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Front cover:

Melbourne's new Museum against the cityscape (pp28-35)
(Photo: Andrew Chapman)

Back cover:

The Competition Pool and Diving Pool at the Schwimmsportshalle, Berlin (pp39-45) (Photo: J Willebrand)

Arup is an organisation of designers. With its constantly evolving skills base, it works for local and international clients throughout the world.

We shape a better world

Transportation for the Sydney Olympics **3**
Bella Clark
Colin Henson
Andrew Hulse

Colin Henson

Sydney's 'Green Games' prioritised sustainability and public transport. Arup's Australian practice contributed in many ways, including assisting the Olympic Roads and Transport Authority with transport modelling and strategy development, crowd modelling for the principal venues at Olympic Park and elsewhere, planning pedestrian traffic flows at the new Olympic Park Railway Station, and designing cycleways both to link the main sites and provide a long-term legacy of improved cycling provision in Western Sydney.

Manchester Aquatics Centre **9**
Gordon Mungall
John Waite
Andrew Woodhouse

Ian Lawson

Manchester's new Centre is designed to be both a venue for the swimming and diving events of 2002's XVII Commonwealth Games, and a major facility for the local community. As such it includes not only international Competition and Diving Pools, but 'leisure water', a health suite, aerobics facilities, etc. It also has a second 50m pool, the first such-equipped centre in the UK. Arup's design services included all building engineering aspects, plus acoustics, fire, computational fluid dynamics, and materials.

Osaka International Convention Centre **15**
Shigeru Hikone
Isao Kanayama
Tatsuo Kiuchi
Joop Paul
Jin Sasaki

Tatsuo Kiuchi

Due to site constraints, Osaka International Convention Centre houses five major facilities - a plaza, an event exhibition hall, an auditorium, a circular conference hall, and various smaller halls - vertically in a massive 104m x 95m x 59m structure. Its location in a highly seismically active zone demanded state-of-the-art seismic performance-based design by Arup, including the most extensive use in Japan of sacrificial 'unbonded braces' for the main structure, and tuned mass dampers in the auditorium.

Osaka Maritime Museum **21**
Pat Dallard
Mark Facer
Shigeru Hikone
Ryoichi Hirose
Arata Oguri
Jin Sasaki

Katsuhisa Kida

The 70m diameter fully-glazed steel dome of Osaka's new Museum seems to float in its offshore location in Osaka Bay, a landmark to attract visitors from the city centre. Arup designed the structure of the dome and the building superstructure it contains, as well as the mechanical systems to maintain comfort conditions for visitors throughout the year.

Melbourne Museum **28**
Peter Bowtell
Erik Guldager-Nielsen
Peter Haworth
Brendan McNamee
Neil Paynter

John Gollings

The new Museum of Victoria in Melbourne is also a major city landmark. Arup engineers delivered structural solutions for its highly varied elements, including the 140m glass wall and cantilevered canopies of the entrance, the partially sunken IMAX auditorium, the multi-coloured skewed cube of the Children's Museum, the extensive Central Facilities and main exhibition areas, the curved forms of the 'Kalaya' Aboriginal Cultural Centre, and the soaring spaces of the Forest Gallery, housing the living heart of the museum.

Watling House **36**
Simon Barnes
Mick Brundle

Arcaid / David Churchill

Arup Associates' design for this office building in the City of London had to balance commercial considerations and the need to provide a healthy and comfortable internal environment for the building's occupants, with the stringent constraints on its height, massing, and external appearance derived from the location in Bow Lane Conservation Area, close to St Paul's Cathedral.

Schwimmsporthalle, Berlin **39**
Nigel Annereau
Mike Banfi
Adam Chodorowski
Clodagh Ryan
David Wall
Mohsen Zikri

J Willebrand

Like the Manchester Aquatic Centre, Berlin's new swimming facility includes international-sized Competition and Diving Pools, plus a second 50m pool and other training, leisure, and therapy facilities. It forms the other half of Berlin's major indoor sports complex initiated by the circular Velodrome described and illustrated in *The Arup Journal*, 4/1997. Arup undertook the full engineering design of the entire complex.

Transportation for the Sydney Olympics

Bella Clark Colin Henson Andrew Hulse

1.
Olympic Park, Homebush Bay.

Introduction

Sydney hosted the Games of the XXVII Olympiad over the two weeks from 15 September to 1 October 2000, with the Paralympic Games following on 18-29 October 2000. This biggest peacetime event, logistically, on the world calendar required massive investments in time and effort, first to bid for and win the Games themselves, and then to deliver effective transport services.

This article discusses a small selection of the transportation components of projects to which Arup contributed[1].

Sydney transport

Background

In the recent policy document *Action for transport 2010*[2], the New South Wales Government released plans to constrain the current trend in increasing car travel and to improve air quality.

