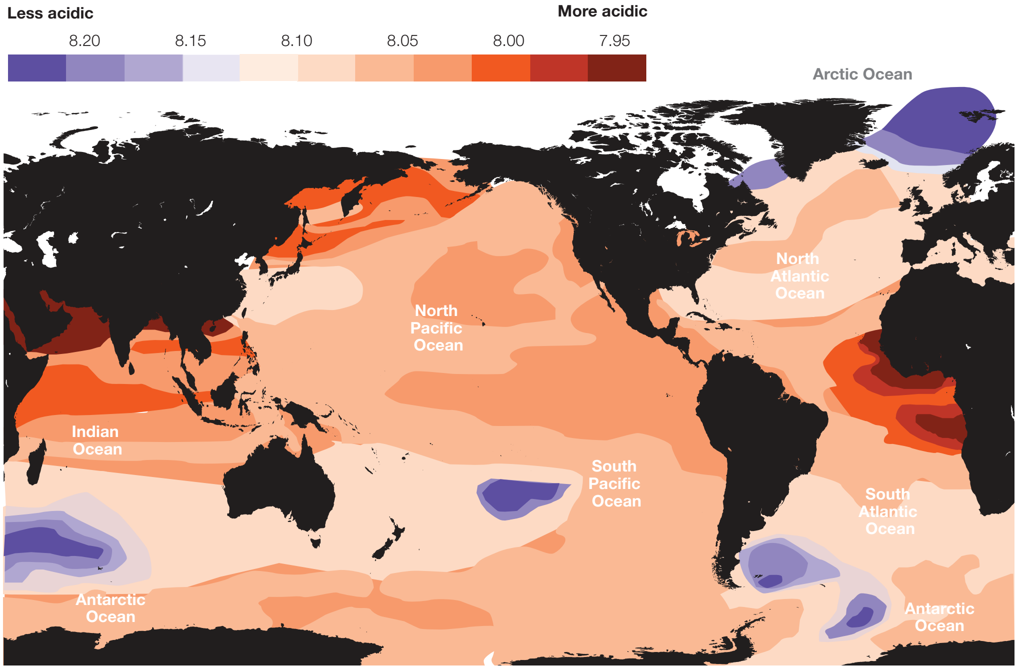
Chemistry and acidification

Phytoplankton are responsible for one half of global photosynthesis output, yet their existence is being threatened due to the increasing acidity of the oceans[10].
The oceans have absorbed approximately half of all CO_2 emissions since the dawn of the Industrial Revolution, while pH has decreased by 30%, resulting in increased acidity (Fig 3). This is due to the increase in CO_2 in the atmosphere, and the subsequent absorption by the oceans. The oceans currently uptake between 30-50% of anthropogenic CO_2 from the atmosphere[12], approximately equivalent to 9980 tonnes of CO_2 per day[13].

By absorbing much of the CO_2 from the atmosphere, the oceans have delayed many of the anticipated impacts from climate change, as they take significantly longer to heat up than the atmosphere and contain around 50 times more CO_2[14]. This is attributed to their immense size, depth, and complex chemistry.

Ocean acidification is increasing and is expected to reduce surface pH by 0.3-0.5 units over the next century – a faster rate of change than during the last 650 000 years[15]. *Prochlorococcus* (a blue-green bacterium) generates approximately 20% of the oxygen in the atmosphere[16]. The Southern Ocean alone (from 40°S) uptakes 40% of the CO_2 absorbed by the total global oceans[17].
The increase in the uptake of CO_2 changes ocean chemistry by decreasing pH[12].

The marine food web depends on the physical chemistry of seawater. A decrease in ocean pH affects the ability of marine calcifiers including phytoplankton, coral reefs, and shellfish to fix dissolved calcium carbonate ($CaCO_3$) present in seawater and incorporate it in their exoskeletons. If these organisms are unable to calcify they essentially dissolve, a phenomenon that has already been observed in several global locations. In Willapa Bay in Washington State cultivated oysters have failed to reproduce since 2005. 80% of larvae have died as a result of a more acidic ocean.



3.

4.

3. Variations in pH levels in the world's oceans.[11]

4. Phytoplankton blooms form off the coast of Argentina.

The larvae are unable to fully form and attach themselves to existing substrates (rocks, other oysters, etc.) If larvae unable to attach they fail to become adult oysters. Oystermen depend upon naturally occurring reproduction for their livelihoods[18].

Regions like the North Pacific Ocean and the Antarctic are particularly vulnerable to a decrease in pH. More corrosive waters tend to be shallower in depth, colder, and affected by upwelling patterns[12]. Surface waters tend to be supersaturated while subsurface waters are likely to become under-saturated with calcite and argonite. In addition, the loss of sea ice during the summer months has exposed new areas of ocean to air-sea gas exchange, increasing the uptake of CO_2. Melting ice reduces the saturation of $CaCO_3$ in seawater by reducing the alkalinity[17].

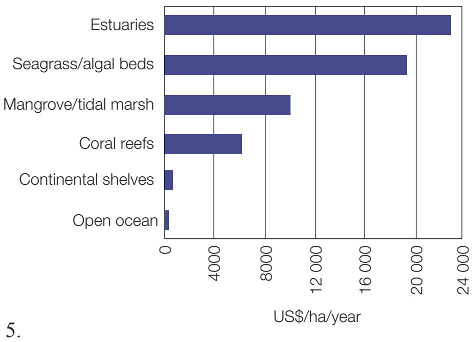
In addition to altering the ability of marine organisms to calcify, ocean pH is affecting low-frequency sound transmission, respiration, and the behaviour of juvenile fish. The chances of survival of baby fish reduce by 50-80% with lowered pH.
The decrease in pH affects the sense of smell, ability to find food, ability to avoid predators, and reproduce[9]. Baby clownfish, for example, are unable to return to their home reef under more acidic conditions[19].

Value of ecosystem services

Ecosystems have an economic value that surpasses the industrial output of the entire globe. This is referred to as "natural capital", defined as the value of ecosystem services that are the naturally functioning biological systems provided for free by the environment[21]. These services are usually taken for granted, as most people do not consider the equivalent monetary value that ecosystems provide. In a healthy biologically diverse equilibrium, ecosystem services are continually renewable resources if they are maintained and not stressed to the point of ecological collapse.

What are these ecosystem services? They include climate regulation, waste processing, nutrient cycling, storm surge protection, recreation, transportation, and food[22]. The open oceans account for some \$8T in ecosystem services, while coastal ecosystems account for \$12T annually of the \$33T global total—higher than the value of all industrial output[20] (Figs 5, 8).

The top five stressors to global ecosystem services are: climate change, fragmented and lost habitat, over harvesting, coastal pollution, and invasive species[5], all of which are facilitated by and enhanced by increases in demand, in consumption, and in coastal populations. The impact of 7bn people is increasingly profound. The financial burden of ill-functioning ecosystems means that humankind will have to find alternative means of providing such ecosystem services, which are currently free. Human disease attributed to coastal sewage pollution is equated to 4M lost "man-years" annually, and a \$16bn economic loss[23].



5.

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7.

Benefits from marine and coastal ecosystems and activities	
Coastal tourism	\$161bn
Trade and shipping	\$155bn
Offshore oil and gas	\$132bn
Fisheries	\$80bn

8.

5. Comparative values for marine ecosystems[20].

6. Deforestation of the mangroves,Ceará, Brazil.

7. The Pacific Oyster has become prolific along the coastal regions of Tasmania, Australia.

8. Benefits from marine and coastal ecosystems and activities[20].

9. 267 different marine species worldwide are affected by plastic debris.

10. Oceanic engines.[7]

11. Proportion of plastic to other types of marine debris.[26]

9.

Convergence zones and plastic

Five major ocean gyres (large rotating current systems) are now laden with plastic (Fig 10). Traditionally, these are nutrient-rich convergence zones, where many marine creatures gather to feed. Today, due to the use and ubiquity of plastic, these gyres are subsurface floating plastic islands. The North Pacific Gyre off Hawaii in the Pacific Ocean has, for example, been estimated to be anything between the size of the state of Texas and the whole continental United States. Appropriately, this gyre has been nicknamed "Great Pacific Garbage Patch".

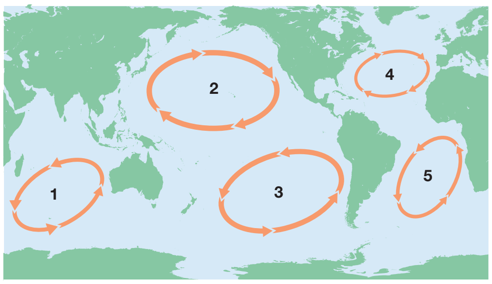
Plastic pollution is a subject of great concern, as plastic takes longer to degrade in the ocean than on land due to temperature. Plastic, which is photodegradable, breaks down into minute particles that are ingested by marine life and compete with zooplankton for surface area and sunlight[25]. In the Central Pacific it has been documented that for every 1kg of plankton there are 6kg of plastic debris. There are around 46 000 pieces of litter per square mile of ocean[14].

Micro-sized plastic particles absorb and concentrate chemicals from surrounding seawater at up to 1M times the ambient ratios in the water[25].

The most prominent form of marine debris over the last 40 years, plastic now litters beaches and the oceans (Fig 11). Its manufacture has increased 25-fold, yet recycling and recovery are less than 5%[27] due to the ubiquity of single-use plastic in current human life: packaging, consumer products, and the numerous shipping containers carrying goods that go overboard every year. Marine-origin debris accounts for 20% of pollution, the remaining 80% is from land.

Marine debris, legacy pollutants, agricultural run-off, and human waste are also subjects of increasing concern. Debris is traditionally considered flotsam and jetsam – ancient and modern shipwrecks, discarded fishing gear, garbage, effluent, waste from cruise ships and ocean liners, and other terrestrially-generated debris.

The impacts continue to increase. 44% of seabirds have been documented to ingest plastic and feed it to their young, who as a result die of starvation. Similar instances have been recorded in fish, turtles, filter feeders, and other marine life; 267 different marine species worldwide are known to be affected by plastic debris[28].



1. Indian Ocean Gyre **2.** North Pacific Gyre (Gabage Patch) **3.** South Pacific Gyre **4.** North Atlantic Gyre **5.** South Atlantic Gyre

10.

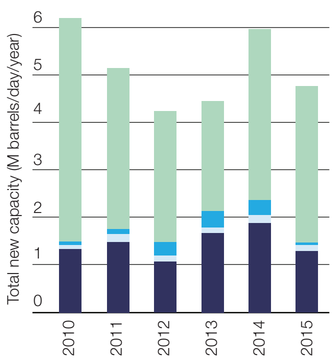
Location	Litter type	% Plastic
Bay of Biscay	Seabed	92%
East coast of Panama	Shoreline	82%
Georgia, USA	Beach	57%
North Pacific	Surface	86%
Mediterranean Sea	Surface	60-70%
Nine sub-Antarctic islands	Beach	51-88%
50 South African beaches	Beach	>90%
80 sites in Tasmania	Beach	65%

11.

Resource extraction

As noted already, the oceans have been treated as an inexhaustible and self-replenishing resource, just as have many places on land have. The oceans have provided a continual bounty for millennia, been the means for global trade and exploration, and constituted a vital resource for countless coastal communities and seafaring cultures.

The delicate balance of healthy global oceans depends upon chemistry, pH, nutrient cycling, seasonal changes, a well-structured food web, and the opportunity to recover from local and globally adjacent impacts. Humans are changing the oceans and this natural equilibrium, more so than at any time in human history. The rise in global population and the advent of the Industrial Revolution helped shape the world we know today. Humanity has been able to travel further, faster, and more efficiently than ever before, due to phenomenally cheap fossil fuels. The glut of cheap energy has allowed exploration and exploitation of previously unknown frontiers, extraction of vast quantities of natural resources, and has shaped the world today. Yet, the breakneck pace at which humanity continues to consume fossil fuels comes at a price. The increase in CO_2 has had impacts on the seas, which absorbed 2.3bn tons in 2008 alone, equivalent to about six years of US gasoline consumption[29].



12.

13.

12. Resource extraction from the oceans[31].

13. Self-buoyant concrete gravity base foundations for wind turbines are being developed by Arup.

As the global demand for mineral resources such as oil, cobalt and copper grows, depleting existing land reserves, so many companies are turning to the oceans as the future of extraction. The resulting rise in commodity prices increases the viability of pursuing reserves that are harder to extract, many of them in the deep oceans and the high Arctic. The oil industry has been a pathfinder, with more than 3000 rigs now operating offshore, weaving a web of infrastructure, pipelines, and support systems. As the Arctic sea ice continues to melt there is a continued interest in the oil reserves of the high Arctic. But the Arctic is a fragile environment. Extraction is not possible year round, and clean-up is much more difficult due to extreme weather and the difficulty in accessing remote locations[30].

Globally there is renewed interest in mining deep-sea sulphide deposits, which yield valuable minerals in greater mineral-to-ore concentrations than on land. Of the estimated 100 000 ocean deposit sites, 54% are in international waters. China recently applied to the International Seabed Authority (ISA) to mine hydrothermal vents in the Indian Ocean.

Policing deep-sea extraction is difficult due to the lack of international regulation, the hidden nature of undersea activities, and the expense of monitoring. Numerous accidents around the world have indicated the environmental and operational risks associated with extracting minerals in deep waters. Many of these activities produce toxic waste, and occur at depths and temperatures where pollution is difficult to clean up and likely to persist far longer than on land, especially due to the extreme nature of the seas[14] (Fig 12).

The oceans, however, have the potential to generate vast amounts of clean energy. With the increasing momentum of their interest in renewable energy sources, governments and companies are looking more and more to the potential energy resources of the oceans, which account for approximately 70% of global solar energy, and almost 90% of total wind energy[32].

The potential energy of the oceans is indeed remarkable. For Europe alone, wind energy resources could reach 340TWh by 2015. Globally, 5000TWh per year could be generated by offshore wind energy generators, which would supply one-third of the current global demand. The EU could generate 10% of demand via offshore wind by 2020[32].

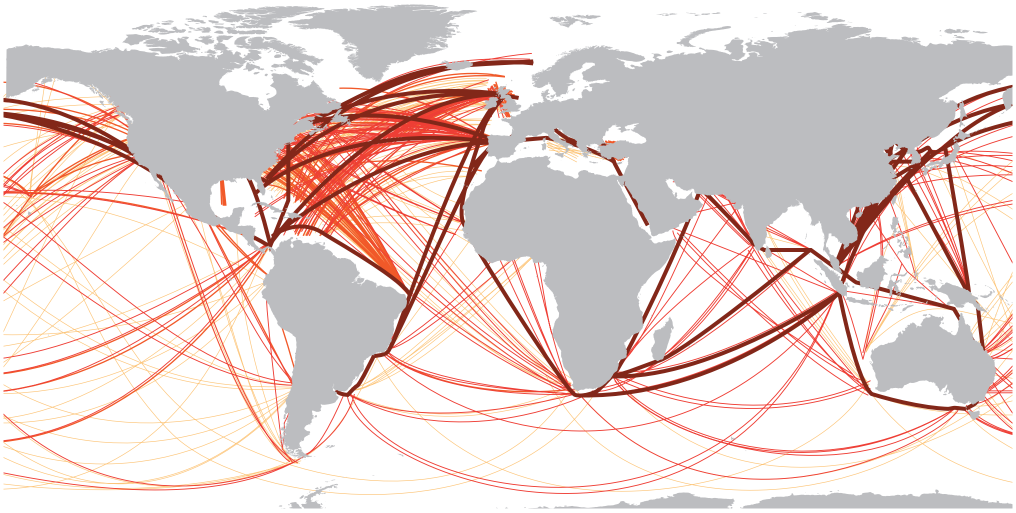
Global trade

Shipping is a major global economic engine (Fig 8). Cargo ships carry finished goods, dry bulk commodities, and wet bulks like crude oil and liquid natural gas. Oil tankers are responsible for transporting some 60% of the oil consumed globally[14].

Shipping is one of the most efficient ways to transport goods in terms of fuel used over distance travelled and the volume of goods. Twenty-foot equivalent units (TEU) is the standard measure of the volume of goods that a ship can carry. In one year alone a large container ship (approximately 8000 TEU) can transport over 200,000 containers[35]. Cargo ships are responsible for one-third of the value of global trade, worth more than $4.6T[36]. To ship a container from Melbourne, Australia, to Long Beach, California, costs approximately $2700; air-freighting the same volume of goods is more than 10 times as expensive.

In 2008, 1.3bn metric tons of container cargo were transported, representing 13bn grams of CO_2 per km travelled. International maritime trade accounts for 2.7% of global greenhouse gas emissions, and fuel consumption continues to get more efficient over time. In 1976, a 1500TEU ship used 96g of fuel per TEU km travelling at 25 knots, but a 12 000TEU vessel in 2007 consumed only 24g per TEU km[35]. There is also a move back to slow steaming and a renewed interest in the use of wind power for trans-shipping. The use of large kites, acting much like sails, on container ships helps to increase fuel efficiency.

14.



15.

14. Shipping is one of the most efficient ways to transport goods.

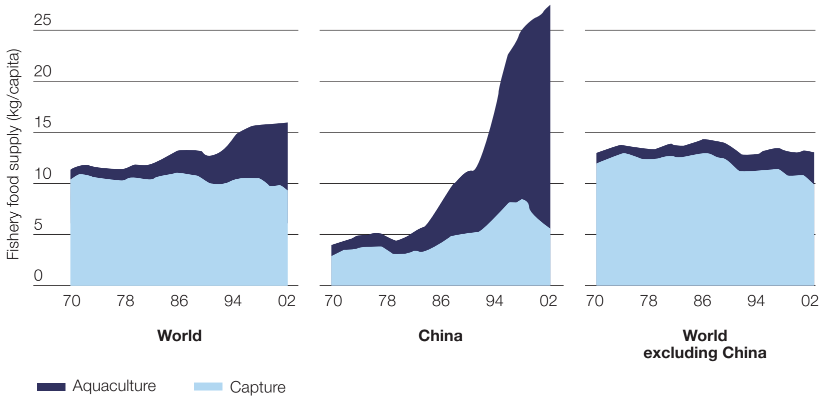
15. Global shipping routes.[34]

16. Relative contribution of aquaculture and capture fisheries to food fish consumption.[37]

“Peak fish”

An inexhaustible sea, and the law of diminishing returns

Seafood is the primary source of protein for 1bn people. In 2001 global per capita consumption of aquatic protein was 16.3kg per year (100.2M tons total), which accounted for 15-18% of protein consumed globally[37]. The oceans are a major lifeline for many coastal communities. Despite the increase in aquaculture (Fig 16), maintaining healthy fisheries is essential for sustaining future populations, and an additional 37M tons of fish will be needed per year to feed the global population in 2030[38].



