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Contents

In *The Arup Journal*, 2/2014, the introduction to the article 'Our inheritance, the next step?' by the late Sir Philip Dowson (re-published in his memory) omitted to note that the fourth founder-partner of Arup Associates in 1963 (with Dowson, Sir Ove Arup and Derek Sugden) was Ronald Hobbs (1923-2006). 'Bob' Hobbs, as he was universally known, later became Chairman of Arup Associates (1981-84) and Co-Chairman with Sir Jack Zunz of Ove Arup Partnership (1984-89).

Front cover: Singapore Sports Hub is a new feature on the city's skyline. Photo: Darren Soh.

Left: Melbourne Regional Rail Link involved building new tracks leading into Southern Cross Station, Melbourne. Photo: Regional Rail Link Media Library.

Melbourne Regional Rail Link

Authors
Jonathon Parker Rachel Nicholls Sinead Collins Rob Turk Paul Carter Kym Burgemeister

Introduction

The Regional Rail Link (RRL) in Melbourne is one of the largest public transport projects ever undertaken in Australia. It has transformed the rail network and created capacity for an extra 23 metropolitan and 10 regional services during each morning and evening peak.

Appointed as the client's technical advisor in a joint venture with KBR, called KAJV, Arup played a pivotal role in providing technical services from concept design through to construction and operation. This article looks at what RRL means for Melbourne and the challenges of building it, focusing on what KAJV did to ensure successful delivery.

RRL was honoured with Infrastructure Partnerships Australia's 'Infrastructure Project of the Year' award in 2014 and will become fully operational in June 2015.

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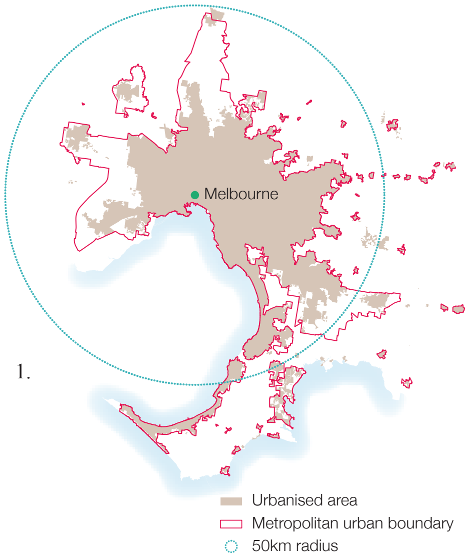

1.

Setting the scene

Municipalities in western Melbourne are amongst the fastest growing per capita anywhere in Australia, far outstripping the growth of traditionally more densely populated areas to the south and east of the city. Additionally, there has been steady and substantial increase in demand for train services from regional Victoria. Passenger volumes for regional train operator V/Line are currently at 60-year highs (Fig 1).

In 2006 the government commissioned a study to look at transport solutions for Victoria. The study recommended constructing a new pair of regional tracks between Melbourne's largest station, Southern Cross, and the city's outer-west. In 2009, federal funding was secured and a budget approved for the project.

The brief

The Regional Rail Link Authority (RRLA), formed in 2009, was briefed to deliver a new pair of regional tracks from Southern Cross Station to the outer western suburb of Werribee, via the suburbs of Footscray, Sunshine and Deer Park (Fig 2).

Approximately 45km long, the tracks were to be built along mixed brownfield and greenfield sites with stations along the corridor being either newly built or substantially modified. Major structures would include river crossings, road-rail grade separations and rail-rail flyovers.

Regional and metropolitan trains would no longer use the same tracks, improving reliability, travel times and frequency of services across the network. The new tracks would service Victoria's three most populated rural centres – Geelong, Ballarat, and Bendigo – with trains from Geelong diverting along a new 26km corridor before connecting to the existing track which already serviced trains from Ballarat.

1. Melbourne's urbanised area is rapidly expanding westward.

2. The route of the Regional Rail Link reflects population growth west of the city.

3. Road over rail grade separations were a key feature of the greenfields section of the project.

4. A new pair of regional tracks was aligned into an existing rail corridor in North Melbourne.

5. Detailed analysis ascertained optimum clearance from bridges achievable on this route.

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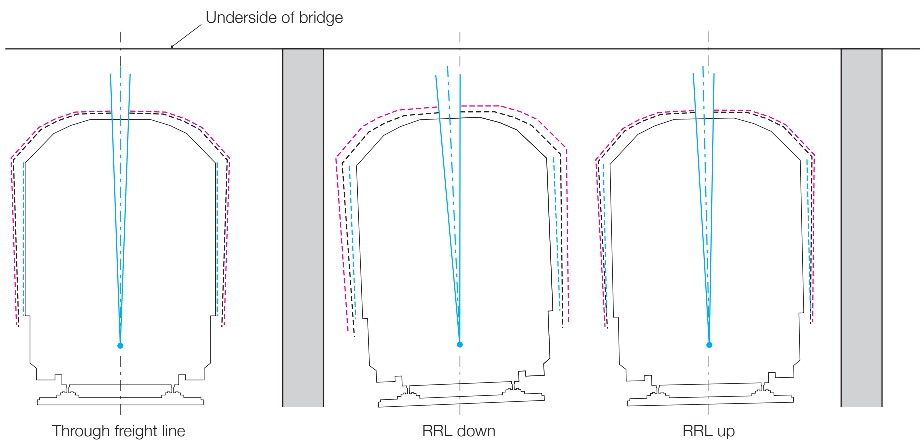

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With the brief established, RRLA needed a technical partner. In late 2009 KAJV was appointed to provide concept designs for the entire corridor. On successful delivery, the design scope was extended to delivery of reference designs, procurement and other technical advisory services throughout the construction phase of the project.

Track design

Creating free flowing regional and suburban services into and out of Southern Cross Station meant removing several bottlenecks on the network to enable regional trains to travel at speeds of up to 160km, with a theoretical headway of only two minutes during peak times. As a result, alignment of the tracks was set out to minimise conflict between the regional, suburban and freight services. Three new rail-over-rail grade separations were required and one was to be fully refurbished.

Equally critical to the task was aligning the new pair of regional tracks into the already congested rail corridor. Much of the corridor was too narrow to lay new tracks without impinging on the existing rail corridor boundaries. At many locations, existing tracks were slewed to one side to create the additional space needed (Fig 4).

Elsewhere, where land acquisition of properties adjacent to the corridor was unavoidable, the acquisition process was progressed to facilitate the construction programme. KAJV's concept designs were relied on heavily to determine the extent of the necessary land aquisition.

Design standards that impacted alignment of the tracks such as clearances to structures, track radius and signals location, were systematically reviewed. Where full constraints could not be fully complied with, a rigorous validation process was followed (Fig 5).

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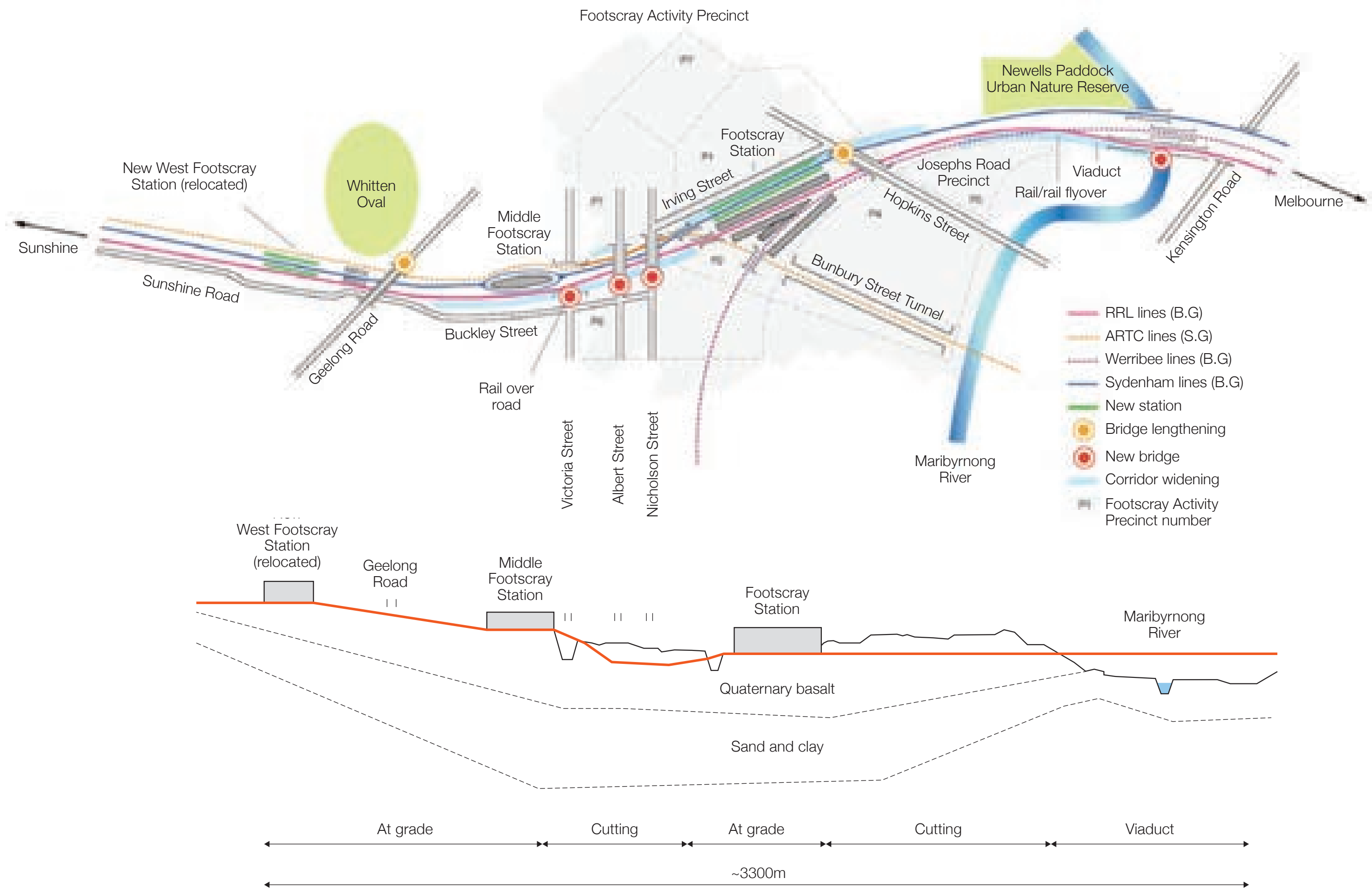

6. Track alignment through Footscray navigated constraints including seven road-rail and rail-rail grade separations and three stations.

7. West Werribee Junction where the new tracks join the existing Geelong line.

8. Yellow girders for Dudley Street Rail Bridge came to symbolise the start of the project.

7.

KAJV's recommended solutions were critical to informing discussions and decisions to determine the most appropriate alignment (Fig 6).

Beyond Melbourne's sprawling suburbs the track alignment was more straightforward. The new 26km rail corridor extends south west from the outskirts of the city's western suburbs to tie-in with an existing rail corridor at Werribee.

Ground conditions and geotechnical challenges

The alignment of the new tracks passes through the basaltic plains of western Melbourne and across significant thicknesses of soft alluvial deposits associated with the Maribyrnong and Yarra river systems.

The basaltic plains are defined by high-strength Quaternary basalt, typically 15m to 30m thick, overlying Tertiary sands and clays. Three new cuttings through the high-strength basalt were required along the rail line to create road-rail grade separations and maximise efficiency of both road and rail operations.

At the concept stage of the project, KAJV investigated the effectiveness of excavation through the high strength rock by carrying out blast assessments to determine potential patterns and weights of explosive charge. Limiting ground vibration and air over-blast pressure to acceptable values for adjacent residential properties was a critical element of this assessment, so contour mapping within a GIS model was an integral part of the blast assessment analysis.

The rail alignment approaching Southern Cross Station is underlain by very soft Coode Island Silt (CIS). This soil stratum is widespread across the western end of the city and it has dictated deep piling solutions for much of Melbourne's docklands.

The historic development of the existing tracks within this soft soils area has been based on re-ballasting and re-levelling the track bed as the underlying CIS settled in response to train loading. Over many decades, this had locally improved the properties of the CIS below the tracks and, over time, required maintenance of the tracks had become less frequent in response to track settlement.

8.

However, some of the new tracks for RRL were to be located in an area of the rail corridor never exposed to train loading so the design of the new track bed had to address the issues of:

- Excavating into very soft silts and the construction challenges this would present
- Disposal of excavated silt which, due to its classification as an Acid Sulphate Soil, would need to be taken to a regulated disposal facility
- The likely settlement of the track bed over time due to settlement of silt under the new train loading.

The approach to the design of the new track bed, therefore, was to minimise its thickness to avoid excavation into the CIS whilst maintaining the required long-term performance of the rails.

To demonstrate the performance of the new track bed, a series of finite element analyses were carried out to model the distribution of load from train wheels through rail, sleepers and ballast (3D analyses) and the overall impact of this loading on the compression of the CIS, and hence track settlement over time (time-dependent 2D analyses). Modelling of the in-situ properties of the CIS was a key parameter for these analyses. Laboratory test data, both site specific and published reference documents, was taken into account together with the historic loading associated with the rail corridor.

Civil structures

The project involved construction of more than 50 new bridges. KAJV developed concept designs for both new and modified bridge structures including detailed design for programme-critical structures such as Dudley Street Rail Bridge.

Dudley Street Rail Bridge

This was the first significant structure to be built on the project. Located just outside Southern Cross Station, it carries metropolitan and freight by-pass tracks over Dudley Street (Fig 8). The bridge set the benchmark for design documentation, application of the rail authorities' standards and quality of construction for the RRL project.

With a clear span of 38.25m, its superstructure consists of two twin half through girder bridges. These are formed from 2.57m-deep steel plate girders and 350WC197 transverse beams made composite with a 230mm concrete slab. Its substructure consists of two in-situ concrete abutments each supported on six bored concrete piles.

Three key constraints influenced the design and structural form of the bridge:

1. Rail tracks adjacent to the bridge were fully operational during construction and rail occupations were limited to two weekends during the construction period. This limitation led to the adoption of a steel superstructure.
2. The bridge is located parallel to two existing concrete rail bridges at Dudley Street which were once part of a series of rail bridges supported on timber piled brick piers and abutments. The location of the timber piles and their structural condition could not be assessed during the design phase due to road and rail access restrictions so to minimise risk a clear span structure, independent of existing infrastructure, was adopted.
3. The existing road network and carriageway clearances on Dudley Street had to be maintained below the new structure. This clearance restriction led to the development of a half through bridge structure.

Steelwork fabrication and installation was carried out by Macfab (Melbourne, Victoria) with Samaras (Adelaide, South Australia) acting as a sub-fabricator. A full trial assembly of the bridge was undertaken in Samaras' Workshop in Adelaide: this ensured fit-up of the end plates bolt holes of each transverse beam with the plate girder web bolt holes and allowed the packer plate at each connection to be machined to achieve fit tolerance.

The 39m-long plate girders were transported – each on a single truck, as complete elements – under police escort from Adelaide to Melbourne, the transverse beams making the same journey on several other trucks.

The steelwork was lifted into position using a 350T crane in a single weekend of rail occupation then pre-cast concrete panels, acting as permanent formwork to the concrete deck, were lifted into position in a separate weekend rail occupation. The remainder of the works were completed while rail tracks adjacent to the bridge were fully operational.

9.

Hopkins Street Bridge

The challenges of widening the existing rail corridor in a constrained brownfield environment led to a range of innovative concept design solutions.

In the case of Hopkins Street Bridge, which services one of the busiest roads in the area, full removal and replacement of the single-span steel composite bridge was considered unfeasible by the roads authority. Options suggested included creating a temporary bridge or placing a new bridge over the existing bridge. After a process of stakeholder engagement, the proposal eventually adopted was to add a span onto the back of the bridge effectively converting it from one span to two.

This unconventional design meant converting the existing northern abutment into a new central pier to support the new span. The concept design proposed placing a large precast concrete corbel onto the back of the new central pier. High-strength steel anchor bars combined with steel spreader plates were suggested to attach the new corbel on to the back of the central pier, thus providing the necessary load capacity for the new span.

To keep Hopkins Street open to traffic during modification works, the concept design allowed for staged construction. This meant that works could proceed to one side of the bridge deck while traffic flows were diverted around. The concept design also allowed for top down construction which meant the bridge deck was installed prior to completion of excavation below the deck. Disruption to traffic flows could be reduced by re-opening sections of the bridge to traffic, despite excavation beneath the bridge being still in progress. This unusual concept design proved an effective solution and was largely adopted in the final design (Fig 10).

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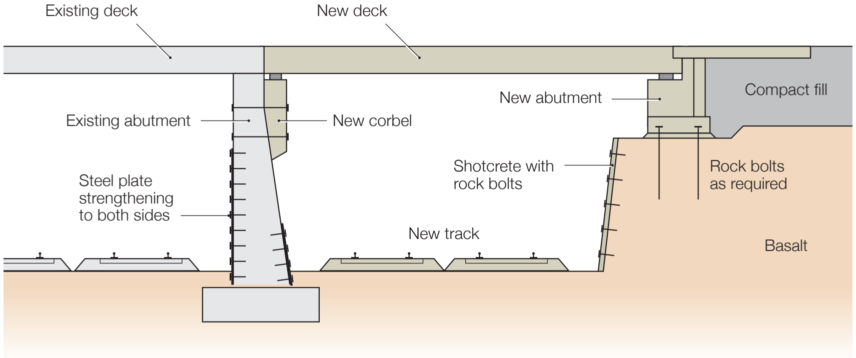

9. Anderson Road: challenges at this brownfield grade separation included minimising rail and road disruption and relocating major services.

10. The design of Hopkins Street was unconventional but it meant the bridge stayed open throughout construction.

11. Precast prestressed concrete is the established method of construction for this type of bridge in Australia.

12. Ballan Road: a typical two-span rail-under-road grade separation in the greenfield environment.

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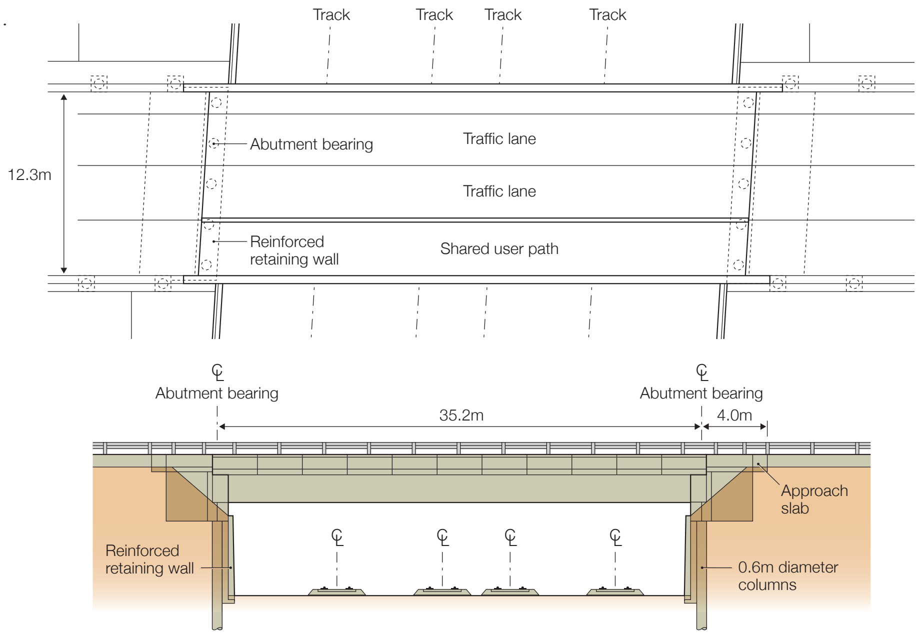

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Grade separations

KAJV carried out concept designs for all 16 new road-rail grade separations along the length of the project, the majority of which consisted of precast, prestressed concrete ‘super tee’ superstructures. This form of construction is common in Australia and is preferred by contractors for its speed of erection, versatility of design and well established design and construction methodologies.

Span lengths varied between approximately 14m and 35m. The longest span resulting in a beam depth of 1800mm. Substructure construction was typically cast in-situ concrete columns with bored piled foundations. Reinforced earth walls were typically proposed for the abutments (Figs 11–12).

Two existing level crossings at Anderson Road in the brownfield environment presented a different set of challenges. Underground services, in particular, required careful attention. At one grade separation, for example, lowering the road meant the relocation of the main aviation fuel pipeline servicing Melbourne Airport to accommodate this (Fig 9).

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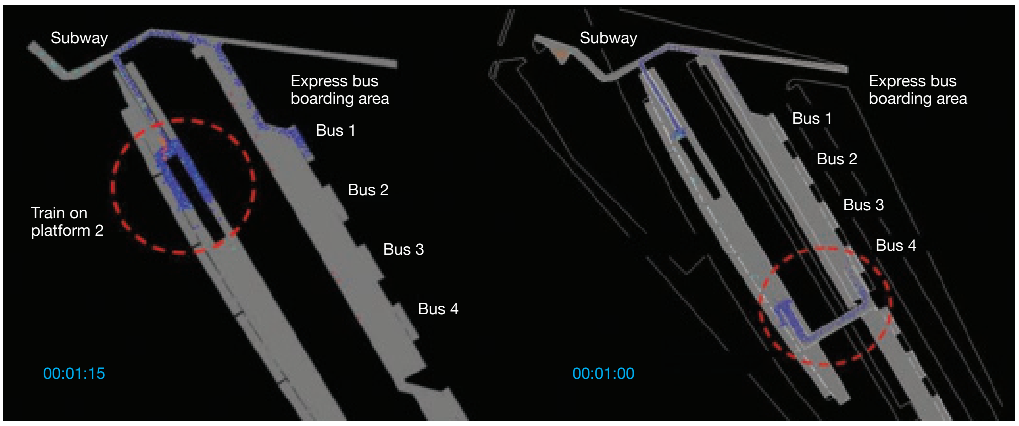

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13. RRL provides critical infrastructure to support growing demands for rail travel in regional Victoria.

14. The inclusion of a new temporary station at Albion Station was modelled as part of the bus replacement strategy.

Strategic framework and travel demand forecasting
During the initial stages of project development and concept design, KAJV established a strategic framework identifying key transport considerations along the length of the rail corridor. An important component was the development of travel demand forecasts using the Department of Transport's 'Melbourne Integrated Transport Model' (MITM).

Working with RRLA and the Department of Transport, KAJV refined and enhanced MITM to better represent travel demand associated with current regional train services and the specification of future transport networks (e.g. planned road and rail projects), as well as testing potential future train operational scenarios for both RRL and metropolitan services.

This analysis provided patronage forecasts for the proposed RRL and metropolitan services and associated road traffic demands.

KAJV used this information to inform capacity requirements for pedestrians at stations, demand for car parking, and traffic capacity requirements at intersections and level crossings.

Travel demand forecasting was supplemented by further studies, as well as discussions with RRLA and key stakeholders, to identify bus stops required for stations along the corridor, short and long term parking needs and the design of a 26km shared path cycling route from Werribee to Deer Park.

Level crossing traffic performance assessment
Safe and efficient operation of road crossings of the rail corridor was fundamental to the concept design. KAJV carried out a series of studies to understand traffic performance at the five level crossings between Sunshine and Deer Park and developed micro-simulation traffic models to represent anticipated level crossing operation after RRL was opened.

This information was used to evaluate traffic performance and improvement options for the proposed level crossings.

Replacement bus strategy
As well as planning the permanent design of the RRL, KAJV informed key elements of construction works planning.

Particularly challenging was developing a strategy to fully close the rail corridor for all train services between Deer Park Station and Footscray Station to allow completion of early works within the rail corridor. Closing this line would impact approximately 18,000 passengers each day so an effective strategy for maintaining passenger movement was required. From a transport perspective, it involved transferring passengers from Albion Station to buses which would take them to Flemington Station where they could use a separate rail line to complete their journey to the city.

The study identified improvements required for this to happen including:

- Changes to key stations to allow safe boarding and alighting
- Transport interchange infrastructure required modifications and additions.
- Number of buses needed to transport passengers between Albion and Flemington Station
- The impacts of running a large number of buses along the road network.

The findings were used to inform construction of a temporary bridge and transport interchange at Albion Station (Fig 14) and a transport interchange at Flemington Station, as well as providing key information to plan the bussing operation. Successfully implemented on a number of occasions, the bussing operation was vital in facilitating construction of the project and, despite some inconvenience for users overall, it generated very little negative feedback.

Best practice station design

Cox Architects worked alongside KAJV to prepare concept designs for the two new stations and major modifications to three existing stations. The KAJV concept designs were used to determine a set of minimum requirements to be incorporated into each station during detailed design.

Footscray Station

The main challenges involved replacing the existing car park and forecourt area with an additional two platforms, lengthening the existing concourse, and redesigning the station frontage. Platforms had to be lengthened from 160m to 250m to allow for longer trains.

Various access solutions for the concourse were investigated including ramps, escalators, lifts and stairs. Unsatisfactory elements of the existing station, such as the excessively steep stairs, were examined and improved where possible.

The importance of conserving heritage architecture was taken into account and historical buildings on the platform were preserved and enhanced, while other notable features at concept stage included providing integrated locked bicycle storage and improved access to the nearby shopping precinct and public transport.

Sunshine Station

The concept design explored options for removing the notoriously uninviting underpass access to the platforms, replacing it with a new high-quality concourse. Similar to Footscray, the station facilities included essential ‘premium station’ elements such as new ramps, lifts, kiosks, waiting rooms, staffing quarters, ticket office and locked bicycle facilities. The other main feature of the concept was the redesign of the existing bus interchange that adjoins the station and is a major transport hub that services up to 12 different bus routes. The station redevelopment allowed KAJV to investigate different bus bay configurations and various layouts were proposed that improved efficiency of movement and enhanced safety for pedestrians within the area.