It intends to fund new rail projects with an average annual budget of $300M to 2010, as well as urban light rail, rapid bus-only transit ways, and cross-regional bus services.

The 'Green Olympics' promised by Sydney during the bid to host the Games were adopted as a way to redress the growing imbalance between the road and public transport systems, to cut air pollution, and to protect the environment.

The thrust was to build enduring physical and management legacies from the Games, including a better transport system.

Olympic transportation

The organisation of the Games' transport was too complex to detail here. It was largely planned and managed by government, with many public servants transferred to Games tasks, supported by consultants where necessary.

The Sydney Organising Committee for the Olympic Games (SOCOG) and Sydney Paralympics Organising Committee (SPOC) ran the events at venues planned and constructed by the Olympic Co-ordination Authority (OCA), using transport provided by the Olympic Roads and Transport Authority (ORTA).

Arup staff were seconded to ORTA for over a year, assisting with transport modelling and strategy development right into the Games period, making tactical decisions at the hi-tech Transport Management Centre (TMC).

Detailed models were used to evaluate transport conditions to and at each venue and event by hour of day, and inform decisions on tactical management for the Games and traffic control. These transport models should be of ongoing value for future planning following the Games, and were developed to maximise this legacy.

There were seven main venue precincts in the Sydney region. Preliminary soccer matches were held in other cities, followed by later matches at Sydney Football Stadium[3], and Stadium Australia.

The main site was Olympic Park at Homebush Bay - at the demographic centre of Sydney and 12km west of the Central Business District (CBD).

The venues are normally accessible by car, but none of them offered private vehicle parking during the Games. Travel was free on the Olympic transport system for ticket holders on the current day and up to 4am the next day.

This system comprised the entire CityRail network serving over 300 stations; the Homebush Bay regional bus routes; and shuttle buses connecting the CityRail stations to baseball / softball, beach volleyball at Bondi, canoeing, rowing at Penrith, cycling at the Dunc Gray Velodrome, equestrian, football, shooting, and water polo venues. Dedicated bus lanes and Olympic transport routes were put in place, with special arrangements for mobility-impaired people.

Transportation at Sydney Olympic Park provided for all new venues for:

- The Olympic Opening and Closing ceremonies
- Archery
- Athletics
- Badminton
- Baseball
- Basketball
- Diving
- Football
- Gymnastics
- Handball
- Hockey
- Modern pentathlon
- Swimming
- Table tennis
- Taekwondo
- Tennis
- Volleyball
- Water polo.

The Centennial Parklands in Sydney East hosted the road cycling event. Darling Harbour, where Arup did most of the transport planning when the area was redeveloped from wharves and rail yards for Australia's Bicentenary in 1988, is by the CBD and hosted Boxing, Fencing, Judo, Volleyball, Weightlifting and Wrestling.

The CBD - where most of the landmark buildings are Arup-engineered - hosted the Marathon over Sydney Harbour Bridge and the Triathlon around the Sydney Opera House precinct. Sailing was held on Sydney Harbour, with its many picturesque vantage points. Ordinary harbour traffic, including the Manly Ferry services, was organised to avoid the sailing courses.

2.
Location plan.

Overview of Arup projects

Multidisciplinary Arup teams provided an integrated package for clients on building and infrastructure projects including those listed below - some of them discussed in the remainder of this article. The Arup Transportation Planning (ATP) staff seconded to ORTA were accredited with special security clearances and uniforms to attend the Transport Management Centre operations control room while the Games were in progress.

- Olympic Stadium crowd modelling
- RAS Showgrounds crowd modelling
- Sydney Airport Olympic Coach Park traffic study for ORTA
- Member ORTA Transport Modelling Panel, Micro-scale
- Olympic Village internal transport system studies (IVTS)
- Sydney International Aquatic Centre
- Sydney Athletics Centre
- Dunc Gray Olympic Velodrome
- Olympic Tennis Centre
- RAS Showground Exhibition Halls
- RAS Showgrounds Sports Centre
- Olympic Experience Centre
- Olympic Station pedestrian modelling and fire egress
- Darling Harbour Exhibition Halls
- Olympic Park campus crowd modelling
- Sydney Football Stadium[3]
- Millennium New Year's Eve test events at Circular Quay and Wynyard Stations
- Darling Harbour Olympic Venue traffic management plan and road safety audit
- Campbelltown Sportsground
- Regents Park Olympic Bus Depot
- Sydney Airport
- Olympic Operational Planning Sydney East Precinct Olympic overlay
- Bay to Mountains Cycleway.

3.
Darling Harbour.

The issues

Sydney is a city of almost 4M people with a sophisticated public transport system: about 70% of commuters to the CBD travel by train, bus, or ferry. Atlanta, home of the 1996 Games, has about 1M inhabitants, with less existing public transport.