16.

The oceans are now demonstrating how vulnerable they are due to increased pollution, over-extraction, over-exploitation, and increased acidification. Every year, over 77M tonnes of sea creatures are extracted from global oceans[10]. The pace is untenable. We have reached “peak fish”. Large-scale industrial extraction has outpaced the ability of ecosystems and food webs to remain self-sustaining and replenish themselves. The trend of fishing down the food web continues, as 90% of major predatory species (Blue Fin Tuna, Atlantic Cod, etc) have been decimated and are either endangered or near to collapse[39]. Globally, fisheries are predicted to collapse by 2048[40]. Over $2T is estimated to have been lost by the global economy over the past three decades due to over-exploitation and under-performance of fisheries[41].

The first commercial fisheries collapse occurred at the end of the 1980s, when local New England, Newfoundland and Nova Scotia fishermen began to notice a rapid decline in the historically robust Atlantic Cod fishery. Fishermen began to protest at what they saw as the end of their livelihoods, due to the impact of foreign industrial trawlers and catcher-processors. By 1992, the Canadian Government closed the Grand Banks off Newfoundland and most of the Gulf of St Lawrence to ground fishing. Similar closures occurred in the United States as well.

This has been one of most significant instances of a commercial fisheries failure and subsequent moratorium on fishing. The Atlantic Cod stocks have not yet recovered, although they were historically one the largest concentrations of biomass in the world[42]. Researchers have looked at logbooks from the 1850s, and estimated from the results of these investigations that there was approximately 1.26M metric tons of living adult cod on the Scotia Bank in 1852. In 2005, no more than 50 000 tonnes of adult cod remained – a 96% decline in approximately 150 years[43, 44].

Factory fishing has increased the quantity of extraction, while the explosions in human population, affluence, and consumption have grown the demand for seafood. Factory fishing fleets have dramatically increased the ability to extract large quantities of fish, while many small-scale coastal fisheries have not been able to compete with industrial extraction and processing methods.

Factory fishing has dramatically increased the size and range of global fishing fleets since the 1960s[45]. Technological advances in ship design, ship building, and shoal imaging allow ships to travel into the high seas and other previously inaccessible territory. This allows extraction of large quantities of fish at greater depths, surpassing the capabilities of smaller-scale coastal fisheries. Vessels now regularly operate at depths of up to 150-200m to access previously undesirable species on seamounts (undersea mountains whose summits do not reach the surface) and treacherous waters[5].

The capacity of the modern global fishing fleet is astounding. One modern North Sea trawler can haul the equivalent of 165 boats from 1910, or 200 000 boats from the 14th century[46]. Currently, 3.5m fishing vessels use the oceans, yet 1% of the global fleet accounts for 60% of the global catch[47].

In 2002 there were 24,406 vessels each with over 100 gross tonnes capacity[37]. These factory trawlers are equipped with vast freezer compartments and processing areas; catch can be flash-frozen, remain fresher, and vessels can stay out at sea for longer periods of time, thus increasing the volume caught and range exploited. The global fleet is now capable of extracting 2.5 times more than is considered a maximum sustainable yield from global fisheries[5]. In 2000 alone, tuna fishermen set 1.2bn long line hooks[14].

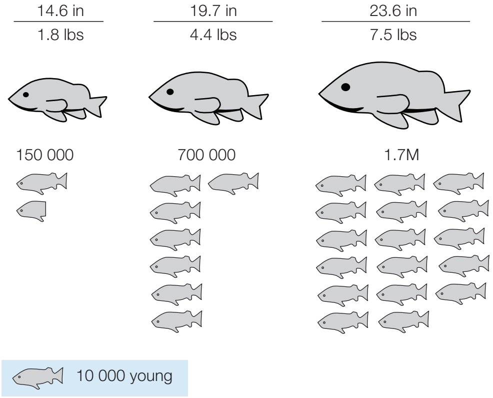
Every year an area totalling the size of Brazil, Congo, and India combined is trawled[48]. Eleven countries are currently involved in industrial fishing, which is having devastating effects on global fish stocks[16]. The practice of trawling has been described as a clear-cutting of the oceans, a destructive practice that destroys ancient deepwater reefs and ecosystems. Trawling can be a highly wasteful practice due to the high levels of bycatch (unintentionally caught seafood). Undesirable species or those of lesser economic value (economic discards) are returned, dead or dying, back into the ocean. Whales, dolphins, sea turtles, seabirds,and other creatures also become casualties of bycatch, which makes up approximately 25% of total fisheries’ landing (some have a much higher level). Shrimp fisheries, due to the small mesh nets, result in 5kg of bycatch for every 1kg of shrimp landed[2].

Shifting baselines

As species have been decimated and many apex predator species are near to collapse, populations of species lower on the trophic index have exploded, because their natural predators are no longer capable of keeping the food web in check. In Chesapeake Bay, the loss of 50% of the shark population since the 1970s has caused an explosion in the quantity of skate[49], now so abundant that it finds its way onto menus in metropolitan restaurants. Similarly, the collapse of Atlantic Cod has resulted in a rebound in sea scallops and lobster, which are now lucrative and viable fisheries[44]. These relationships between different species and populations indicate and further reinforce the notion that the oceans linked systems have direct and sometimes surprising feedback loops.

Just as skate wing now appears on menus, other previously undesirable species have been renamed and appear in supermarkets and on dinner plates[50]. Patagonian toothfish became "Chilean sea bass", to make it more desirable to consumers. Similarly, slimehead was renamed "Orange roughy". Renaming species indicates continually shifting baselines as to what is "normal". What was once considered trash or undesirable is now a fashionable delight, suggesting a change in perception as well as a rebranding of species[51].

The Orange roughy fishery, however, peaked and collapsed within four years. The fish's ability to rebound, as with other long-lived species, is threatened as they do not reach sexual maturity until they are 30 years old, and can live up to 200 years[2] (Fig 17). Deep pelagic species can be particularly vulnerable and slow to recover due to late sexual maturity, which diminishes reproductive capacity, particularly so in the case of sharks, which do not reach maturity until 5-20 years old and only produce 8-10 pups every other year[53]. By reducing mature populations, humans are fishing down the food web.



17.

19.

Delta	Issues: Pressure on space	Flood vulnerability	Freshwater shortage	Ageing or inadequate infrastructure	Coastal erosion	Loss of environmental quality and biodiversity
Yellow River delta (China)	••	•	••	•	•••	•••
Mekong River delta (Vietnam)	••	••••	••••	••	•••	•••
Ganges-Brahmaputra delta (Bangladesh)	••••	••••	••	••	••••	••••
Ciliwung River delta (Indonesia)	••••	••••	••	••	•	••••
Nile River delta (Egypt)	••••	••	••••	••••	••	••
Rhine River delta (The Netherlands)	•••	••	••	•••	••	•
Mississippi River delta (USA)	•	••••	•	••••	••••	••••
California Bay (USA)	••	••••	••••	•••	•	•••

• relatively minor problem, now and in the near future
•• currently a minor problem, but is likely to increase in the near future
••• currently already a big problem, future trend uncertain
•••• currently already a big problem, likely to increase in the near future

18.

Humanity and the coasts

Roughly 40% of human populations live on or near the coasts. With the loss of coastal buffer zones, the coasts have become fragmented and degraded by continued development, encroachment, and numerous anthropogenic impacts. Low-lying coastal populations are particularly vulnerable to rising sea levels, coastal flooding, extreme weather events, and subsidence. The 2004 Indian Ocean tsunami killed 230 000 people, proving how vulnerable coastal communities and populations are to severe weather and climate events, which are exacerbated by the loss of mangroves, coral reefs, and coastal wetlands[54]. Reefs and mangroves protect the shore from tidal and wave action, which continues to be diminished as near-shore habitat is destroyed and fragmented.

Low coastal land comprises 2% of global land area. However, more than 10% of the global population lives in these low-lying areas, and in low and middle-income nations roughly 20% of the population, rendering the poor disproportionately affected[54].

Mega-delta regions like Dhaka, Calcutta, and Shanghai are particularly vulnerable to rises in global surface temperature[54] (Fig 18). In Bangladesh, for example, 60% of the population lives below the 10m mark[54]. Though embankments protect much of its coasts from storm surges, crop yields are notably low when these fail and saltwater intrudes into these low-lying areas[56].

20.

Medical application	Original source
Anti-inflammatory agent	Gorgonian coral (genus Pseudoterigogorla)
Anti-tuberculosis agent	Gorgonian coral (genus Pseudoterigogorla)
Orthopaedic implants	Coral skeleton
Anti-viral drugs	Sponge (Cryptotethya crypta)
Anti-malarial agent	Sponge (genus Cympbasetela)
Anti-cancer drugs	Sponge (genus Jaspis) Tunicate (Ecteinacidia turbinata) Bryozoan (Bugula neritina) Seahare (Dolabella auricularia)

21.

17. The larger/older an animal is, the more offspring it can ultimately produce. If all the mature reproducing members of a species are fished out, it becomes increasingly difficult for it to fully recover and for the overall population to rebound.[52]

18. Deltas at risk.[55]

19. Children of Dhaka.

20. Coral reefs support 25% of all marine life.[59]

21. Medicines from the "coral reef medicine cabinet".[60]

Hidden species

There is more genetic diversity in the biomass of the oceans than on land, so the oceans are critically important to the future of biodiversity. Mangroves, estuaries, and coral reefs are the oceans' nurseries. They shelter and nourish spat, larvae, and juvenile marine species. They are essential to maintaining global biodiversity. Yet these essential ocean nurseries are disappearing and face the continued threats of rising sea levels, dead zones, upstream pollution, increase in global surface temperatures, acidification, and encroachment of human populations.

The Census of Marine Life[57] recently concluded a 10-year study, gathering as much knowledge about marine life as possible. Among its findings was that just three expeditions to the Southern Ocean yielded some 700 likely new species. One litre of seawater can host up to 20 000 different species of microbe[58]. In 2004, 13 000 new species were "discovered"[47]. Given the number of species that this would indicate are yet to be discovered, there is an untapped potential associated with the coral reefs, mangroves, and estuaries of the world.

The most biologically diverse oceanic systems are the coral reefs, which support an estimated 25% of all marine life[59]. Over 100 000 reef species have been named and identified to date, and it is estimated that 1-3M species are yet to be discovered and identified. But coral faces threats of cyanide poisoning, coastal pollution, and bleaching events; we are destroying the oceans before we can even begin to know their full potential.

More than half of all new drug research associated with cancer is based upon marine organisms[59]. Research is being done on the anti-inflammatory, anti-viral, anti-tumour, and anti-bacterial potential in sea sponges, tunicates and sea hares[1] (Fig 21). The loss of present biodiversity means that humans could devastate not only future biodiversity but also future biomedical research[1].

22.

Conclusion

Planning and preservation are crucial to the future of the oceans. Marine Protected Areas (MPAs)[61] cover less than 1% of the oceans, compared with the approximately 12% of the global land surface that is preserved. The World Parks Congress recommends that 20-30% of all ocean habitats should be protected as part of a global network[3]. MPAs are critical to the future of marine life, which many people depend upon for a primary protein source.

In recent years marine spatial planning (MSP)[62] has started to gain more momentum and be considered a critical aspect of the regulated marine environment. Both MPAs and MSP are crucial tools for the future health of the oceans. MPAs act to preserve remaining ecosystems, while MSP simultaneously considers the multitude of needs and uses of the marine environment by both humans and the oceans. As humanity moves away from a fossil fuel-dependent economy, the oceans will play an increasingly important role in providing energy. As shipping continues to be a global economic driver, more MSP will be critical to providing buffer zones for marine ecosystems while still allowing global trade. Both uses require MSP and a holistic approach. Preservation and planning are the future, and need to represent the new norm for all who use and have an impact upon the global marine environment.

The oceans are critical to planetary health and modern global life – air, water, food, trade, etc. They represent both the global past and the global future as mechanisms for facilitating trade, providing food, and ensuring biodiversity. While humans have had and will continue to have a significant impact on them, there are ways that impacts can be mitigated, primarily through regulation, preservation of remaining vital ecosystems, and co-operation between nations to protect the greatest global common areas.

Arup and Drivers of Change

Drivers of Change is a research programme begun in 2006 by Arup's Foresight network, dedicated to investigating – from social, technological, environmental, economic, and political standpoints – the likely future developments and changes in global phenomena that influence the work of Arup. Card sets analyse in detail such leading drivers as energy, waste, climate change, water, demographics, urbanisation, poverty, food, and oceans. Most of these topics have been the subject of scholarly overviews by the leading researcher in past editions of *The Arup Journal*. http://www.driversofchange.com/doc/

22. The city of Vancouver, built, like so many cities, on the fringes of an ocean that is constantly being encroached upon.

Author

Elizabeth Jackson is a graduate analyst with Arup in the San Francisco office. She was the lead researcher on oceans in the Drivers of Change programme.

Image credits

1, 6-7, 9, 14, 19, 20, 22 *iStockphoto*; 2, 3, 5, 8, 10-12, 15-18, 21 *Elizabeth Jackson/Brad Wharton/Nigel Whale*; 4 *NASA*; 13 *Arup*.

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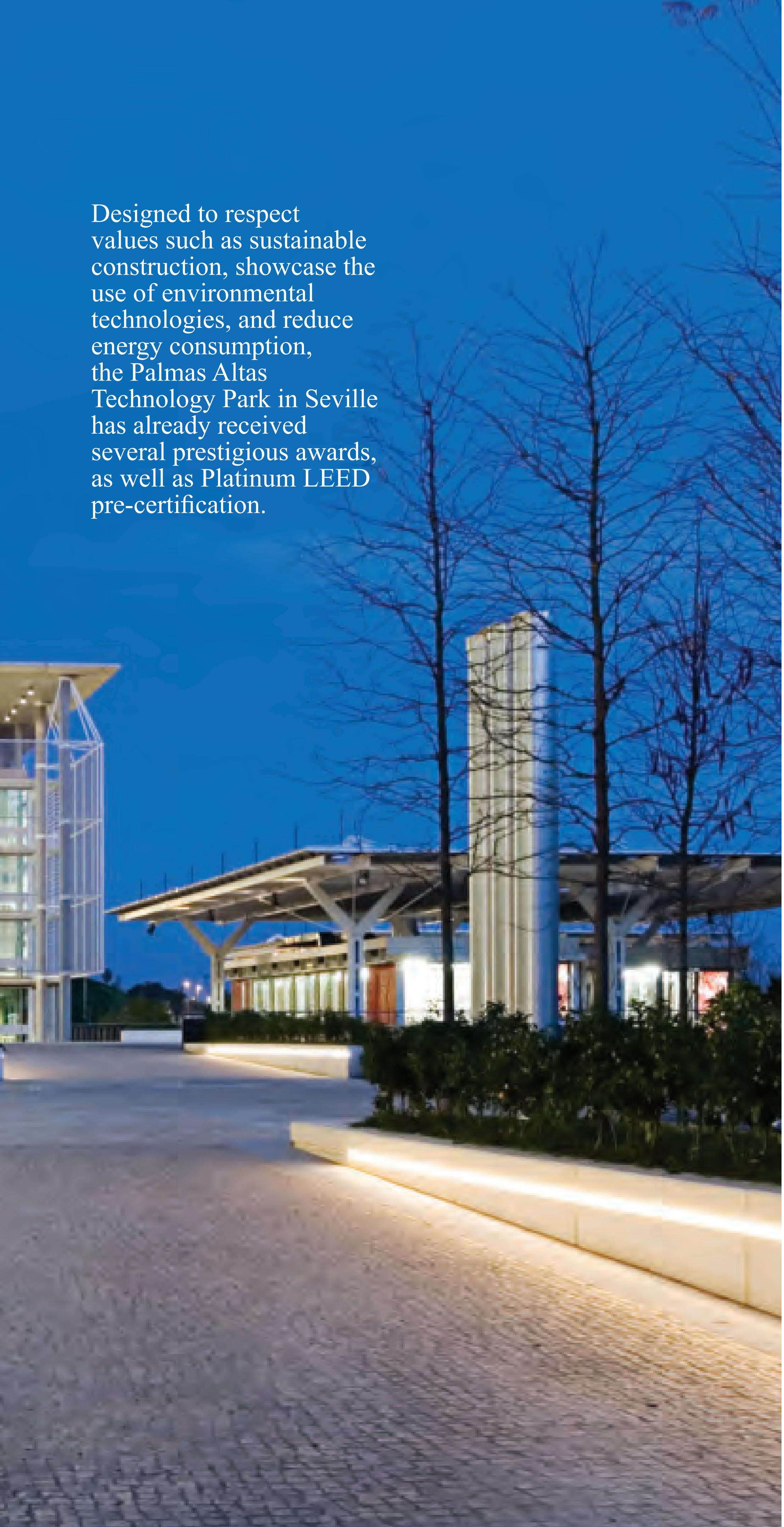
Designed to respect values such as sustainable construction, showcase the use of environmental technologies, and reduce energy consumption, the Palmas Altas Technology Park in Seville has already received several prestigious awards, as well as Platinum LEED pre-certification.



1.

Palmas Altas Campus

Location
Seville, Spain

Authors
Pablo Checa Mark Chown
Alejandro Fernández Ignacio Fernández
Marta Figueruelo Calvo
Matías García del Valle
Enrique González Karsten Jurkait
Ramón Rodríguez

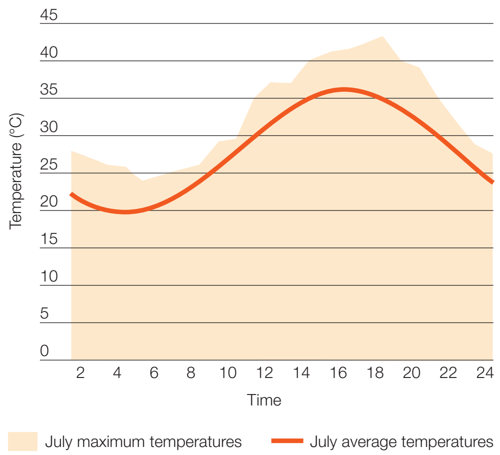
Introduction

When architects Rogers Stirk Harbour and Partners, together with Vidal and Associates, contacted Arup's Madrid office in 2005 to join them in the competition for the new Abengoa headquarters in Seville, the design team knew that it was about to embark on a special project.