All stations were designed for the Level 4 Green Star rating which is regarded as industry best practice. Station sustainability features included rain water storage tanks, solar panels and water sensitive urban design.

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Wyndham Vale and Tarneit Stations

Reflecting the government’s desire to provide essential public transport infrastructure in the growth areas to the west of the city, the project included two new stations at Wyndham Vale and Tarneit. Built entirely on greenfield sites, these stations did not have the same demanding physical constraints as stations located in the brownfield environments (Fig15).

The concept designs for both new stations featured large car parks designed to accommodate the large projected commuter catchment in these areas. At Wyndham Vale the station was built into an extensive cutting due to topography and to amenity. In both cases, the design ultimately built remained highly consistent with the design set out in the concept phase (Figs 16–17).

15. Aerial shot of the new Tarneit station with car parks for commuters from the large catchment area.

16. Tarneit Station: KAJV concept design.

17. Tarneit Station: on completion.

Acoustic design
Although there was no established railway noise policy in Victoria when work on developing RRL started, the Planning Minister decided the environmental assessment should include the consideration of any noise impacts.

KAJV started the assessment by building a computer model using the Nordic Method (Kilde) in *SoundPlan*. However, the lack of source sound-level data meant the team also had to embark on the largest rolling stock noise survey ever undertaken in Victoria. Hundreds of individual noise measurements were made of the various electric, diesel-multiple-unit (DMU) and diesel locomotives used on the network. The base noise levels were then normalised for measurement distance and number of carriages prior to linear regression to determine speed-related source noise levels.

A key input to the model was the future railway operating schedule, including detailed understanding of hourly train flows, type and number of carriages. The acoustic team worked closely with Department of Transport rail planners to devise a representative schedule. In addition, *SoundPlan* was used to generate noise level contours and individual noise level predictions at thousands of properties adjacent to the rail corridor and to auralise potential railway noise levels at representative properties.

Even in the absence of established railway noise criteria, this process proved valuable. The acoustic assessment was key to the environmental submissions for the project and the predictions were used to determine whether noise mitigation was necessary at various locations near the railway corridor. The preliminary noise mitigation design was subject to multi-criteria analysis, overseen by Arup's Management Consulting and Economics group, and the outcome supported the use of noise barriers and glazing treatments in some locations.

The resulting RRL noise model was the largest, most detailed railway noise assessment ever undertaken in Australia. It encompasses the entire 45 km railway corridor from Southern Cross Station, through Sunshine, Deer Park, Tarneit and Wyndham Vale, including all metropolitan, regional and freight movements within the corridor.

The Department of Transport developed a new Victorian 'Passenger Rail Infrastructure Noise Policy' mid-way through the project in 2013. This provided a solid policy framework for mitigating railway noise where it was predicted to exceed prescribed daytime or night-time averages, or overall maximum noise levels.

Sustainability
The sustainability approach of RRL, from design through to construction, has been one of its outstanding features, culminating in the project winning the 2014 Premier of Victoria's Sustainability Awards for Buildings and Infrastructure.

The way sustainability targets were integrated within the project represented a step change compared with how sustainability targets had traditionally been approached within large infrastructure projects in Australia.

This step change emanated from the RRLA's Sustainability Policy and the associated vision, objectives and targets that KAJV were instrumental in forming.

The RRLA Sustainability Policy defined seven objectives for the project which were to be met by achieving 22 supporting targets. A focus of KAJV's research was to define targets that rewarded an outcome, rather than a process, leaving responsibility for target achievement with each of the relevant design and contracting teams. This research built on extensive understanding of the sustainability opportunities within the infrastructure sector.

Conclusion
The RRL is the largest transformation of Melbourne's railway network in a generation. It will help to open up areas to the west of Melbourne and allow them to prosper. Removing rail bottlenecks and upgrading stations will benefit communities along the line and provide a lasting legacy for the people of Melbourne.

Arup in its joint venture with KBR played a key role in successfully delivering RRL. Working closely with the client over the lifetime of the project, Arup brought together a team of experts spanning a range of disciplines and drew on skills locally and internationally. The services provided were critical to overcoming many of the challenges the project faced along the way.

18. At Maribyrnong Crossing in Footscray, the team developed a structural solution sympathetic to the heritage-listed truss bridge. KAJV prepared concept designs and undertook consultation with key stakeholders including Melbourne Water and Heritage Victoria.

19. The Maribyrnong Crossing is linked by a viaduct on either side. The new adjoining rail-rail grade separation allows RRL tracks to pass through Footscray Station.

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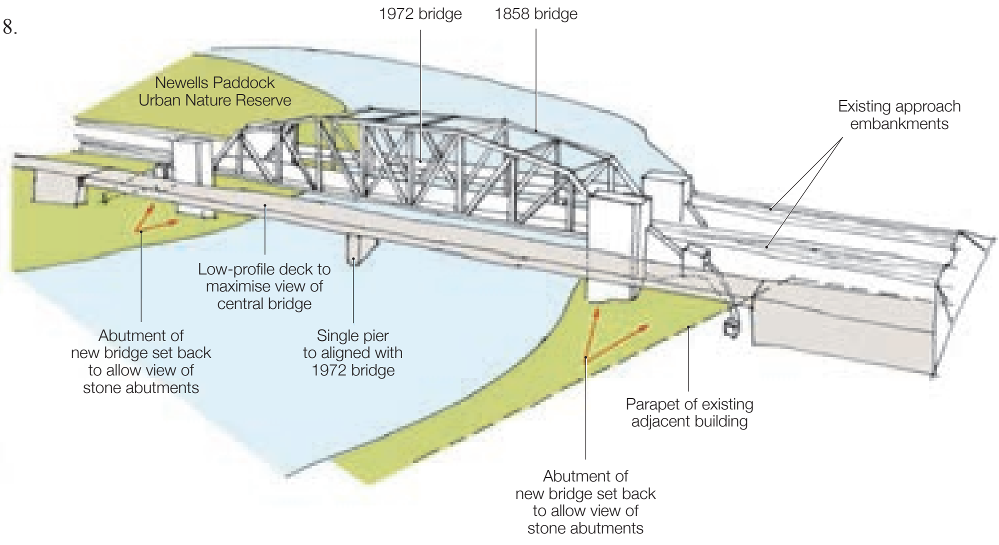

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Authors

Jonathon Parker is a Senior Engineer. Initially Design Manager, later seconded to RRLA as Technical Advisor during the delivery phase.

Rachel Nicholls is Principal. Geotechnical Team Leader initially, later assumed role of Project Director.

Sinead Collins is a Senior Engineer. Bridge designer, in particular responsible for Dudley Street Bridge.

Rob Turk is an Associate and Sustainability Manager.

Paul Carter is a Senior Engineer, Transport Planning and Technical Leader.

Kym Burgemeister is an Associate Principal and Acoustics Team Leader.

Project credits

Client: Regional Rail Link Authority (RRLA) Civil, civil structural, building structural, transport modelling and planning, GIS, noise and vibration, track, signalling, security, tunnelling, geotechnical, project management, architectural, landscape architecture, fire, building services, risk, sustainability, environmental, hydrology, project office set-up management consulting and economics: *Arup – Prasad Adhava, Niruma Akhter, Sarah Alper, Elisa Anderson, Joseph Anderson, Justin Arifin, Robert Armstrong, Shobha Baheti, Elmer Bandalan, Malcolm Barr, Paul Bartholomew, Martin Beeton, Kelvin Bong, Mark Bridger, Tim Bryant, Kym Burgemeister, Jeff Burleigh, Paul Carter, Nigel Casey, Argoon Chuang, Daniella Ciavarella, Diana Coelho, Liam Cole, Sinead Collins, Matthew Collits, Stacy Conroy, Joseph Correnza, Bob Couzin Wood, James Crocaris, Steve Dalton, Simon de Lisle, Clive Domone, Barry Drew, Peter Duggan, Trevor Duncan, Jaime Ericksen, Peter Fanous, David Farrell, Adrian Fazio, Jared Fetherston, Vincent Fok, Ken Fong, Marco Furlan, Matt Gardiner, Andy Gardner, Hugh Gardner, Will Gouthro, Chris Graham, Phillip Greenup, Jonathan Griffin, David Hanson, Chris Harrison, Chris Harvey, Gerard Healey, Andrew Herriman, Duncan Hollis, Martin Holt, Greg Hopkins, Min Huang, Peter Hurlstone, Karim Issa, Perry Jackson, Matt James, Peter Johnson, Bruce Johnson, Jess Johnson, Callan Jones, Nick Joveski, Nerissa Kamat, George Kazantzidis, Robin King, Russell Kolmagorov, Stefan Konstantinidis, Hannes Lagger, Andy Lewis, Jenny Lo, Chris Lyons, Robert Macri, Michele Mangione, John Mcgain, David Mchugh; Cameron Mcintosh, Sarah Mcintosh, Mick Mcmanus, Joe Metcalfe, Brendan Molloy, Rachel Nicholls, Judy Nicholson Kelava, Gareth O'halloran, James Oakley, Karen Oj, Jonathan Osborne, Jin Pae, Gavin Palmer, Jonathon Parker, Joe Paveley, Jim Peacock, Kalyan Peddi, Lucy Pike, Derek Powell, Tim Procter, David Riley, Marius Roman, Hywel Rowlands, Stephanie Sarta, Helen Searle, James Selth, Alex Shah, David Shrimpton, Charles Shum, Daniel Simmonds, Greg Simpson, Colin Sloan, Trent Smith, Julia Smithard, Charles Spiteri, Jayanthiraj Steven, Nathan Stevens, Alex Stewart, Jess Suett, Anna Thiele, Przemyslaw Tomczyk, Tony Vidago, Philippe Vienot, Rob Warner, Jen Watson Stewart Bird, John Wheadon, Leigh Williams, Ashley Willis, Jonathan Wright, David Young, Sarah Zhang.*
Joint Venture partner: *KBR*

Image credits

1 *The State of Victoria, Department of Transport, Planning and Local Infrastructure*; 2,5,6,8,10,11,14,18 *KAJV*; 3,4,7,9,12,13,17,19 *Regional Rail Link Media Library*; 16 *Cox Architects.*

Stormen - art and music in the Arctic

Location
Bodø, Norway

Authors
James Beer Matt Atwood William Algaard George Ellerington Ian Knowles

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1. Store Sal – this world-class concert hall converts into an equally effective theatre.

2. Daylight streams through floor-to-ceiling windows that frame a view of the fjord from the library.

3. Stormen seen from the harbour, library in the foreground, concert hall tucked neatly behind.

Introduction

A wind-swept harbour in the Arctic Circle is an unlikely setting for a new arts centre, particularly one that has attracted international attention for its quality and versatility.

Yet 'Stormen' – comprising a library, a theatre that converts into a concert hall, bars, clubs, reading rooms and various performance spaces – has brought unexpected fame to the small town of Bodø in Norway. Influential London-based magazine The Architects' Journal selected Stormen as its 'Building of the Year' for 2014, while Christian Lindberg, Principal Conductor of the Arctic Philharmonic Orchestra, says Stormen's concert hall is one of the very best in the world.

DRDH Architects worked in close collaboration with Arup on the acoustic and venue design of Stormen, which is actually two buildngs: Bibliotek and Kultuhus. Bibliotek, with its library, reading rooms and performance spaces, is located on the waterside edge of the site, its huge windows affording the visitor a panoramic view across the fjord. Kulturhus, abutting the town centre on the inland side of the plot, has a 944-seat theatre/concert hall; a 250-seat multi-purpose drama and recital hall and a 400-seat basement jazz and rock music club.

The buildings are designed to operate as a cultural hub, morning to evening. Bibliotek, with light cascading through waterside windows, is the ideal place for study and daytime events while Kulturhus is undoubtedly the busiest part of Stormen at night. All the facilities in Kulturhus can be used simultaneously, if required.

History, quest and competition

The seeds of Bodø's quest for a vibrant new cultural centre were sown in 1940 when a German bombing raid left much of the town in ruins. Reconstruction was necessarily hasty and inexpensive, with prefabricated lightweight housing and stone-clad commercial buildings predominating. In later years further public buildings were constructed on a grid system that has given today's town its current shape.

This piecemeal post-war development, necessary to meet the needs of a population grown from 6,000 to more than 50,000 in little over 50 years, meant that by the 1990s the local authority, Bodø Kommune faced a conundrum: should it consolidate the grid or take a completely new approach to regeneration?

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A decade of debate ensued until, in 2008, a decision was made: Bodø Kommune announced an international design competition for a waterside cultural quarter, offering entrants the choice of either inner-city regeneration or consolidation. Many entrants plumped for regeneration but London-based DRDH took a very different approach, consolidating its design with the existing town centre and locating the library in a prime waterside position.

Arup's role

DRDH turned to Arup, both for help in developing their ideas to win the competition, then later to construct Stormen. DRDH was attracted by Arup's international capability, proven skill in concert hall design and expertise in spatial integration and transformation. There was also a good 'cultural fit' – Arup's unique structure accorded well with the DRDH ethos.

Arup's appointment was across a multidisciplinary portfolio comprising acoustic and venue consulting; mechanical, electrical and structural engineering (to concept design); and fire planning (during construction). The early days of the project were focused on an intense period of design development. Work on site started in 2011 and was completed in November 2014.

The key elements of stormen

Within Bibliotek, the dominant volume is the reading room. This airy space houses an array of shelves and study areas. In summer, its floor-to-ceiling glazing offers visitors inspirational views and glorious midnight sun. In winter, when daylight is at its scarcest, it provides a welcoming public gathering space against inclement weather. Bibliotek also houses a community studio – a space for small lectures and where local aspiring artists can perform. Every detail is meticulously designed: the performance technology is carefully detailed to allow it to be hidden or removed, so the space can be used for art exhibitions (Fig 4).

Kulturhus, the performing arts building, houses three venues and a full range of front-of-house and backstage facilities: Lille Sal is a 250-seat multi-purpose drama and recital hall; Sinus is a 400-seat jazz and rock club; and the undoubted centrepiece is Store Sal, a 944-seat theatre and orchestral concert hall.

Designed to be a truly multi-functional space, with no compromise in acoustic or operational standards for either theatrical or orchestral performances, Store Sal is the most complex of all the spaces within Stormen. The restrained, elegant architecture belies the deep collaboration required between DRDH Architects and Arup to make the space effective.

4. A bright and open stairwell accesses library and study rooms.

5. Ballerinas from Bodø's ballet school performed The Nutcracker in Store Sal, accompanied by the Arctic Philharmonic Orchestra.

6. A view of the town from The Green Bar in Kulturhus.

5.

6.

The challenges

Stormen's engineering challenges sprang partly from the technical and architectural aspirations of the design, partly from the nature of its environment.

Availability and cost of materials was an issue. Bodø's Arctic location meant that shipping a suitable quantity of structural steel was prohibitively expensive, while a commercially-viable supply of ready-mixed concrete was available only due to the concurrent construction of a major new hospital in the city. Long periods of sub-zero winter darkness added to the construction challenge.

The team also had to take into account control of aircraft noise – Bodø's airport, only 1.5km away from Stormen, is a major base for the Norwegian Air Force.

Programming aspirations for the arts centre were high, and simultaneous use of all venues was planned which meant they had to be in close proximity and available for concurrent use. With the city centre site constrained on three sides by existing roads, plus the harbour to the north-west, achieving the client's spatial requirements and architectural design was necessarily detailed and compact. The proximity of high-performance spaces combined with reduction of surrounding volumes led to complex structural, acoustic and operational challenges.

Changing brief

The client's aspirations further developed as concept design progressed. Developments in the regional music scene emerged that had significant implications for the design of Store Sal. Two local orchestras were combined to form a new regional orchestra – the Arctic Philharmonic – and the local annual music festival, already gaining in national importance, was expanded.

It became apparent that the original competition requirement for a proscenium theatre that could occasionally accommodate an orchestra was only half the story. In reality, the client required a world-class concert hall which could act as a base for the Arctic Philharmonic and a theatre of equal quality. They needed an exceptional multi-functional venue capable of rapid conversion between concert hall and theatre.

Scope change identified, rapid and significant redesign was required. A traditional orchestra shell was neither practical – because space limitations precluded its storage – nor suitable because it would fail to deliver sufficient acoustic performance. Electro-acoustic enhancement fell short of the client's aspirations so a bespoke solution was required: the hall had to be physically transformed:

- The ceiling of the auditorium needed to be raised to create sufficient volume to achieve concert hall reverberance
- The stage flytower and wings had to be closed off with suitably massive reflective surfaces to create a concert hall 'shoe-box' geometry
- A secondary suspended reflector array was required over the orchestra platform to achieve the early reflections necessary for performers to communicate clearly
- Surfaces finishes and materials required review and dual design to achieve dual functionality
- Extensive and sophisticated variable absorption elements had to be deployed
- Spatial transformation systems would have to change the venue's geometry to reveal or hide acoustic finishes and specialist technical systems as required.

The Arup Venues team is expert in multi-functionality using spatial transformation technology. So the efficient design concept and competitive procurement strategy subsequently devised meant the complex, novel moving shell system could be built for similar cost to a traditional shell with an acoustic enhancement system.

The following sections outline the acoustic and technological concepts involved.

Acoustic transformation

The client required an audience capacity of about 1000. In orchestral mode, a reverberation time (RT) of about two seconds is required for optimum performance. For 1000-person capacity this equates to a room approximately 18m high and 18m wide. In theatre mode, however, such a volume is excessive – the ideal RT being closer to one second.

The desired reduction in RT was achieved by:

- Exposing absorption in the stage area and flytower
- Deploying variable acoustic drapes at technical balcony level
- Deploying a system of bespoke tracked unity-absorbing sliding wall panels that cover more than a third of the auditorium side and rear wall areas.

To prevent excessive low frequency absorption, panel storage enclosures were carefully designed and lab-tested to ensure that in orchestral mode the absorptive panels themselves were effectively isolated from the room. This was achieved by providing suitable mass and stiffness to the enclosures and by ensuring that all gaps into the enclosures are sealed when the panels are retracted (Fig 12).

Spatial transformation

An array of innovative technologies enables Store Sal to be truly dual-purpose. As a theatre, its large stage, full-height flytower and variable-sized orchestra pit enable it to host complex theatrical and televised shows (Fig 7). When transformed to a traditional shoebox concert hall it can deliver world-class symphonic performances in a critically-acclaimed acoustic (Fig 8).

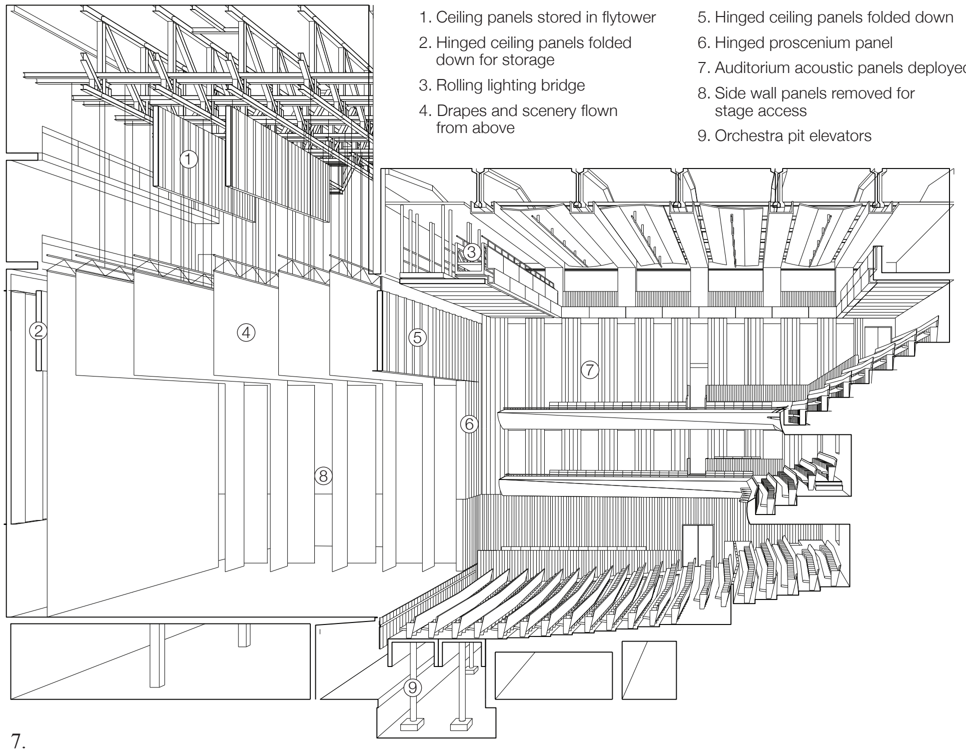
As well as the acoustic and storage issues associated with use of a conventional orchestra-shell already noted, a particular problem is that as freestanding towers grow in height, the base area and weight also expand. This makes tall towers very difficult to store efficiently. For these reasons such a shell was both undesirable and impractical.

Instead, the orchestra is enclosed by a system of suspended movable wall and ceiling panels. The 14m-high wall panels move easily on an overhead track system and store tightly against a side stage wall behind the theatre fly galleries. Acoustic reflectors and motorised ceiling panels can be flown or folded into place above the stage and, together with the wall panels, these dramatically change the acoustics and aesthetics of the space. In theatre-mode a pair of the side wall panels hinge around to form the sides of the proscenium arch with the top completed by folding down one of the ceiling panels.

Acoustic isolation

To be acoustically effective, each performance space must be free of noise from building services, external sources or other venues in the complex. As a world-class concert hall Store Sal, must achieve the particularly stringent background noise level requirement of NR15, the industry standard for new concert halls. Extremely high levels of inter-venue acoustic isolation are required to ensure these criteria can be maintained so that classical recitals can be held in Store Sal while pop music concerts are staged in Sinus directly below.

This has been achieved by constructing Sinus and Lille Sal as independent isolated concrete boxes, mounted on elastomeric bearings, with no solid connections to the rest of the building (Fig 9). The resulting level of isolation has been highly successful.



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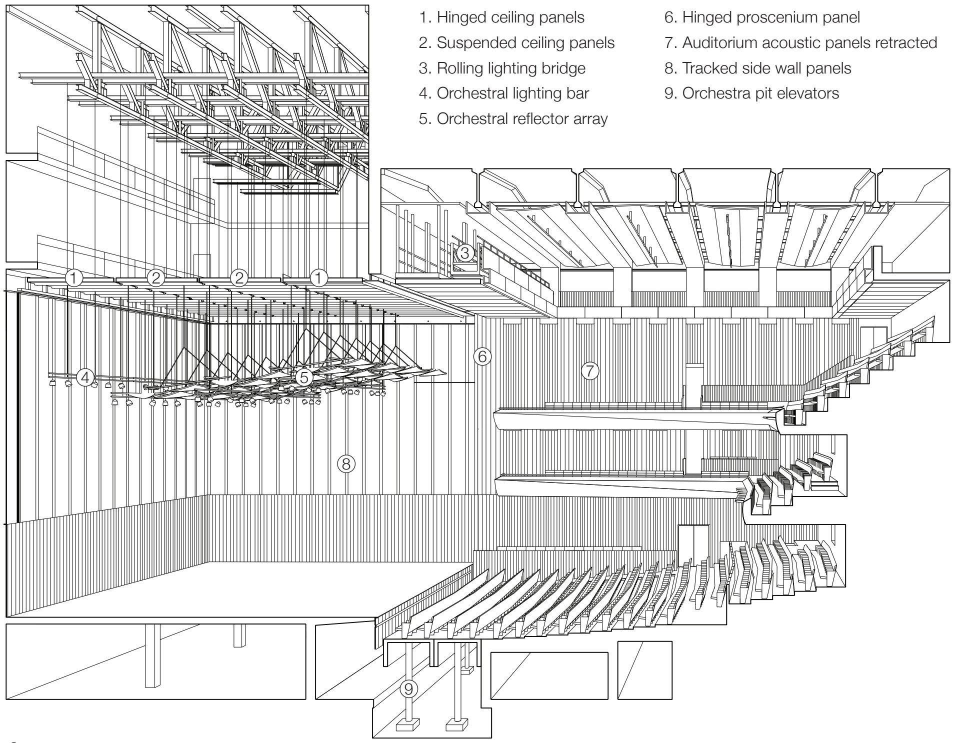

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7. Store Sal in theatre mode.

8. Store Sal in concert hall mode.

It is known to be greater than 90dB but has not been accurately measured because it's not possible to safely generate a high enough sound level in one venue to measure the transmitted level in the other.

The result is a set of spaces that give the venue operators complete flexibility in which events can be scheduled at any time, without fear of disturbing adjacent performances.

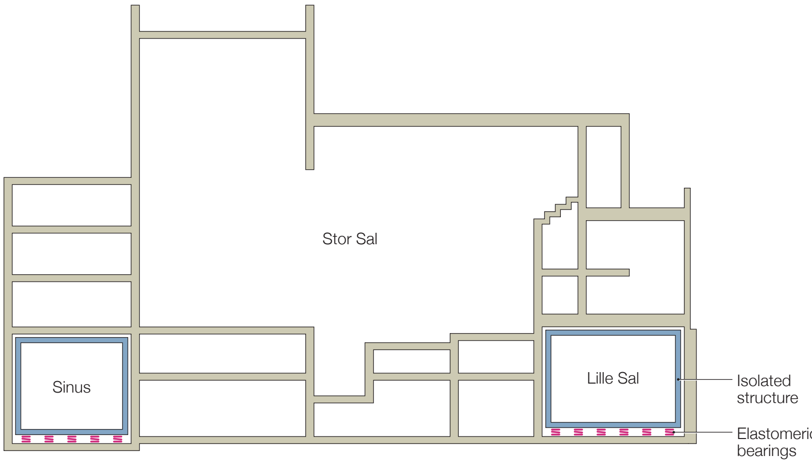
Structure

The ambitious use of such a compact building volume – with three independent performance venues partially below ground – created significant structural design challenges. Not only did the team need to solve the coordination challenges typical for buildings of such technical complexity, but the vertical stacking of primary and acoustically-isolated structures meant developing creative solutions for load paths both during construction stages and in the final configuration.