Whilst most venues were newly built for the Games, the lead time since the bid win was announced in September 1993 permitted 12 major Olympic test events, attracting some 80% of 3.6M patrons by public transport, to be held at most of the venues for over a year ahead of the Games.

These included the Sydney Royal Easter Show agricultural fair, for which Arup undertook crowd modelling for 1.2M attendance (with a peak day of about 300 000), the Bledisloe Cup rugby union with attendance of 110 000 at Stadium Australia, and the Sydney Olympic Park Railway Station, with peak throughput approaching its design capacity of 50 000 passengers per hour.

By declaring school holidays during the Games period, the transport system's capacity was deemed adequate.

The main potential problems for road and rail were the relative lack of redundancy in the transport links, dictated by the historical origins of roads and tramways along ridges between bays, and limited crossings of the Harbour.

During the Games, road closures affected the areas round all the venues. Many had 'Clearway' (no parking) restrictions, and blanket on-street parking bans extended up to 3km from venues to 'park-'n'-ride' satellite car parks.

The main Homebush venue had only 10 000 car parking bays, almost all dedicated for official Olympic and media use.

In key areas like the CBD there were limited road closures to create pedestrian areas, supplemented by bus loops, etc. The Olympic Family of officials travelled from the main accommodation in the CBD to the Homebush Bay venues on road by designated cars or buses, or by water up the Harbour and Parramatta River.

For the first time, virtually all the 10 000 athletes and 5000 officials who look after them lived in one location, the new Olympic Village close to the venues. There was no public access to the Village during the Games (though it is now becoming a residential suburb of Sydney). Up to 12 000 media personnel had to be transported, to cover over 300 events for a global audience estimated at over 3bn people.

4.
Bus access, Homebush Bay.

Olympic Operational Planning

Arup was awarded this consultancy in collaboration with architects Daryl Jackson Robin Dyke in March 1998. The Sydney East Precinct comprised an interesting collection of venues, some already familiar to the Arup team:

- Beach Volleyball - Bondi Beach
- Triathlon - Sydney Opera House (Arup!) and Botanic Gardens
- Road Cycling - Centennial Park to Bronte Beach
- Football - Sydney Football Stadium (Arup)
- Marathon - North Sydney to Homebush
- Interstate football at the MCG in Melbourne (Arup crowd modelling), Bruce Stadium (Canberra), the Gabba (Brisbane), and Hindmarsh Stadium (Adelaide).

Links with the airport

Sydney has only one international airport, linked to the city by underground rail since May 2000; Arup received the highest national awards for excellence in engineering this New Southern Railway.
Sydney Airport is operating close to its notional capacity defined by curfews and noise sharing in normal operation. Despite recent spend rates of millions of dollars per day on airport terminals, parking and two underground rail stations, decades of political indecision over expanding or duplicating the airport continue. Despite 22M passenger movements per year (66 000 per day) and over 50% of Australia's air cargo, Sydney Airport lacks the landside development of the largest hub airports like Atlanta.

The airport gateway was important because 15M out of 20M Australians live more than six hours by road from Sydney, and most international visitors and Olympic Family and freight for the Games had to fly in over long distances. The airport had to handle 150 000 passengers from 200 countries, more than 1100 aircraft on peak days, 7000 disabled athletes and visitors , and 350 horses.

The scale of the task was daunting: transport plans indicated that passengers on the CityRail network over a core 17-day period could more than double - from 14M trips under normal circumstances to 34M from 15 September to 1 October 2000.

The rail network operated 24 hours with almost two thirds of travel directly associated with the Games: 31% involving Olympic venues, 34% Olympic sightseeing, and 35% non-Olympic trips. Almost 6.8M trips were anticipated involving the Olympic Park Railway Station - an average of 400 000 trips per day on 419 timetabled trains per day. There were teething problems with bus shortages transferring from the last days of the school term, but prompt action seconding scores of Government bus experts overcame problems of rostering and dissatisfaction amongst the 4500 Games bus drivers.

Australia's biggest-ever fleet of low floor wheelchair accessible buses was assembled, with 220 accessible buses out of a total fleet of 3350 dedicated buses.

Flows of 500 buses per hour were expected at the Homebush precinct alone. Special legislation was required to transfer accessible buses from regular services to Olympic services.

The stadia at least appeared to offer precisely the facilities required to stage the events, but Olympic requirements are quite special, not least in that over 30 different functional groups had to be accommodated and often segregated.

Arup was presented with several engineering challenges along with the general planning task, and a wide range of skills was applied.

The Sydney Opera House precinct was a splendid arena for Triathlon, but engineering the course and facilities to cater for the influx of people and equipment in this sensitive setting required particular attention. The Moore Park precinct, containing Sydney Football Stadium, had special transportation planning needs for public and private vehicles and for crowd movements.

Arup's studies and designs in these and others areas were fundamental to the process of proving the technical, financial, and operational viability of the venues. They also provided the base schemes and defined the scope for the subsequent detail design, construction, operation, and maintenance packages.