The aspirations that Abengoa, a sustainable energy technologies manufacturer and solutions provider, communicated in its competition brief were challenging. Abengoa wanted to merge its various offices in Seville onto a single site, with the option to bring related businesses onto the campus to form a technology park.

The campus was to reflect the spirit of excellence, technological leadership, and strict respect for the environment that characterises Abengoa itself, while staying within a very limited construction budget (not to exceed average market costs) and meeting a tight schedule.

2.



3.

Awards
Royal Institute of British Architects (RIBA) Award for Architectural Excellence

American Institute of Architects (AIA) Environmental Excellence Award

European Prime Property Award for outstanding sustainability in real estate.

Key statistics

Office area (Abengoa headquarters)	27 800m²
Office area (speculative)	19 200m²
Common facilities	3500m²
Parking	35 000m²
Plaza	10 500m²
Total	96 000m²
Cost	€132M

1. (previous page) Southern façades and main entrance.

2. Generic design options: (a) tower, (b) compact, (c) linear, and (d) fingers.

3. July temperatures in Seville.

4. Microclimates have been created within transition spaces by utilising water and shading.

Four years later, in September 2009, their Royal Highnesses the King and Queen of Spain officially inaugurated the campus – Palmas Altas had become a reality, with Abengoa already in occupation. Construction costs had been kept even lower than originally budgeted, and the project went on to win several major awards.

This article describes what happened in those four years, and how Arup helped turn a major challenge into a resounding success.

The competition

The design team's initial response to Abengoa's competition invitation was to not present a single solution, but instead opt for a "standing dialogue" between itself and the client. To this end, the competition entry included generic options that reflected four different social models: "the tower", "compact", "linear" and "fingers". These were then rated against various criteria (social, economic, environmental, and real estate) to allow Abengoa to decide on the model that best suited its aspirations (Fig 2).

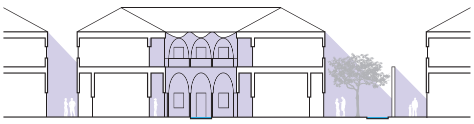
One aspect was the environment for the users of the complex – not only the internal office areas but also the semi-external and external spaces, where people would socialise and move between the various buildings. This was a particular challenge in Seville, where temperatures regularly exceed 40°C in the very hot summers (Fig 3).

At the same time the team had to minimise energy consumption – one of the pillars of the brief– and the various disciplines worked closely together to develop a range of ideas that would help achieve pleasant inside and outside environments for each model, and with very low energy consumption. Several options emerged:

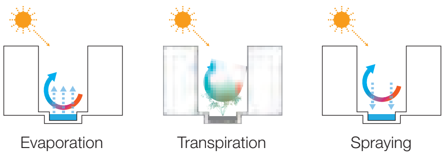
- Microclimates could be created by the use of patios* – an established tradition in Andalusia. This was especially attractive as it would allow stable microclimates to be created while increasing coolness in the hot summer months (Figs 4, 5).

* Here the word "patio" refers to an internal courtyard, as typically found in Andalusia.

4.

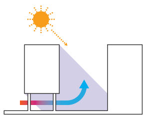


a)The use of patios is an effective way to create stable microclimates. Andalucía has an established tradition of taking advantage of the patio's physics to increase comfort and provide coolness during the peak summer months. The patio's orientation and design are important for effectiveness.

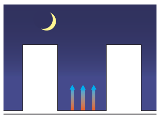


b) Patio temperature can be reduced in various ways. Use of water is very effective, whether implemented by pond evaporation, plant transpiration, or spraying (fountains).

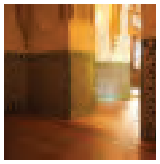
c) These can be very local in effect, but at Palmas Altas they are combined with other passive and active methods of introducing cooling air to occupied spaces.



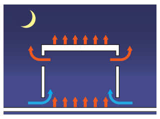
d) The patios also provide a mechanism for releasing heat at night, particularly effective here due to Seville's temperature range and low day-time humidity (but dependent on the patio geometry).



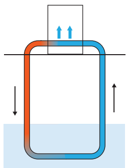
e) Thermal mass and heat-radiating, exposed surfaces can be used effectively. These are not new ideas, eg use of hard mineral surfaces of particular ceramics in traditional Andalucían architecture.



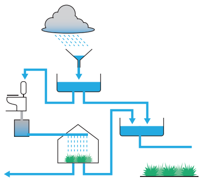
f) The use of thermal mass (which effectively delays the absorption and release of thermal energy) is essential to flush the buildings at night. An exposed concrete structure and leaving the surface of the slab exposed to airflow help to achieve this effect.



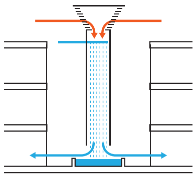
g) The thermal mass of the local aquifer can be used to advantage when storing coolth, but this requires a permit from the relevant authorities and a complete environmental study.

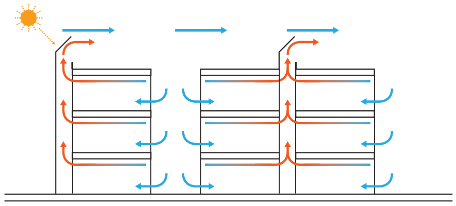


h) Arup proposed moderate use of water, as well as recycling, re-collection, and storage of rainwater. In Seville water is a precious resource and its role in environmental strategy is vital.



i) The team investigated a drip system to provide cooling to the patios. With this, air is forced through a cooling chimney that employs water drops for evaporation cooling, providing a volume of cold, humid air to the patios. This cool air can then be dispersed around the office spaces.





j) Solar chimneys can boost air flow through the buildings, introducing cold air from the patios through the other floors. South-facing glazed chimneys heat up the air that rises through thermal convection, and release it – supported by wind as available – above roof level.

5.

- To improve these patio microclimates, the use of water was considered (evaporation ponds, spraying, plant transpiration, etc). Collecting and storing rainwater for reuse would offset water consumption.
- By utilising the large day/night temperature difference (over 15ºC) in Seville (Fig 3), buoyancy-inducing design measures would allow ventilating/cooling spaces at no cost.
- Using thermal mass would absorb the heat of the day and release it by ventilating the buildings at night.
- Geothermal energy and/or biomass were further possibilities.

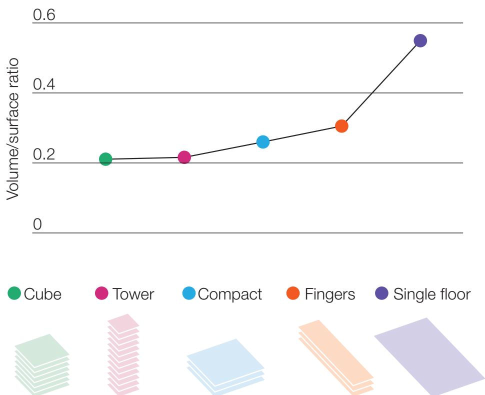
Continuing the approach of offering generic options, these ideas and their possible integration into the project were presented as part of the competition entry.

Abengoa liked this proposal's open, two-way communication approach, as well as the presented options for a cost-effective sustainable design, and duly awarded the competition to the team in June 2005. Further dialogue with the client homed in on the most appropriate option for developing a full design – a process in which sustainable aspects played an important role.

5. The patio microclimate.

6. Surface/volume ratio of generic design options: Linear is similar to fingers and not illustrated separately; "cube" and "single floor" added as the most and least efficient hypothetical cases

7. Heat loss/m² for generic design options.



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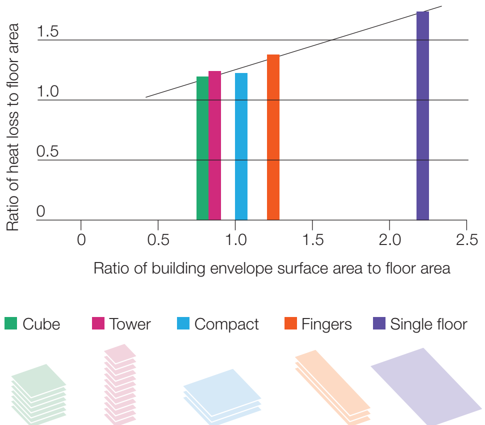

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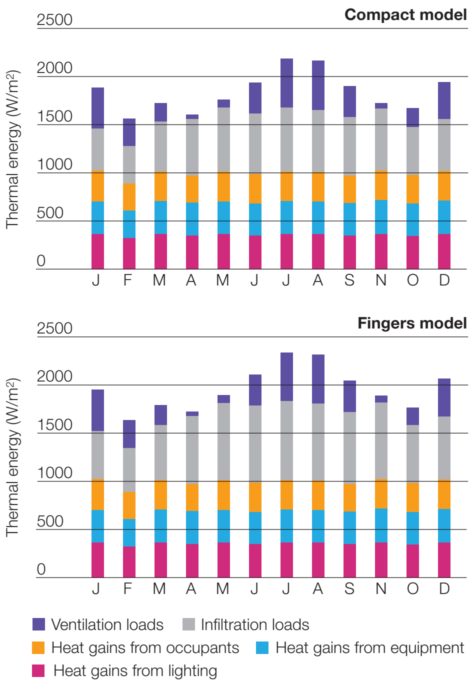


8.

9.

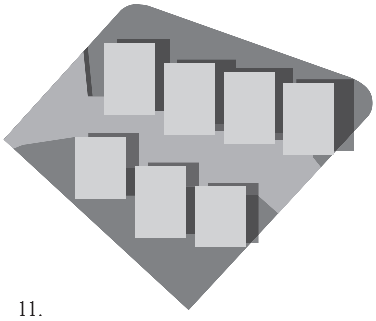
10.

8. Analysis results for compact and fingers models.

9. The final design provides outside views while maintaining efficient solar protection.

10. Aerial view during construction.

11. Compact block model.



11.

Sustainability approach: energy consumption

Abengoa's unwavering commitment to sustainable construction and the use of environmentally-friendly but economically viable technology challenged the design team to develop a scheme that successfully met these criteria. The design principle was to initially minimise energy demand by a range of passive measures, and then cover the remaining demand using the optimal energy source for each case. Broadly, this embraced three strategies:

(1) Minimise external loads by intelligent design of the building geometry and envelope.

(2) Minimise internal loads by controlling energy use and maximising efficiency.

(3) Cover the largest possible proportion of the remaining demand by "clean" energy from alternative or renewable sources.

Passive measures: geometry
The first step was to evaluate options for the massing and shapes of the buildings. The various models were assessed against the three basic sustainability principles – social, economic and environmental – and the team began by analysing the different typologies in terms of the efficiency of the volume-to-façade surface area and thermal performance (Figs 6, 7).

The single floor option was discarded first, and even though the "tower" and "cube" options had the best results in terms of thermal and volume-to-surface area efficiency, neither matched Abengoa's aspirations for staff interaction. They were thus also discounted, leaving the "compact" and "fingers". Comparative studies were made for both, looking at external loads, the use of daylight, and the effectiveness of natural ventilation and thermal mass (Fig 8).

Natural ventilation was discounted, as it was found to be suitable only in the "fingers" model and then for just three months of the year, while at the same time having important cost, operational, and security implications. As a result – and also due to architectural considerations – thermal mass was also discounted as an option and as a selection criterion.

After analysing the remaining aspects, the compact block model (Figs 10, 11) seemed the most appropriate:

(1) It minimised external loads (heat gains and losses, leakage) and façade costs by reducing the surface area of the building envelope in comparison to the "fingers" option.

(2) It offered an optimal balance between natural lighting and external loads.

(3) It allowed the creation of a moderate microclimate in transition spaces and a buffer zone between outside and inside through creation of the patios.

Passive measures: building envelope
With the geometry defined, the team turned to the building envelope. Again, the façades had to meet certain client and architect requirements:

- achieve a balance between daylight and energy saving
- provide outside views while maintaining efficient solar protection
- ensure a good quality finish
- meet all these requirements within the limited budget.

Daylighting efficiency is usually measured by the "daylight factor" – how much of the daylight available outside penetrates the building – and is measured at 0.85m above the floor (typical desk height). To bring daylight from the glazed façade elements deeper into the interior where the daylight factor tends to be low, transparent (or at least translucent) sections of the façade need to rise as near to ceiling level as possible (the part of the façade below 0.85m does not affect the daylight factor and can thus remain opaque).

The architectural team did not want an opaque external façade from floor to desk height, but a fully glazed façade was undesirable from the thermal point of view. The solution was a "floating spandrel" that visually broke the opaque part of the façade but still reduced unwanted heat gains and losses through it (Fig 12).

Thermal insulation and airtightness

Due to the combined effect of (1) Seville's mild winters, (2) the reduced volume-to-surface area ratio of the chosen building geometry model, and (3) a base load of internal heat gains, thermal insulation played only a secondary role in the façade design. The team chose an overall target U-value of 2.0W/m^{2}K for the glazing – still about 40% above Spanish code requirements for this climate zone – to limit the heating needs to a minimum while staying within the range of a standard façade specification (ie not requiring expensive coating or inert gas fills). The final calculated U-value of the combination of the double-glazed surfaces and the profiles was 1.98W/m^{2}K, which gave the desired performance.

While infiltration would not have as large an effect in winter as in colder climates, it would contribute to the overall summer cooling loads, so the façade detailing aimed for a good airtightness standard. To ensure the final design would meet these requirements, the unitised system was tested and found to perform excellently, with 1.5m^3/m^2/hour at 600 Pa (A4 classification in EN 121521).This greatly improves on the minimum required by the Spanish code (50m^3/m^2/hour).

Solar shading

The hot climate and long hours of sunshine necessitated a balance between daylighting gains and unwanted heat gains. Firstly, an optimum solar factor for the glazing was investigated. The solution proved to be a module with a solar factor of 35% and 50% light transmittance, achieved with a selective coating on the inside surface of the outer pane of the double glazing.

However, the façade clearly needed further external elements to control solar gain and possible glare into the interior. The most efficient solution depended on the façade orientation, as the sun would be high in the sky when passing across the south facades, but much lower when passing over the east and west. This variation in sun position was taken into account in the external shading element design, which also had to honour the desire for transparency and high quality of finish.

Long cantilevers extending from the floor slabs give shading from the higher sun angles, while to allow for the lower angles of late morning and early afternoon, the south façades were additionally equipped with meshed screens that span across the cantilevers and provide additional solar protection without blocking views.
The further up or further east or west the sun is, the more the mesh blocks it, achieving exactly the desired effect for these south-facing façades (Fig 13).

The east and west elevations needed a different approach. Here the low-standing sun makes a mesh less efficient, so the team opted for louvres with horizontal slats, fixed at the edges of the cantilevers. The vertical distance between louvres and depth of slat were set according to the sun path on each orientation (the buildings do not align 100% north-south) so as to block the sun during summer but let in daylight for natural lighting. To increase penetration, the top faces of the slats are white, reflecting daylight to the interior ceiling, while the bottom faces are dark blue to suit the building's colour scheme (Fig 14).

The resulting overall solution is a balanced combination of glass, coloured louvres and metal fabric, providing an efficient and transparent building envelope. Shade is abundant in the mid-day hours, there are no glare issues, and the cleaning and maintenance can be conducted easily with access from the cantilevers.

Maximising efficiency

Once the passive strategy had been analysed and optimised, the team turned to active measures to optimise energy efficiency.
The first target was air-conditioning, which tends to consume the most energy in a building in this climate zone. Four systems were selected for comparative energy study: fan coils (the standard Spanish solution), variable air volume (VAV), underfloor supply, and chilled beams (Fig 15).

The team used in-house Arup thermal simulation software to compare the predicted energy consumption and costs of each in the "compact" model. The chilled beam option proved to be the most energy-efficient and was chosen for the buildings Abengoa itself would occupy. For the speculative offices, the more conventional fan coil system was considered to be most appropriate, mainly because of its low initial cost and wide market acceptance.

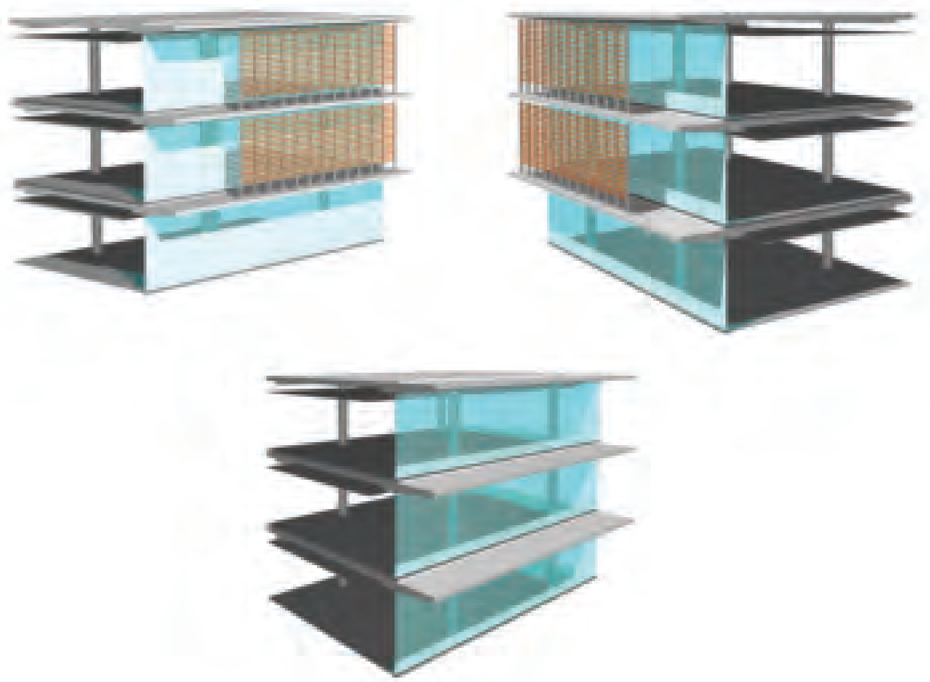
For the chilled water supply the team proposed a variable volume pumping system instead of a constant volume system (the Spanish industry standard), and convinced the client to accept the higher installation costs by demonstrating the improved operating results (energy analysis results suggested a three-year payback period).
Apart from flow rates, the water supply temperature also has to be carefully controlled by an intelligent building management system (BMS) to eliminate risk of condensation.