A particular challenge was the requirement to position the primary rear support wall of Store Sal above the ceiling of Lille Sal in order to achieve the space planning which was fundamental to fitting the three venues into the building volume.

Lille Sal employed an inner concrete box independent from the primary supporting structure, so the scheme was developed such that the rear wall of Store Sal could span the full length of Little Sal, and then distribute the loads to other walls in the opposite plane. However, it was essential that the propping required to support the weight of the formwork and wet concrete of the wall in the temporary condition could not penetrate the completed ceiling of Lille Sal. The concept therefore integrated a system of precast beams that could provide support in the temporary condition while retaining a compact and efficient framing arrangement in the final configuration (Fig 10).

The Arctic Circle premium on structural steelwork meant steel was only used where absolutely required for cantilevering balconies and flytower grid. The generally preferred structural framing solution was precast concrete which was used where possible, though achieving the ambitious and highly integrated layouts meant the majority of the structure was cast in-situ (Fig 11).



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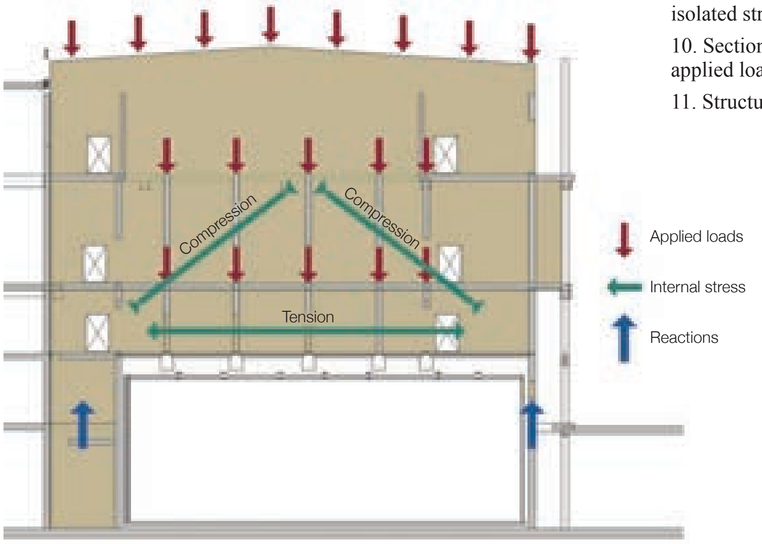

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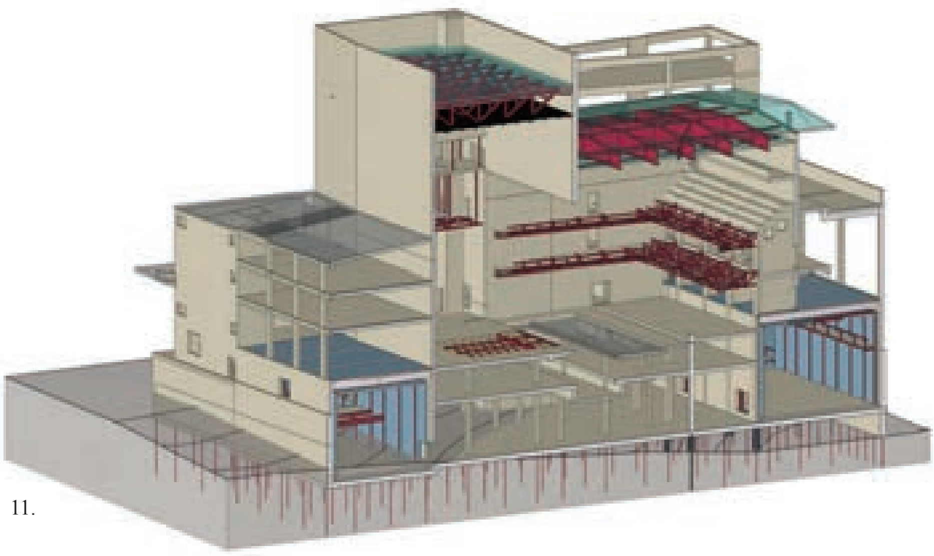

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9. Section showing isolated structures.

10. Section detail showing applied loads.

11. Structural model.

12.

Seating and sightlines

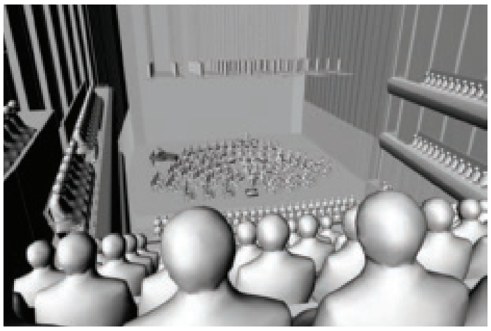
Theatre use requires a deep fixed stage area. For dramatic performances, the audience needs to be relatively close to the stage to see performers' facial expressions.

In orchestral use, a large area of rear wall is required for effective envelopment reflections. In addition, balcony overhangs need to be minimal and high to ensure that all seats enjoy the reverberant field.

As a result, the optimum rake required for the stalls seating needed to be as shallow as possible without compromising sightlines, while balconies above were more steeply raked (Figs 13–14).

The Arup team carried out detailed design optimisation of sightlines, followed by visualisation studies (using *Microstation* and *Rhino*) throughout the hall to give confidence that the acoustic and visual requirements were satisfied.

Changes in hall occupancy can lead to changes in reverberance due to differences in the absorption between occupied and unoccupied seats. If not carefully managed, this phenomenon can give rise to an acoustic shift between an unoccupied orchestral rehearsal and a sold-out performance. An acoustic that doesn't change between these two states gives artistes confidence that what they experience when they rehearse is what they will hear when they perform.



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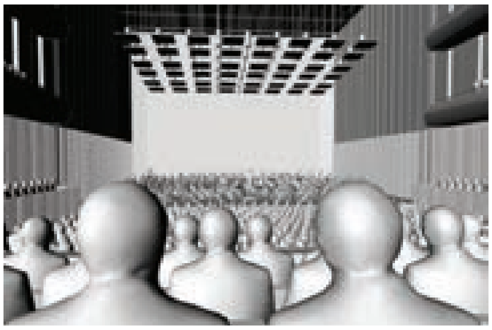

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To minimise acoustic shift, seats were specified to provide a very similar amount of absorption when occupied or unoccupied. These are tip-up seats with absorbent undersides which only see the room acoustic when they are unoccupied. Laboratory testing was done prior to installation to confirm the seating performance.

Ceiling and balcony-fronts

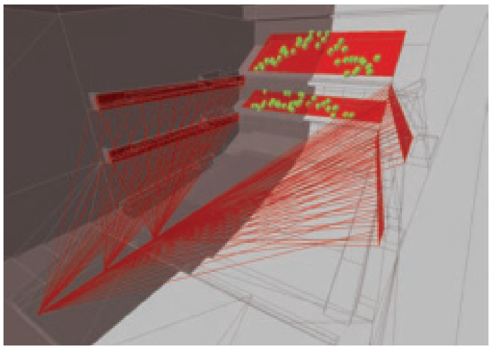
Having established the acoustic and theatrical concept for the room, various elements of detailed design were undertaken to optimise the room's performance.

Parametric genetic genome optimisation processes in *Grasshopper* and *Galapagos* were used to optimise the profiles of the ceiling and balcony-fronts to ensure even coverage of early energy to the two balcony levels. The geometric optimisation was performed using three on-stage source positions (downstage, mid-stage and upstage).

Ceiling and balcony soffit panels were designed to scatter sound from the stage in order to prevent strong specular reflections or image shifting, and to provide every seat with early reflection energy with a range of time delays and from a range of locations.

Using similar techniques, side balcony-fronts were optimised both to maximise sound reflections from stage towards the audience on the first and second rear balconies and to ensure even coverage with no 'hot spots'. The initial balcony-front design was a vertical profile, the optimisation routine changed the surface calculating the optimum warp/twist to be applied to the surface (Figs 15–17).

The optimisation performed in *Grasshopper* is based purely on ray-tracing to calculate the specular reflections of incident sound paths – but sound is not always specularly reflected. Reaction to incidence on a surface depends on a number of factors including the surface finish, geometry and panel size. So, in order to check the resultant acoustic parameters, the results from the geometric ray-tracing optimisation were also analysed with *Odeon* to take into account scattering and diffraction (Fig 18 overleaf). To achieve the precision-engineered surfaces resulting from the optimisation exercise, the ceiling and balcony-fronts were constructed from calcium sulphate panels. These were chosen both for the high density of the material and its ability to be accurately machined.



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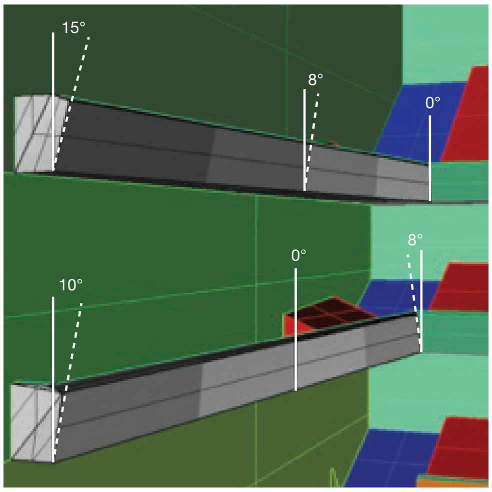

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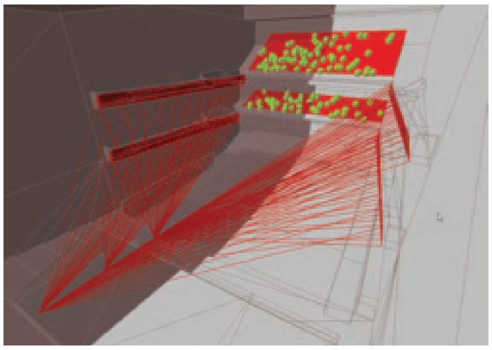

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12. Stor Sal with auditorium acoustic panels revealed.

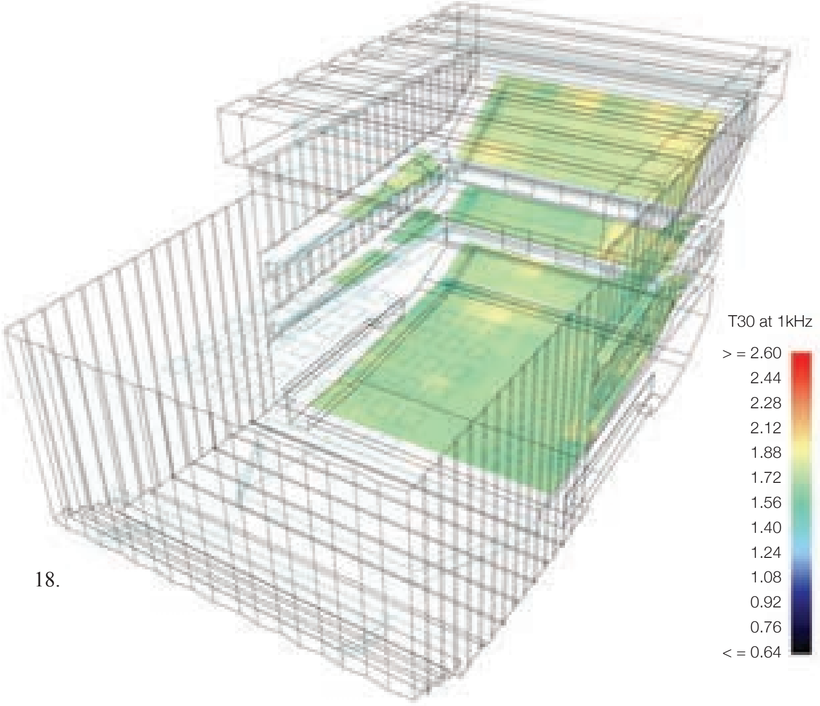
13. Sightline visualisation from the balcony.

14. Sightline visualisation from the stalls.

15. Initial balcony-front reflection coverage.

16. Optimised balcony-front warped/twisted profile.

17. Optimised balcony-front reflection coverage.



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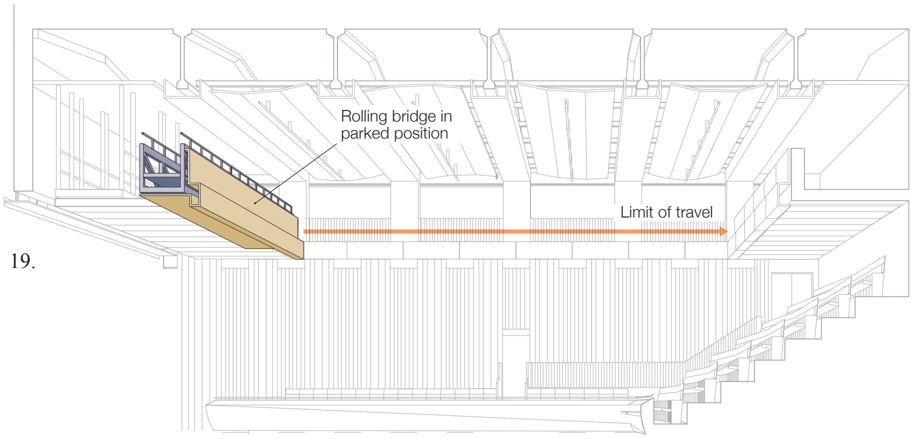

19.

18. Optimised predicted performance using *Odeon*.

19. Motorised movable lighting bridge.

20. A colourful and welcoming play area for younger visitors to the library.

Orchestral reflector array

Orchestral ensemble reflectors are essential platform elements in concert halls where the platform-to-ceiling height is significant and the orchestra is large. Once the height of the stage exceeds 12m and the width of the stage is more than about 15m, the useful reflections from the stage walls and ceiling are reduced in power, affecting the ability of players to hear themselves and other sections of the orchestra. The suspended reflector array provides those reflections, assisting the musicians with their timing, tuning and ensemble.

Ensemble reflectors also provide some high frequency early reflections to the audience, especially from the string section.

The design of the reflector array is a complex matter. Five main design criteria need to be addressed. These are:

- Number of reflector panels
- Location of reflector panels relative to the platform
- Size of each reflector panel
- Curvature of the reflector panels
- Height of the reflector array over the platform.

Two acoustic design elements are assessed. These are the 'cut-off' frequency, determined by the size of the panels and their height (the greater the cut-off frequency, the better) and the coverage of the reflected sound on the platform.

Overhead ensemble reflectors are typically suspended above the orchestra, usually at about 8m above the platform to provide a reflecting surface. In Store Sal, they are suspended through slots in the ceiling panels. The array was adjusted in collaboration with the orchestra to optimise the sound on the platform and assist in providing a beautiful string tone in the auditorium.

Auditorium walls

To assist with room acoustic control, bespoke tracked timber panels in the auditorium walls reveal semi-rigid glass wool panels behind acoustically transparent fabric. These materials are used because their full bandwidth acoustic absorption properties are more tonally effective than soft drapes or banners. Various areas of the wall panels can be exposed to suit the performance and programme type.

Lighting bridge

Staged performance work requires front-of-house lighting. Luminaires require access for rigging, focusing and maintenance but in orchestral mode traditional theatre lighting bridges at high level are acoustically undesirable because they reduce the volume, add to the absorption in the space and block useful reflections from the ceiling. They obscure optimised ceiling finishes, also, and can detract from the architectural concept.

To resolve this conundrum, Arup developed an innovative motorised moving bridge, similar to an industrial gantry crane. This spanning access walkway is designed to roll from front to back of auditorium to enable rigging and focussing of lights hung on the fixed overhead bars, access to strong points in the ceiling and provide lighting positions for theatre use (Fig 19).

The bridge is accessed by technical staff via a number of safety interlocked gates, spaced out along the galleries high above both sides of the auditorium. The bridge is finished with architectural panelling on the audience side and disappears when 'parked' above the proscenium for orchestral concerts, leaving the ceiling completely unimpeded.

Side-wall, proscenium and ceiling panels
Tracking side-wall panels (14m high) move from their parked position to one side of the stage and complete the side-wall enclosure to the orchestral platform. These are sufficiently massive, stiff and diffusing to provide adequate ensemble reflections to the performers and are shaped to project sound into the auditorium. To make the system simple to use and avoid the need for motorisation (thus reducing maintenance and complexity) they are hung from low friction steel wheels and may be hand-rolled (by one person) into their parking position.

The proscenium is formed by large vertical and horizontally hinged panels. The proscenium header hinges upwards into a horizontal position covering the front part of the flytower. The side panels (10m high) hinge through 90° forming the front part of the orchestra enclosure when stored.

Three more ceiling panels are used to visually and acoustically close off the flytower: two rotate and are stored vertically in the flytower, while the upstage panel is hinged so that it hangs down against the back wall.

The back wall itself is timber clad to match the side walls and ceiling panels, and is the only fixed element on the platform. Although unintended during design, this surface has also proved very effective for projection of scenic video during concerts despite its uneven, oak veneered finish.

Conclusion
Arup's unique multidisciplinary skills alongside DRDH's excellent design vision and careful site supervision added up to an effective partnership which delivered a flexible, elegant, efficient building – a good example of Ove Arup's vision of total architecture in action

Rory Olcayto, writing in the January 2015 edition of The Architects' Journal delivered an emotional verdict:

"Strange as it may sound, Stormen's off-white concrete walls and columns, its room-like staircases and lofty reading rooms, its cosy bars and basement clubs, and its regal theatre-cum-concert hall, all painstakingly-calibrated, all exquisitely constructed, exude a kind of intelligence. Poetry is useful here, so let's reach: like Byron's high mountains; Stormen is a feeling. And that feeling is Bodø itself. Stormen is the feeling of a town."

20.

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(1) OLCAYTO, R. (2015) Building study: Stormen Concert Hall and Library, Bodø, Norway. *Architects Journal*.

Authors
James Beer is a Consultant with the Acoustics and Venues team in the Winchester office. He was responsible for the project managing the venue technical systems during construction and was involved in the design of the sound and communications systems.

Matt Atwood is a Senior Consultant in the Venues team in the Winchester office.

William Algaard is an Associate Director in the London office. He led the structural and building services concept design.

George Ellerington is an Associate in the Winchester office. He was responsible for the concept and detailed design of the Store Sal shell system and for technical planning of the performance spaces.

Ian Knowles is a Director of the Acoustics and Venues team in London. He led the multi-disciplinary design of the project from competition to completion.

Project credits
Client: *Bodø Kommune* Architect: *DRDH Architects, London* Acoustics, Venues, SMEP Engineer, Fire Consultant (review) – *Arup: William Algaard, James Beer, Craig Bowden, Richard Bunn, David Connery, Ned Crowe, Luca Dellatorre, Ed Elbourne, George Ellerington, Philip Hives, Ray Houghton, Matthew King, Ian Knowles, Ian Pegrum, Anna Piasecka, David Ripley, Luke Robertson, Alessio Rocco, Stephen Secules, Alex Wardle, Sam Wise* Project Management: *Ramboll Norge, Trondheim* Structural Engineer (Detailed design and construction): *Norconsult AS, Bodø* Services Engineer (Detailed design and construction): *Norconsult AS, Bodø* Acoustic Consultant (Local collaborator): *Brekke Strand, Oslo* Façade Engineer: *Ramboll Façades Ltd, London* Fire Consultant: *Norconsult AS, Bodø* Lighting Consultant: *Norconsult AS, Oslo*

Image credits
1–4, 12, 20 DRDH Architects / David Grandorge; 5, 9 Nigel Whale; 6 Arup / George Ellerington, 10–18 Arup; 7, 8, 19 DRDH Architects

1.

Singapore Sports Hub

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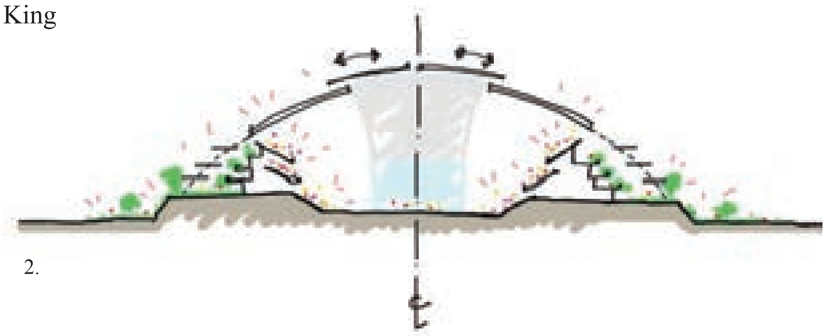

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1. Singapore Sports Hub,
opening night, June 2014.

2. Stadium design conceptual sketch.

Introduction

Singapore celebrated the opening of Asia's first integrated sports, leisure, entertainment and lifestyle destination – the Singapore Sports Hub – in June 2014. Located on a 35 hectare waterfront site, within easy reach of the city centre and international airport, the Sports Hub is key to the Government of Singapore's urban development plan and central to its 2020 vision for a sustainable, healthy and expanding population.

The design of the precinct capitalises on its location. It is well connected and inclusive thanks to easy accessibility from the Mass Rapid Transit network, adjacent expressways, local pedestrian networks and the island-wide park connector system to surrounding residential areas.

At the heart of the Sports Hub lies the new National Stadium conceived as a unifying protective canopy that connects all parts of the Sports Hub master plan. The dome to the stadium has a span of more than 310m, making it the largest free-spanning dome structure in the world – an awe inspiring event space. Air-cooled, and designed with a movable roof and retractable seating for a wide range of sport and leisure events, it is a state-of-the-art stadium.

This article focuses on how the architecture and engineering for the National Stadium was defined. It provides an overview of the inputs that shaped the design of the wider precinct – from the original masterplan design to specialist engineering concepts developed for integrated energy infrastructure, environmental and microclimate design, acoustics, fire engineering, pedestrian modelling, blast resilience, sports and feature lighting design.

The background
In 2001, the Singapore Government published a paper recommending redevelopment of the existing National Stadium at Kallang Bay into a multi-use sports hub. A feasibility study was commissioned to look into the type and size of facilities to build, taking into consideration local community requirements and the potential for international events.

A commercial model was developed to ensure all facilities would be fully utilised; a public-private partnership (PPP) was established to take responsibility for event planning in addition to building, operating and maintaining the Sports Hub for its first 25 years; and a design competition was organised.

Dragages Singapore Pte Ltd, part of the French company, Bouygues Construction, formed a team with Arup and DP Architects. The team offered the mix of local knowledge and international experience needed to meet the complex requirements of the brief and the consortium was successful, being selected as winner of the competition, from a shortlist of three, in January 2008.

Following further changes to the brief, AECOM joined the team as the project went into detailed design phase.

Arup's role
During the competition phase, Arup's sport and urban design teams in London, led by Glen Plumbridge and Malcolm Smith, integrated work from offices in Manchester, Singapore, Sydney and Melbourne with input from specialist designers in London, America and Australasia.

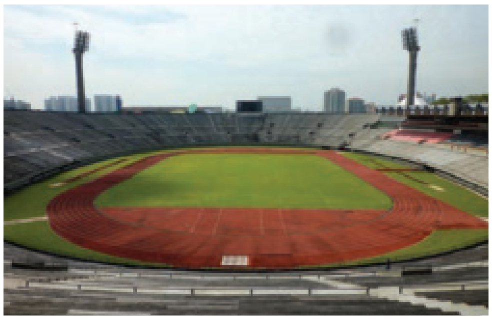
At detailed design stage, 70 architects and engineers were working on the project. By project-end more than 600 Arup employees had been involved, with approximately 80 relocating to Singapore to assist in the delivery effort.

The post-competition and delivery phases were led by Andrew Henry (Project Manager), Mike King (Structures Lead) and Clive Lewis (Architecture Lead).

3. The former Kallang National Stadium.

4. Designed to orientate towards the CBD, the National Stadium is in constant dialogue with the city.

5. The waterfront, tree canopy and shaded walkways are key elements of the scheme.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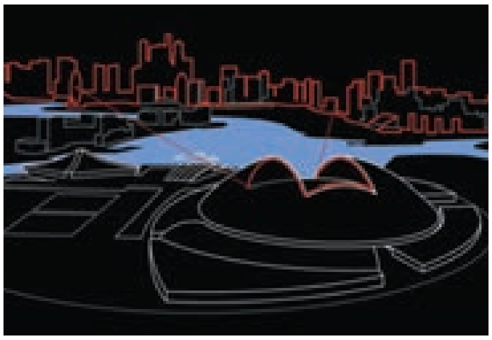
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Success in delivering the project was truly the result of global collaboration with Dragages, Arup, DP Architects and AECOM working together as a team. Expertise in sports design, architecture, masterplanning, structural and environmental design enabled the team to put forward place-sensitive and often ground-breaking ideas.

The site
Arup's urban design team recognised the potential of the old Kallang sports stadium, on its prime waterside site, to make the Sports Hub a feature of Singapore's famous skyline.

The silhouette of the city, and the connection between stadium and city, were essential keys to the form and layout of the masterplan.