Bondi Beach Volleyball

Beach Volleyball was a major challenge, both technically and in terms of community acceptance. Bondi Beach is an Australian icon, and here a temporary stadium for 10 000 spectators had to be built in a potentially susceptible environment which can sometimes experience extreme weather conditions, has minimal support infrastructure, and is in the public spotlight. There is no rail access and a limited road network to this popular venue and tourist destination. A spectator shuttle bus ran from the Beach Volleyball venue to Bondi Junction station, with separate arrival and departure ranks and a circular route for spectator and workforce buses, accessible pick-up and drop-off, taxis, hire cars, chartered coaches, bicycles, and construction and servicing.

The main transportation planning challenges included maintaining traffic and obligatory pedestrian access during construction, and the approvals process to enable road closures and adjustments to the adjacent intersection configurations. In July 2000 more than 50 000 people finished the annual City To Surf fun run at Bondi Beach, where all the logistics requirements had to be laid over the ongoing construction activities. As an interesting sidelight, a perhaps unique set of beach traffic signals was installed, to advise bathers and walkers when it was safe to cross between the construction site on the beach and the waterline!

6.
Lifeguard, Central Boulevard, Homebush Bay.

5.
Temporary velodrome on Bondi Beach under construction.

The 'Green Games'

Background

In bidding for and winning the Games, Sydney had the active support of many environmental groups including GreenPeace and Green Games 2000. In 1993 the Environment Committee of the Sydney 2000 Olympic Bid prepared the environmental guidelines for the summer Olympic Games as a contribution to the Olympic movement.

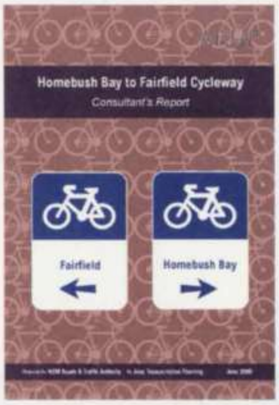
Following Sydney's successful bid, Australian environmental groups decided to establish Green Games Watch 2000 as the community's environmental watchdog for the Sydney Olympics. Its aims included sustainable development, provision and management of facilities, government and industry accountability, and use of international best practice to showcase Australia's environment industries.

Bay to Mountains Cycleway

Through more than 30 cycleway and bike plan projects in Australia, Arup has a pre-eminent reputation in this area. The firm conceived the idea of a cycleway to link local bike plans into a comprehensive plan, and with the CAMWEST bicycle user group was commissioned by GGW2000 to develop the Bay to Mountains Cycleway concept.

The guidelines indicated that, to reduce environmental and other transport costs, host cities should provide cycleways and pedestrian walkways to Olympic sites and link them to public transport interchanges. The Arup report detailed a link from Homebush Bay to the Olympic Mountain Bike venue to safely connect several Olympic venues such as the Dunc Gray Velodrome, as well as provide a longer-term legacy of improved cycling facilities in Western Sydney.

The cycleway passes by the Olympic Bus Depot, Regents Park; Arup was appointed by ORTA to undertake all design and specification of this, the largest Olympic bus facility. Over 1000 buses were parked, washed, security checked, refuelled, and repaired on the site at any one time; the facility operated 24 hours per day and accommodated hundreds of staff and bus drivers. ATP worked closely with other Arup disciplines to provide an integrated design package.



Homebush Bay to Fairfield Cycleway

Consultant's Report

Fairfield ←

Homebush Bay →

Planning for pedestrians

Arup in Sydney is also acknowledged as expert in crowd modelling and movement issues. As well as to transport interchanges, they applied pedestrian models to investigate evacuation from the Olympic Stadium, surrounding venues, and public areas. Co-operating with specialist crowd and venue managers working with the OCA led to very sophisticated investigation devices to improve pedestrian circulation. For example, on peak days at Olympic Park, unidirectional pedestrian streams were encouraged to reduce impacts between streams of people. Whilst this is logical (a traditional example of one-way movement is that of pilgrims at Mecca), informing Olympic crowds for this one-off event required considerable management and communication skills, with public address (PA) systems designed by Arup Acoustics.

At critical flow intersections, such as the main Olympic Boulevard and the exit from the Olympic Park Station to the Stadium, temporary pedestrian bridge flyovers 15m wide were built to grade-separate streams of walkers.

To dissipate crowd pressures at the ticketed venues, and provide foci for revelry, Olympics Live Sites were created - and to bring the excitement of Olympic competition to the streets of the CBD via large video screens.