Various heat recovery systems were analysed for the fresh air supply. The code asked for a minimum 45% efficiency, which the team sought to improve. In the end the client was convinced to opt for hygroscopic thermal wheel heat exchangers with a free cooling option, with up to 75% efficiency and the capacity to recover latent heat. Again this was achieved by demonstrating reduced operating costs compared to installation costs, with an estimated payback time of less than three years.

Another aspect of air supply was control of temperature and humidity, as these affect condensation in active chilled beams as much as chilled water temperature.
Again this needs careful BMS control.

Office lighting-related energy consumption is another important part of any building's overall consumption, so the team investigated ways to minimise this.

12.



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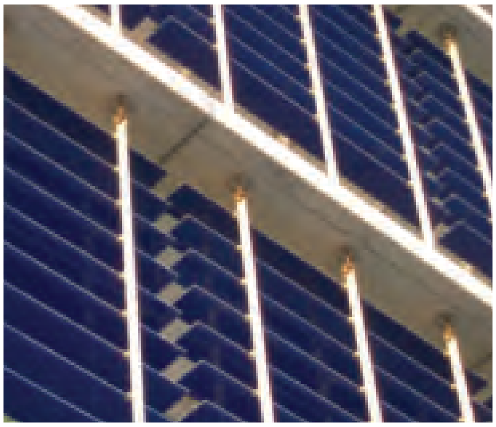
12. Floating spandrel.

13. Preliminary studies for façade solutions: east, west, and south.

14. Louvred façade on a western elevation.

15. Comparison of annual energy consumption.



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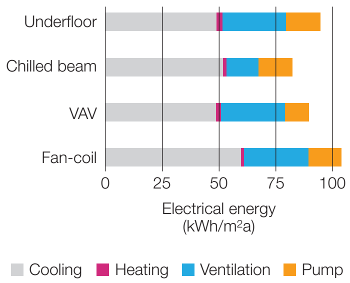


15.

The following were implemented:

- high-performance fluorescent luminaires
- high-frequency electronic ballasts, with estimated running cost savings close to 30% over conventional ballasts
- switching by zones plus use of daylight sensors, allowing luminaires to be dimmable in areas closest to windows
- sensors in areas of transient occupancy, such as toilets.

This direct reduction in electrical energy use also led to lowered overall cooling loads and corresponding energy consumption, with the additional benefit of reducing the capacity and size of both the room systems and the central systems.

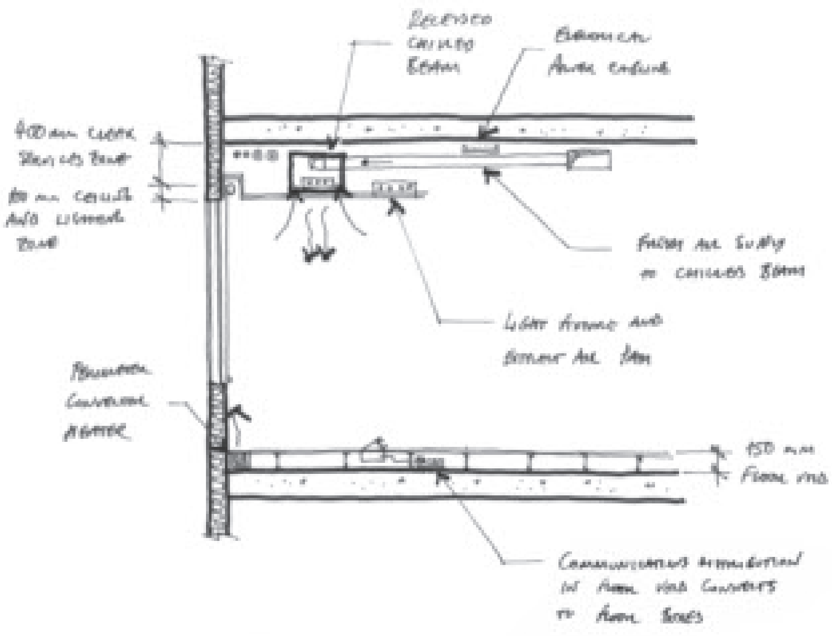
The active chilled beam system

Suitable for both heating and cooling, chilled beams are finned tubes supplied with chilled water, using the natural effect of convection to cool the space (Figs 16,17). Their lack of moving parts allows a very shallow installation depth and quiet operation.

Passive chilled beams rely solely on natural buoyancy and stratification to drive the airflow over the fins, while active chilled beams guide fresh air from the mechanical ventilation system over them, increasing output. Chilled beams have only limited cooling capacity, due to the flow temperature of the chilled water needed to prevent condensation. This requires an efficient façade design that limits external loads – which is among the passive design features of Palmas Altas.

The main advantages of the variable flow chilled beam system are:

- considerable energy savings (pumping for water distribution, fan power for air circulation, and improved COP of the central cooling equipment)
- possible use of free waterside cooling or ground source cooling systems
- relatively small size of central equipment
- precise control of the conditions (individual thermostats for small groups of chilled beams)
- very low noise levels in occupied spaces
- reduced installation/floor-to-floor heights.



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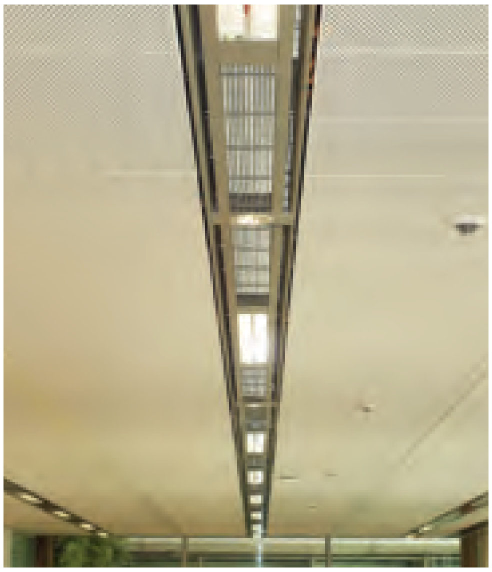


17.

16. Section through active chilled beam system.

17. Active chilled beam system.

18. How tri-generation works.

19. PV panels on the pergola.

To increase output, the team chose an active chilled beam system. The Seville location with its relatively mild winters meant there was little demand for heating, so the team opted for a perimeter system instead of providing the chilled beams in all zones with heating; the selected system is hot water convectors along the building perimeter.

Central heating and cooling plant

Just as for the room air-conditioning, the team made a comparative study of the options for the central plant that supplies the room systems. Initially three conventional options were studied: air-cooled heat pumps with and without heat recovery, and air-cooled chillers with conventional boilers.

It was concluded that the expected low annual heating consumption ($6kW_eh/m^2a$) would not justify installing a conventional gas boiler. An alternative proposal was direct electrical heating, but due to the related CO_2 emissions and penalty on primary energy consumption that this would involve, the team looked for alternative means of heat generation and cooling.

The eventual solution was to take advantage of surplus heat from a tri-generation process for both heating and cooling complemented by some direct electrical heating, whose fuel consumption and CO_2 emissions would be more than offset by the electricity generated by the plant.

Tri-generation

Tri-generation is a further development of cogeneration or combined heat and power (CHP). "Traditional" CHP systems produce electricity and heat, but to work economically they need constant heating demand balanced with electricity demand – not normally the case in office buildings. The tri-generation system resolves this dilemma by using the waste heat of the generator engine to generate cool water by means of an absorption cooling system; this creates a reasonably continuous demand throughout the year (Fig 18).

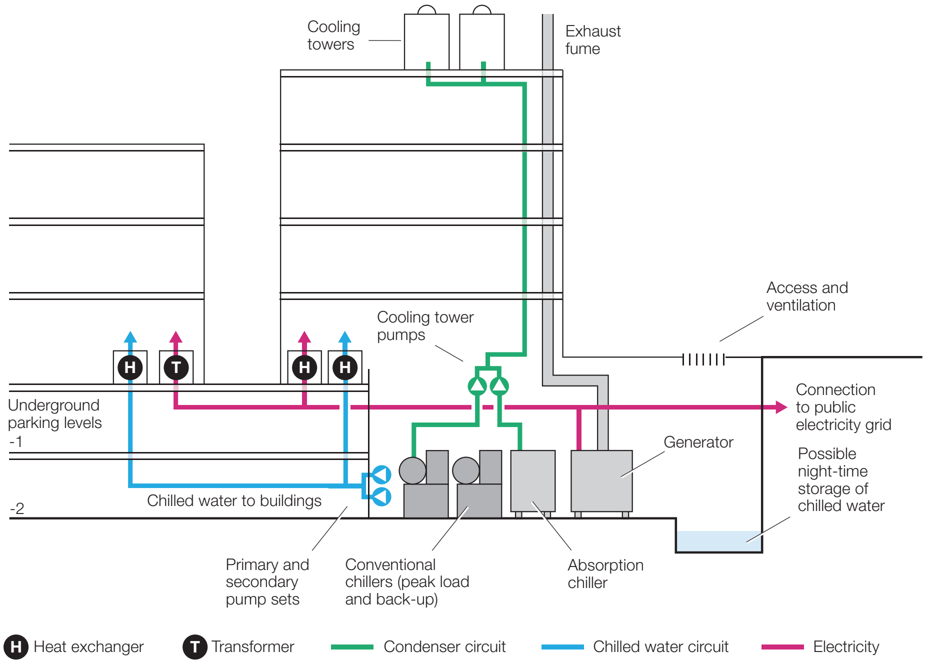
CHP engines can run on various fuels. For Palmas Altas a natural gas engine was chosen due to limited space, reliability of supply, and client preference (for the same reasons biomass was discounted).
The equipment was sized to cover minimum combined requirements for heating and cooling the buildings occupied by Abengoa, and to stay within the most favourable feed-in tariff for the electrical energy produced (maximum $1MW_e$); this exceeds the energy demand of the buildings occupied by Abengoa. The system's output is dictated by the heating or cooling load; any excess electricity not used in Abengoa's offices is exported to the grid, earning Abengoa additional income through feed-in tariffs.

Other renewable and alternative energy measures

With the energy demand reduced through these passive and active measures, the team focused on the use of renewable energy sources, with the aim of reducing fossil fuel consumption and associated CO_2 emissions, and satisfying as much as possible of the energy demand locally. The ultimate goal was a self-energy balance, with near zero net operation-associated CO_2 emissions.
In addition Abengoa, as a manufacturer and provider of alternative energy solutions, was keen to showcase some of its own technologies, which influenced the choice of systems.

Photovoltaic solar energy

The Spanish building code requires all new office buildings to cover a certain percentage of their electrical energy demand from photovoltaics, and Spanish legislation* offers a guaranteed tariff for alternative energy fed into the grid – on very favourable terms. Starting with the minimum required to meet the code, the team investigated options for integrating PV panels in the building envelopes, aiming for as much peak capacity as possible while remaining financially viable (eg north-facing façades or façades shaded by other buildings were not considered).



18.

The pergolas that protect the buildings from the strong Andalusian sun were ideal for installing the panels. Nothing else was competing for these lightweight surfaces, which were also not shaded by any other construction; the PV panels could replace the roofing material, avoiding the need for additional support structure and saving material; the pergolas were intended to be translucent, which was achievable by spacing the PV cells; and finally the undersides of the pergolas were open to ventilation – optimum conditions for the cells, which need to reject excess heat for optimum performance (Fig 19).

The final solution, taking into account architectural considerations and shading of the façades, was a combination of polycrystalline panels (almost opaque) and amorphous panels (translucent), providing $174kW_p$ of power; this exceeded minimum code requirements and offered another source of income for Abengoa.

19.

* The publication of Royal Decree 436 in 2004 established the feed-in tariff paid for electricity exported from PV installations up to 100kW to 575% of the average electricity tariff over 25 years. The conditions in the Royal Decree, combined with public grants and funding made available at the same time, made grid-connected facilities a profitable investment, and gave PV installations connected to the grid an unprecedented boost. As a result, Spain increased the renewable contribution to its overall demand from 9.9 % in 2004 to 18.2% in 2009, exceeding the Government's objectives for this period and reaching them years earlier than planned. This increase was even more drastic for the contribution from PV installations, increasing from 0.01% in 2004 to 2.6% in 2009.

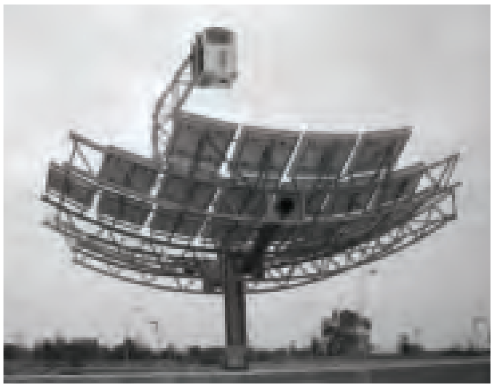
Dish/Stirling system

Although neither technology has yet reached the market competitiveness threshold, fuel cells and dish/Stirling-based thermoelectric solar systems have already been proven in numerous prototypes and marketed by several companies in Europe and the USA. Both have promising potential market penetration in the medium term and form part of Abengoa's business strategy, with its energy division already developing activities and projects related to electricity production using hydrogen and fuel cells.

To showcase the technology at the campus, it was decided to install a 10kW, 8.5m diameter dish/Stirling system, prominently located at the entrance (Fig 20). The energy produced powers an electrolyser that produces hydrogen from demineralised water, with any surplus electricity used in the campus's internal grid. The hydrogen is then used to power a 2.4kW fuel cell system that supplies part of the external lighting of the campus with electricity.

One of the family of concentrated solar power technologies, this system comprises a large-diameter parabolic mirror with a Stirling external combustion engine at its focus, and is emerging as the one of the thermoelectric solar applications with the most potential for integration into buildings.

The dish tracks the sun continuously, so that the rays are reflected onto its focal plane, thereby obtaining a Gaussian-shape concentrated solar energy map and several dozen kW. The Stirling engine is an external combustion engine using the thermodynamic cycle of the same name. It has two advantages that make it well suited for this application: the corresponding thermodynamic cycle has the highest maximum theoretical efficiency of all such processes, and it is an external combustion engine; ie it absorbs heat for its process.



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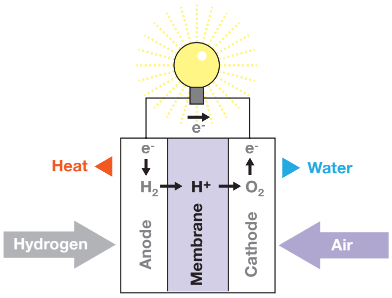

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20. Dish/Stirling system installed at Palmas Altas.

21. Enclosure for fuel cells.

22. Principle of the fuel cell.

23. Solar trough on the roof.

23.

Fuel cell technology

Fuel cells are based on an electrochemical mechanism in which the energy of a chemical reaction is converted directly into electricity. Unlike electric cells or batteries, a fuel cell does not run out or need recharging; it works as long as the fuel and the oxidiser are supplied from outside the cell.

A fuel cell comprises an anode into which the fuel (in this case hydrogen) is injected, and a cathode into which an oxidiser (in this case air) is injected. The two electrodes of a fuel cell are separated by an electrolyte ionic conductor. Through an external circuit containing the load, the OH- ions generated in the cathode are conducted through the electrolyte to the anode, where they combine with hydrogen to form water (Figs 21,22).

Concentrated solar collectors

Abengoa markets another concentrated solar system, the solar trough. Here, solar energy is concentrated linearly to produce hot water, but at higher temperatures than the conventional flat convector typically used in buildings; it can for example be used for industrial processes (and for other media than water). The system also tracks the sun and not only monitors sunlight intensity, but considers wind speed, temperature, and water pressure in its control of flow rates so as to achieve optimum efficiency at any given moment.

A series of these collectors, with a total peak output of 64kW, was installed on the roof of one of the buildings occupied by Abengoa (Fig 23); the size of this system was dictated by available roof area ("competing" with the PV cells and "green" roofs on each building) in the building at a reasonable distance from the absorption chiller.

The hot water produced by the solar collectors is used to cover part of the cooling loads, feeding into the same hot water circuit that supplies the absorption chiller; for this purpose the hot water is stored in a tank, before supplying the chiller.

Rainwater harvesting

Seville's climate not only has hot summers, but is also characterised by scarce water, so the team was keen to reduce the campus's impact on local freshwater resources. Apart from reducing consumption generally (eg by low-flow taps and the choice of autochthonous plants for the landscaping design), a major opportunity to reduce freshwater usage lay in collecting rainwater to irrigate the landscaped areas (the use of rainwater in Spain is legally restricted to a few applications). (The use of greywater was discounted after payback analysis, in which the campus concept influenced the payback period.)

As building rainwater collection tanks would also increase embodied energy and materials use, the team set out to establish an optimum size for the tanks. Seville's rainfall and the consumption of the plant species proposed for landscaping were studied, taking into account the strict LEED (Leadership in Energy and Environmental Design) requirements for maximum coverage of irrigation needs by re-use of rainwater in the driest months, with minimum irrigation.

The analysis showed the benefit of storing rainwater to increase linearly with the size of the tank up to a certain size, beyond which there was no further benefit. This optimum of 300m^3 was adopted for the campus.

Environmental certification

From the outset, Abengoa aspired to obtain an internationally recognised certification that would acknowledge its efforts to develop an environmentally friendly project in design and construction as well as operation. Among possible certifications, the USGBC (United States Green Building Council) LEED and the British BREEAM (Building Research Establishment Environmental Assessment Method) emerged as the preferred options.

Arup's sustainability team played a key role in making the final decision, providing Abengoa with a detailed comparative analysis of the two sets of requirements. Not least because Abengoa is very active in the US market, it decided to seek LEED certification, albeit only towards the end of the project.

In recognition of the many sustainable measures in its design and construction, the project achieved a LEED Platinum pre-certification, and is currently working towards final certification. A significant part of the credits secured are due to design measures stemming from the advice of Arup's sustainability team (eg low-energy design, air quality control, local user controls, energy metering, daylight use, rainwater use, etc), as well as having LEED Approved Practitioners in the team.

Structural design

While sustainability considerations played some role, for example in material selection (eg use of recycled steel for reinforcement bars), the main challenges for the structural design were cost and speed of construction, as Abengoa had set challenging targets for the overall budget – which had to include sustainable technologies – and the construction programme. As most of the budget was to be spent on the active and passive measures already described, the structural design had to be very cost-effective to compensate.