Local stories which influenced the team included that of the Kallang Roar: the sound of the 50,000 strong crowd in the old stadium that could be heard across Kallang Basin, in the city itself.

These considerations all contributed to shaping both the masterplan and the form and orientation of the stadium which is a horseshoe-shaped bowl, within an open-ended roof form, rotated to focus on the heart of the city.

6.

The masterplan

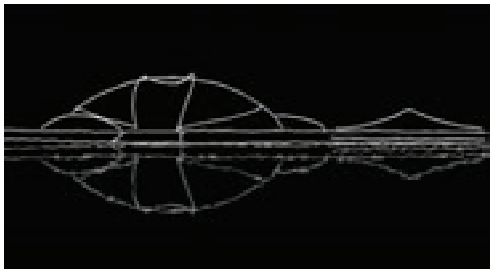
In addition to urban design work, the team had to develop solutions to deal with poor ground conditions. The site comprised reclaimed land (it was originally developed as Singapore's aerodrome in 1935) which meant an elevated stadium concourse was required to avoid building large areas of basement.

This requirement led to a breakthrough in the masterplan: an elevated stadium created a natural two-storey plinth into which all other facilities could be integrated. The result enabled efficiency in site planning that allowed for large plaza areas, waterfront promenades and landscaping around the precinct.

To organise the core elements in the brief – the new stadium, the existing Singapore Indoor Stadium, the new aquatic centre, two multi-purpose indoor arenas, retail and office space – the team defined an architectural hierarchy comprising three typologies:

1. Primary iconic structures – the National Stadium and the existing Singapore Indoor Stadium building
2. Secondary structures – the aquatic centre and the multi-purpose indoor arenas with their characteristic roof forms which abut the stadium's unifying plinth level
3. Plinth – comprises a circle of two-storey buildings around the stadium perimeter. The roof-level of the buildings aligns with the Sports Promenade.

The architectural team was passionate about how the stadium related to its surroundings, the intention being to attract public interest and drive participation in the wide range of sports facilities on offer. In order to achieve this, they introduced pedestrian routes across the site to connect key elements, such as the metro and the waterfront, via a mixture of tree canopy and shaded walkways. Routes around the perimeter of the stadium itself were developed into what is now the 100Plus Sports Promenade.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6. Overview of key facilities within the Sports Hub.

7. Early sketches determining the distinct silhouette of the Sports Hub – the dome structure of the National Stadium complementing the inverted peaked roof of the Singapore Indoor Stadium.

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National Stadium architectural design
The decision to develop the iconic dome envelope to the stadium was driven by the local climate, the site location and the proposed event programme.

The tropical climate required a unique architectural response because visitors needed protection from sun and rain, both inside and outside the stadium. A dome was structurally the most efficient form to achieve the extended spans required to cover this area. The brief asked for a retractable roof to shade spectators during events, and early calculations indicated that less steel would be required to support the moving roof using a dome rather than a cantilever roof structure.

In terms of location, the dome structure complemented the existing Kenzo Tange's Singapore Indoor Stadium (SIS).

Renders of the two buildings silhouetted above the water line convinced the team they had generated one of Singapore's most impressive skylines – the simple dome form of the new National Stadium juxtaposed against the inverted curve 'peaked' roof of the SIS building.

The architecture was designed to complement the SIS building – the silver reflective metal roof and steel exoskeleton, the neutral tones of the concrete base, and the lush green plinth, with facilities such as restaurants integrated, were all key elements.

The event programme was also an important consideration. The dome form would reinforce the acoustic energy of the crowd for sports events and create a dramatic setting for concerts, providing a vast projection surface for interactive sound and light displays. The open-ended design would provide breathtaking views out across the city and provide all types of events with the skyline of Singapore as their backdrop.

8. The stadium roof opened to the sky.

9. The stadium roof in its closed position.

10. The impressive city skyline visible from the open end of the stadium.

10.

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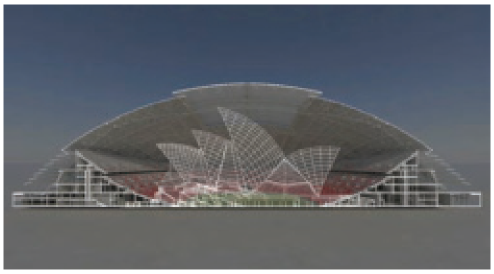

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Integrating the bowl and roof
The new stadium is the only one in the world custom-designed to host football, rugby, cricket and athletics. Arup's challenge was to design a 55,000-seat stadium bowl for optimised viewing of these sports while minimising the footprint of the roof dome.

The brief required the lower-tier bowl to be retractable and for spectators in all tiers to benefit from an energy-efficient cooling system. The development of the cross section to the seating bowl was critical to maximise the benefit of introducing a moving tier system.

In 2006/7 there were only two stadia in the world with retractable seating and a permanent athletics track – Stade de France in Paris and Oita Stadium in Japan – and both of these stadium were biased to either football or athletics viewing. In Singapore, however, the seating bowl needed to achieve the best balance for both athletics and football viewing.

To achieve this, the Arup sports venue design team developed a section profile which located close to 30,000 seats within the retractable lower tier bowl, with sightlines developed to allow these seats to move 12.7m closer to the football pitch.

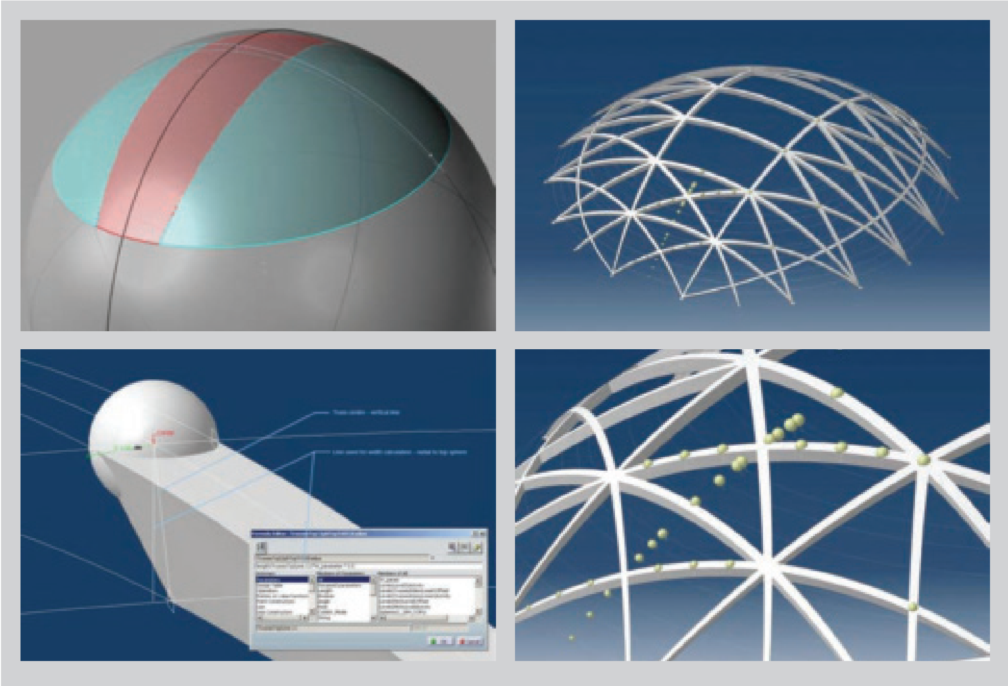
Using parametric bowl generation software to complete optimisation studies, the team arrived at a 3D form for the bowl and simultaneously studied the impact of reducing the geometry to the stadium roof. The final design for the bowl enabled the long span at the dome to be reduced to 310m. However, at this diameter, it was still the largest free-spanning dome structure in the world.

11. Roof structure as an integral part of the stadium's architecture.

12. Sydney Opera House would sit comfortably inside the stadium.

13. Digital Projects – 3D model for architecture development of the roof.

14. Architectural visualisation of the roof structure.



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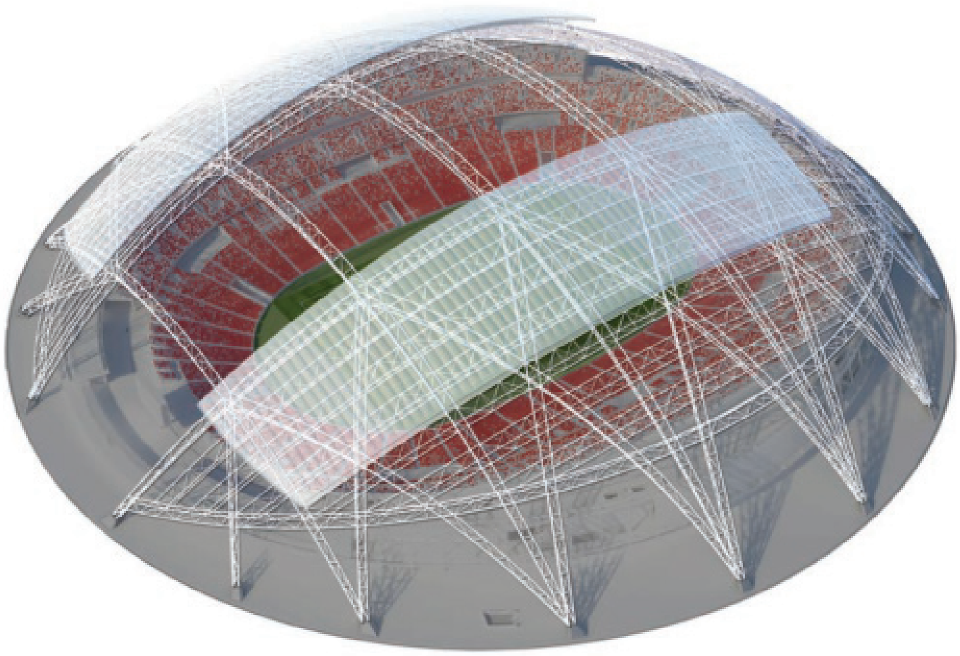

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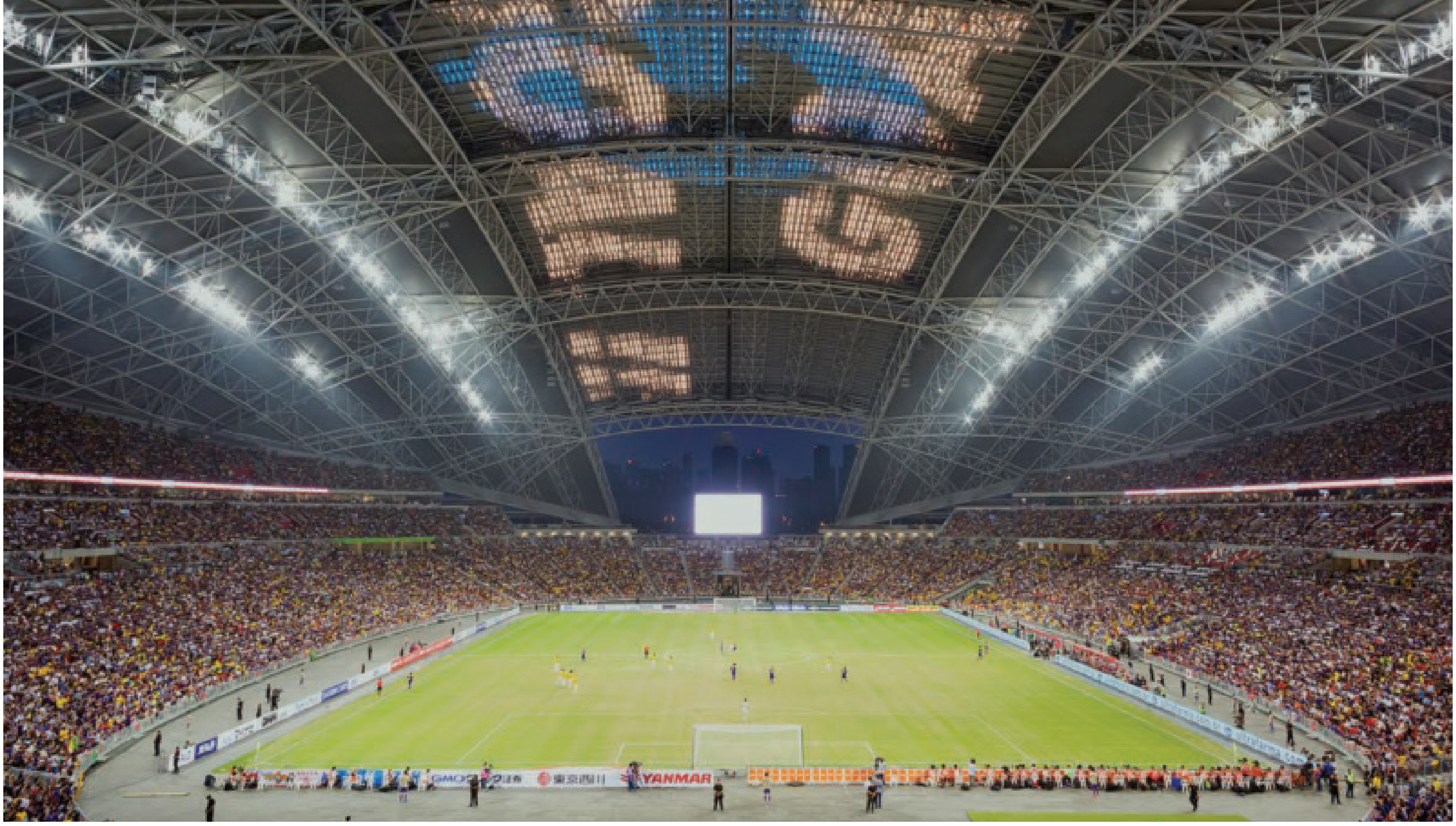
Roof architecture and structure

The dome roof form was chosen as it is inherently a highly structurally efficient geometry for a roof structure of this scale, especially one that integrates a retractable roof. Singapore is a unique location – no significant seismic activity, low wind and, of course, no snow load – so it presented the Arup team with a unique architectural and structural opportunity.

The initial target was to reduce steel weight by leveraging the inherent efficiencies of the shell roof form. One outcome of this was reduction in the depth of the primary structure as it came to ground. Two control surfaces were established to define this – a sphere to the top and a torus to the bottom surface – with the roof structure reducing from a maximum depth of 5m to the centre of the dome to 2.5m at the base. This optimised structural solution provided an architectural benefit at ground level by reducing the proportions of the structure to something more in keeping with the human scale.

Reducing dead load wherever possible was a key goal and the team estimated that for every 10kg of weight added to any part of the shell structure, a further 4kg would need to be added to hold it up. This was a strong influence in the design of the moving roof structure, as well as the moving / fixed roof cladding design. The result is a dome which uses one third of the steel weight per square metre compared to other large-span structures of this scale.

The team wanted to simplify the detailing of all complex node intersections across the entire roof and develop a standardised family of node details that could be replicated wherever possible. This required an update to the geometry of the roof to achieve a more symmetrical design than the competition-winning roof geometry. An additional parallel truss was added, the main gutter trusses were realigned, the geometry of the roof opening was adjusted and the diagonal trusses simplified.



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16.

17.

15. The moving roof, constructed from translucent multi-layered ETFE pillows, can be illuminated at night.

16. Mock-up of the movable roof.

17. The roof is made of multi-layer ETFE pillows and embedded with LEDs, turning it into a large digital screen.

Moving roof cladding
A lightweight cladding system was required for the moving roof to provide shade to the seating bowl and reduced solar heat gainwhile at the same time offering translucency so that the event space could be naturally lit during the day.

A multi-layer ETFE pillow was chosen to meet these design requirements and at the same time provide the opportunity to illuminate the moving roof at night. Sized at 20,000m^2 the moving roof is one of the largest addressable LED screens in the world and an unmistakable feature on Singapore's skyline.

The team worked closely with the appointed subcontractor (Vector Foiltec) to achieve the best visual arrangement of pillows. The original intent was for the patterning of the fixed roof to be reflected in the moving roof geometry. However issues related to structural movement and water ponding soon dictated a different design solution.

The flexibility of the moving roof structure required a design with sliding bearings so it became important to avoid small pillow modules because intersections between extrusions would need to be a fixed joint (something that would not work structurally). Also, as an actively inflated roofing system, it carried the risk of pillows deflating (either through puncturing or pump failure) so water ponding was a serious design concern. The decision was taken to change the pillow format to long extruded pillows that ran parallel to the short edge of the moving roof. In this way, water would not be retained to the moving roof area, and junctions between extrusions could be minimised.

Fixed roof cladding

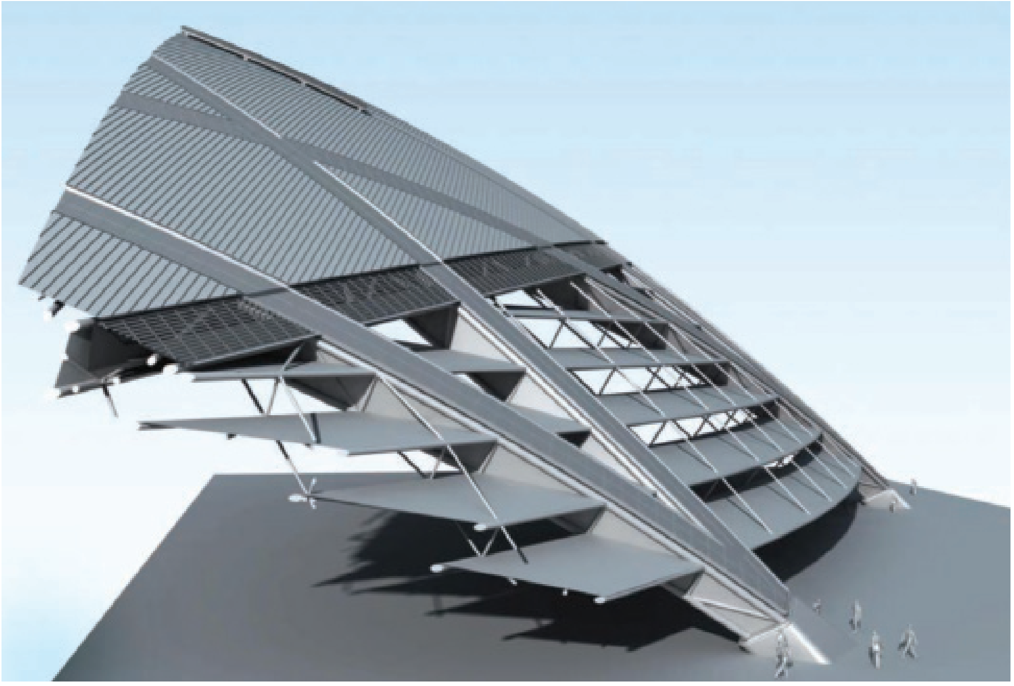
The architectural treatment of the fixed roof cladding expresses the design and geometry of the structure, while meeting environmental performance requirements to ensure spectator comfort within the stadium.

The main areas of the roof dome are clad in a profiled aluminium rain screen cladding system, while the structure is expressed using a recessed smooth panelised cladding system. The team worked with the appointed subcontractor (Craft) to develop an integrated cladding solution that met the design intent architecturally, achieved the weight constraints structurally, met technical requirements related to acoustics, provided thermal insulation and enabled access for maintenance.

The result was a 'super lightweight' cladding construction that weighed less than 30kg/m^2 (a significant reduction when compared to a standard standing-seam construction that would typically weigh 60kg/m^2 or more for the same technical performance). This was achieved through the design of a 'unitised' cladding system that had a number of significant advantages for the roof envelope:

- The soffit lining could be adapted to be either perforated or solid to achieve the acoustic requirements for the stadium (achieving the same performance with a trapezoidal deck would have been a major challenge)
- The cladding system could be built on the ground, to improve accuracy and tolerances, and lifted into position using the same cranes that constructed the roof steelwork
- The number of construction workers required on the roof at any one time was reduced – a health and safety benefit, as well as a reduction in construction programme time and cost.

A unique part of the architecture of the NST dome is the visible expression of the structural geometry within the roof cladding. Recessed scupper areas were aligned to the primary structure, with the cladding to these zones continuing through the Sports Promenade to complete the visual expression of the roof structure to the support location at ring beam level. The diagonal 'scupper' zones are integrated into the night time illumination of the roof with LED node lighting.



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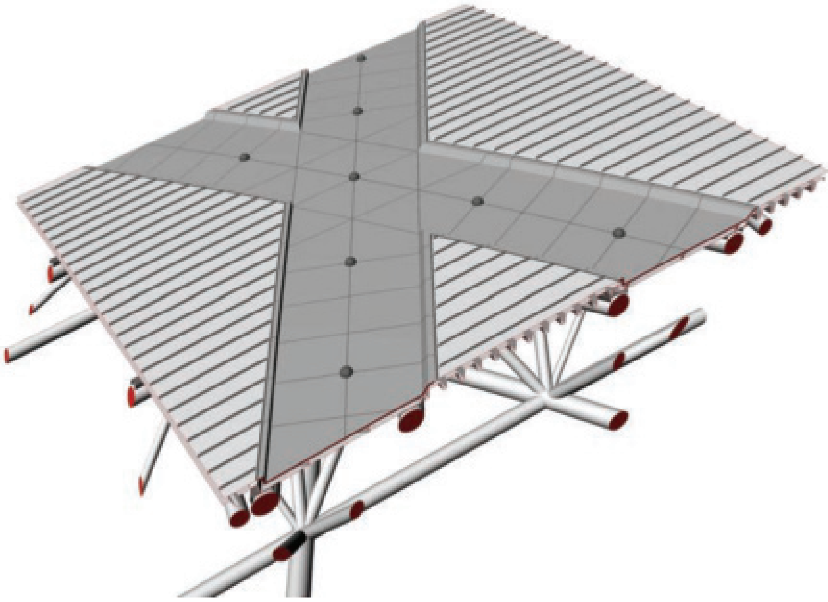

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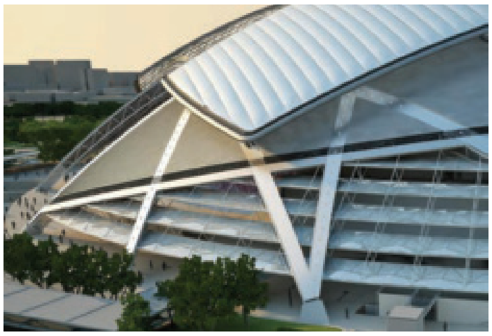


20.

18. Detail of cladding systems – between fixed roof and giant louvres over the Sports Promenade.

19. Detail of fixed roof cladding system.

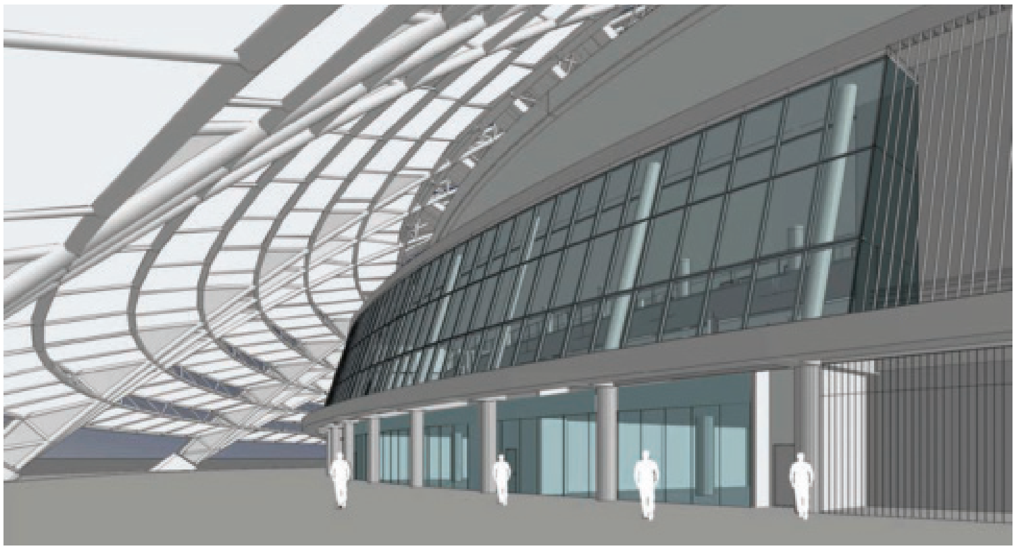
20. Architectural rendering showing movable roof and ETFE pillows, fixed roof aluminum standing seam cladding and giant louvres PTFE fabric cladding.

21.