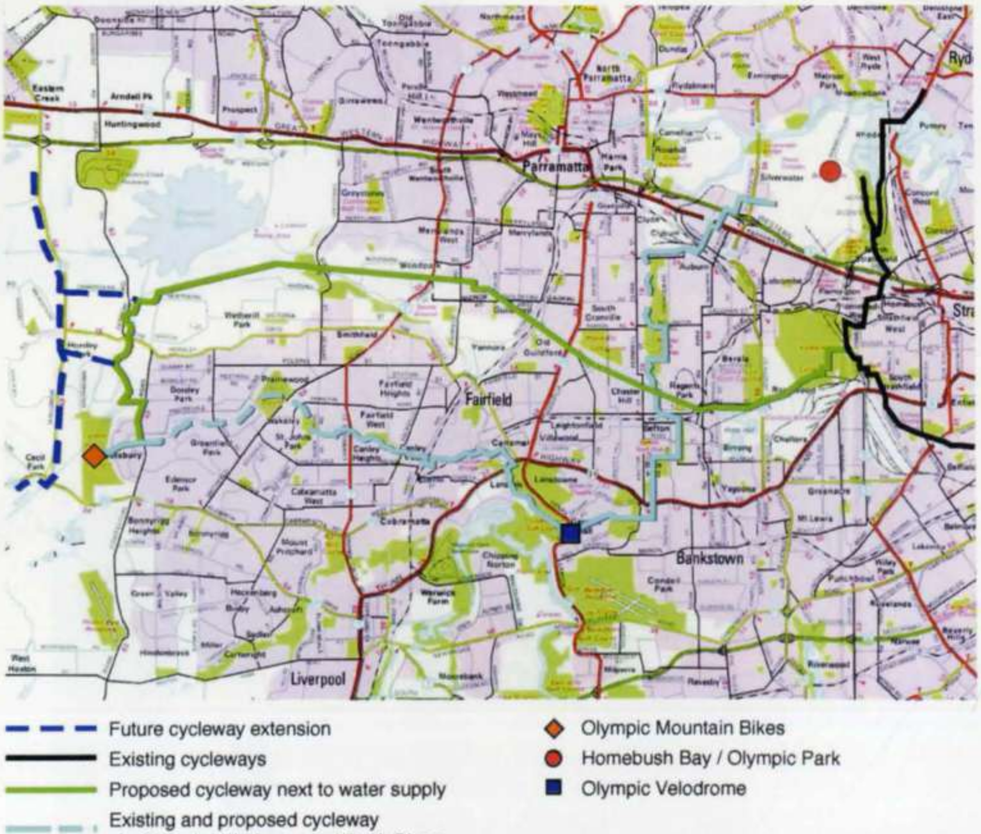
Arup provided crowd movement advice (and acoustic / PA design) on the layout and capacity of three key Olympics Live sites at Circular Quay, Martin Place and Belmore Park / Sydney Central Station. These provided free open-air venues for live entertainment, big-screen TV, al fresco dining, pin trading, etc. The Sydney Symphony Orchestra, Christine Anu, and James Morrison were among the star-studded line-up that performed at free concerts across the city for the duration of the Games within the six Olympic Live Sites. These operated daily until late at night between 14 September and 3 October.

Martin Place presented popular music, cabaret, and comedy from Australian contemporary performers including Christine Anu and Julie Anthony. From 11pm-2am the site was transformed into a dance club with DJs. Alfred Street at Circular Quay had a contemporary circus theme. Australia's finest circus performers, including Rock 'N' Roll Circus and Legs on the Wall, wowed audiences with amazing acts of physical theatre.

Belmore Park presented the best of Australian jazz from artists such as the Bernie McGann Trio, and Ten Part Invention, as well as showcasing emerging local rock / pop bands.

7 left:
Arup masterplanned
the Bay to Mountains Cycleway.

8.
Cycleway routes
for Olympic venues.



Olympic Park Railway Station

Introduction

Arup was commissioned In May 1996 by the OCA to act as consultant for pedestrian modelling issues in the design of the Olympic Park Railway Station. Arup was responsible for identifying how the station could be operated to cater for 50 000 people per hour, the location and size of station elements, and for crowd management advice. Key features of the study included producing a pedestrian simulation model of the station calibrated to Sydney conditions, close involvement with the design team to test and refine station layouts during the design process, and a fire and life safety study using fire engineering principles.

9.
Entrance to Olympic Park Station.

The brief

This is more than just a station: it is at once a gateway to the Homebush Bay Redevelopment, an integral element of Games promises, and part of the Metropolitan network. The OCA required Arup to provide a building which could handle large arriving and departing crowds, satisfy all relevant fire and life safety guidelines, and achieve design excellence. It had to cater for up to 50 000 passengers per hour during the Olympics and 36 000 passengers per hour at other times, and also has to operate safely as a suburban station at times of ordinary low demand. 50 000 arriving or departing passengers can only be moved if trains with 1700 people on board operate at two-minute intervals - nearly equivalent to the combined flow through Sydney Town Hall station in the 3.5 hour CBD morning peak.