To meet these strictures, the team opted for simple and effective solutions including the extensive use of waffle slab, widely used in Spain and appropriate here due to its optimum ratio between construction time, cost, and simplicity.

Several options were studied before this floor type was decided upon, even to the extent of changing the column grid. Prefabricated hollow planks were suitably quick and economical to install but did not work with the perimeter cantilevers or the building stability, as additional elements were needed to meet these requirements. Another option was the use of flat slabs for the floors, but due to their higher self-weight, the optimum grid was considerably smaller than desired (8.1m x 8.1m), and the material costs were higher than the waffle slab option.

Entrance atria

The architectural design of the entrance atria needed special structural treatment, as it included columns that run clear from plaza level to the roof (16-20m tall) with a maximum diameter of 600mm. The specialist analysis for these slender columns achieved the desired goals perfectly from the architectural, structural, and constructional viewpoints.

Prefabricated cantilevers

Another way to meet the required speed of construction was to use prefabricated elements wherever possible. This facilitated the rapid construction and commissioning of the structure, raising quality level and reducing health and safety risks by providing a safer environment during fabrication than would have been the case with in situ techniques. The overhangs that shade the façades were prefabricated, ensuring the desired structural and aesthetic qualities, and reducing construction time to the build rate of the slabs.

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The structural system of the cantilevers had to fulfil a range of requirements, making their design a crucial element in the whole structural concept. Enough cantilever length was needed to provide sufficient shade, the geometry had to be consistent with the architectural design, and it had to be possible to fix the elements of the second skin of the façades at their extremes. These requirements went beyond the bounds of normal prefabricated structures, so the team had to develop a bespoke design.

The final design consisted of a tapered element with hollow sections to reduce weight, supported by a series of connections to the slab in the form of specially formed reinforcement bars.

A further challenge was to break the thermal bridge between the outside and inside of the building that would have existed if the cantilever had simply been an extension of the floor slab, where it would have acted as a radiation fin leaking the heat or coolth of the controlled internal environment to the outside. Breaking this thermal bridge required a physical separation along the length of the slab edge between the cantilevers and the slab to which they were connected.

Different connection solutions were considered to allow construction to be as fast as possible, ranging from a series of metal brackets to support the concrete element to providing threaded connections for securing the overhang once the slab was built. The final solution combined ease and speed of execution while keeping construction costs within acceptable margins.

With this solution established, the team had to find a way to build a total of 6km of these cantilevers within the construction programme; effectively the cantilevers had to be built in parallel with the slabs. This posed a significant logistical challenge, solved by producing the cantilevers in a local factory, timed to be delivered when the corresponding slab section was to be cast. With this approach the team managed to build the entire complex as designed on programme, to the required quality, and within budget (Figs 24-27).

Façade engineering

The logic behind the façade design has already been illustrated in the sections on the passive low-energy design; the following outlines some of the technical solutions.

Curtain wall design
Given the repetitiveness of the façade design and the grid dimensions, the team decided to use a unitised curtain wall system to speed up construction and improve quality.
The unit size was significant (2.7m wide x 3.7m high), so large vertical mullions were required. The architectural preference was for them to be slim, with the ability to extend out of the window pane to provide the required strength, so the team designed a bespoke vertical steel reinforcement plate connected to the aluminium curtain wall at four points, with a different visual language so it that could be read as a structural addition to the window frames.

During tender stage the façade contractor proposed a thermally bridged T-shaped aluminium profile with a similar inertia to the bespoke design. For cost and speed of installation reasons, this alternative was accepted by the team, and formed the final detail.

Sun shading elements: metal screens
The sun protection screens on the south facades are of a stainless steel mesh, post-tensioned against the base of the roof-level cantilevers. The architectural team wanted to leave the ground floor clear for access, so a horizontal rigid beam connected above the entrance level to the main concrete columns was devised, allowing the screen to be tensioned without having to tie it to the ground (Fig 28).

Sun shading elements: louvres
The louvres for the east and west elevations had to be thin to provide maximum transparency (Fig 29). After studying several options, the team selected glass as the most appropriate material; each louvre is a laminated glass pane with two coloured PVB (polyvinyl butyral) interlayers, so as to achieve a different colour on each face. The lamination also provides the required stability redundancy in case of failure.
The external substructure and the top and bottom fixings to the concrete overhangs were designed in extruded aluminium; the fixing system offers high installation tolerances and easy maintenance.


28.


29.

Construction sequence for the façade cantilevers.

24. February 2008: Start of construction of cantilevers in factory.

25. March 2008: First cantilever element on site.

26. July 2008: Removal of props from cantilevers of first building.

27. August 2008: First building completed.

28. Stainless steel mesh screen for shading on the south façade.

29. Louvres for shading on the west façade.

30 (overleaf). Typical south façade.

Services installations

Much of the MEP design has already been described as part of the sustainable design approach; this section provides the remaining details and data to complete the picture.

The design was driven by two main factors:

- the various environmental measures and the solutions proposed for each installation, which reflected the project's sustainability aspirations
- future flexibility in terms of property use and ownership that would allow each building to operate independently of the others with minimal changes.

HVAC

With the desire for flexibility in terms of use and ownership, different approaches were taken for the buildings to be occupied by Abengoa and those earmarked for modular leasing.

For Abengoa's headquarters, chilled water production is from two 1800kW$_t$ water-cooled chillers and the 700kW$_t$ absorption chiller that runs off heat generated by the cooling of the tri-generation combustion engine; together they cover the chilled water needs throughout the year. Heat for sanitary hot water and space heating is provided from the excess heat generated by the tri-generation combustion engine and a back-up gas boiler. Free cooling for chillers was discounted due to Seville's climate conditions.

Heat rejection for these chillers is by hybrid cooling towers with heat exchangers to reduce system volume/risk of *legionella*.

From this central plant, two separate rings distribute chilled water (7º/12ºC) and hot water (80º/60ºC) to the various buildings, circulated by consumption-dependent variable speed pumps. In each building, pumping stations and heat exchangers distribute chilled and hot water to terminal units (active chilled beams and convectors) and air-handling units.

To cool the buildings earmarked for modular leasing, a conventional fan-coil solution was chosen for its low installation cost, high market acceptance, and flexibility to adapt to the different office layouts of future tenants. The fan-coils are supplied with chilled water from air-cooled chillers on the roof of each building.

Heating requirements for office buildings in Seville, in particular with high-performance façades, are low and limited to early morning in the coldest months for the Palmas Altas Campus. For this reason it was not considered appropriate to install a complete system of boiler-based hot water production and distribution, and the team instead opted for fitting the fan-coils in the leased office spaces with electric heating. The corresponding primary energy balance and CO_2 emissions were lower than a four-pipe system, considering the electricity produced by sustainable methods as well as the savings in embodied energy for the omitted hot water distribution system.

Electricity

As with the HVAC design, the electrical supply and distribution system differs between Abengoa's own offices and the commercially let spaces.

The general supply to the campus is via a medium voltage ring (20kV) that distributes electricity throughout the complex. From this, a series of transformers in the different buildings are fed (two 630kVA transformers in each building occupied by Abengoa, one 630kVA only for common services in each commercially-let building, and two 800kVA additional transformers in the Energy Centre), from which the main consumers and boards are supplied in LV (low voltage) (400V). This strategy limits distribution losses by running higher voltages as far downstream as possible; at the same time it reduces electricity costs for Abengoa, as the Spanish tariffs for medium voltage are considerably better than for low voltage.

The offices earmarked for modular leasing were then fitted with low voltage meters in each module, grouped by building, to allow metering and charging tenant by tenant.

Electrical energy for the supply of the campus's consumers is usually taken from the grid, but the system also allows using the energy generated by the 1MW$_e$ tri-generation system instead.

The tri-generation system – which covers roughly 20% of the campus peak load – also forms part of a dual backup system that ensures continuity of supply should the mains supply fail. The first backup system comprises conventional diesel generators for life safety services (fire pumps, pressurised stairwells, etc.); the tri-generation system complements this basic back-up, providing continuity for priority loads (initially UPS feeding office power and IT, office lighting, and ventilation of HVAC system) via an intelligent electrical power management system based on continuous consumption metering and automatic load shedding.

Carbon footprint and running costs

To illustrate the benefits of the low-energy design to Abengoa, at the end of the design the team undertook a final analysis of the energy and energy cost savings, and the corresponding reductions in CO_2 emissions. It is estimated that Abengoa will benefit from annual energy cost savings of approximately €500 000 compared to a conventional design, and an equivalent saving of 1700 tons of CO_2 – with the building constructed at slightly below average market prices.

Conclusions

Built to a tight schedule and budget, the Palmas Altas Campus was completed in mid-2009 and is now considered a benchmark for sustainable construction in Spain. Abengoa is delighted with its new headquarters, where the staff now enjoy a modern and social environment that complies with the company's aspirations for sustainable development.

The requirement for economic viability is often criticised by advocates of sustainable design; similarly it is often expected that sustainable designs require a higher initial investment. However, the architectural and engineering teamwork on this project showed that it is possible to combine a tight budget with outstanding performance and obtain as a result a benchmark sustainable construction project that sets new standards.

For the members of the Arup project team, in addition to the satisfaction of work done during these four years, this project has shown that even the most difficult challenges can be overcome through the efforts of a team strategically guided towards the achievement of a great goal.

30.


B

31.

31. Western façades, showing the original “compact” architectural concept realised.

32. Typical office interior.

32.

Authors

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Project credits

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Image credits

1, 4, 9, 12, 19, 21, 30-32 *Víctor Sájara*; 2 *Rogers Stirk Harbour and Partners/Vidal y Asociados arquitectos/ Nigel Whale;* 3, 6-8, 15, 18, 22 *Nigel Whale*; 5 *Arup/ Nigel Whale*; 10 *Abengoa/Palmas Altas*; 11, 13 *Rogers Stirk Harbour and Partners/Vidal y Asociados arquitectos;* 14, 29 *Matías García del Valle;* 16 *Archie Campbell;* 17, 23 *Marta Figueruelo Calvo;* 20 *Alejandro Fernández;* 24-28 *Arup.*

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Scotstoun House redevelopment

The renewal of Arup's Edinburgh office involved balancing the constraints of upgrading a listed, purpose-designed 1960s building with the firm's 21st century requirements and the need to achieve an energy-efficient, sustainable design.

1.

Location
South Queensferry, Scotland

Author
Douglas Wylie

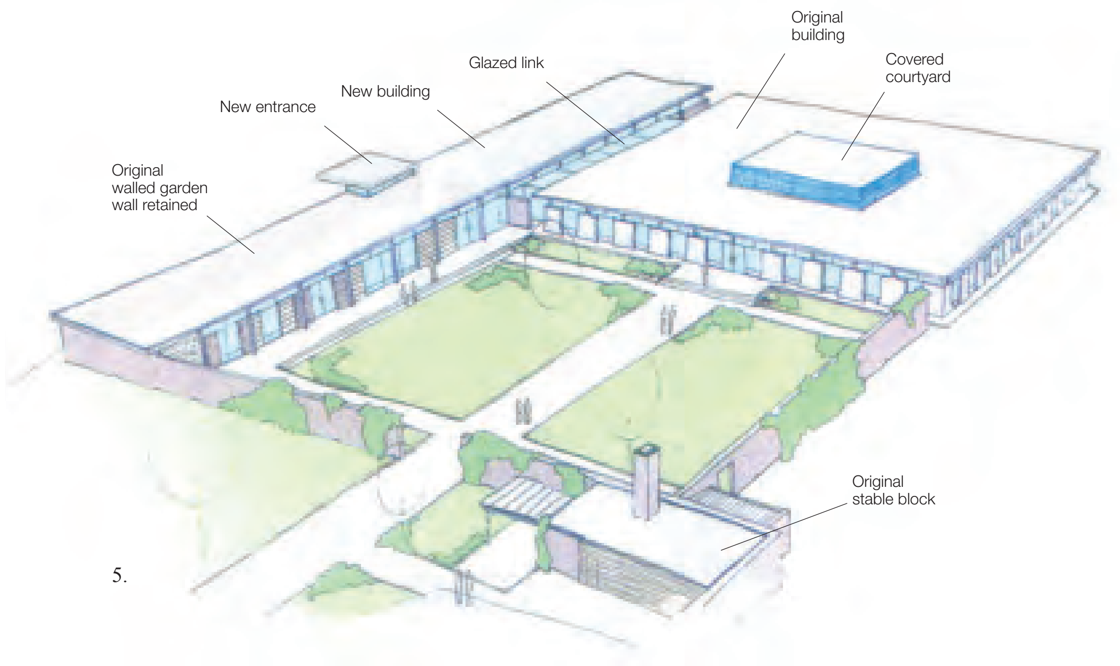
Introduction

Ove Arup & Partners (as the firm was then known) first began to practise in Edinburgh in 1960. Over the next few years its local staff numbers increased, until they occupied several small offices in the centre of the city. It was clearly desirable that all should be housed in a single location, and so the firm's own integrated practice, Arup Associates, was commissioned to design a new purpose-built office. This was a low single-level structure within the walled garden of a previously demolished country house (the original Scotstoun House) in the grounds of a 2.43ha estate at South Queensferry, 8km west of Edinburgh.

South Queensferry is strikingly located on the south bank of the Firth of Forth, between the southern ends of the cantilever Forth rail bridge and the suspension Forth road bridge.

Scotstoun House was designed principally by the late Peter Foggo of Arup Associates during 1964/65 and occupied in December 1966. It has therefore been owned and used by Arup for 45 years. The story of the initial design and construction was detailed in *The Arup Journal*[1]; now, over 40 years later, the *Journal* again features the same building.

2.



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The scheme

By the early 2000s, the original building had started to show the limitations of its 1960s technology, and was also becoming a constraint on the way Arup wanted to work. A development plan was therefore prepared to bring new life into it, and provide a contemporary environment to suit the firm's needs now and into the future. Local architects HAA Design and cost consultants Neilson Binnie-McKenzie were engaged, while all other structural, sustainability, and other engineering design elements were carried out by Arup.

The original building had been Grade B listed by Historic Scotland in October 2005. This introduced significant challenges with regard to achieving the desired BREEAM (Building Research Establishment Environmental Assessment Method) "Excellent" rating[2], and the development therefore became a detailed balance between preserving the qualities of Scotstoun House and meeting the needs of a 21st century office building. This involved maximising the original building as a working space and complementing this with a new extension containing support functions. The link between old and new created a useful intermediate zone for break out, group working, and informal interaction.

The main principles of the development lay in opening up the original space, converting the open courtyard which it formerly enclosed for more offices, and extending along the eastern boundary of the walled garden that lies immediately to the north. This east-facing new-build component houses a new main entrance and reception area, meeting rooms, toilets, print room, and staff area. The original stable blocks to the north beyond the walled garden were converted into mechanical and electrical plant space, facilities for staff showers, an independent remote conference room, and a new cycle shed to store up to 20 bicycles.

1. The original Scotstoun House (left) and the new extension (right).

2. *The Arup Journal*, July 1967.

3. Original entrance.

4. New entrance.

5. The scheme.

The structure

The original building comprised timber joists, boarding and roofing felt, all supported on steel universal beams spanning between precast concrete wall units. The roof overhangs the external walls to provide a cut-off from solar glare.

The northern half of the new extension utilised the original east-facing stone garden wall, which required underpinning for stability and support. New precast concrete columns support glulam beams connected back onto it.

In the southern part of the new extension, structural steel links onto the original overhanging steel beams give a 1m band of glazing between the new extension and the existing structure. The overhead glazing allows natural light into the informal seating area below.

Innovation

The new design was required to show innovation, creativity, and technical excellence. The main project objective was to create a world-class environment for employees and visitors, combined with an energy-efficient, sustainable design. To achieve this, the project team took a hierarchical approach.

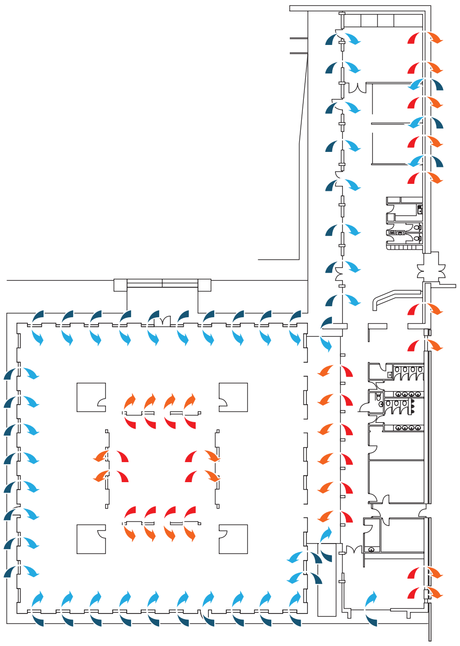
First the building form was optimised, so that by considering building massing, orientation, and envelope performance, it was possible to enable a highly energy-efficient building. Only once the building performance was optimised were the specific low energy systems selected.

Ventilation
Dynamic thermal analysis was used to design the building as fully naturally ventilated. The original office was 24m deep, and great care had to be taken to control air movements through the redeveloped building. This was achieved by building in place of the courtyard an atrium pod, which draws air from the perimeter through the offices in a controlled manner. The natural ventilation strategy was also tested using bulk airflow calculations for various wind directions to ensure that the passive approach would operate correctly throughout the year. The natural ventilation scheme is further enhanced by the use of phase-change thermal mass incorporated in the ceiling.

Use of natural light
Rising energy costs, coupled with the requirement to reduce carbon footprint, make the need for feasible and effective ways to introduce natural light into buildings greater than ever. The deep plan existing offices at Scotstoun House presented considerable challenges with regard to maximising natural light, and this was remedied in the redevelopment by incorporating solar tubes ("sun pipes") throughout. These introduce natural light at ceiling level, and give a 60% reduction in energy consumption, as well as assist the natural ventilation by reducing heat gains. The 90 solar tubes were specifically designed for the project, and form a zero energy light source of particular use in winter months when there is less daylight from the external glazing.

Proven benefits of solar tubes:

- reduce energy costs – eliminate the need to use artificial lighting during the day
- increase worker productivity
- reduce staff absenteeism
- improve working environment
- increase property values
- give the truest and most vivid colour rendition
- help to meet government targets for reducing carbon footprint
- minimise solar gain in summer and heat loss in winter
- require no maintenance
- are more secure than traditional skylights
- are easily installed into existing buildings or new build.