21. Giant louvres providing shade and shelter to the Sports Promenade.

22. Rendering of Sports Promenade looking towards the hospitality space.

23. Early rendering of Sports Promenade with greenery integrated.



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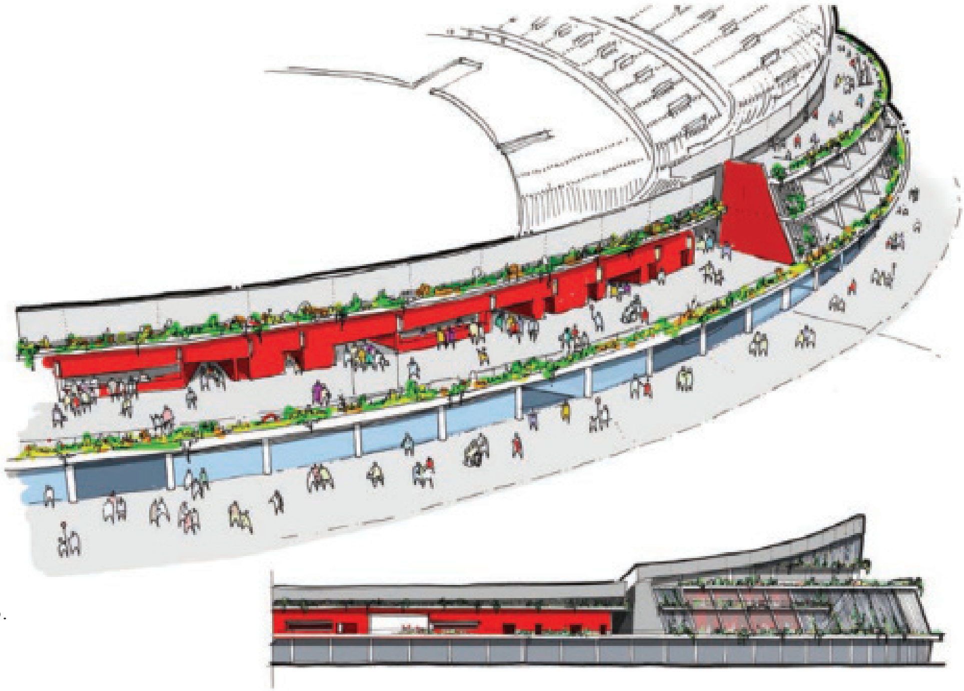


23.

Sports Promenade

The giant louvres provide natural ventilation and protection from sun and rain for the Sports Promenade. Clad in PTFE fabric, the louvres align to floor levels within the stadium enabling views to the outside.

For rain protection, the design needed a 30 degree overlap between each louvre. Arup used optimisation software to achieve the best fit within these constraints while minimising the physical area of louvre fabric. The giant louvres are an integral part of the building physics design as they shade internal glazed façades and allow natural ventilation into the stadium bowl – a key part of the low-energy bowl cooling strategy.

Internal façades

The internal façades and slab edges are the visible external face of the stadium within the Sports Promenade, so they are important in the architectural language of the building.

The internal façades organise entry locations at Level 3 of the stadium, provide break-out zones and viewing decks to the premium concourses at Levels 4 and 5, provide open-sided concourse areas for general spectators at Levels 4 and 6 and provide two large glazed restaurants to the centre of the north and south façades.

This space defines the 'tropical stadium' concept, introducing lush green landscape through the design of sky terraces and planters to slab edges. A continuous planter runs to the edge of the Level 4 slab and connects with a vertical planter screen.

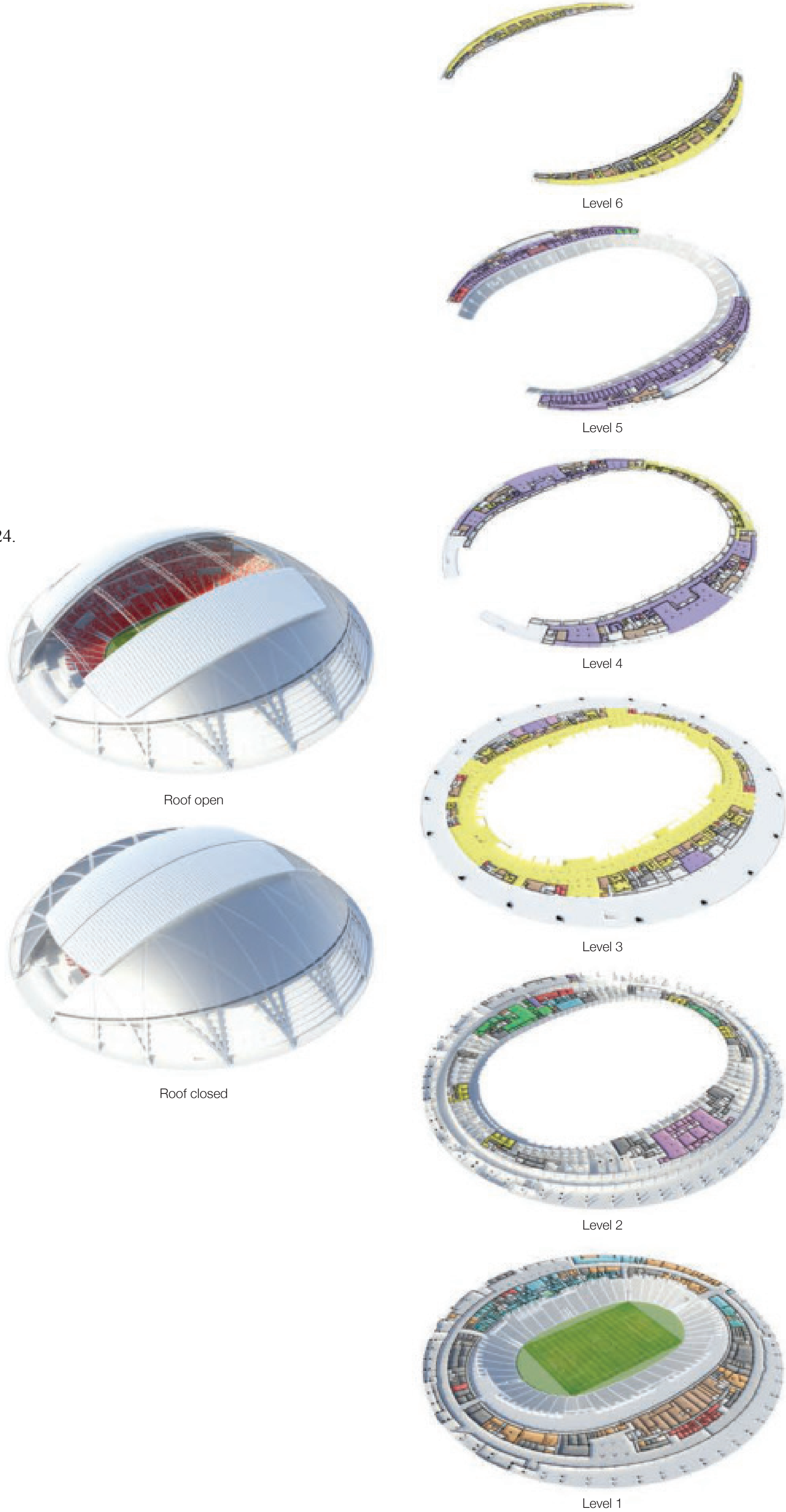
The internal façade is defined by three-arc geometry that simplifies the elliptical form of the façade in plan. As the façade is inclined, this was an important design decision because it allowed all façade elements to be defined as part of the surface of a cone rather than a more complex two-way curved geometry.

With this simplified geometry set up, the internal façades were developed to conform to a set of glazing, balustrading and planters typologies which could be repeated around the 800m façade to the stadium.

These were organised into five main façade zones – premium entrance plus glazed restaurant, upper tier escalator access, lower tier access plus break out balconies, open-sided concourse plus sky terrace and solid core zones.

This created a legible façade specifically designed to assist with wayfinding and orientation for spectators arriving at the stadium within the Sports Promenade.

24.



24. This drawing of the stadium shows how the facilities on each level stack up, coming together to form a coherent whole.

Internal layouts

Level 1 – players village; venue operations; plant
This is the main 'back of house' zone within the building, with the players' village to the north, venue operations and storage facilities, catering facilities, refuse areas, and plant all accessed from a wide service access road. At level 1, adjacent buildings occupy the zone within the ring beam and outside the service access road, with the indoor arena, office, retail and aquatic centre integrated into the footprint of the dome.

Level 2 – VIP entry; media; offices; plant
This level provides additional plant space, offices for the consortium management team, work areas for media, a secure VIP entry to the north of the stadium, parking for 50 cars and access to a dedicated lift to the VIP suite at level 5.

Level 3 – main entrance level
Level 3 is the entry level for all ticket holders. Access to entry locations is via the Sports Promenade which provides a covered pedestrian route to all facilities within the precinct. Level 3 is also the lower tier concourse level.

Level 4 – premium concourse
Provides up to 3,000 premium ticket holders with access to two main restaurants, four extended concourse zones, break-out balcony areas and landscaped roof terraces to the open end of the stadium.

Level 5 – premium suites
With 62 suites ranging in capacity from 10 – 30 persons, and a VIP suite for 60, this level is served from a central elevator access with balcony views over double-height restaurants to the north and south stands, and breakout balconies with views into the Sports Promenade.

Level 6 – upper tier concourse
Catering for 12,000 general spectators, the upper tier concourse is designed as an open-sided floor plate, with panoramic views through the louvres to the precinct around the stadium and the city beyond.

25.

Structural design

A specialist team within Arup was tasked with developing bespoke software to manage inputs from the various design software used in the design process (the latest BIM modelling software was essential to the integrated architectural design and engineering of the Sports Hub, particularly the stadium roof).

The design team wanted a feedback loop so that one software could inform another of defined positions, co-ordinates and dimensions for the roof elements.
A parametric model was built in *Digital Projects* (*DP*) allowing the roof structure to be quickly assessed structurally and redefined as the design developed.

The parametric *DP* model was linked to Arup's structural analysis software *General Structural Analysis* (*GSA*) via bespoke in-house software allowing optimisation of the roof's form via varying truss depths, layout, arch rise and other parameters that define its geometry. The efficiency of this process was key to be able to iterate through numerous design solutions during design development.

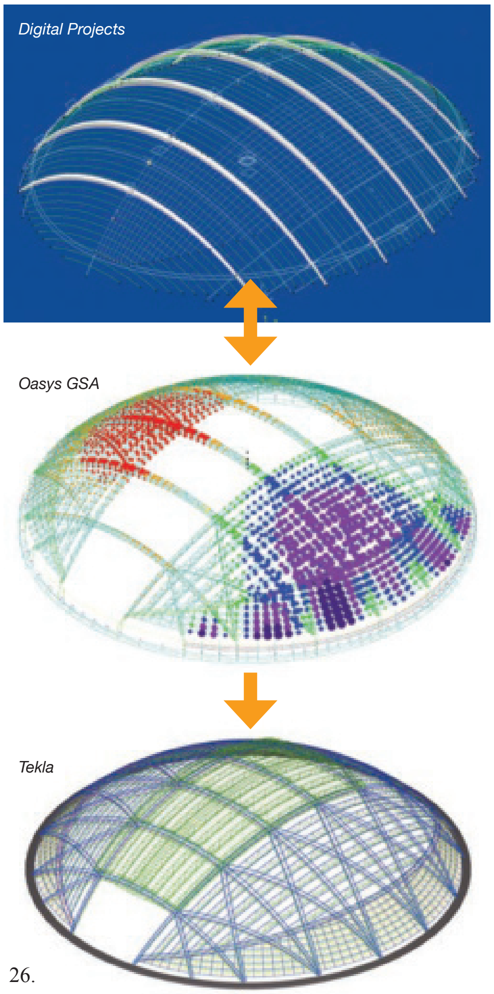
Once imported into *GSA*, the structure was optimised using in-house software, developed specifically for the project, that employed an interactive approach based on 'fully stressed design'. Then, with the structural sizing optimisation complete, the structural analysis model was converted into a Tekla Structures BIM model from which all the construction drawings were produced.

Additional software was written to extract further design information from the analysis model (such as connection design forces and fatigue stress concentration factors) and embed them within the Tekla model. This process allowed the BIM model to be issued to the steel contractor containing all the information necessary to deliver the roof's complex structure.

The parametric model was used to control a multitude of other relationships between elements which it would have been impossible to achieve using conventional software. Each parameter was treated in the same way – structural and architectural requirements were considered, an optimised parameter agreed and inserted into the geometric control model for the roof.
In time, a fully editable 3D model of the stadium roof was completed which defined every constraint imposed on the roof and could be used independently by every member of the team.

Stadium roof structure

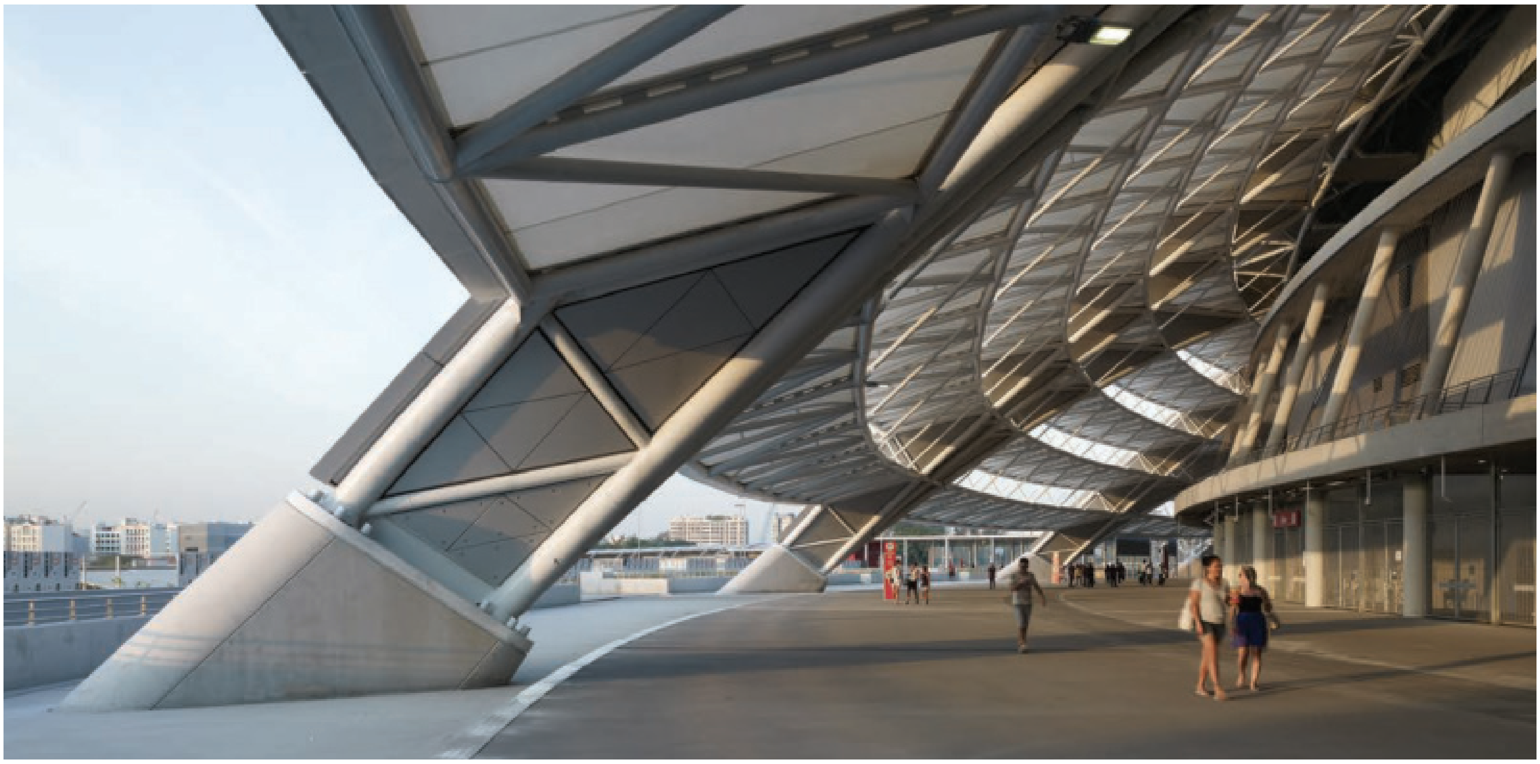
The 310m-span roof rises to a height of approximately 85m from pitch level (76m from the elevated post-tensioned concrete ring beam). Comprising a fixed roof and two movable roof components, the structure totals approximately 7,400 tonnes of structural steel plus connections.



26.

25. National Stadium under construction in December 2013.

26. Feedback loop established for information transfer between architecture, engineering and construction models.



27.

The fixed roof spans clear across the stadium with no support taken from the stadium seating 'bowl' concrete superstructure. The fixed roof also directly supports the movable roof via a series of 'bogies' running on the parallel 'runway trusses' that span perpendicular to the pitch axis. The structural dome form of the roof imparts large tensile forces into a post-tensioned concrete ring beam, built approximately 9m from ground level, which acts to restrain the roof from spreading.

A fundamental principle in the design of the fixed and movable roofs has been to create a very stiff fixed roof and a flexible movable roof structure to minimise the tendency of the movable roof to rack or skew and jam during operation.

Fixed roof structure

All loads on the roof structure are transmitted to the concrete ring beam by a network of triangular-formed primary trusses creating a very stiff 3D shell or dome structure.

These primary trusses comprise:

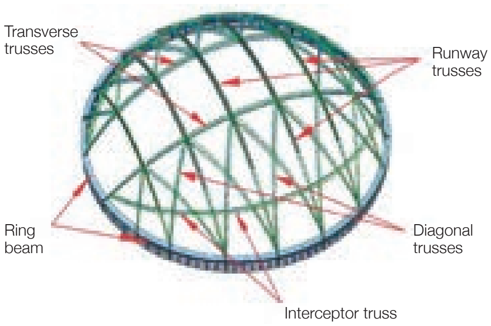
- Six parallel runway trusses spanning across the stadium, perpendicular to the pitch axis
- Two transverse trusses that are parallel to the pitch and form the long edges of the roof opening
- Diagonal trusses linking corners of the rectangular forms described by the transverse and runway trusses
- Interceptor trusses which define the junction between the fixed roof cladding, supported on the secondary trusses above; and the giant louvres, clad in PTFE fabric, below.

The primary trusses form the principal steel load carrying members in the roof. They vary in both depth and width with a minimum depth of approximately 2.5m at the base nodes and a maximum depth of approximately 5m at the centre of the dome. All trusses are 3D triangular trusses fabricated from circular hollow sections (CHS) with chords sizes of 457mm diameter and 508mm diameter.

There is an opening in the roof, approximately 220m long and 82m wide, over the football pitch. The shell action of the fixed roof is affected by the opening in the roof, where point loads from the bogies on the runway trusses result in additional bending in those trusses. Across the opening, the primary trusses act in bending and compression to support the movable roof as the roof closes. The ring beam and ring beam support column pairs restrain the thrust forces generated as the steel roof tries to spread, and transfer vertical forces at each of the roof nodes to the columns below. Vertical forces are then carried by the columns into the bored pile foundations.

The secondary trusses are 3D triangular trusses but span in one direction only and match the depth of the primary trusses at each location where they meet. The trusses are formed using CHS of maximum chord size 356mm diameter and are faceted at all truss node points to match the spherical geometry of the roof. Both top and bottom chords of the secondary trusses connect into the primary trusses.

The giant louvres that enclose the Sports Promenade are made up of trusses in horizontal planes spanning between the diagonal and parallel runway trusses as well as trusses in vertical planes suspended from the interceptor trusses. All trusses are formed from CHS sections. The connections between the louvre framing and primary trusses are detailed to ensure that the louvres do not form part of the global roof framing system and only exert load on it, rather than attract load from it.



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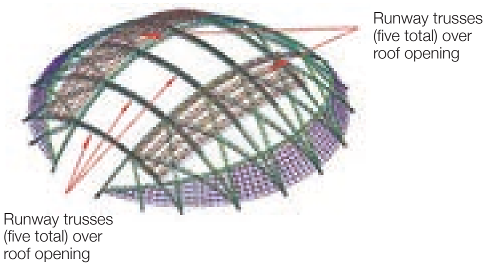

29.

27. Sports Promenade – public access area around the stadium.

28. Fixed roof primary trusses and ring beam.

29. Fixed roof secondary trusses

30. There is an opening in the roof, approximately 220m long and 82m wide.

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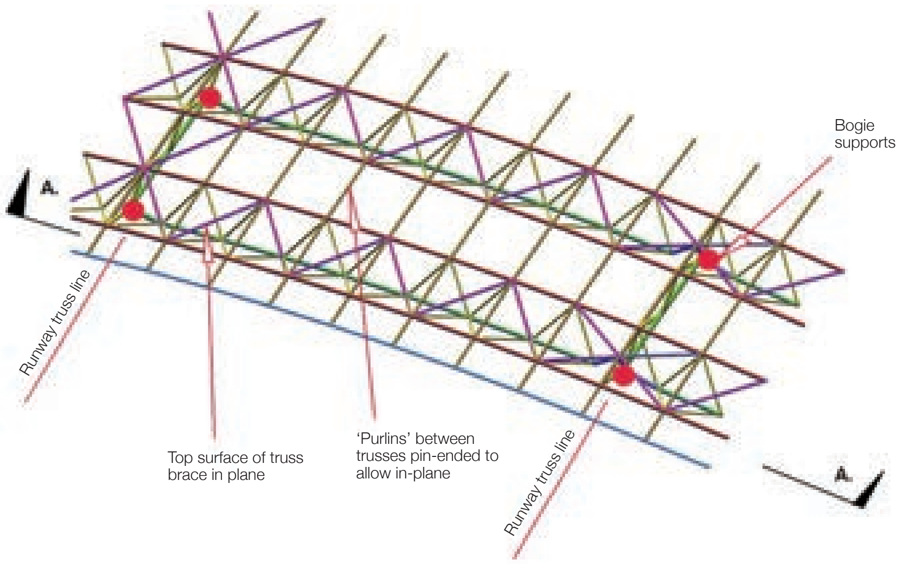

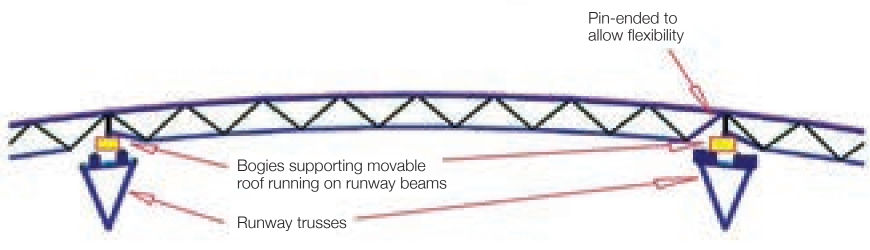

31. The movable roof lighting forms the largest addressable LED screen in the world.

32. Movable roof truss detail.

Movable roof structure

Similar to the fixed roof, the movable roof is made up of 3D triangular trusses which span approximately 48m between the runway trusses.

There are four spans of movable roof trusses between the five supporting runway trusses.

The movable roof framing has been developed to minimise interaction between the movable and fixed roof structures. This is achieved by introducing physical pin connections at the purlin or link members between the parallel trusses forming the movable roof as well as lateral sliding bearings between the movable roof and its supporting bogies. The end detail where the trusses are supported on the bogies is also pinned at one end to avoid continuity of the trusses over these runway truss supports.

The articulation of connections, as well as the use of bearings, is intended to allow the movable roof, to follow the fixed roof displacements without introducing large stresses in the structure or significant horizontal loading at the support points.

The cladding of the movable roof is a lightweight ETFE inflated pillow system, with the pillows supported on 'T' brackets welded directly to the top CHS of the moving roof structure. The ETFE system has been designed to allow for a considerable amount of movement with PTFE sliding bearing integrated into the design.

Moving roof

Main features	Operates whilst the stadium is in use Operates in moderate rain
Closing time	20 minutes
Bogies	20 bogies per panel, five braked (one per arched truss)
Mechanisation details	16 winches (8 per panel, located in clusters of four on two arched trusses) Power and control signal transfer via energy 'drag link' chain
Movement monitoring	Control system is operated from main control room using purpose-written software. Roof position tracking and synchronisation is achieved by an encoded rail track monitoring bogie positions. Absolute linear encoders mounted on bogies allow the roof movement to be controlled to within millimetres. For redundancy and safety, a secondary encoded head is mounted side by side to the primary position and counter checking position. This 'anti-skewing' system ensured at any time a maximum skewing position difference of 35mm between any of the 5 trusses.

Movable roof systems

During the competition phase of the project, Arup developed designs for the moving roof mechanism based on a range of drive options. The geometry of the dome roof and the desire to reduce steel weight led to selection of a cable drive mechanism, a significant benefit being that it allowed for less stringent control on the deflection criteria between the fixed and moving roofs. This in turn allowed for efficiencies in roof steel weight.

The moving roof is unique in that it is asymmetric in plan and maintains an open end. To minimise structural depth and weight, cross pitch runway trusses supporting the moving roof tracks were inserted. The preliminary design was completed with a movable roof comprising a 3m structural depth and a cable driven system that linked to winches located inside the stadium. This solution minimised the amount of equipment required on the roof and followed similar proven schemes such the one at the Oita Stadium, Japan.

Further refinement, later in the design process, included relocating the winches onto the moving roof structure itself. This removed the need for cables to return into the lower levels of the stadium, simplifying the internal planning of stadium and avoiding the need to protect spectators from the possibility of cable failure. It also prevented large forces being imposed on the fixed roof at each cable drop location reducing steel weights to the long span structure to the fixed roof.

Roof position tracking and synchronisation is achieved by an encoded rail track monitoring bogie positions. Absolute linear encoders mounted on bogies allow the roof movement to be controlled to within millimetres. For redundancy and safety, a secondary encoded head is mounted side by side to the primary position and counter checking position.

This ‘anti-skewing’ system ensured at any time a maximum skewing position difference of 35mm between any of the 5 trusses.