Design process

Hassell Architects were assisted by Arup in designing a functional brief for operations and vertical transport elements. The process involved the design team collaborating closely with the client; refining the station layout using PEDROUTE pedestrian simulation software to determine optimum location sizing, crowd densities, and flow rates; calibrating this model to Sydney conditions by measuring crowd movements at Town Hall and Bondi Junction Stations; and passenger loading and unloading time trials using a Tangara double-decker train, with volunteer members of the public representing all age groups and including people in wheelchairs. Arup quickly identified that the only way to move up to 1700 people through the station every two minutes was to have a simple design ensuring that arriving and departing crowds do not mix.

To that end, operational parameters were defined as:

- All passengers would alight from the train to the central island platform.
- Sufficient vertical capacity had to be provided to clear 1800 people in two minutes.
- Departing passengers would board the two trains from the two side platforms.
- Departing passengers would be managed onto the side platforms to ensure that overcrowding did not occur at platform level.
- During periods of low passenger demand, the central platform could be used for arriving and departing passengers.

Fires and life safety

The station was designed using the latest performance-based approach to fire engineering. Arup Transportation Planning and Arup Fire worked together to advise on fire and life safety issues and determined the required safe egress time (RSET) and hence the available safe egress time (ASET). The RSET was determined as 7.6 minutes, calculated by using criteria meeting and exceeding those required by the State Rail Authority.

Allowing for a safety factor, Arup suggested that the ASET of the station should be 15 minutes.

The station's infrastructure includes four escalators, two lifts, four sets of 3.5m wide stairs serving the centre platform, and 2.3m wide ramps, one lift and five 3.1m wide stairs on each side platform.

10 below:
Olympic Park Station, Homebush Bay.

11.
Sydney Olympic Velodrome interior.

The result

The Premier of New South Wales, Mr Bob Carr, officially opened Sydney Olympic Park station in March 1998, describing it as 'a wonderful example of a building of practical use and architectural beauty'.

This assessment was reinforced by receiving in June 1998 the prestigious NSW Royal Australian Institute of Architects' Sir John Sulman award for Outstanding Architecture, and subsequently other prizes.

The station demonstrated its ability over two years of Olympic and test events, including easy access based on consultation with a wide range of people with disabilities. It thus provides an equitably accessible environment for the public, be they parents with young children in strollers, or people with disabilities in mobility, hearing, or vision.

Sydney Olympic Tennis Centre

Integrated design economies by Arup's multi-disciplinary team allowed not only the introduction of the elegant roof and surrounds, but provision of full Olympic-mode seating capacity from the outset, rather than as a later, temporary, addition to the 10 000-seat bowl. This will be described fully in the next edition of *The Arup Journal*.

The complex also includes two show courts, seven other match courts, six practice courts, and a players' facility / administration building, all on a large reclaimed site. The venue hosted the Olympic and Paralympic tennis events, and will become the headquarters of Tennis NSW.

The location of the tennis centre at the busy end of the Olympic Boulevard and across a watercourse required detailed analysis of bus and traffic flows at different event scenarios, and crowd movement analysis of the key flow elements of the ticketing / access controls and the three pedestrian bridges across the wetlands.

12.
Sydney Olympic Tennis Centre.

Sydney Olympic Velodrome

The Velodrome design provides column-free viewing and internal circulation: slender 'V' columns support the ring beam, and brace the most economical of all the large Olympic roofs to the ground.

Despite the structural economy designed in by Arup, the frequent sloping columns around the perimeter constrain pedestrian movement from the elevated concourse.

This required extensive consideration of crowd movement issues both for the non-Olympic and the critical Olympic mode, where the capacity was boosted from 3000 to 6000 patrons by adding temporary stand seating on the concourse level and a raised emergency egress concourse around the perimeter.

A complicating factor was the need to separate seating, gangways, vomitories; and circulation for the 'Olympic Family'; general spectators; OCA secured areas for officials and media; and an 'infield' trackside population.

Crowd travel speeds were calculated and geometries analysed through several iterations with the OCA and Swiss temporary seating contractors, for ingress, egress, and emergency egress. Egress travel time calculations were provided to Arup Fire and discussed as part of their fire safety strategy for the Velodrome.

Persons with mobility constraints such as wheelchairs, and potential conflicts with traffic and parking around the Velodrome, were considered.

Paralympic Games

Immediately following the Olympics, the Paralympics exceeded all expectations, with 1.4M tickets sold. This provided an unexpected transport challenge as the Paralympic transport budget was a small fraction of that available for the Olympics, and many of the tickets were ground passes, with no control over times of arrival or departure.

The city was back at work and school, with full commuter loads on roads, buses and trains. The dedicated team of 50 000 Olympic volunteers again saved the day, keeping people informed, guided, and entertained with good humour. Even the cynics and those feigning lack of interest were again caught up in the spirit, and the proud achievements of people with disabilities.