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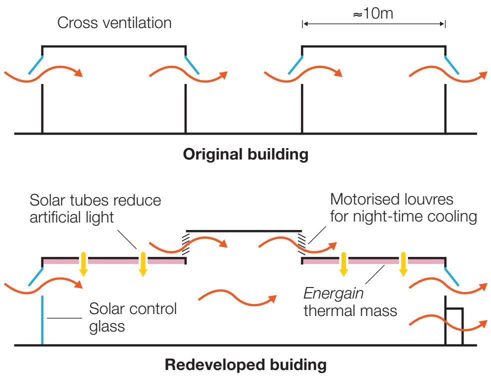

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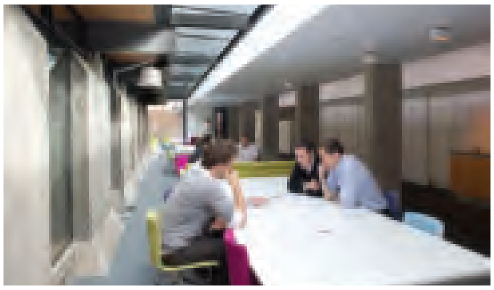

9.

6. Natural ventilation air flows.

7. Ventilation in the original and redeveloped building.

8. Solar tubes on the roof.

9. Glazing between the original and new build.

10. The new front entrance, with part of the re-used original garden wall forming part of the façade to the right.

Sustainability

Mechanical approach
The team took a holistic approach to the design process, integrating the disciplines of architecture and building services and structural engineering. The end result is an exemplary sustainable and low-energy environment, utilising passive design techniques alongside renewable energy technologies.

The most significant challenge for the project followed from the Grade B listing that Historic Scotland placed on Scotstoun House, which imposed several constraints such as retaining the existing wall and elements of the internal furnishings. In addition, the project was subject to the 2008 Scottish Technical Standards for energy usage, the performance requirements of which were difficult to achieve given the listing constraints. However, not only did the team achieve the standards but exceeded the performance significantly.

The planning constraints required that the building achieve BREEAM "Very Good" rating, and again this goal was exceeded by the project being certified as BREEAM "Excellent". It was required that a minimum of 15% reduction in carbon emissions by the systems serving the building be provided by low-to-zero carbon (LZC) technology. As Grade B listing limited significantly the type of LZC system that could be used, this planning condition was achieved through the use of a biomass boiler.

Low carbon design features: energy metering, monitoring and targeting
The creation of a low carbon design was a key aspect of the brief. As already noted, the project is extensively daylit and uses natural ventilation throughout the occupied spaces, thereby negating the need for mechanical cooling.

Comprehensive integrated control was required, and the chosen system successfully integrates the control of the electrical and mechanical services, with comprehensive monitoring and metering. As an example the gas and water meters are monitored, the latter enabling any leaks in the buried distribution mains to be identified.

The lighting system's electricity consumption is also extensively metered, and the data from this help to optimise the lighting control, which in turn assists in maximising the performance of the daylighting strategy. The internal and external environments are comprehensively monitored for temperature, relative humidity, CO_2, and light levels. The system includes a weather station, the output of which has been used to validate the original modelling of daylighting against measured values.

Green procurement; use of recycled/ recyclable materials
The existing building's structure and façade were retained and re-used. As well as the length of garden wall incorporated as part of the façade of the new extension, another section of it was demolished, stored, and rebuilt within the building as part of the new redevelopment. On-site material was stored and crushed for granular fill and hardcore across the site and under roadbases.

The Scotstoun House redevelopment maximised the use of natural, inert and recyclable materials, as well as elements of prefabrication to reduce construction waste. The re-use of the existing building, structure, and facades and the use of on-site crushed aggregates minimised the need for new construction materials. The project made extensive use of Green Guide[3] A-rated materials; and insulation materials with zero ODP (ozone depletion potential) and GWP (global warming potential) of less than 5[4].

10.

Building performance in use

The redeveloped building has achieved an EPC (Energy Performance Certificate) A-rating[5], a significant achievement for the refurbishment of a 1960s Grade B listed building. Even with the restrictions imposed by the listing, the permitted U-values of the building elements are significantly better than required by the UK Building Regulations. For example, the U-value of the glazing is 1.6.

Optimisation of thermal comfort within the naturally ventilated interior is in part achieved by the use of the phase change thermal mass that is incorporated into the ceiling construction. Solar-powered "windcatchers" have been provided for the natural ventilation of internal meeting rooms.

The extensive use of the solar tubes throughout has led to a much improved working environment with a very uniform level of daylighting and less use of artificial lighting. Low energy LED lighting for outdoor lighting with solar powered bi-directional road studs is used to define the external roadway.

11.

Electrical services

With the introduction of a raised access floor, a new power and data distribution system was required. This comprises a 63amp single phase and neutral underfloor busbar, with fused tap off units connecting to floor box units. Each workstation has a dedicated floor box sited directly under the desk with two 13amp twin outlets and two Cat-5 (Ethernet) IT lines.

Supplementing the solar tubes throughout the main office area are direct suspended T5 luminaires (low-energy 16mm diameter fluorescent lamps) with Cat-2 anti-glare louvres. Lighting control is by the integrated mechanical and electrical control system. The KNX switch regulates the DALI (digital addressable lighting interface) control gear within each fitting and interfaces with the daylight and PIR (passive infrared) sensors.

When the natural light via the solar tubes achieves an illumination level of 350lux, the control system regulates the artificial lighting. From dusk onwards the luminaires activate, supplying a uniform level of 400lux. Calculations indicate a resulting 60% energy saving.

In the open plan courtyard space, recessed modular 300m² light fittings with single 42W compact fluorescent lamps were installed with light sensor and movement PIR controls. Downlights have been installed in the front of house area, again with PIR control. In the car park, low-energy pole-mounted LED fittings have been installed, with solar-powered LED road studs in the entrance road to the office.

The energy performance achieves a lighting load of approximately 10.2kW over an area of 1700m^2, or 6W/m^2. The lighting performance gives a task illuminance of 400lux, uniformity of 0.8, glare factor of 19.5 UGR (unified glare rating), and complies with *BSEN 12464-1*[6].

The fire alarm system comprises traditional analogue addressable smoke and heat detectors in the new-build extension and an air aspiration system within the original building. The security system has been developed to work in tandem with other Arup offices. The building operates on a closed door system with access and egress only by means of swipe proximity cards.

Each staff member has a dual-purpose ID and security card which allows control of who accesses the building; the system allows Edinburgh staff to access other Arup UK offices and vice versa.

There are full audiovisual facilities in the two main meeting rooms, with the remaining meeting rooms wired out to accept future AV equipment.

Construction

The contract was let in February 2009 and the main contract and fit-out period was 74 weeks. This construction period fell in line with the overall programme and the building reopened in July 2010. The project was completed within the set budget.

The staff had been decanted to temporary office accommodation within the grounds of Scotstoun estate. On the return to the refurbished office it could clearly be seen that the original 1965 building had been given a new lease of life, with a greatly improved working environment for all staff and a welcoming and relaxed experience for visitors.

12.

13.

14.

15.

11. Open-plan office with indirect/direct lighting.

12. External courtyard.

13. The biomass boiler.

14. Break-out space in the new build.

15. The original stable blocks have been converted into mechanical and electrical plant space, facilities for staff showers, conference room, and cycle shed.

Author
Douglas Wylie is a Project Director with Arup Scotland in the Edinburgh office, and was Project Manager for the refurbishment of Scotstoun House.

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(4) http://en.wikipedia.org/wiki/Global_warming_potential

(5) http://www.epcrating.co.uk/

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Project credits
Client: *Arup Group* Architect: *HAA Design*
Structural and services engineer, environmental and lighting designer, and project manager: *Arup – Wayne Butler, Patrick Elsdale, Graeme Moncur, Sarah-Jane Stewart, Gary Wilkie, Douglas Wylie*
Quantity surveyor: *Neilson Binnie McKenzie*
Contractor: *Ashwood Scotland*

Image credits
1-3, 6-8, 12-13 *Arup;* 4, 9-11, 14-15 *McAteer Photography;* 5 *Arup/HAA Design.*

Kurilpa Bridge

Location
Brisbane, Australia

Authors
Ian Ainsworth Kathy Franklin

1.

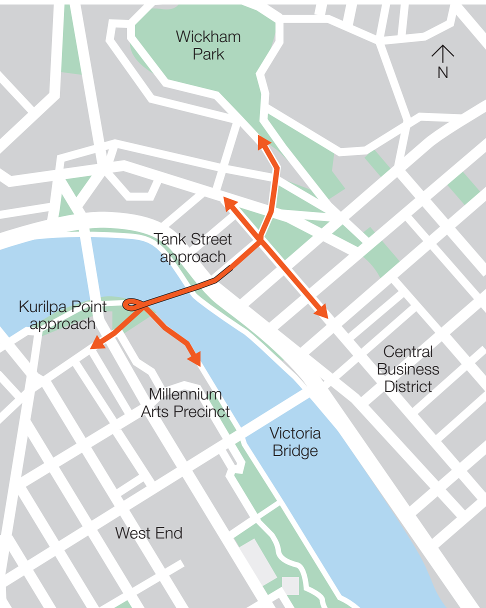
To create a vital inner-city pedestrian and cycle link across the Brisbane River, Arup engineered the world's first large-scale "tensegrity" bridge.

Introduction

In 2006, Australia's Queensland State Government established a design brief and an extremely challenging "not to be exceeded" budget for a new bridge in the state capital, Brisbane, to "provide a link from the Queensland Gallery of Modern Art in the South Bank Precinct to Tank Street in the Central Business District". The objective was to deliver by 2009 a landmark pedestrian and cycle bridge – "architecturally striking", and sympathetic and complementary to its prominent location.

The creative partnership of contractor Baulderstone, engineer Arup, and architect Cox Rayner produced the 430m long "tensegrity" Kurilpa Bridge (Fig 1), a bold fusion of art and science featuring a striking array of masts, cables, and flying steel spars. The use of "tensegrity" (the term[1] was coined by Buckminster Fuller) in a major structure has been something of a holy grail to architects and engineers around the world for decades, and the successful completion of the Kurilpa Bridge represents a genuine world first.

Timing was critical, so as to meet a very important milestone for the Government. Kurilpa Bridge was officially opened as planned on 4 October 2009, in time for Queensland's sesquicentenary (150th anniversary) celebrations.



2.

Background

Brisbane is at the centre of one of Australia's fastest-growing regions. All levels of government are responding to growing population numbers, needs and expectations with an unprecedented level of urban planning and infrastructure development, within which efficient and attractive pedestrian and cycle path networks are increasingly important.

In the mid-1990s, local and state planners identified the need to provide such links across the Brisbane River to connect the Central Business District (CBD) with the city's cultural precinct at South Bank. The first of these, the award-winning Goodwill Bridge (also engineered by Arup), was completed in 2001, and its 3M+ crossings per annum since then reflect the increasing popularity of walking and cycling as healthy, low carbon alternatives to motorised transport.

The Goodwill Bridge's success prompted the Government to proceed with a second inner city pedestrian and cycle crossing, this time linking the northern end of the CBD with Kurilpa Point (Fig 2). The location was selected to provide a key commuter route from the rapidly developing West End area to the CBD, and to provide access for residents and visitors from the CBD to the new Millennium Arts Precinct, including the iconic new Gallery of Modern Art (GoMA) and the redeveloped State Library of Queensland.

The planning logic for the location was compelling, but the new bridge would have to pass over the Riverside Expressway (Brisbane's busiest road corridor), provide river navigation clearance, and land on the river bank beside the GoMA. All this, combined with the very flat grades required by the relevant codes and Queensland Government guidelines for disabled access, presented substantial geometric, constructional, and aesthetic challenges.

In late 2006 the Government invited design-and-construct consortia teams to submit concepts for a design competition; it defined the available construction budget (A$55M), the landing points each side of the river, and key performance requirements (maximum grades, deck width, clearances to river and expressway, and extent of shade cover to deck).

Three shortlisted teams prepared and submitted concept designs in late 2006 for judgment by an intergovernmental panel of architectural, urban planning, and engineering experts.

Arup teamed with the architect Cox Rayner and Baulderstone for the competition. Arup and Cox Rayner had worked together on many landmark building projects, and two pedestrian and cycle bridges of similar scale and complexity to the Kurilpa Bridge (the Goodwill Bridge and the double helix Marina Bay Bridge in Singapore). Both Cox Rayner and Arup had previously collaborated successfully with Baulderstone – a major contractor and experienced bridge builder with credits including Brisbane's iconic Story Bridge.

In March 2007, the then Queensland Premier Peter Beattie announced the winning design to be the Baulderstone/Cox Rayner/Arup team's "tensegrity bridge". The factors that shaped the winning design and influenced the judging panel's decision included:

- sculptural quality and aesthetic "fit" with the GoMA
- visual lightness and structural efficiency
- the innovative "world-first" nature of the design as a demonstration of the State Government's "Smart State"[2] commitment to science and technology.

Key statistics
- bridge deck 430m long x 6.5m clear width between handrails
- 500m^3 of concrete and 500 tonnes of steel
- nearly 7km of high strength steel cables

Awards

Royal Australian Institute of Architects Queensland Chapter, Karl Langer Award for Urban Design

Australian Steel Institute, Queensland 2010 Steel Awards: Winner, Structural Engineering Steel Building Design Award

Australian Steel Institute, Queensland 2010 Steel Awards: High Commendation Infrastructure Projects Structural Engineering Steel Design Award

Engineers Australia Queensland 2010: Engineering Excellence Award for Project Infrastructure over $20M*

Engineers Australia Queensland 2010: Engineering Excellence Award for Innovation*

Engineers Australia 2010 Australian Engineering Excellence Award*

2010 Consult Australia Awards for Excellence – "Project of the Year" and Gold Awards (Transport and Civil)

1. Kurilpa Bridge at night.

2. Kurilpa Bridge provides a new pedestrian and cycle link across the Brisbane River between Kurilpa Point and the northern end of the Central Business District.

Concept design and tensegrity

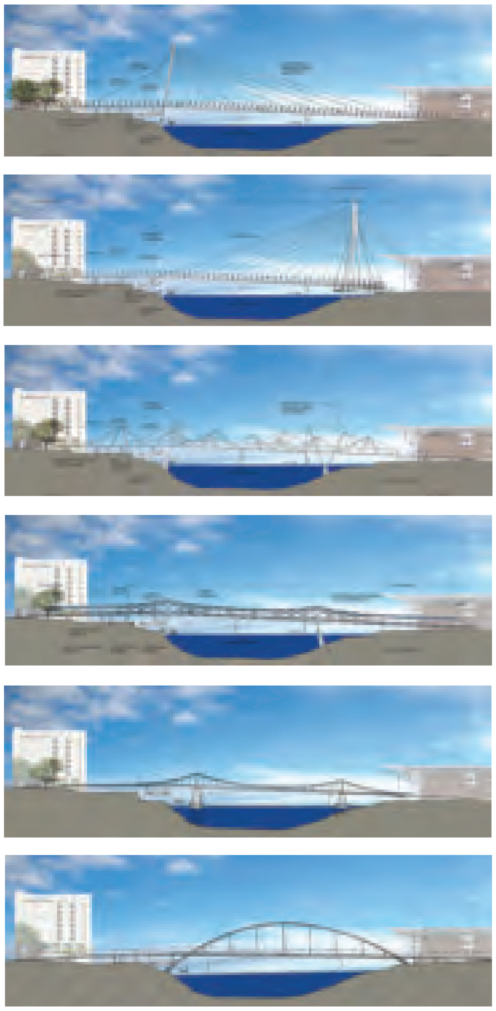
The team had considered a wide range of possible forms and materials. The overall form was restricted by the geometrical limitations imposed by the specified landing points, the clearance requirements, and the maximum permitted grades for disabled user access. These dictated the minimum level of the underside of the structure and the maximum deck level, effectively limiting the depth of structure below the top of the deck to less than 1m.

The main bridge forms identified as potential solutions were cable-stay, arch, suspension, tube, and tensegrity mast-and-cable (Fig 3).

The large masts required for conventional cable-stay forms were too visually dominant, given the GoMA's proximity, and the poor ground conditions and construction access restrictions on the north bank due to busy existing roads would significantly compromise the efficiency of arch and suspension forms. The team also also found that successfully integrating the required continuous shade awning was problematical with all these. Tube forms were promising from a design standpoint but potentially difficult to construct given the deep and fast-flowing river.

Faced with the shortcomings of conventional forms for the particular characteristics of the Kurilpa Bridge site and client brief, Arup and Cox Rayner looked to devise a new form that incorporated the buildability and shallow structural deck of mast and cable structures without monumental masts.

Drawing inspiration from Buckminster Fuller and the work of sculptor Kenneth Snelson[3] (Figs 4-6), Arup conceived a viable and efficient structural form based around an innovative mast/cable arrangement. This not only satisfied the need for a visually light, shallow, and buildable form that would sit comfortably beside the GoMA, but the innovative, whimsical, and apparently random structural array would be radically different from the norm – a true fusion of art and science.



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3. Bridge form options considered in design competition.

4. Kenneth Snelson at work on "Easy-K" sculpture (1970).

5. "Easy-K", by Kenneth Snelson.

6 Early Kurilpa tensegrity elements visualisation.

7. Plan view showing three principal elements of the bridge.

8. Arup visualisation.

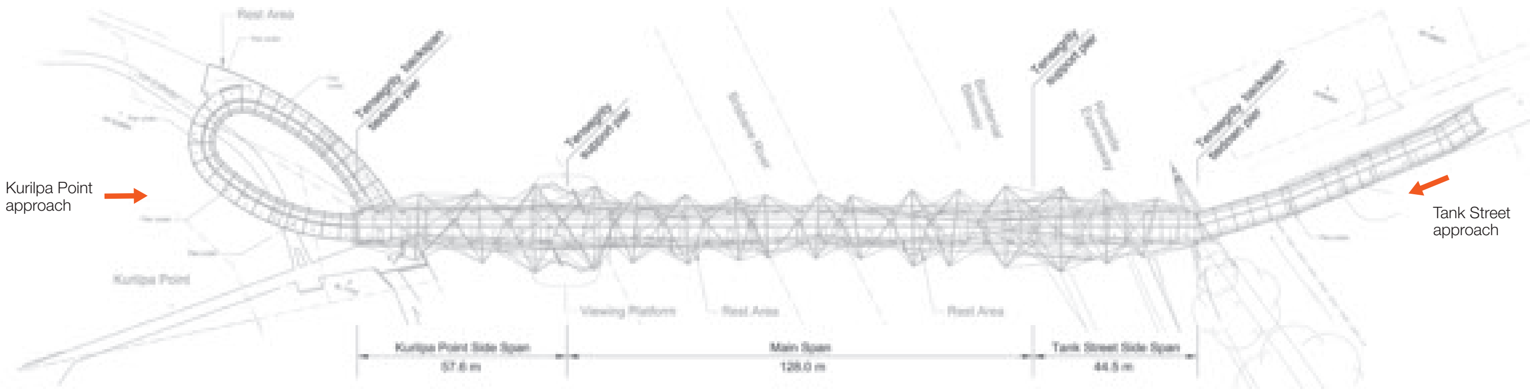
9. Vew from below, with deck framing visible.