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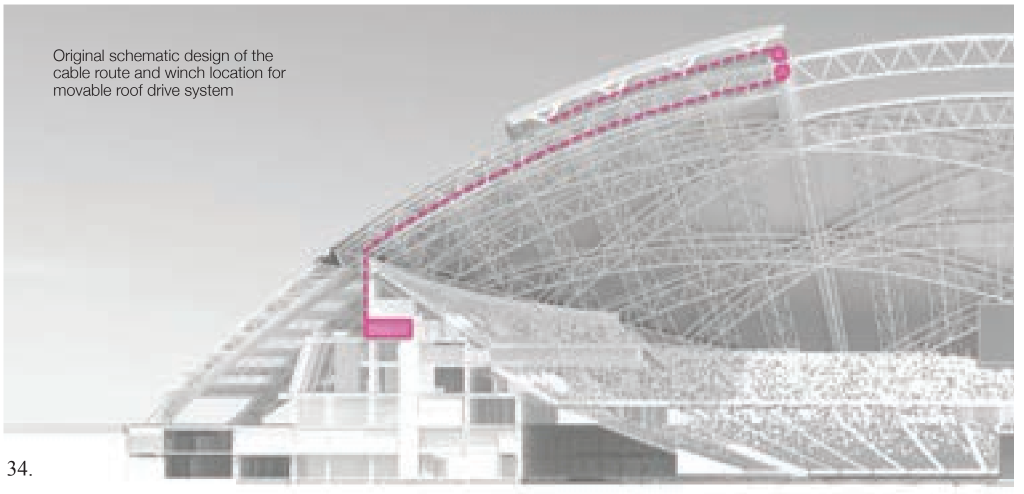

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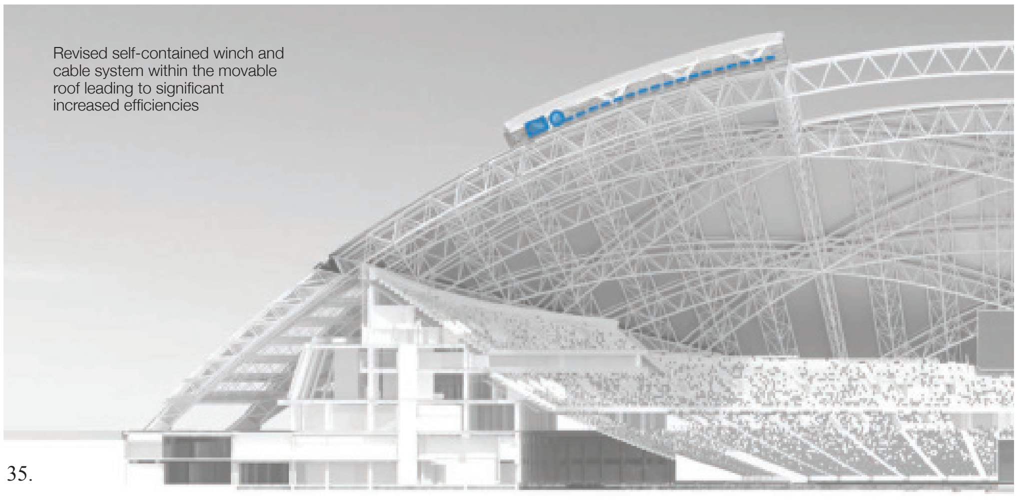

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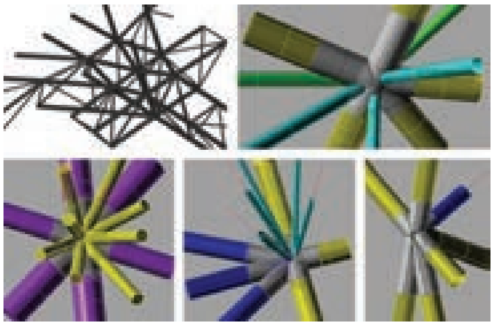
33. Snapshot of 3D model illustrating Arup’s reference design for movable roof transportation system.

34. Original design for movable roof drive system.

35. Revised design for movable roof drive system.



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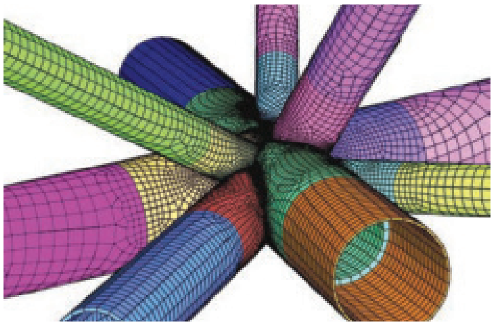

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40.

36. Complexity and variation in the fixed roof connection nodes.

37. Finite Element Analysis model of a fixed roof connection node.

38, 39. Thrust block under construction.

40. Completed thrust block.

Fixed roof connections
A number of different connection types were investigated for the complex geometry of the tube-to-tube connections of the fixed roof. Three key factors were assessed when selecting the connection detail: fatigue sensitivity (use of stiffener plates, slotted plates and cruciforms within connections can greatly reduce the fatigue life of connections), ease of fabrication and ease of design.

A connection formed from one thickened member through the connection and profile cutting and welding all other members to it was selected as the preferred fabrication option and the least fatigue sensitive detail, although more challenging to design. The thickened member through the connection is referred to as a 'thickened can'.

In summary, the following design approaches, in order of preference, were applied to the different types of connections across the roof:

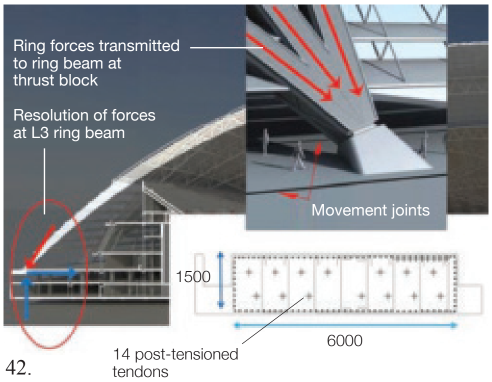
- CIDECT with conservative assumption on mulitplaner correction factor
- Capacities calculation in accordance with AWS D1.1.
- Finite Element Analysis (FEA).

Ring beam
The elevated ring beam is an integral component of the overall NST roof structure. The ring beam and the column pairs below form the primary support for the roof structure and act together to restrain the lateral thrusting forces of the roof dome structure.

The ring beam has a diameter of more than 310m and is formed from a 6m-wide by 1.5m-deep post-tensioned concrete beam with local thickenings to 2.0m deep at the column pairs below the roof support nodes (also referred to as 'thrust blocks'). The thickenings deal with the large shear and bending forces being experienced by the ring beam due to the roof load transfer. The ring beam circumferential length is approximately 1km.

The roof structure is symmetrical in the NE/SW axis and asymmetrical in the NW/SE axis. The ideal geometry for the ring beam to balance the roof loads would not have been circular as constructed but more a faceted pear shape between roof node positions.

41.



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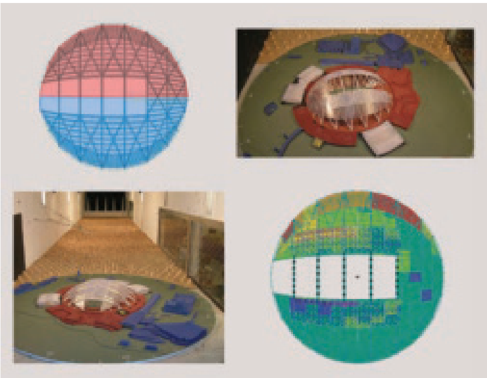


43.

41. The stadium under construction.

42. Ring beam section and actions.

43. Wind loading analysis.

Both architecturally and practically, it was determined to create a circular ring beam geometry with the ring beam column pairs working in portal action radially to resist any forces not funicular to the ring beam circular geometry.

The ring beam post-tensioning is developed via 14 tendons of 17 strands (each 15.2mm in diameter) placed in 2 rows of 7 tendons. Each post-tensioned tendon is approximately 100m long and stressed from both ends. The post tensioning ensures that under service loads the ring beam remains un-cracked. Under the worst case ultimate load cases some cracking of the ring beam occurs although it never goes into net tension at any section around the ring beam.

Wind loading

Working closely with CPP (Sydney) the design team recommended adopting an 'influence surface' method to determine critical simultaneous patterned wind loads across the roof.

In this analysis, the time-histories of the wind pressure measured simultaneously over the entire roof from the wind tunnel tests are combined with structural weighting functions to determine the highest magnitude and worst pressure distribution that cause critical design scenarios for direct application to the structural analysis. Such a method enables wind loads to be more accurately determined, considering the area and potential lack of correlation of the wind.

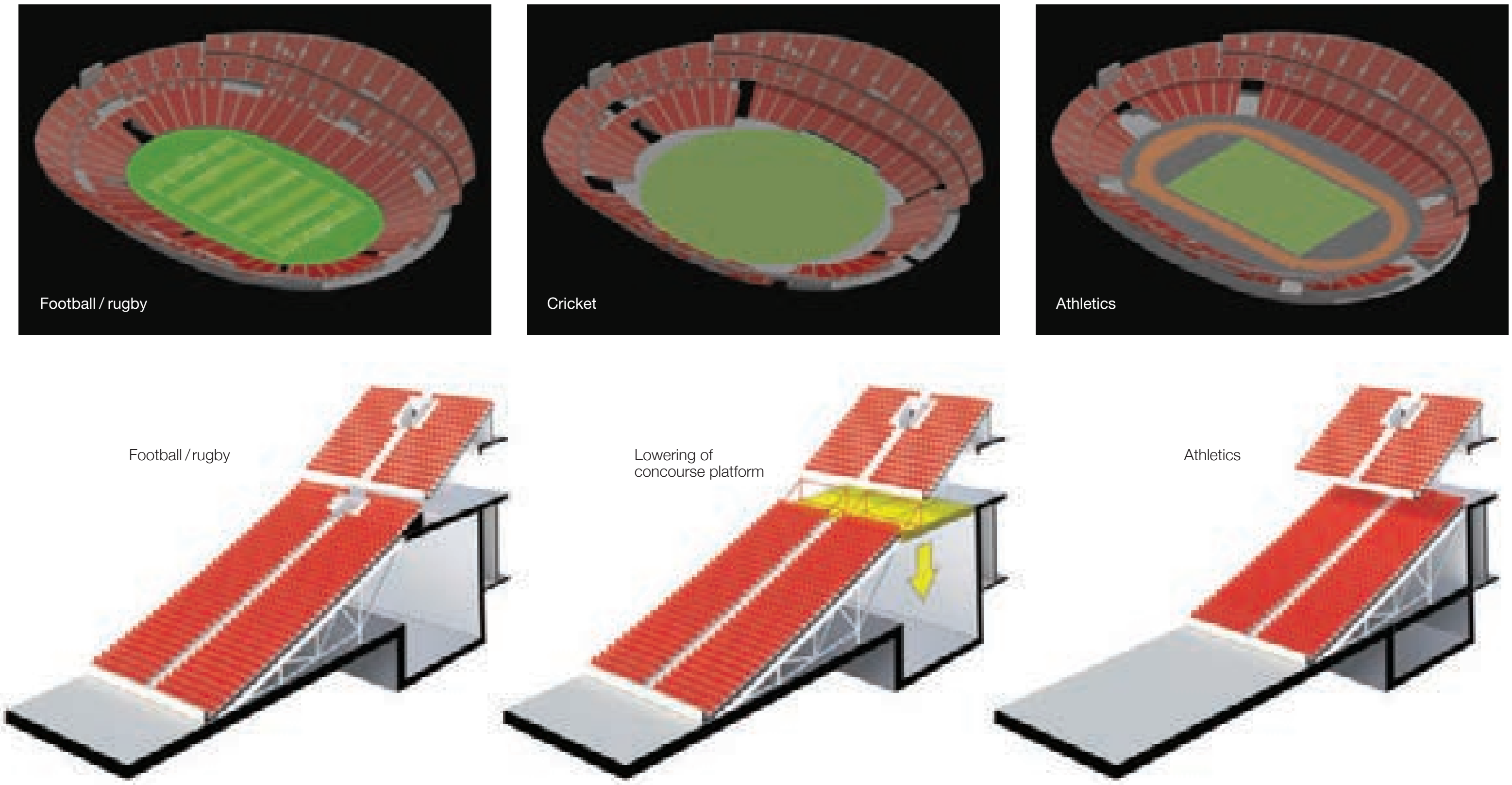
The roof was wind tunnel tested in quarter closed, half closed, three quarter closed to investigate the possible effect of the intermediate position of the movable roof on the wind load. It was found that the quarter closed roof generated higher edge pressures and overall loading on the roof when compared to the other intermediate positions.

Roof construction sequence

The construction sequence affects both the internal forces and deflections in the structure. An allowance of 10% utilisation on the fixed roof structure, excluding the louvres, was assigned to deal with locked-in stresses associated with the construction methodology.

A construction method was discussed with potential steel subcontractors and outlined in the structural tender drawings. This erection sequence was assessed by the design team and determined to produce locked-in stresses less than the 10% allowance.

This figure was advised to the bidding steel subcontractors and the erection methodology of the winning steel subcontractor (Yongnam) developed to work within this allowance.



44.

Moving tier systems

During early design phases the Arup team developed various options for the moving tier mechanisms.

The design challenge was unique. With a permanent athletics track and the extended requirements of football and cricket viewing, the moving tier systems needed to accommodate a wide range of movements (up to 12.7m) while maximising seating capacity for each mode and being capable of conversion from one format to another in a target 48 working hours.

The team investigated a variety of options of independently-movable segments in the lower 30,000 seat tier – from as few as eight, to as many as 50 – and a mixture of sliding and hinged movement systems was developed and investigated.

The design eventually adopted proved to be the best means of resolving the geometric complexity, as well as improving operational efficiency. This is how the system works:

- Eight main sliding elements minimise the number of gaps between seat modules
- As the lower tier moves inward from athletics to football mode, a 12.7m gap opens up which needs to be filled for pedestrian flow and to support supplementary seating.
- A lifting mechanism was adopted to fill this gap with 49 independent concourse platforms. This meant introducing a trench below the platforms through which the lifting mechanism could move
- Turnaround time was enhanced by introducing a serapid machine to lift the platforms. The serapid is a mobile proprietary lifting machine which runs in its dedicated 4m deep trench around the full perimeter of the arena and lifts or lowers each of the concourse platforms one-by-one
- The adopted moving system reduced the number of sliding components and achieved simplification of sliding tier movement mechanisms using air skates, hydraulic jacks and PTFE sliding pads.

Acoustics

The Arup acoustics team provided technical input into the acoustic design of both the National Stadium and the wider sports precinct. For the National Stadium they generated a hybrid acoustic quality which would ensure the best acoustic for both sports events and concerts.

In a sports venue the roar of the crowd is an essential part of the atmosphere. The acoustics of the stadium bowl were designed with this in mind, providing natural reinforcement of the crowd noise by including sound reflecting surfaces within the space coupled with the level of acoustic control that was necessary to ensure the PA system would meet intelligibility targets and concerts could be hosted without reflecting sound to the field of play.

Another issue for careful consideration was the potential for heavy rain to generate noise. Detailed studies were undertaken to ensure that the lightweight ETFE cladding would not impact on audibility of sound within the National Stadium event space.

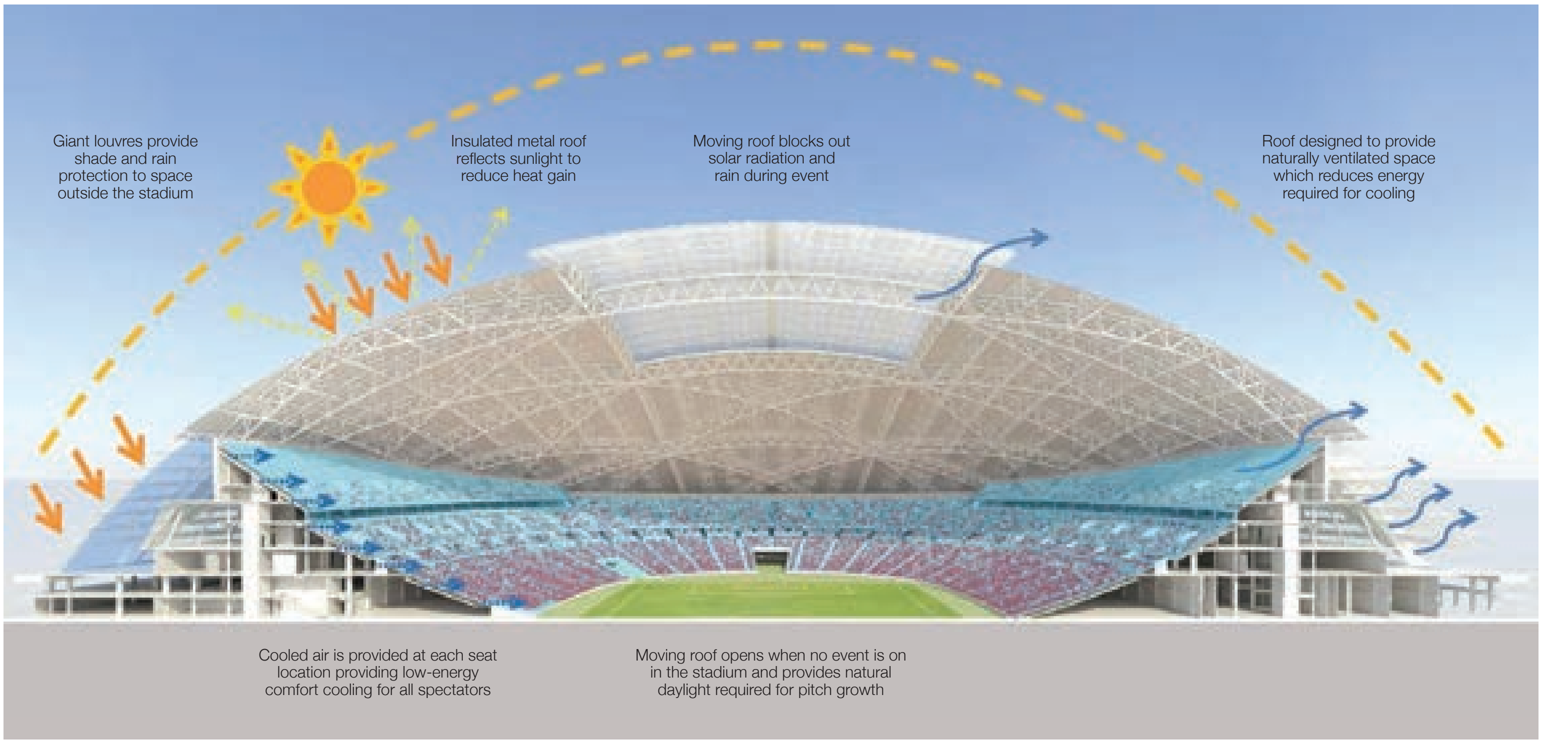
45

46

44. The three modes of retractable seating and transition phase.

45. Singapore Chinese Orchestra Concert – first of its kind to be held in the newly opened National Stadium.

46. The National Stadium during the World Club Rugby 10s tournament – the first elite sporting event at the venue.



47.

Blast engineering
As both a world-class sporting facility and a place to host major events, the Singapore Ministry of Home Affairs (MHA) identified the stadium as a building of 'national importance'. The stadium and its surrounding precinct therefore needed to be designed with long term resilience in mind.

Under the design leadership of Patrick Condon (Dragages Design Leader), Arup's blast engineering experts determined the blast hardening measures that could be introduced with least effect on facility operations.

The Arup, Dragages and MHA teams assessed and refined the design, constructing extremely large numerical analysis models for critical structural elements like the dome roof and the support ring beam and support columns.

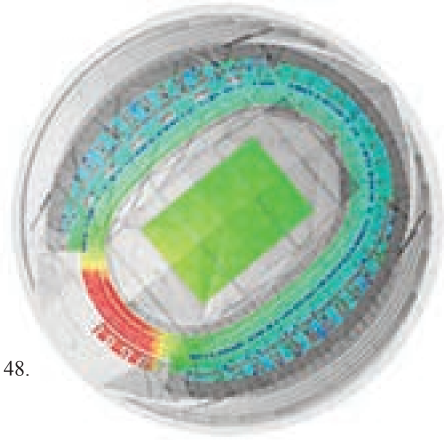
Potential threat scenarios were formulated, and the associated loading determined, and the response of the building structure and fabric assessed using sophisticated numerical analysis techniques.

For some of the bespoke building, elements response testing was undertaken to accurately determine the structural response. These results were fed into the analysis to improve the reliability of the computational analysis.

Bowl cooling
Sustainability was central to the design of Sports Hub from the early stages of the competition design. The team's initial challenge was to make the stadium as energy-efficient as possible. Passive design solutions were targeted first with shading to seating, insulation to roof cladding and to the performance of the ETFE pillows of the moving roof.

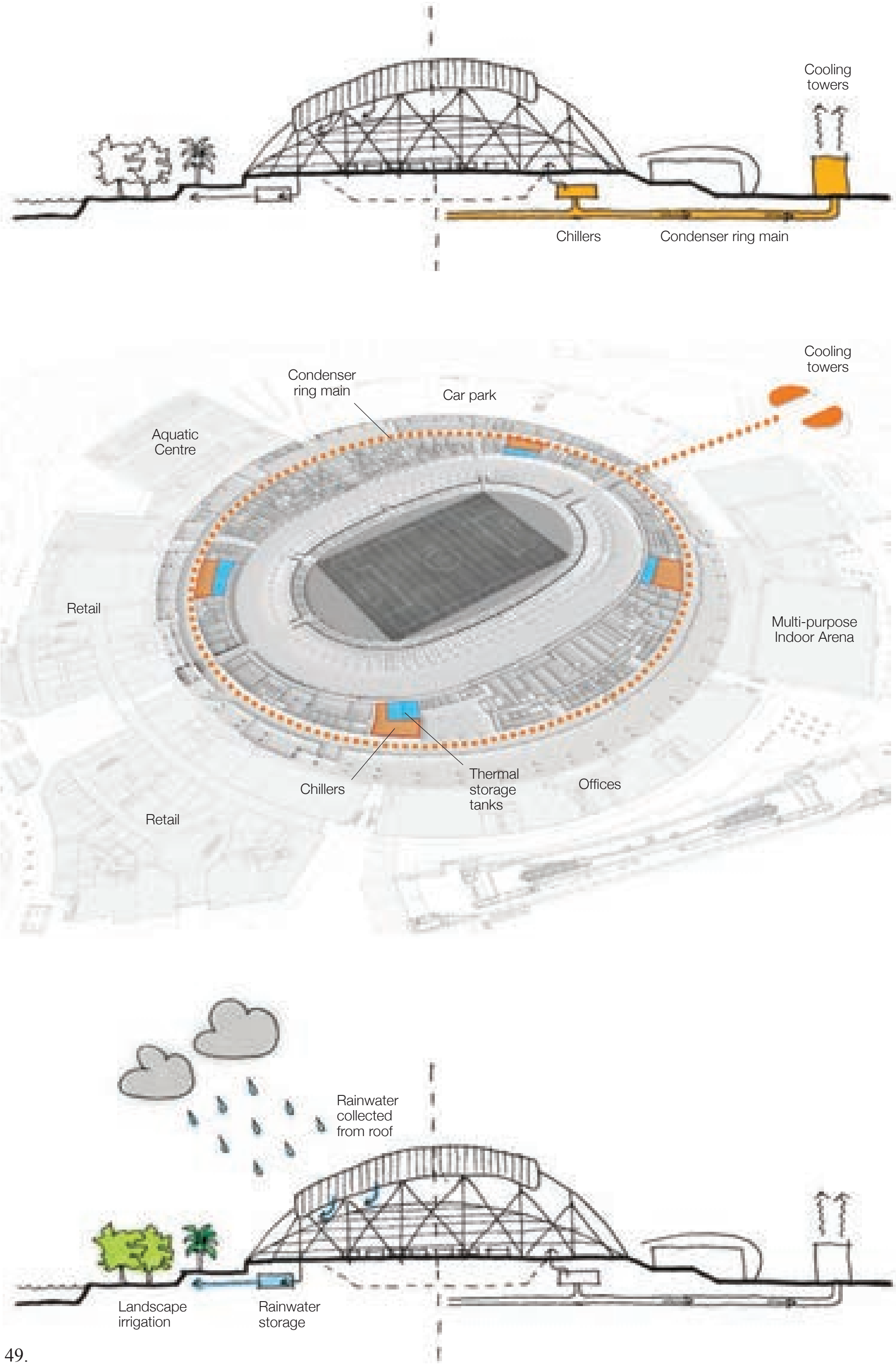
When it came to designing the bowl cooling system, the Arup team wanted to push the boundaries of innovation while creating an environmental solution that was technically robust and economic to build and run.

The seated volume of the stadium is only around 1/40 of its entire volume, so local cooling could achieve substantial reduction in energy use. When the team looked at what defined comfort in a tropical climate they found that whilst air movement was important it was most effective if delivered to spectators' in a specific way.



48.

Working in close collaboration with a leading UK university, the team designed a mannequin with temperature sensitive artificial skin and tested it in a mock-up of three rows of stadium seating while simulating Singapore's climate and the stadium's proposed cooling system. The trial results confirmed the model could be scaled up to a 55,000-seat stadium successfully. The team calculated that this localised approach to cooling reduced energy use by more than 60% when compared with a typical modern American stadium.



49.

Local cooling provides greater flexibility in times of lower seat occupancy because ventilation to unused seating can be switched off as required. The bowl cooling energy is then fully offset by a 700kWp Solar PV system. Although the bowl cooling system does not target specific comfort for athletes on the pitch, the moving roof reduces solar intensity at ground level to less than one-tenth of open sky conditions.

Sustainable masterplan

With the stadium at the centre of the precinct, the team's mechanical engineers realised that an efficient solution needed to balance the intermittent energy demands of the stadium with the everyday energy demands of the surrounding buildings.

Their proposal integrated thermal storage tanks into the design, which are pre-cooled before an event, and allow for peak demands of the stadium seating to be met from the same plant that provides cooling to the adjacent office, retail, indoor arenas and aquatic centre.