Conclusion

The world inevitably focused on the Games' athletic feats, without much attention to the 'hardware' of Games transportation - railway stations, bridges, and buses.

However the enduring 'green' legacy for Sydney and international visitors will be the emphasis on public transport and walking as an enjoyable way to travel for cultural and sporting events throughout the metropolitan area. The mode shift from private to public transport, already sustained during the two years of Olympic test events, has exceeded all expectations. A major factor in this shift has been public acceptance of new transport systems and management. Juan Samaranch proclaimed the Sydney Games 'the best ever'.

In managing all forms of transport, the Games provided an exciting focus for all the transport agencies and professionals to set an enduring example to the world.

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(3) THOMPSON, P, *et al.* Sydney Football Stadium. *The Arup Journal*, *24*(1), pp5-10, Spring 1989.

Credits

Clients:
Olympic Co-Ordination Authority
Olympic Roads and Transport Authority
Transport consultant:
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Illustrations:
1: *Sydney Morning Herald*
2: Claire Noble
3, 7, 8, 10: Arup
4, 6, 9: Colin Henson
5: Richard Drew
11: Peter Bailey
12: Peter Hyatt

Manchester Aquatics Centre

Gordon Mungall
John Waite
Andrew Woodhouse

Introduction

2002 will see the XVII Commonwealth Games held in Manchester, England; there is already activity, and a buzz of expectancy in the air.

Hosting these Games has pushed the city to invest heavily (supported by Sport England through National Lottery funding) in new world-class facilities like the Manchester Aquatics Centre, completed in July 2000.

Funding for it was supplemented by the City Council and three universities (Manchester University, UMIST and Manchester Metropolitan University). The Centre is less than a mile from the city centre, at the focal point of the three universities.

A key driver of the development was to provide a successful facility for the local community, with the flexibility to become a venue for 2002's swimming and diving events.

The business plan thus developed around a public facility and not a major venue location - swimming events generally attract relatively low spectator numbers. The building design and architecture had to embrace the need to adapt to the Games' requirements, whilst providing health and fitness facilities for public usage to increase revenue potential.

In 1996, Arup was invited and ultimately appointed to join Newcastle-based architects FaulknerBrowns* - building on the team pedigree established on the Ponds Forge International development in Sheffield which hosted the XVI World Student Games in 1991[1]. This saw Arup's Manchester and Newcastle offices working together, respectively producing the structural engineering and the mechanical, electrical, and public health engineering designs.

Other Arup specialists advised in key areas: building and electro-acoustics, fire, computational fluid dynamics (CFD), and materials selection and specification.

The original concept included the Diving Pool (25m, with movable floor) and main Competition Pool (Olympic-sized 50m, eight lanes, with two sections of movable floors and booms) required for the Games, supplemented by an area of 'leisure water', health suite, fitness suite, aerobics studio, crèche, administration, and catering facilities.

1.
The additional 50m training pool in the basement.

Procurement strategy

The City Council carried all the financial risk, even though they provided only 20% of the funding, so they desired a design-and-build contract to reduce their financial risk. Sport England, however, thought that this would not secure satisfactory quality on such a complex project. If design-and-build was unavoidable, the client and design team wanted contractor input as early as possible.

At scheme design stage, the Council tendered for a buildability consultant to advise on detailed design. Following this input, the Council set up a two-stage tender for a fixed price design-and-build contract. The first stage was based on preliminaries, mark-up fees, statement of methods, and suitable experience; the second was to procure the sub-contractors and value engineer the works packages in association with the appointed contractor.

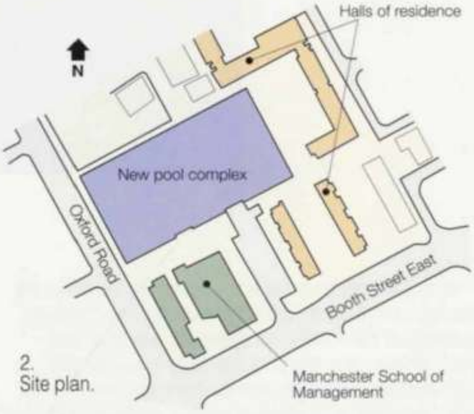
After these two tenders, a £22.5M contract was awarded and the design team, except for the quantity surveyor, was novated to the contractor.

Coincidentally Laing succeeded in winning the buildability role, and also the construction contract.