Key site characteristics

The Brisbane River is large, tidal, and subject to flooding, as the recent event of January 2011 made spectacularly clear. It is approximately 250m wide at the bridge location, with a 100m wide main navigation channel.

The required river vessel clearance for the Kurilpa Bridge, 11.4m above the highest astronomical tide level, was slightly greater than that of the existing road bridges immediately upstream and downstream.

The geotechnical conditions were challenging, with varying thickness layers of soft sediments overlying phyllite and basalt bedrock. The land foundations are a mixture of driven precast concrete piles and bored cast-in-place concrete piles, while the river foundations comprise driven tubular steel liners filled with reinforced concrete.



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Superstructure form and details

Overall the Kurilpa Bridge has three main sections: the 120m Kurilpa Point approach, the tensegrity bridge itself (three spans of 58m, 128m, and 45m), and the 82m Tank Street approach (Fig 7). The approaches are separated from the central tensegrity bridge by expansion joints and bearings that allow the three main superstructure elements to expand and contract independently.

Kurilpa Point approach
This is a reinforced concrete spiral ramp, constructed over land, with seven spans up to 20m supported on reinforced concrete blade piers. The deck cross-section tapers from a central 780mm deep spine to 280mm deep edges.

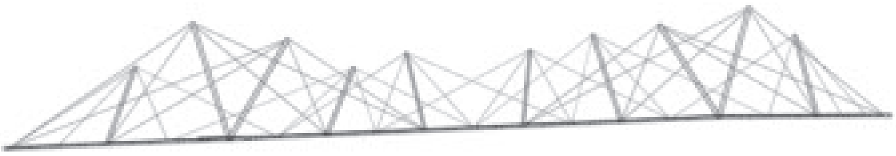
The tensegrity bridge
This comprises a composite steel and concrete deck structure, the series of steel masts and cables, and the integrated tensegrity array of steel ties, flying struts (spars) and steel-framed tensegrity canopy (Fig 8). The side-spans cross shallow river water at Kurilpa Point and the Riverside Expressway on the City side.

The overall structure is approximately balanced, eliminating the need for massive abutments and allowing construction by the balanced cantilever method. Unconventionally subtle tie-down points at the outer ends of the side-spans counter the weight supported over the large river span. They also allow for an intriguingly slender first support in the hub of the Kurilpa Point junction, and a support on the city side compact enough to be constructed within the very narrow fork at the divergence of North Quay and the Riverside Expressway. The support points flanking the navigation channel are more conventional, with reinforced concrete twisted blade piers on pilecaps in the river.

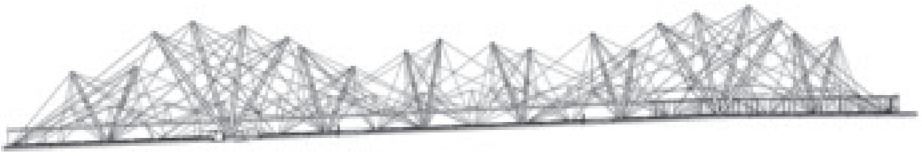
The 6.5m clear width deck is made of full-depth precast panels, typically 4.9m long, 3.4m wide, and 200-250mm deep, joined by in situ concrete stitches that are supported by and act compositely with structural steel crossbeams. The panels incorporate cast-in fixings for balustrades, electrical and hydraulic services conduits, and rebates for recessed light fittings.

The crossbeams are rolled steel I-sections, typically 530mm deep, connected to the concrete deck by headed steel shear studs, and supported by longitudinal edge beams suspended from the masts and high-strength cables. The edge beams are fabricated steel box sections typically 900mm deep and 450mm wide, with top and bottom plates 25-40mm thick, and 12-16mm thick side plates. A curved steel plate fairing attached to the outside face of each edge beam ensures aerodynamic stability of the bridge cross-section under all service and ultimate design wind speeds (Fig 9).

Basic concept for the major and minor masts and cables.



As-built masts and cables on the upstream side, with geometry refined by small random offsets to tops of masts.



“Creative chaos”, with upstream and downstream masts and cables shown.

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Pairs of major raking tubular steel masts spring from the tops of the main support piers on either side of the main span on both sides of the bridge, setting the locations for an approximately coplanar (lying in the same geometric plane) series of minor secondary masts. Longitudinally and transversely, the major and minor masts are offset from the perpendicular, which both simplifies details by preventing cable/mast and cable/cable clashes, and provides the structure’s signature “randomness” without significantly reducing structural efficiency.

Lateral restraint is provided to these masts by secondary cables connected to flying struts that are themselves pure tensegrity elements, each being connected only to cables. A simplified elevation (Fig 10) shows how the “creative chaos” of the final randomised multi-mast and cable arrangement was developed from a regular geometry, and how the different mast and main cable patterns on each side of the bridge deck combine with the flying struts (“spars”) and secondary cables to produce further “chaos”.

The tensegrity array of flying struts and cables that hovers above and beside the deck fulfils three critical functions:

- It suspends the canopy, allowing it to float above the deck with no apparent means of support.
- It laterally restrains the tops of all the masts, preventing them from buckling sideways under the loads arising from the suspension of the deck and lateral wind and seismic loads.
- It works in unison with all the masts and cables to resist twisting and lateral forces arising from patch loads on the deck (eg crowds on one side), and wind and earthquake loads.

Fig 11 identifies the various tensegrity bridge elements; typical element types and sizes are as follows:

- masts: fabricated tubular steel sections up to 30m long with section sizes varying from 610mm diameter x 6.4mm wall thickness to 905mm diameter x 19.1mm wall thickness
- major mast cables: high-strength spiral wound galvanized wire ropes 30-80mm diameter
- spars: circular hollow sections up to 23m long with section sizes 457-508mm diameter
- spar cables: high strength stainless steel spiral wound cables 19-32mm diameter.

Tank Street approach

This consists of an abutment plus two spans over the busy arterial North Quay (26m) and the entry to a federal courts complex (24m). To provide the required road clearance the available structural depth below deck level for the two spans was extremely limited – around 200mm. To satisfy this and to facilitate minimal road closure, each span comprises upstand prestressed precast concrete edge beams supporting a shallow in situ deck slab.

Substructure

The chosen river foundations – permanent tubular steel liners driven to rock and concrete filled – allowed spoil to be removed from within without risk of contaminating the river. Permanent rock anchors were also used where needed to resist tension forces from superstructure tiedowns and river vessel impacts.

The reinforced concrete river pier pilecaps were constructed using precast permanent concrete soffit forms supported on a temporary steel grillage. After the soffit forms were placed, the main body of each pilecap was constructed in the dry at low tide. The pilecap on the Kurilpa Point side is about 23m long x 10m wide x 3m deep supported by 14 1200mm diameter x 20mm wall thickness tubular steel piles. The pilecap on the north bank is approximately 15m x 10m on plan, up to 2m deep, and supported by three 1067mm diameter x 16mm wall thickness steel piles and a series of permanent anchors drilled into the steeply sloping riverbank bedrock.

The river piles and pilecaps were designed to safely resist the specified river vessel impact event – head on (parallel to the navigation channel) from a 1500T displacement barge travelling at 10 knots. In addition the bridge’s superstructure was designed for accidental impact from the superstructure of an overheight river vessel.

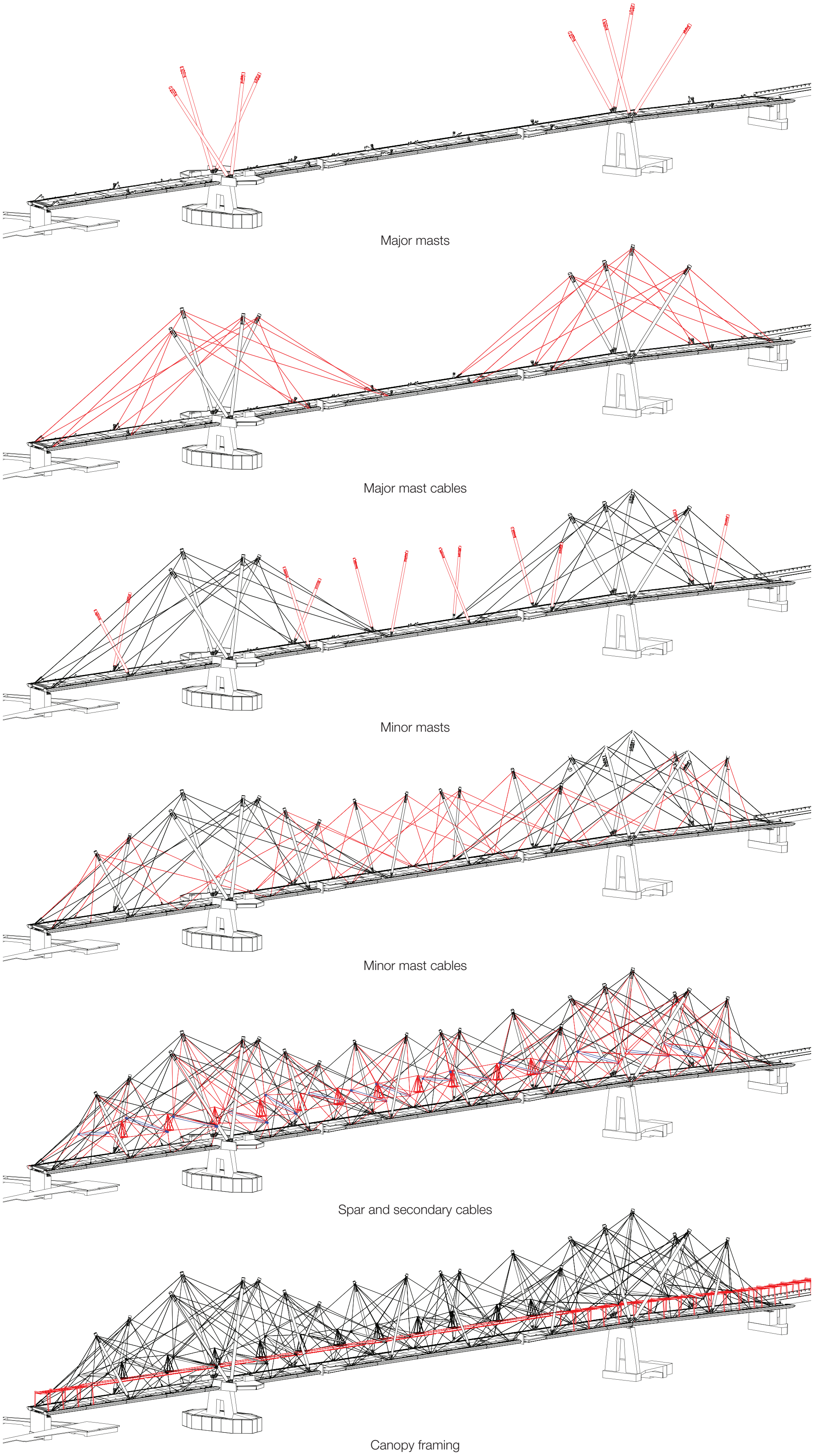
The twisted concrete blades that form the bridge piers not only add visual interest, but also resolve the very tight geometry at the northern end of the main tensegrity span where the pier is required to fit between an existing low-level bikeway and the existing Riverside Expressway at high level (Fig 13).

10. “Creative chaos”.

11. Structural systems.

12. “Floating” canopy.

13. Twisted concrete bridge pier by the Riverside Expressway on the Tank Street side.



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14. Cantilever construction.

15. 3-D finite element *GSA* model image of bridge.

Construction stage modelling and design

A key aspect of bridges that span over major river and road corridors is the need for the structure to support itself at each stage of the erection without temporary falsework. Working closely with the contractor, the team designed the bridge to be cantilevered out from each of the two major river piers, effectively using the permanent structure to construct itself (Fig 14). In May 2009 the two halves met precisely as predicted by computer modelling, completing the deck structure.

The superstructure erection had to be planned with the utmost precision to ensure that the bridge would assume its theoretically correct geometry when the thousands of prefabricated pieces were bolted together. The deflections of cable structures are notoriously difficult to predict accurately, particularly initially when cable tensions are small – the effective extensions of a cable with low tension are large, whereas in a highly stressed cable they are small.

This non-linear axial stiffness can be visualized by thinking of how it is easy to move the end of a sagging rope by pulling, whereas pulling a taut rope generates little movement.

When erecting large complex structures, two basic approaches can be taken to ensure that the completed project has the correct geometry. The first is to constantly monitor the position of the structure during construction, making adjustments along the way. The second is to accurately prefabricate all the components, and then confirm by scenario planning and sophisticated analysis that connecting them together without adjustment will result in an acceptable final geometry. For Kurilpa Bridge the complexity of the structure and the time constraints necessitated the second option, with the constructors forced to rely on the accuracy of the designers' predictions.

Working closely with the contractor from the outset, Arup developed a superstructure erection methodology based on balanced cantilever erection from each river pier, using accurate length components (checked and adjusted if necessary before installation), in a sequence that ensured all parts would be in their theoretically correct positions with all cables prestressed by the weight of the structure. Purpose-written software was developed to allow thousands of separate construction stage analyses to be run and checked.

The accuracy of this modelling was demonstrated when the two bridge halves met precisely at mid-span in May 2009. At completion, the deck was within 25mm of the theoretical profile.

Structural dynamics

The bridge is relatively light, but has a comparatively long main span and a complex array of masts and cables. All this plus its unique design meant that it could be subject to unusual dynamic or aerodynamic effects, with no precedents or "rules of thumb" upon which to draw. As a result, extensive wind tunnel, dynamic and fatigue analyses were required to comprehensively investigate and resolve all potential dynamic phenomena.

Where analysis could not preclude the possibility of adverse behaviour, such as lateral deck vibration (synchronous lateral excitation, or SLE) and minor mast vortex shedding, precautionary mitigation measures had to be designed and installed. The very tight timeframe made it impossible to complete the structure and then measure as-built responses to determine whether additional damping was required to prevent damaging or annoying vibration, or whether significant mast vibrations due to vortex shedding would in fact be generated.

It was therefore necessary to design and install tuned mass dampers (TMDs) suspended from the underside of the centre of the main span to ensure satisfactory lateral response to synchronized pedestrian loading from large crowds, and also to design and install dampers to limit the response of minor masts to potential wind-generated vortex shedding.

Dynamic properties

A linear modal analysis was carried out, and the finite element model (Fig 15) included detailed modelling of the concrete deck, piers and abutments, and small amplitude displacement foundation stiffnesses. Due to the geometry, several cables in the support structure are fairly low stressed and careful consideration was given to the effective cable stiffnesses to account for cable sag.

The dynamic behaviour was found to be complex due to the proportion of structure self-weight above the deck (masts, cables, spars and canopy). This led to many lateral torsional modes and significant coupling between mast and deck motions.

The lateral modes were found to be sensitive to the lateral stiffness of the piers supporting the major masts, so a sensitivity study was carried out to bound the lateral stiffness, including consideration of variation in soil stiffness and the potential for future scour around the foundations. Following the completion of the bridge structure, modal identification tests using ambient vibrations were carried out to identify the frequencies of key modes (Table 1).

Aeroelastic stability of deck

Aeroelasticity covers a range of effects in bluff body aerodynamics whereby structural motion interacts with the fluid flow causing the motion. Classical flutter, galloping, and vortex shedding, for example, need to be considered in designing long-span bridge decks. Kurilpa Bridge has a very shallow deck and closely spaced, low-frequency vertical and torsional modes. This led to concerns that the deck could become unstable aerodynamically at wind speeds lower than the ultimate design wind speed, so this aspect of the design was investigated. While normal for major long-span road bridges, this is not commonly required for shorter-span bridges.

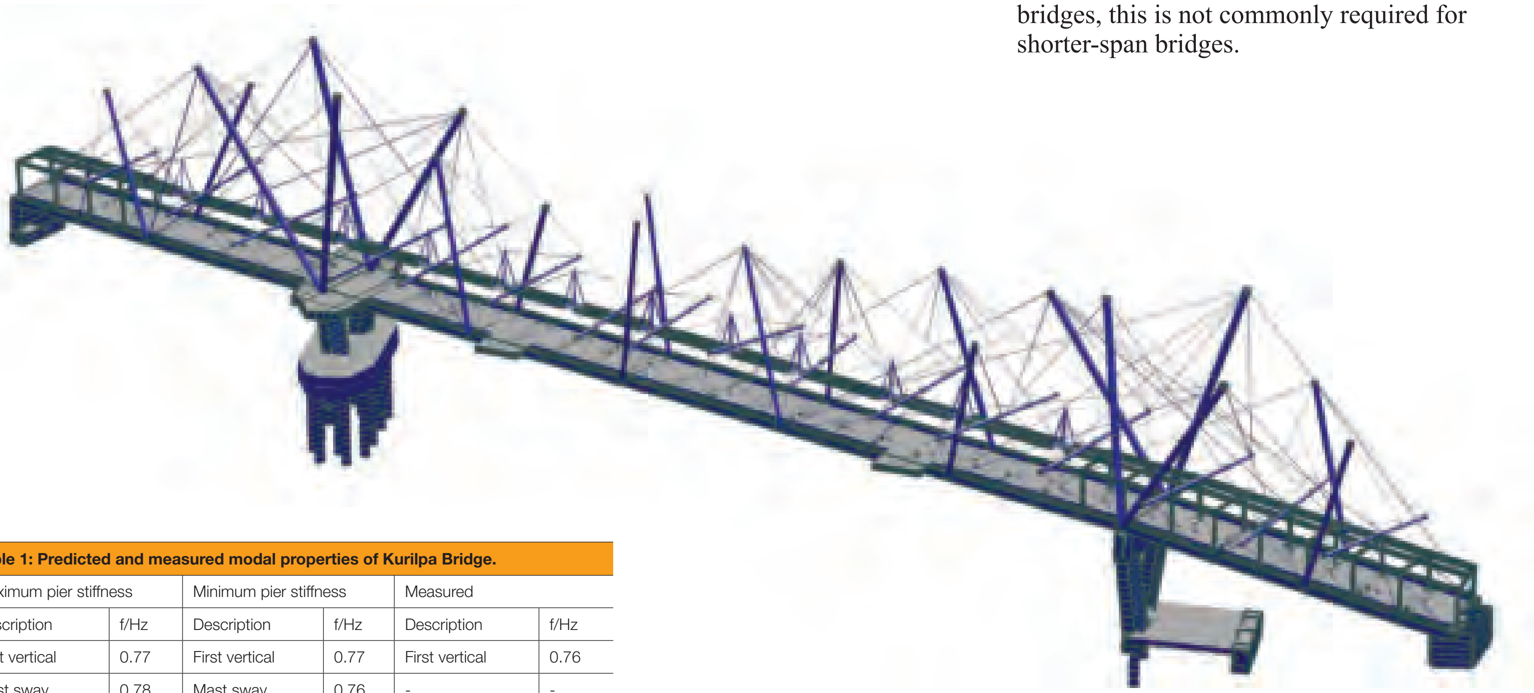

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Table 1: Predicted and measured modal properties of Kurilpa Bridge.