The space-efficient centralised services strategy developed at Sports Hub aligns with the Singaporean Government's long-term strategy for the future development of the city of Singapore and is a unique example of how different scale facilities, with different load requirements and usage patterns, can be designed to work off a combined system customised to meet regular and peak event load requirements.

Extensive landscaping has created a high-quality, natural waterfront environment around the stadium precinct. In fact, the Sports Hub Consortium's dedication to achieving a sustainable design for the stadium and the Sports Hub precinct was recognised during the 2012 BCA Awards at which it was awarded 'Green Mark GoldPlus' Award.

47. Low-energy design.

48. Solar radiation studies for roof performance.

49. Some of the stadium precinct's award-winning sustainability measures.

Fire engineering
The stadium is surrounded by adjacent sports facilities and other buildings, and spectators enter and exit the stadium via the Sports Promenade. To achieve the required fire safety performance, Arup's team had to demonstrate that the Sports Promenade provided equivalent performance to an external open-to-sky area to satisfy both local code compliance and the requirements of the Guide to Safety at Sports Grounds (5th edition) for a place of safety.

A similar process was required for the design of roof steelwork, where for design and cost reasons, the preference was to avoid intumescent paint. The scale of the roof meant the majority of steelwork was too remote to require additional protection. However the issue had to be addressed to the base of the roof.

Both of these issues were solved through detailed fire analysis which was used to define and limit the fire load to the Sports Promenade. This required limitations to be imposed on vehicles, a detailed assessment of the natural ventilation achieved via the giant PTFE louvres and an agreed management routine for the area during events.

For the moving tiers, the design challenge was greater because of the susceptibility to damage of fire protection applied to moving components. Simplified structural analysis was undertaken to narrow the scope of the finite element analysis to the worst-credible fire scenario. Subsequently, Strand 7 was used to conduct the non-linear structural performance in fire and fire protection minimised to a limited number of critical elements.

The proximity of adjacent buildings meant that in many areas detailed analysis of spread of flame from one building to another needed to be understood so that fire management could be operated on a building-by-building basis. For the aquatic centre a similar approach was developed to that for the NST. For the retail areas, the escape strategy was subject to detailed negotiation with the local authorities.

Pedestrian modelling
Setting standards for the safety of spectators within the precinct, and ensuring quality experience for people arriving and departing from the various sports venues, was an extensive piece of work for the pedestrian modelling team. Their work informed every aspect of the masterplan and in some instances the form and shape of the sports venues.

The design of the precinct was tested against five onerous pedestrian movement scenarios, including simultaneous events at the stadium, the aquatic centre, and the indoor arena; in dry and wet weather conditions; and at low and high security levels. Testing and accepting the performance of these low probability occurrences demonstrated operational flexibility and design tolerance regardless of event, function or weather.

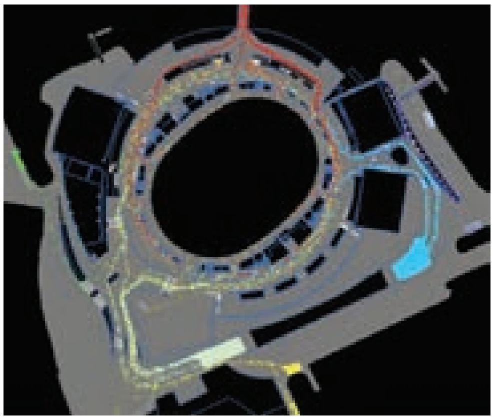
Each scenario was tested dynamically using Legion pedestrian simulation software. The modelling predicted the movement of the 55,000 to 65,000 people within the site given their forecast origin and destinations. The combination of design, route choice options, mode choice, operations and infrastructure capacity created substantial and complex emergent movements which had to be understood and communicated in simple terms.

Performance outputs from the models provided confirmation of capacity elements such as circulation widths, queue zones and vertical transport capacities, as well as layout and operational strategy.

The key areas of focus included circulation routes, holding space, weather protection and security screening. The final design was tested across all areas and the overall results were presented to the Land Transport Authority (LTA).

LTA acceptance of the performance formed a major part of the approvals process for the final design.

Feature lighting
At competition stage, the feature lighting was developed by Arup's architects working with Light Cibles locally in Singapore. Then Arup's lighting team took the competition-winning imagery through the Urban Redevelopment Agency (URA) design review process to approval.



50.

Key areas of focus were the LED illuminated moving roof panels, which could project images onto the moving roof cladding visible externally, and the LED lighting to highlight the characteristic pattern of the roof cladding on the fixed roof scupper.

The lighting design requirements for the moving roof were carefully balanced with environmental modelling constraints. To reduce solar energy within the stadium a relatively opaque cladding surface was required. However this worked against the requirements of the moving roof lighting.

Detailed modelling was done to balance internal visible surface temperatures against light transmittance requirements for night time illumination. Using a full-scale mock-up of the moving roof, built on site, Arup worked with Dragages' sub-contractor to develop an optimised solution which relaxed the solar energy transmission to 8%, ensured that internal surface temperatures didn't exceed 40°C and allowed for an intensity of night time illumination to the top surface of the ETFE cladding.

The final design solution incorporates over 20,000 LED pixels, each illuminating a 1 x 1m square area of moving roof cladding. Each 200 x 100 pixel screen has a level of resolution that can project both static and moving images and text. The completed NST moving roof lighting forms the largest addressable LED screen in the world.

For the fixed roof scupper lighting, a similar process was implemented using a full scale mock-up of the fixed roof cladding to test different lighting solutions.

51.

52.

50. Pedestrian modelling was an important element of the design.

51, 52. Feature lighting makes the stadium a spectacular landmark in the city at night.

The URA wanted the team to achieve a full wash to the scupper zone. Using the mock-up, the team demonstrated how a more discreet fixing could achieve the desired night time illumination affects. The final design solution incorporates more than 2,500 modular LED lights into the scupper cladding to create a well-integrated architectural lighting solution.

The final design, fabrication and implementation of the moving roof and fixed roof feature lighting was completed by Light 10 – a local lighting specialist.

Conclusion

Arup has a long-standing track record of bringing the best of its international expertise to large projects around the world – and there is no better story to tell than its role in delivering the design of the Singapore Sports Hub.

A key tenet of design at Arup is the concept of ‘total architecture’ or holistic design. This philosophy was evident in the way design teams were organised to foster collective thinking in developing Singapore Sports Hub. It was apparent, also, in the effectiveness and efficiency of the collaboration with Dragages, DP Architects, AECOM and the many other parties involved in bringing this magnificent project to fruition. This was truly a team effort.

Innovative ideas were nurtured, unique concepts were developed and delivered, to make the Sports Hub a venue perfectly matched to its location. It meets all its objectives: providing sporting facilities for the city’s residents, a spectacular setting for international sporting fixtures and world-class concerts and – perhaps most importantly of all – a home for the National Day Parade when the people of Singapore come together to celebrate their city’s independence.

A magnificent sporting and event facility, the Sports Hub will serve Singapore well for many decades to come.

Authors

Chia Wah Kam, a Principal in the Singapore office, was Project Director and Qualified Person for the National Stadium roof.

Andrew Henry is a Principal in the Singapore office and he was the Project Manager.

Clive Lewis was the lead sports venue designer.

See Lin Ming, a Principal in the Singapore office, was Qualified Person for the National Stadium seating bowl.

Mike King, a Principal in the Singapore office, led the structural design team.

Malcolm Smith is an Arup Fellow and a Director in the London office. He led the urban planning team.

Scott Munro, an Associate Principal in the Singapore office, led the bowl cooling design.

Ruth Wong, an Associate Principal in the Singapore office, led the fire engineering team.

Peter Hoad, a Principal in the Singapore office, led the blast engineering team.

Nick Boulter, an Associate Principal in the Melbourne office, led the acoustic design team.

Project Credits

Owner: *SportsHub Pte Ltd*; Client and Main Contractor: *Dragages Singapore Pte Ltd* Architect (Sports Venues): *Arup Associates & DP Architects Pte Ltd* Architect (retail, leisure, office): *DP Architects Pte Ltd* Mechanical & Electrical Engineer: *Squire Mech Pte Ltd* Landscape Architect: *AECOM* Steel Contractor (National Stadium, OCBC Aquatic Centre and Arena): *Yongnam Engineering & Construction Pte Ltd* Sports venue design, civil, structural, fire and maritime engineering, geotechnics, acoustic, audio visual and multimedia, building physics and environmentally sustainable design, security and risk consulting, lighting design, advanced technology and research (moving structures), specialist technical services (sports lighting, bowl cooling, pedestrian modelling and arena consulting): *Arup – Nizar Abdul Rahim, Hector Abella, Riccardo Abello, Sonja Abhyankar, Ivy Abo, Paul Adams, Kelly Adighije, Pedro Afonso, Ian Ainsworth, Michael Alder, Andrew Allsop, Joseph Amores, Erik 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1-2, 4, 7-19, 22-24, 26, 28-39, 42-47, 49-50, 53 *Arup*; 3, 52 *Poh Yu Khing*; 25, 40, 41 *Clive Lewis/Arup*; 5-6, 20, 51 *SHPL/Oaker*; 21, 27 *Christian Richters*.

Bosco Verticale – a forest in the sky

Location
Milan, Italy

Authors
Luca Buzzoni James Hargreaves Valeria Migliori

1.

1. View of the residential towers of Bosco Verticale in Porta Nuova, Milan.

2. Plaxis analysis of the existing tunnels and surrounding soil underneath the site.

Introduction

Bosco Verticale – literally the vertical forest – is the wonderfully evocative name for two residential towers in Milan, Italy. Rising 110m and 76m from the ground, these new homes are located in Porta Nuova, one of the largest urban redevelopment projects in Europe where they will eventually form part of a new residential and commercial area interspersed with parkland.

The balconies of the apartments, duplexes and penthouses extend outwards by approximately 3.5m to host an abundance of trees, shrubs and plants, creating the overall effect of a huge hanging garden. In total, 900 trees measuring between 3m and 6m have been planted, together with 5,000 shrubs and 11,000 floral plants on terraces up to the 27th floor.

Arup worked with Boeri Studio and Hines Italia on the design and development of this new model for regenerating the urban environment. Its intention is to inspire greater biodiversity to combat Milan's increasingly high levels of pollution. The vast amount of greenery on the building will create oxygen and humidity while absorbing CO_2 and dust particles. The design also includes photovoltaic systems to provide renewable energy (Fig 1).

Following the proposal to create Bosco Verticale at Porta Nuova, 70% of the area designated for redevelopment has been assigned to public parkland. The rest of the complex will comprise new public, residential and commercial buildings, including the new Italian headquarters for Google.

Arup's role

Arup provided structural and geotechnical designs and consultancy on acoustics, vibrations, ground-borne noise and tunnelling. This included advanced design solutions relating to the effects of two railway tunnels under the site which required dedicated design of a base-isolation system for the main buildings. Arup's Milan office, where most of the design was developed, co-ordinated the project with teams from the Midlands Campus and London contributing.

Initially, Arup was appointed for geotechnical and structural design from concept to construction, including site support. Specific peculiarities of the site and design required input from other Arup experts, however. Arup offices in Europe and the Americas were involved in assessing the effects of the two metro tunnels beneath the site; the potential acoustic and vibrational effects of trains on the buildings and design of mitigating measures; and advice on wind tunnel tests relating to the structures and the trees, including structural design of safety elements for the biggest trees.

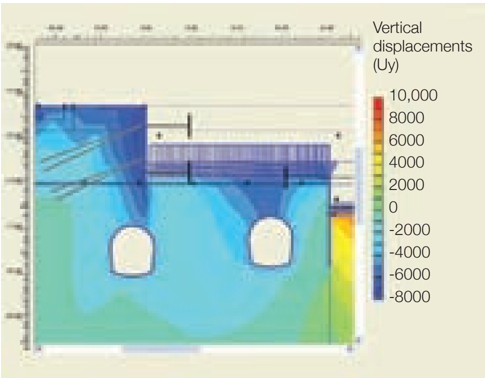
The holistic integrated approach Arup brought to the project helped define options for solving unconventional problems in demanding situations on a compact and challenging site.

Structures and geotechnics

Despite the good soil characteristics of the site and limited influence of the water-table, several physical and geometrical constraints required thorough geotechnical design. In particular, detailed interaction analysis with the existing metro tunnels and the adjacent buildings was required (Fig 2).

The presence of existing buildings adjacent to the site, the M2 metro tunnels underneath the North portion of the site and the new Metro 5 tunnel under construction on the east side, required specific design of several diaphragm wall typologies with many different temporary restraint solutions (e.g. soil nailing with different number and length of ground anchors, temporary propping from within the site and cantilever solutions with no temporary restraints).

The existing tunnels were assessed through desk-studies, surveys and in-situ tests to allow detailed analyses of the structure during the planned construction of the new buildings typically only 3.5m above the tunnel crowns. The behaviour of tunnels was analysed for the direct effect of the new buildings; the construction of diaphragm walls and excavation; and the indirect loading effect of the towers. The analyses predicted the evolution of settlements and stresses in the tunnels with an incremental finite element load-analysis carried out with *Plaxis* software.



2.

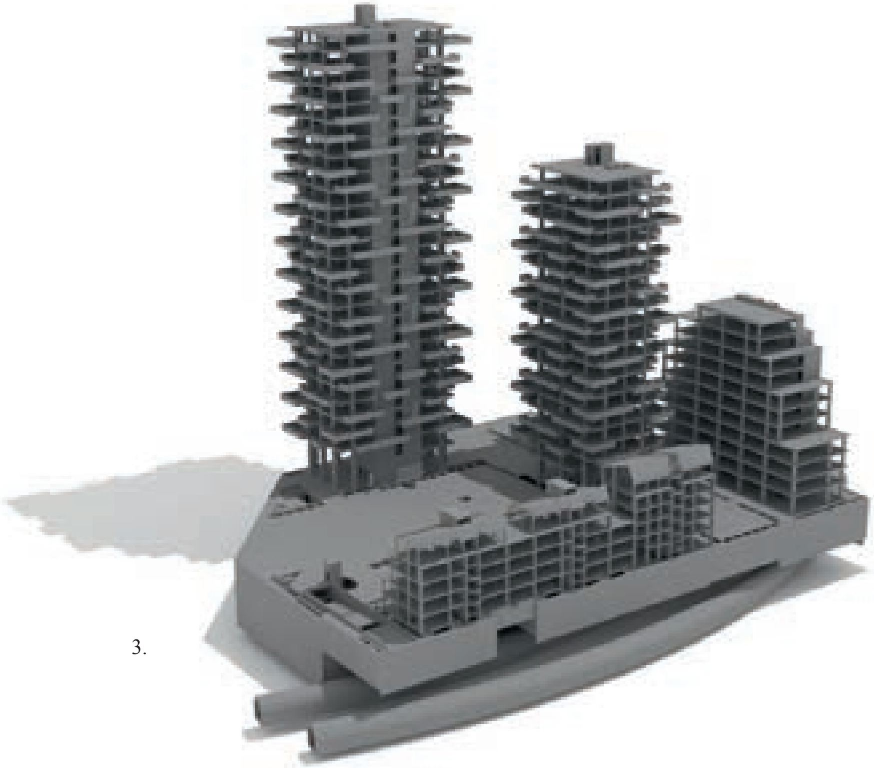
During construction of the buildings, the train tunnels were monitored to control possible unexpected effects and verify that real behaviour matched numerical predictions. The monitoring system was wirelessly connected to a dedicated network that enabled continuous checking of the performance of the existing structure against defined limits. In case of undesired behaviour, two different levels of alarm were pre-defined to alert the company running the trains and advise on the need for further checks or temporary stoppage of the line (Fig 3).

The two residential towers have shallow foundations, thanks to good soil performance and a concrete structure. (In the diagram, tower 'Confalonieri' or Tower D is 76m tall and has 20 floors above grade, tower 'De Castillia' or Tower E is 110m tall and has 27 floors above grade). Concrete was specified with grade from C28/35 up to C60/75 for the columns and for some of the base walls of the cores (Fig 4).

For the 2m thick foundation raft of tower 'E', C30/37 low-heat pozzolanic cement mix was requested and one continuous pour of 2,100m3 was adopted in 12 hours.
The development of heat within the pour (at the end of June with an external temperature between 20°C minimum at night and 37°C maximum during the day, protected with thermal insulating panels) was monitored with thermal couples and the maximum difference of temperature between the core and the surface was 20°C with a peak at the core of 65.4°C.

For Tower D the base isolation system illustrated in the next section of this article required a double foundation scheme with a 1.6m thick raft and a suspended false-foundation raft sitting on springs.

Both towers have an eccentric concrete stability core, perimeter rectangular columns and post-tensioned concrete slabs and beams. The system adopted for the slabs and beams allowed Arup to reduce the depth of the elements, control deflections and vibrations and improve the capacity of the big cantilevers with the relevant design loads requested for the terraces.



3.

4.

The typical thickness of the slabs is 28cm both inside the apartments (with a maximum span of approximately 10m) and in the terraces (where the cantilevers are up to 3.5m when measured perpendicular to the columns' line or approximately 7.5m in the corners). The terraces have been designed for a live load of 4kPa and - due to the trees and planters - for a uniform line-load, in addition to the structural weight of the planters, of 13kN/m and 7kN per tree every 3m, centre-to-centre.

3. *Revit* model of the development with the two existing tunnels in the foreground.

4. Pouring of the foundation raft of tower E

The presence of trees on the terraces has additional important effects on the structure. In addition to the imposed dead load, the effects of wind transmitted by the trees to the slab and induced vibrations had to be taken into account. Wind loads on the trees were estimated based on literature information and best practice then confirmed through wind tunnel tests.

Unbonded post-tension was adopted initially both for slabs and beams. However, bonded post-tension was eventually used for the slabs to provide additional safety against possible corrosion of the live end of the stressing tendons that for the slabs are protected only by the parapet cladding and might be exposed to weathering should the protecting anchorage block fail. Beams are always within the façade line and beam tendons' ends can never be exposed so unbonded post-tension was confirmed.

Because of the layout of the terraces, different every six levels, cantilevering slabs were poured on a self-supported cantilevering scaffolding which didn't rely on support from the levels below but only on the proper connections to the internal portion of one single slab below and to the columns (Figs 5–6).

Finally, despite the low seismicity in Milan (i.e. approx. 0.05g peak ground acceleration with a likelihood of exceedance of 10% in 50 years or 475 years return period) all the buildings in the Porta Nuova redevelopment have been designed for seismic resistance, with a special focus on Tower D. This was because the tower is isolated at the base to mitigate the effects of ground-borne vibrations and noise induced by the metro trains, as illustrated in the following section. The isolation system in the tower shifted the first natural period from approx. 1.5s to almost twice as much at 2.9s (Fig 7).

Base isolation, in addition to mitigating the effects of trains pass by, enhances the seismic performance of the structure by increasing the resilience of the building and its structural and non-structural components to earthquakes.

However, as will be explained in the next sections, the increased flexibility of the building could introduce undesired effects due to wind. These potential effects were mitigated with viscous dampers that helped increase the intrinsic structural damping up to 1.5% critical, as peak acceleration would have exceeded the acceptable limits set by the international practice and codes.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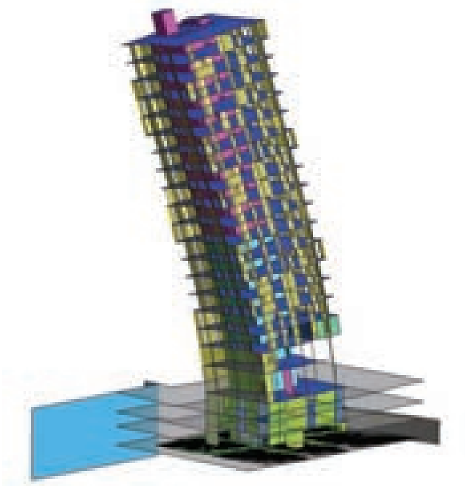
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5. Tower E under construction.

6. Self-supported cantilevering scaffolding by Peri.

7. Dynamic analysis of Tower D.

Base isolation system

Description

The Porta Nuova site is above line M2 of the Milan Metro system between the Garibaldi and Gioia stations in central Milan. The line comprises two tunnels with a tunnel crown elevation less than 20m below the ground surface.

Rail systems generate ground-borne vibration (GBV) partly because of irregularity in the wheel tread and rail head surfaces and partly because of the dynamics of the track structure and vehicles. The transmission of rail GBV to the building structures is a particular risk on this site given the close proximity of the track to the ground surface combined with the fact that the buildings have basement structures. It is also a risk for this development since several of the buildings are located over or close to the metro tunnel alignment in plan.

The risk can only be fully evaluated and have meaning in relation to the performance criteria of the building. The building function is residential and in Italy the vibration criteria applicable to the comfort and perception of humans in buildings is covered by the UNI 9614:1990 code. The acoustic criteria mean that structure-borne noise has to be discriminated from air-borne noise. The latter is essentially what is transmitted into the building through the façade and is not related to GBV. The GBV, generated mainly by the metro, is transmitted into the building structure causing the walls and floors of residential spaces to vibrate which in turn generates sound pressure in the enclosed air-space; this is known as structure-borne noise. Acoustic criteria generally set limits on total noise – i.e. air-borne plus structure-borne.

This risk was mitigated by designing a suitable base isolation system and performance evaluation was carried out at the design stage to show conformance with the vibration and noise criteria. Base isolation was incorporated into the design of several buildings on site, including Tower D for which vibration isolation had implications for the seismic and wind performance of the building because of the height of the structure.

Site assessment

Vibration surveys were carried out on site before construction started so that the site vibration performance could be quantified and the need for isolation confirmed in the first instance. The vibration survey also enabled the vibration characteristics of the site to be determined, in particular the frequency of the GBV energy arising from metro train pass-by events, which helped to inform the selection of a suitable frequency for the base isolation. It was necessary to measure the vibration at elevations corresponding to the foundation structures and hence bore holes were created on site. The accelerometers were placed into special canisters, designed by Arup, and lowered into the bore holes. The vibration data was processed so that it could serve its main purpose which was to be used as a dynamic load in the subsequent modelling and analysis.

The system

Base isolation systems involve floating the building structure on an array of resilient elements which can be elastomer bearings or helical steel springs (Figs 8–9). To meet the criteria for this project it was predicted that isolation frequencies of 3.5Hz or lower would be necessary, which is only possible to achieve with helical steel springs. Base isolation works by transferring vibration on the active side (the lower/ground side in this case) into movement of the springs so that structural vibration on the passive side (the building structure) is reduced. The effect is frequency dependent and as frequency increases the amount of isolation increases - an important consideration for structure-borne noise which can be problematic at frequencies in the range 25 to 200Hz.

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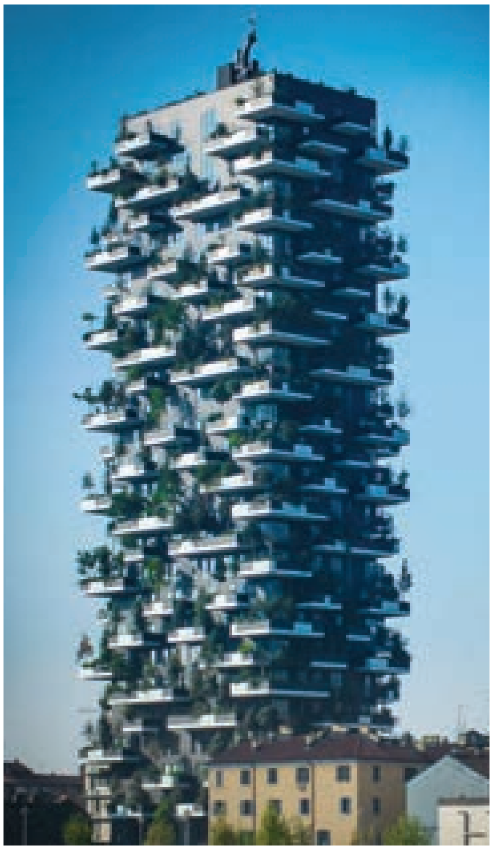
8–9. Helical steel springs isolators installed in the foundations of tower D.

10. Tower E



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In the case of Tower D isolation frequency of 2.4Hz would be required to meet the criteria in full. When considering spring products, the isolation frequency is related to the axial spring stiffness as this is the stiffest direction for helical steel springs and because it is very common to need to isolate vibration in the vertical direction. Helical steel springs are simple flexible structures and hence have horizontal stiffness which is generally less that the vertical stiffness. The ration of vertical to horizontal stiffness, or stiffness ratio, was 2.5 for the 2.4Hz isolation frequency product.

The standard isolation frequency for spring units is 3.5Hz. These are widely available and cost-effective. Spring products of 2.4Hz are non-standard and more expensive.

However, the seismic loads for the building must also be accommodated by the isolation system and horizontal loads, in particular, place the greatest seismic demand on a tall building such as this one. Hence low horizontal stiffness was an important requirement of the isolation system and a stiffness ratio of 2.5 was studied and found to be too low.

A special seismic isolation product was therefore considered which although it had a higher isolation frequency than ideal, at 3.1Hz, had a much higher stiffness ratio of 7 which was shown to lead to higher, but nonetheless manageable, seismic demand for the building structure. The higher isolation frequency inevitably led to less vibration isolation, which had to be checked. It was also necessary to check the building performance under wind loads and in the presence of the 3.1Hz seismic isolation.

The structural design had to be modified to enable spring elements to be placed in the cut-plane and on the principal structural load paths in plan. (Access to the spring units is necessary for installation, adjustment and maintenance in future years). The spring units selected were also pre-stressed according to the vertically supported loads. This means that the springs do not deflect as the building structure construction progresses above the springs. The pre-stress in each spring unit had to be released upon construction completion to realise the isolation function.

The spring units are under high vertical static load from the building structure and hence tend to be held securely in place vertically and horizontally due to friction. However, a resilient adhesive-coated mat is placed at the top and bottom of the spring units to ensure the springs are securely located.

A further important aspect of the isolation design is that it must not be impaired by bridging the cut-plane with a structural load path. For the building structure itself, this will obviously not be the case, so architectural detailing must take account of this by either avoiding the bridging altogether or where it is necessary ensuring the structure is very flexible.

Analyses and design

To evaluate the performance of the isolation system at design stage and compare it with the performance criteria, it was necessary to develop a finite element model of the building structure and carry out dynamic analysis. The analysis also enabled the required isolation frequency to be confirmed and the design of the spring array developed so that the springs were loaded evenly within the cut-plane and the loads were within the spring capacity.

The first stage of this process for Tower D was to develop a system that would isolate vibration. The second stage was to consider if and how this system must be modified so that the building performance under seismic and wind loads conformed to those criteria. A feasibility study was performed ahead of a commitment to incorporate the isolation within the structural design.

The important direction for the seismic loads is horizontal and hence the shear stiffness of the isolation system needs to be relatively low, a common feature of seismic base isolation. As noted above this means the ratio of vertical to horizontal stiffness must be high for the spring units.

Wind loads contain most energy at very low frequencies and hence interact with tall buildings which have sway modes at these frequencies. Hence motion at the top of Tower D was the most important consideration. The base isolation system effectively removed stiffness from the foundation structure of Tower D leading to a reduction in the natural frequency of the sway mode and greater movement. Such modes have little structural damping partly because the base isolation system also has very little damping, with structural damping in the spring elements expected to be less than 1% critical. The building structural mode also is expected to have little structural damping since it tends to be floating on the springs and while there is strain energy in the structure this is small compared to say a conventional cantilever type structural mode.

The solution was to incorporate an array of viscous dampers within the cut-plane to increase the intrinsic structural damping of 1.0% critical to an effective structural damping of 1.5% critical. In this way energy of wind-induced sway motion could be absorbed to the point where it was possible to conform to NBCC (National Building Code of Canada) criteria.

The performance of the system was tested for GBV, total noise and wind vibrations after construction to prove the adequacy of design and validate the initial assumptions and analysis criteria. Actual performance showed a very good fit with the design numerical simulations.

The trees
The effect of the trees on the terraces of Bosco Verticale on the structures and overall safety of the design were assessed through detailed analysis including two sets of wind tunnel tests.

The different species selected were analysed and possible geometries defined, in order to allow the definition of the wind forces and the likely point of application. Working with the botanical consultant for the project, the expected maximum surface exposed to wind was defined for all the species, together with the location and height of the resulting centroid.

After Arup's wind engineering team in London had defined a detailed wind climate analysis for the site, the structural stability of the trees was tested in two different wind tunnel test campaigns.

The first set of tests in the wind tunnel facility of the Politecnico di Milano assessed the forces on the trees in a 1:100 scale model (Fig 12). The value is a compromise between the need to build models as large as possible and keep low blockage values (the boundary layer test section in the wind tunnel is 14x4m).

The large dimensions of the model are useful both for reproducing the geometric details and to achieve a Reynolds Number that is the most meaningful of full-scale conditions. The defined geometric scale is also compatible with the scaled simulation of the boundary layer. The Towers D and E are manufactured as a 'rigid aerodynamic model' – a static model that reproduces the geometry of the full-scale structure (aerodynamic surfaces and details).
The model of the buildings includes trees on the terraces chosen to have aerodynamic drag coefficients equivalent to full-scale trees, according to available literature.

Wind tunnel tests were carried out in a scaled simulation of the natural wind characteristic of the site. For this purpose the existing and planned buildings in the surroundings were modelled. (The most significant volumes within a radius of 600m assuming a centre among the towers). The whole area of the towers and the surroundings were placed on a turntable (diameter 13m). In this way it was possible to investigate all relevant wind exposures defined without any change in the test set-up.

11. On the balconies, restraining cables for the trees are clearly visible.

12. Physical model at 1:100 scale for wind tunnel tests at Politecnico di Milano.

13. Wall of Wind at Florida International University for real-scale tests on trees.

14. Rendered view of the restraining device for the biggest trees.

15. Installation process of a tree in Tower E.


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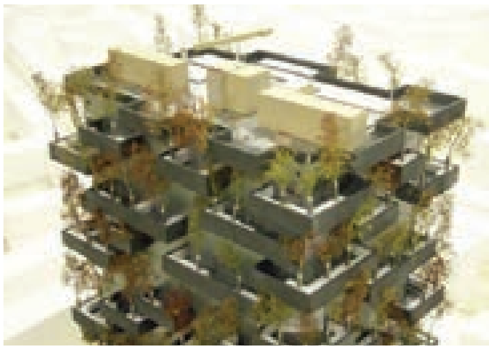

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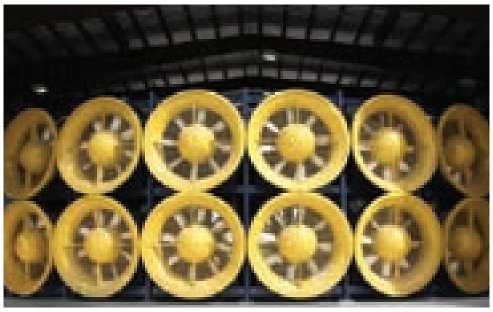

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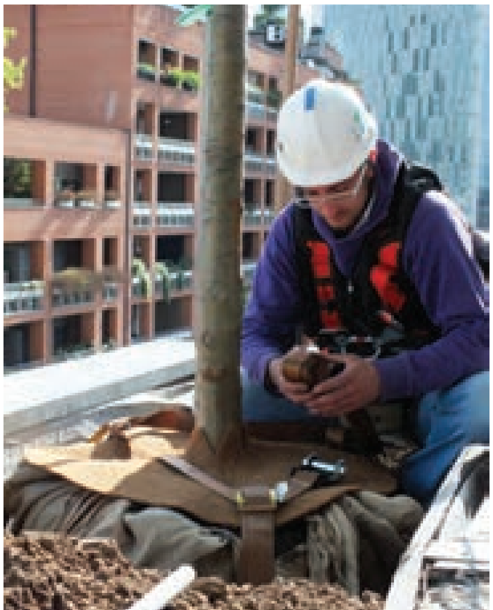

Aerodynamic forces on a few selected trees were measured by means of purpose-built dynamometers. The instruments measured the components of the aerodynamic force parallel to the plane of the floor. In addition, speed-up measurements on the terraces and roof were performed using 15 Irwin probes. These instruments allowed measurement of the magnitude of the wind velocity at a given position at a height of 20 mm from the floor of the terrace (corresponding to a height of 2m in full-scale).

The second set of tests, carried out in the open-flow facility of Florida International University, was designed to verify the forces on real trees. The study was carried out with the 12-fan Wall of Wind (WoW) hurricane simulator located on FIU's College of Engineering and Computing Campus in Miami (Fig 13).

Following the results of the analyses and tests, three restraining devices were designed: all the trees have temporary elastic bands that connect the root bulb to a steel mesh embedded in the soil; all the medium and large trees have a safety cable to prevent the tree from falling in case the trunk breaks as a consequence of large wind-storms; the largest trees, in locations most exposed to wind, have a steel safety cage that restrains the root-bulb and prevents it from overturning under the most severe windstorms (Fig 14).

While the elastic bands are designed as a temporary restraint until the roots are fully developed, the restraining systems for the largest trees are designed for the entire expected life of the building to provide a permanent safety solution for the stability of the trees.

The different solutions were soft-tested, with fully detailed 3d mock-ups and real mock-ups, to prove ease of installation and possible interferences with non-structural requirements before starting production. The connections of the steel cages to the concrete parapets, for instance, were coordinated with the water-proofing requirements of the planters and approved by the insurance company responsible for the water-tightness of the system (Fig 15).

Conclusion

Bosco Verticale is a novel approach to an issue facing many cities around the world – how best to mitigate the effects of urban pollution while providing homes for an expanding population. The result is a visually stunning architectural solution, providing sustainable and ecological benefits.

Winning the International Highrise Award 2014 underlined Bosco Verticale's international significance. This award, sponsored by the Deutsches Architekturmuseum, the City of Frankfurt am Main and Deka Bank, is presented every two years to the world's most beautiful and innovative high rise.

Authors

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Project credits

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Image credits

1–4, 7, 10, 11, 14, 15 *Arup*; 5, 6 *Peri*; 8–9 Gerb; 12 *Politecnico di Milano*; 13 *Florida International University*.

UCSF Medical Center at Mission Bay

Location
Mission Bay Campus, University of California, San Francisco

Authors
Alisdair McGregor Raj Daswani

1.

Introduction
California has seen an upsurge in new hospital design and construction in recent years driven by regulatory requirements to replace or upgrade existing facilities to new seismic standards. University of California, San Francisco (UCSF) has taken the opportunity to develop its medical research campus at Mission Bay to meet these standards and simultaneously create an exceptional level of sustainability.

Arup has worked on the project from the outset, integrating sustainability and project delivery across the site and providing structural, mechanical, electrical, and plumbing engineering services for the medical center complex adjacent to the biomedical campus.

The medical center opened on 1 February 2015 – on time, under budget and widely acknowledged as an exemplar of best practice in hospital design. It is one of the first hospitals in California to be awarded LEED Gold Accreditation (Leadership in Energy and Environmental Design).

This article focuses on the sustainability aspect of Arup's brief and the integrated delivery concepts Arup and UCSF introduced to achieve such outstanding results.

The project
UCSF Medical Center at Misson Bay is located on a 14.5 acre site in the former dock and warehouse area of the city. It comprises:

- UCSF Benioff Children's Hospital, San Francisco, with emergency and pediatric primary care and specialty outpatient facilities (183 beds)
- UCSF Bakar Cancer Hospital for adult patients (70 beds)
- UCSF Betty Irene Moore Women's Hospital for cancer care, specialty surgery and select outpatient services; and a 36-bed birth center
- UCSF Ron Conway Family Gateway Medical Building
- An energy center, helipad, parking and support services.

The patient bed units are arranged along wings facing north and south above a podium containing the diagnostic and treatment functions. This orientation optimises daylighting potential.

UCSF Medical Center at Misson Bay provides comprehensive diagnostic, interventional and support services, and uses advanced robotic and imaging technology during surgery, in an environment centered on the compassionate care of patients and their families. Integration with the biomedical campus strengthens collaboration between researchers and clinicians.

1. UCSF Medical Center at Mission Bay opened on 1 February 2015, on the target date set six years previously.

2. Daylight, fresh air and green space is accessible from all patient, caregiver and public areas.

2.

Designing for health
Arup subscribes to the view that a sustainable healthcare facility minimises negative health impact on the surrounding environment while promoting healthy outcomes for patients and staff. This is different from defining sustainability in terms of a LEED rating because there are unique opportunities and challenges in developing sustainable design for healthcare. Reducing the risk of airborne infection transmission and creating more therapeutic environments, for example.

The Green Building Council, which runs the LEED certification scheme, recognises that designing for health is an integral part of sustainable design. This is evidenced by the fact that the US Green Building Council, Northern California Chapter, launched the Building Health Initiative in 2014 with Arup as a founding member. (For more information, please visit www.usgbc-ncc.org/buildinghealthinitiative).

Achieving a fully-sustainable hospital requires an integrated team approach, so a series of workshops was organised at the start of the UCSF project to enable the design team and UCSF clinical and operational staff to determine key goals and strategies. Using benchmarking studies of current best practice, leading-edge discoveries from evidence-based design research, LEED guidelines, the Green Guide for Healthcare (www.gghc.org) and the specifics of the site and programme, the workshops delivered the following set of principles. They decided UCSF Medical Center at Misson Bay must incorporate:

- Light and views
- Fresh air
- Green space
- Healthy materials
- Clear wayfinding
- Anticipatory design (or flexibility for future change).

Specific targets that followed from the principles included commitments to create healthy, vibrant habitats to increase biodiversity and a pledge to ensure the project did not use potable sources of water for irrigation. The new hospital must achieve 50% reduction in energy use compared with a typical hospital of similar size and provide abundant access to daylight, fresh air and green space from all patient, caregiver and public areas. A clear, rigorous protocol was to be established for assessing all materials and products used.

Energy and thermal comfort studies
Energy reduction is key to sustainable healthcare design. Although the cost of energy is far less than staff costs, energy costs are still significant in a low profit-margin business.

Arup's engineering, lighting and architectural teams worked closely with the architect to optimise the façade design during the schematic/concept design phase. Common goals of maximising daylight and views, minimising solar gains, and creating a highly thermally and visually comfortable environment were established early in the process to frame an iterative 'optioneering' process whereby various façade designs could be qualitatively and quantitatively assessed and improved.

As the architectural team developed glazing, shading and layout options, the engineering team guided the design with a set of peak load thresholds, each of which – if exceeded – would trigger a more energy-intensive, and physically larger, perimeter HVAC (heating, ventilation and air-conditioning) system.

The lighting team tested the options for natural light levels and penetration, further informing the design with indicators such as the potential for artificial light reductions.

Energy and thermal comfort studies were carried out to highlight the lifecycle, economic, and qualitative benefits of elements such as high-performance glazing and external shades.

3.

Analysing heat gain
Hospitals are 'plug and process load' intensive buildings. Heat gain from loads as they are used over the course of the day and night, affect the sizing and operation of the mechanical cooling systems that maintain patient and staff comfort. Unlike typical office equipment, diversified load information for medical equipment is not readily available. Therefore, traditional methods of accounting for heat gain from these loads is based on rules of thumb, together with conservative safety factors or a summation of name plate power rating.

Overestimating loads results in unnecessarily large ductwork, excessive and under-used airflow capacity and mechanical systems running at non-optimal, part-load conditions most of the time. Seeing the opportunity for energy savings, the engineering team studied equipment heat gain using purchase order equipment cut-sheets, coupled with time-of-use or concurrent-use diversity factors.

These diversity factors were developed through a series of focus group meetings with end-users of the medical equipment specified for the project. This resulted in a more realistic concurrent peak heat gain estimate.

The operating rooms proved to be a particular challenge in terms of predicting equipment loads. Surgeons needed some of these rooms capable of cooling to 65ºF, while accommodating a significant quantity of diagnostic equipment. Working with clinical staff, the engineering team created a spreadsheet of all the equipment with heat gain and diversity factors estimated. Computational Fluid Dynamics (CFD) was used to model two different air supply strategies to check for minimum turbulence over the operating table.

For patient rooms, three alternate air supply systems were studied and compared with the typical constant volume-reheat systems seen in typical US hospitals:

- Variable air volume with exhaust air tracking to ensure the correct pressure differential to the corridor
- Constant volume (fresh air requirement only) with chilled ceilings
- Constant volume (fresh air requirement only) with chilled beams

All systems studied used 100% outside air – a choice which had already been shown to be cost-effective for other hospitals in the San Francisco Bay Area and greatly reduces the risk of airborne infection transfer.

Each system was analysed with different heat recovery options. Variable air volume with run-around coil heat recovery had the best lifecycle cost performance for the hospital, saving more than $3m over the presumed 20-year life of the system, the initial investment costs being recovered within 12.5 years.

Renewable energy
Generating clean energy on-site was a project goal from the outset and the project team recommended 54 photovoltaic arrays with a total connected capacity of 500kW.

They developed a design in which the trellises supporting these arrays have been carefully coordinated around air handling units, exhaust fans and other major rooftop equipment. When installed, the PV panels will provide a visual screening to the air-handling units and shade the roof to reduce summer temperatures at the air intakes.

Therapeutic design
Green spaces at urban hospitals have become increasingly important. In many hospitals lots of patient rooms look on to roof areas typically filled with mechanical equipment. Converting these spaces into rooftop gardens improves the view, but complicates mechanical designs.

At Mission Bay, the buildings are terraced to provide outdoor access at virtually every floor. The extent of rooftop green space is amongst the highest of any urban hospital in the US. There are 24 separate gardens and outdoor areas of respite providing a total green space of more than 1.1 acres on the roofs and 3.2 acres on the ground.

5.

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3. Heat gain from equipment loads in operating rooms was assessed and managed.

4. Clean energy will be generated on-site from photovoltaic arrays on the roof.

5. Younger patients and visitors can enjoy well-planned play areas.

The most important aspect of these roof gardens is accessibility. At a pediatric hospital providing respite for the parents is especially important. At Mission Bay, gardens and outdoor areas of respite are integrated at almost every nursing unit on every floor.

Adding therapeutic garden spaces does, however, increase potable water use. In locations with adequate rainfall – or consistent rain throughout the year – rainwater collection strategies are adequate. But in dry climates or climates with long dry seasons – such as that in San Francisco – rainwater collection becomes untenable due to large tank requirements.

To resolve this problem at Mission Bay, the design team used the cooling tower blow-down as an irrigation water source with minimal extra filtration and some dilution, saving almost 3.5 million litres of potable water per year.

Planting the roofs with gardens provided added benefits in terms of handling stormwater. Stormwater draining from a green roof has higher water quality than that coming out of a typical on-grade bioswale and the flow of stormwater from a roof garden is slowed, eliminating the need for a retention tank. The result is reduced impact on San Francisco's city storm-water system.

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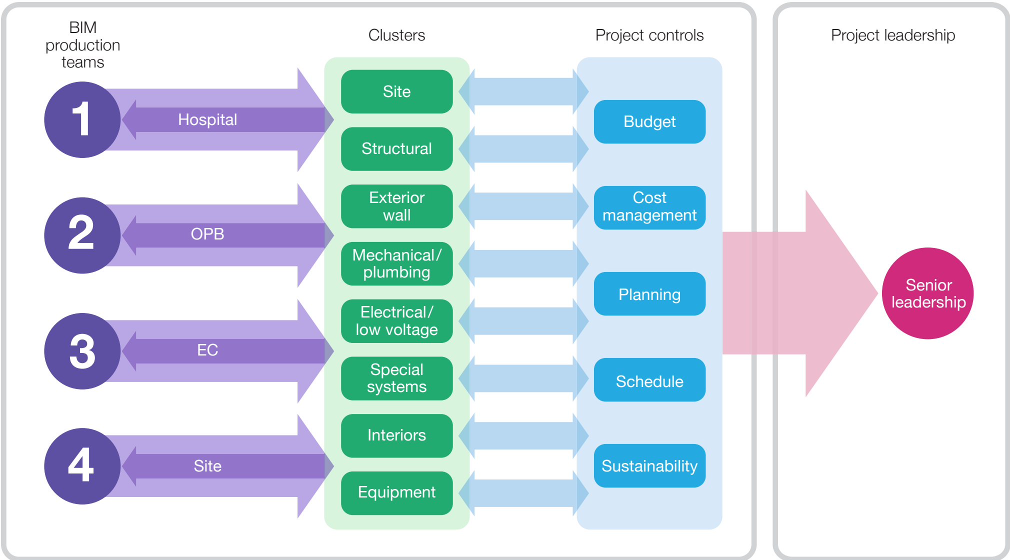

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6. An aerial view of the building.

7. Integrated Project Delivery and BIM meant the project was delivered exactly on schedule.

8. Maximising daylight and views and minimising solar gain were mutually dependent objectives, successfully met.

8.

Integrated delivery

Integrated Project Delivery (IPD) is fast emerging as a proven approach for efficiently designing and constructing large projects. Mostly used in the private sector, it has been comparatively unusual in a public service context. However, UCSF decided on this route for its project, adopting an integrated and highly collaborative approach, combined with Building Information Modeling (BIM).

Based on the best value selection process, DPR Construction was awarded the project in 2008 and 13 key subcontractors for disciplines including MEP, structural steel, precast, exterior glazing, fire and fire alarm, drywall, pneumatic tube, elevators, and control were brought on board. This integrated, collaborative team approach was to be a distinctive feature of the project.

Integrated Center for Design and Construction (ICDC)

In early 2009, the team initiated the creation of a virtual organisation, which included the major subcontractors for MEP, drywall and concrete. A traditional approach of completing design and then cutting costs to meet budget was replaced with an integrated effort to find opportunities to reduce costs through a collaborative process based on specific cost targets by trade. Teams 'virtually constructed' the building looking for ways to optimise coordination, prefabrication and productivity and lean processes.

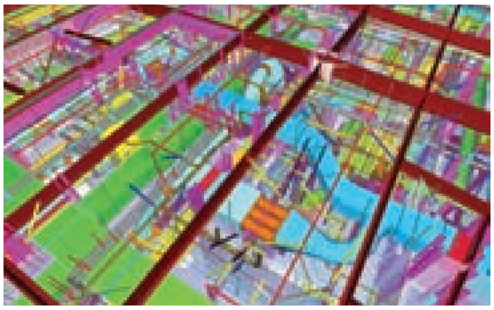
A detailed three-dimensional model was created using BIM. Costs were reduced without reducing performance and the schedule was managed through target costing and the use of *Last Planner*™ techniques.

With the virtual organisation established, UCSF opened the ICDC. Located on the Mission Bay site, the ICDC hosted more than 250 people from 19 firms including architects, engineers, contractors, project staff and subcontractors, working as one highly integrated team rather than individually and sequentially.

The co-location of project participants enhanced collaboration and meant questions were answered and issues resolved quickly and efficiently. In fact, the project team surpassed its goal of getting 60% of questions answered in less than 20 minutes.

9. A BIM diagram.

10. High performance glazing and external shades are key to energy management and thermal comfort.



9.

Last Planner™ BIM techniques were used weekly to identify upcoming commitments, actions and other items - a date was assigned for each - and the outcomes were tracked to determine whether or not commitments were met. Well-run traditional projects improve to a commitment rate of 70 to 75% whereas the UCSF team regularly exceeded its target of meeting 80% of commitments or more.

Detailed BIM

Because a number of key subcontractors were brought into the process nearly two years prior to the start of construction, the project team carried out a virtual build of the hospital, energy center and outpatient building complex in a fully detailed BIM model during the Construction Documents (CD) phase.

BIM for the project consisted of all studs, including king studs, all seismic supports and every piece of backing – levels of detail far beyond the normal coordination and clash detection conducted at the design stage.

For the mechanical (HVAC) trades, it made most sense for the contractors to own the building model and for Arup engineers to document other drawings and specifications, including equipment schedules, details and notes. The team then worked out dates when the mechanical engineers would provide the mechanical contractors with HVAC load calculations, including airflows and terminal box zoning diagrams for each area of each building.

There was a slightly more traditional approach to the electrical discipline drawings. All circuiting was done by the design engineer but along the same project timeline.

The design team had to schedule their work effort to match the construction sequence. Completing detailed design and construction documents in small, 25,000-square-foot batches meant that areas needed to be complete from an architectural design standpoint prior to the detailed BIM effort starting. This created a major shift in the way designs were completed.

This process, and the level of detail required, revealed unnecessary waste much earlier so that the issue could be resolved in BIM well in advance of an in-the-field construction plan being set in motion.

Target costing

One of the ICDC's early goals was to find ways to reduce project costs using a tracking system called Project Modification or Innovation (PMI). Unlike value engineering, which reduces costs by potentially reducing the scope of the design, PMIs reduce waste by finding more efficient ways to meet the scope of the design and thus reduce costs.

For instance, sound attenuators were originally designed into the ductwork to limit transmission of noise between the rooms. However, when all items were reflected in BIM to the level of detail required, it emerged that sound attenuators were unnecessary to meet the sound requirement of the project. Eliminating them saved nearly $1m.

Another PMI was submitted when the process showed that the planned fire alarm system had voice-announcing capabilities and could be used instead of purchasing a separate public announcement system.

The team reached the cost savings target six months ahead of schedule. Approximately 280 PMIs were identified including eliminating redundant items, finding more efficient ways to route pipes and conduit and identifying opportunities to take advantage of market conditions in purchasing.

Contractors and engineers working side-by-side identified opportunities to prefabricate components or even sections of the facility, such as walls with piping and conduit, leading to reduced material and labour costs, less waste and increased productivity for the project.

10.

11.

11. UCSF Medical Center at Mission Bay provides comprehensive services in an environment centred on the compassionate care of patients and their families.

Keys to success

There were many benefits to the integrated approach compared with traditional project delivery. Chief amongst them were:

- Producing a fully BIM-coordinated set of documents prior to construction bid, which helped reduce risks of costs and delays
- Identifying more opportunities for prefabrication
- Reducing the inefficiencies inherent in coordinating a set of documents after bid

The most significant change, however, was in the mind shift required from each team member. Instead of designing in small batches, they had to think in terms of completing a zone at a time with the submittal process being derived from the production schedule. They were successful in this. In the ICDC everyone committed to working together as a virtual integrated organisation to achieve optimum results for a world-class project, setting new standards in project delivery.

Conclusion

Achieving sustainability in large hospitals requires a leadership level of commitment from the owner and the UCSF team clearly demonstrated this. It also requires a holistic approach and a clear plan that integrates sustainable concepts into all aspects of the project from the start of the project, and this was achieved through the ICDC.

In January 2015, UCSF Medical Center at Mission Bay, became one of the first hospitals in California to be awarded LEED Gold Certification (Leadership in Energy and Environmental Design).

It is a further tribute to the success of this project that the UCSF Medical Center at Mission Bay received its certification of completion eight days early and opened to patients on 1 February 2015, on the target date set six years previously.

Authors

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Project credits

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Image credits

1 *UCSF/Mark Citret*; 4, 6 *UCSF, 11 UCSF/Brooke Duthie*; 2, 3, 5, 8, 10 *Stantec and Rien van Rijthoven*; 7, 9 *DPR Construction*.

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