Maximum pier stiffness		Minimum pier stiffness		Measured	
Description	f/Hz	Description	f/Hz	Description	f/Hz
First vertical	0.77	First vertical	0.77	First vertical	0.76
Mast sway	0.78	Mast sway	0.76	-	-
Mast sway	0.89	Mast sway	0.89	-	-
Torsional/lateral	1.08	Lateral/torsional	1.05	First lateral	1.02
Lateral/torsional	1.31	Torsional/lateral	1.18	Lateral/torsional	1.17
Second vertical	1.25	Second vertical	1.25	Second vertical	1.29

Wind tunnel studies were commissioned specifically to look at the aeroelastic stability of the proposed cross-section, while sectional wind tunnel tests were carried out using a spring-supported model of the bridge with mass and stiffness adjusted to represent the critical modes of vibration. The primary modes of concern were the fundamental vertical and torsional modes of vibration of the deck. The complexity of the structure also gave rise to lateral-torsional modes with significant mast movements, but when investigated these were found to be aerodynamically less critical due to their high modal mass.

The 2000-year site-specific three-second gust and hourly mean design wind speeds calculated from *AS1170.2*[4] were combined using the procedures in *BD49/01*[5] to give a design "sustained gust" wind speed for aeroelastic stability of 53m/s.

The basic deck section with bluff rectangular edge beams did not satisfy the required design wind speed criteria, due to a potential torsional galloping response (sometimes referred to as "single degree of freedom torsional flutter response") at 39m/sec – similar to the aeroelastic effect that caused the Tacoma Narrows Bridge failure.
Given the closely spaced vertical and torsional modes, a classical flutter response involving both vertical and torsional response was initially expected, but this was not observed in the wind tunnel. No vortex shedding response was observed in the wind tunnel (Fig 16).

Design solution
Edge fairings provide an economical method of improving aerodynamic performance of bridges. A range of fairing shapes were wind tunnel tested including bull-nose, circular and elliptical (Fig 17). The bull-nose fairings gave an acceptable aerodynamic performance and were not only judged to be aesthetically acceptable, but enthusiastically endorsed by the architect as an improvement to the original square-edged profile (Fig 18).

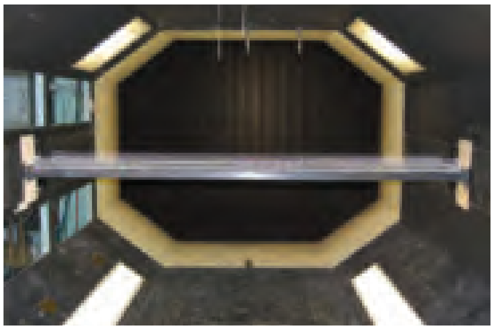
16. Sectional wind tunnel model.

17. Possible edge fairing configurations.

18. Completed bridge showing bull-nose fairings.

19. Installed tuned mass dampers.

20. Dynamic properties measurements during TMD tuning.



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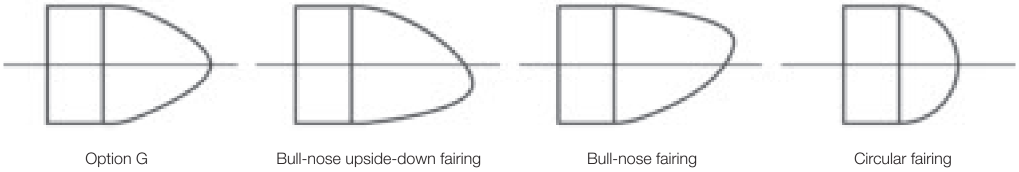

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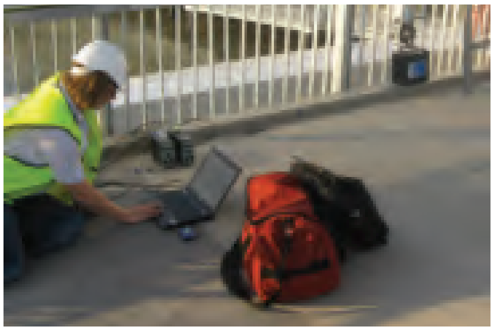
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Table 2: Results of SLE susceptibility calculations.

Maximum pier stiffness				Minimum piwer stiffness			
Description	*f/Hz*	*Critical crowd size*	*Required damping*	*Description*	*f/Hz*	*Critical crowd size*	*Required damping*
Torsional/lateral	1.08	STABLE	STABLE	Lateral/torsional	1.05	1.1 persons/m^2	1.1% crit
Lateral/torsional	1.31	0.5 persons/m^2	2.3% crit	Torsional/lateral	1.18	1.2 persons/m^2	1.0% crit

Pedestrian-induced vibration

The vertical and lateral response of the bridge under dynamic pedestrian loads was checked in accordance with current international best practice[6,7] in addition to meeting the requirements of *AS5100.2 2004*[8]. The following design scenarios were considered to ensure the bridge's serviceability for normal use:

- single pedestrian walking at footfall rates of 1.0-2.6Hz
- continuous pedestrian streams and dense walking crowds up to 1.7 people/m^2
- a small jogging group of up to 10 people.

The responses of the bridge were predicted to be acceptable with the exception of potential SLE due to crowd loading.

Assessment of susceptibility
As Kurilpa Bridge is a major urban footbridge that may experience dense crowds during a public event, a design crowd density of 1.7 people/m^2 (5000+ pedestrians) was chosen (above this, walking becomes difficult).

All lateral modes with frequencies below 1.5Hz predicted for Kurilpa Bridge were checked for susceptibility to SLE, and the critical crowd density that would cause the bridge to become laterally unstable was calculated in each case. If the density predicted was >1.7people/m^2, SLE would not occur, but if the density was above 1.7people/m^2, SLE was considered possible.

Remedial measures were then investigated that would either stiffen the mode out of the range of concern or increase the critical crowd density to >1.7people/m^2. The calculations assumed a structural damping level of 0.7% critical. This is higher than the typical 0.5% critical damping assumed for steel-framed bridges due to the nature of the supporting structure, but was confirmed following measurements on the completed structure.

Design solution
To reduce susceptibility to SLE, ways to increase the lateral stiffness of the river piers and the structural damping of the lateral modes were considered. Lateral TMDs were selected as the most economical and least visually intrusive solution. Three 3.2 tonne lateral TMDs under the bridge deck at the centre of the main span (Fig 19) were designed to provide sufficient additional damping for all modes in the full range of pier lateral stiffnesses predicted during design when tuned with respect to the measured frequencies of the lateral modes (Fig 20). The design takes account of the fact that TMDs add less damping to modes with higher modal masses, but less damping is required in these modes as more people are required to cause instability.

Background to synchronous lateral excitation

Synchronous lateral excitation is the phenomenon whereby pedestrians may "lock in" to the lateral sway of bridge decks, causing significant lateral motions[9]. SLE will tend to happen on bridges with low frequency lateral modes that directly coincide with the frequency of lateral forces due to walking.

Pedestrian lateral force input has been measured experimentally and found to increase linearly with deck velocity, effectively introducing a negative damping term to the equation of motion. The bridge thus becomes laterally unstable if the energy input by the crowd during each vibration cycle exceeds the energy that may be dissipated through damping in the structure. This occurs when the crowd walking across reaches a critical number.

There is ongoing research into the exact mechanism of "lock-in" and lateral pedestrian load modelling, but the design methodology proposed following the remedial works on the London Millennium Bridge[9] has proved robust in assessing the susceptibility of bridges to SLE and designing mitigation solutions.

Vortex shedding excitation of masts and spars

As vortices are shed from alternate sides of bluff bodies in fluid flow, an oscillating force is induced. If the natural frequency of the structure is close to the frequency of this force, resonance may occur and, if unchecked, vortex shedding can lead to noticeable responses and/or fatigue problems. Excitation may occur on different elements at different times depending on the local wind speeds, natural frequencies and element diameters.

Assessment of susceptibility
The Kurilpa Bridge masts were assessed for aeroelastic stability under vortex shedding. The masts are partially fixed at their bases and the connections have geometries that are potentially sensitive to fatigue damage.

The Vickery-Basu method, as incorporated in several codes and standards (most clearly in the new Eurocode 1), was used for assessing vortex shedding response. It compares a predicted "negative aerodynamic damping" with the inherent structural damping of the structure; when the latter exceeds the former, the member is considered stable. Since the masts are mostly welded (and the bolted joints are under compression), the inherent damping will be low and may start to approach levels of material damping of perhaps only 0.10-0.15% of critical.

The vortex shedding susceptibility calculations carried out were based on structural damping of 0.24% critical (as specified in Eurocode 1) in addition to any positive aerodynamic damping arising from movements of the rest of the structure, but included a safety factor of two against instability to account for the possibility of lower damping levels.

The modal properties were taken from the bridge finite element model, and 250 structural modes were considered – taking in all that were potentially at risk from vortex shedding excitation. The major masts were found to be stable, but the minor masts potentially unstable.

The pin-ended spars were also shown to be theoretically susceptible to vortex shedding response, but this risk was considered less severe as their motions were unlikely to cause structural damage and would be caused by along-deck winds. Along-deck winds will have increased turbulence from the surrounding terrain and adjacent bridge structure, which reduces the probability of vortex shedding occurring.

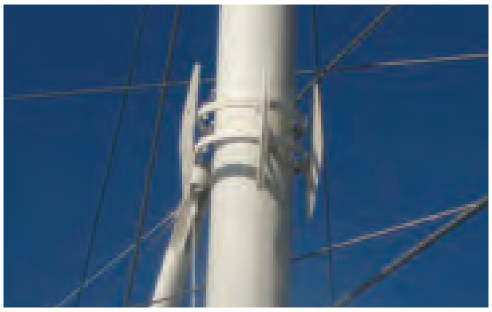
Design solution
Measures were taken to reduce the risk of excessive vortex shedding response and potential structural damage of the minor masts. Helical strakes, adding additional mass to the masts, or adding damping, were all considered as ways to control vortex shedding response. Additional damping was the preferred solution as it had the least impact on the aesthetics and proposed structure.

Hanging chain dampers were not possible due to the inclination of the masts, so external ring impact dampers were used. TMDs were considered, but the difficulty of tuning to each mast frequency made them impractical. The ring dampers were designed in close consultation with the architect for minimal impact on aesthetics and lighting, and ability to be maintained or replaced at a future date. Each has a steel annulus weighing between 100kg and 250kg (depending upon mast size and frequency), supported by three steel cables just over half-way up the mast, and able to move relative to it (Fig 21). Impacts between the mast and the ring dissipate the energy that any vortex shedding excitation puts into the masts, and are softened by visco-elastic pads that absorb energy and reduce sound.

Lighting and power

Kurilpa Bridge uses lighting to create an extra dimension of interest for users and passers-by (Fig 22). An arrangement of LED luminaires is programmed to produce an array of different effects, and can also be tailored to cater for special events, festivals, and sporting rivalry. This is currently one of the world's largest bridge LED lighting installations. Arup needed to decide how best to use lighting to reveal the architectural and structural features of the bridge, and the ability of LED to dynamically change colour enabled this. At dusk the bridge is revealed in a white light, but later in the evening the dynamic effects are unleashed to display a more playful personality. The possibilities of LED are limited only by the imagination.

Kurilpa is also one of the world's first large-scale solar-powered pedestrian bridges, with 84 photovoltaic panels positioned on the Kurilpa Point approach ramp to power the LED lighting. Depending on the lighting configuration, the solar panels supply 75-100% of the power required, with surplus electricity fed into the grid. As well as giving energy savings, using LED minimises ongoing maintenance and reduces operating costs.



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21. Mast damper.

22. LED lighting.

23. More than 30 000 cyclists and pedestrians use the bridge each week.

23.

Benefits to the community

These are many, ranging from the obvious value of an essential piece of transport infrastructure delivered on time and on budget, to less tangible but equally valuable public health and urban fabric enhancements.

Sustainability and "delightful efficiency"
The bridge was designed in accordance with best practice sustainability and whole-of-life principles, but the team additionally strove for "delightful efficiency" – where the delight and amenity that innovative, excellent design can bring to projects encourage the community to both use facilities and embrace the cultural and behavioural changes necessary to address climate change.

Here, the public is indeed voting with its feet, resulting in clear public health benefits and reduced emissions from the resulting lower vehicle usage.

Importance of cultural heritage
Kurilpa Park, where the bridge lands on the South Bank, has rich historical significance. It is named after the traditional owners of this stretch of the river who once used the area as a meeting place, walking along narrow riverbanks and pathways.

Kurilpa is an indigenous name – translated as "place of the water rat" – and was selected as the bridge name by public competition and in consultation with the Turrbal and Jagera clans who lived in the area; both were consulted from the outset due to the history of the land being utilised for the bridge landing. Indigenous stories can be read at various points along the structure and form an important component of its public art.

Kurilpa Bridge thus offers a new perspective of the city – the skyline, the GoMA and the State Library, the flowing river, the aboriginal people who inhabited this place, and their ancient culture and spiritual connection to Kurilpa.

Social usefulness
With 1500 people moving into south-east Queensland every week, the demand for improved pedestrian and cycle pathways continues to grow. More than 30 000 cyclists and pedestrians use the bridge each week to get to work, to visit the cultural precinct, or simply enjoy the Brisbane River. Usage will continue to grow as city residents and visitors discover the delight and convenience of Kurilpa Bridge (Fig 23).

Environmental responsibility
A key initiative was to assist the State Government to deliver on the "Toward Q2: Tomorrow's Queensland"[10] plan to reduce Queensland's carbon footprint.

The structurally efficient design of the bridge, the replacement of motor vehicle travel with walking and cycling, and in particular the use of low-energy LED lighting and the generation of solar energy from photovoltaic panels all make a significant contribution to CO_2 emissions savings, which are estimated to be 1000-2000 tonnes/year.

Conclusion

Kurilpa Bridge is a landmark project that is architecturally striking yet sympathetic to its prominent location. Not only has the bridge achieved the client's requirement that it not detract from the GoMA, but it is acclaimed as a fine piece of civic sculpture in its own right.

Opened on time and on budget in October 2009, it breaks new ground through the incorporation of tensegrity structure for the first time in a major bridge. Importantly, the design does not obscure the view of the river but enhances its beauty and accessibility, and its connections. Pedestrians and cyclists enjoy a dynamic experience, with the projecting decks affording spectacular views and creating intriguing urban spaces.

The addition of a DMX controlled lighting system provides spectacular lighting for special city-wide festivals or events, and the use of low-energy LED lighting and photovoltaic panels ensure that this is energy-efficient and socially responsible.

This new landmark for Brisbane provides a key connection from the city to Brisbane's highly awarded arts, cultural and leisure precinct. The bridge demonstrates that infrastructure can be functional and delightful, and that design-and-construct project delivery can and should produce innovation of the highest order when skilled designers and constructors adopt a truly collaborative approach. Many Arup offices and staff worked long and hard to ensure the success of the project, and the authors thank all of those involved for their effort and expertise.

In January 2011, southern and central Queensland suffered from disastrous flooding, including a major flood in Brisbane. An extraordinary combination of torrential rain over the river catchment and high tides resulted in the Brisbane River reaching levels approximately 1m above the 100-year flood level. The floods caused an unprecedented amount of damage to buildings and infrastructure, and tragically resulted in a number of deaths. Kurilpa Bridge, however, was not damaged by the flood, and reopened to the public as soon as water levels receded.

24.

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Kathy Franklin is an Associate of Arup in the Sydney office. She was lead dynamics engineer for the Kurilpa Bridge.

Project credits

Project owner: *Queensland Government, Department of Public Works* Client and contractor: *Baulderstone* Architect: *Cox Rayner Architects* Structural, civil, geotechnical, electrical, traffic, security, communications and hydraulic engineering, and specialist lighting design: *Arup – Ian Ainsworth, Andrew Allsop, Richard Andrews, Mark Arkinstall, David Beattie, Ainslie Blunck, Peter Burnton, Tristram Carfrae, Matthew Clarke, John Collado, Amy Cook, Charlene Cooke, James Cruz, Matt David, Alistair Deane, Trevor Duncan, Greg Eberhardt, Alex Edwards, Kane Ellis, Ken Enright, Kerry Farley, Alex Farrow, Owen Francis, Kathy Franklin, Sreejith Gangadharan, Joe Gattas, Paul Guger, Marek Halas, Ross Higgins, Helmut Houken, Eliza Howell, Dan Hyde, Christopher James, Lesson July, Peter Kastrup, Greg Killen, Kevin Legenza, John Legge-Wilkinson, Jonathan Lindsay, Mark Lindsay, Angus Low, Peter Macdonald, James Marsden, Alastair McConville, Jason McKenzie, Lisa McMillan, Dorothy Mao, Daniyal Mian, Samir Mustapha, Eoin O'Donovan, Ender Ozkan, Valeria Pascucci, Scott Paton, Dejan Pijetlovic, Daniel Powell, Richard Quinn, Charles Shum, Chris Sloman, Andrew Smith, Charles Spiteri, Ed Spraggon, William Spraggon, Peter Suryadi, Anthony Ungless, Philippe Vienot, Roger Vincer, Matt Walden, Chris Webb, Drew Yates.*

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