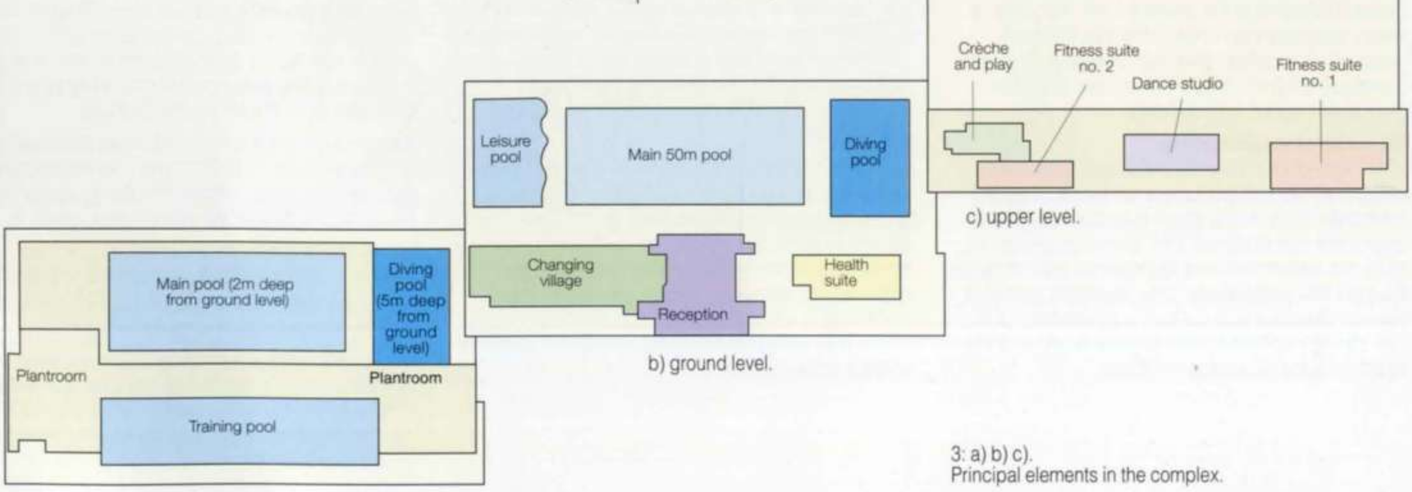
This method proved successful, leading to project handover 10 weeks early. At a late stage the successful operator added additional fitness areas in lieu of the crèche, but the fees and additional contract value for this were funded separately by the client. The early appointment of major subcontract elements like the mechanical and electrical services allowed builderswork information to be confirmed early in the process, assisting the structural design.

At the same time as the initial design, the Amateur Swimming Federation of Great Britain (ASFGB / English Institute of Sport) was seeking high quality training facilities for Britain's top swimmers.

It proved possible to excavate additional basement area to include a second 50m pool (four-lane with a movable floor over half its length), together with specialist land training and sports science / medicine areas. Although this was achievable, it imposed significant pressure on the size and location of the mechanical, electrical, and water treatment plant areas. However, the design was approved and additional funding was arranged.



2.
Site plan.



c) upper level.

b) ground level.

a) basement level.

3: a) b) c).
Principal elements in the complex.

4.
Architect's perspective of roof structure.

Notable features

- The Centre is the first such complex in the UK with two 50m pools.
- It is believed to contain the world's largest area of movable floors and booms which can be reconfigured to form pools of varying sizes and depths, aimed at maximising flexibility of use and hence revenue.
- The building form reflects the requirements of the diving platforms and controls the acoustics.
- Floodlighting is positioned to avoid unwanted reflections, to enable ease of maintenance, and to meet the requirements of FINA (Fédération Internationale de Natation Amateur).
- Energy conservation measures include small-scale combined heat and power and desiccant dryers.
- The site is extremely confined.

Enabling works

An existing student hall of residence had to be demolished to allow the landmark building to be 'eased' into the student heartland, neatly bounded by other halls of residence, university faculties, and the busy Oxford Road.

These works also included construction of a multi-storey car park (1000 spaces), for pool users and staff and students of the University of Manchester.

One major constraint on the site's southern boundary was the 'Works 4' sewer, one of Manchester's main sewers, which runs the length of the Centre's southern elevation. It is around 15m deep, oval in cross-section, and about 3.4m high. Special permission was needed for the foundations to be located adjacent to the sewer's outer line. Also, a new connection had to be made into the brick sewer to take surface and foul discharge from the development (including 50 litres / sec from the backwashing of the pool filters).

Structural engineering

The 110m long, 55m wide building is contained under a single superstructure envelope without a movement joint. At the apex, over the 10m diving board, the roof is almost 20m above ground level, while the basements and foundations are 7m below the pool hall water levels. The geometric profile of the roof structure was set by the constraints of the site, diving platform spatial requirements, and the need for good spectator sightlines.

5.
Craning in a complete pair of main ribs.

The roof structure spans from masonry-clad concrete towers on the south elevation over an intermediate support at the rear of the spectator seating, and then arches over the pool hall onto thrust blocks founded 5m below ground on the north side. The main roof is supported by four pairs of main semi-arch ribs, cross-braced across its full width. The form of these ribs changes about the apex of the building from tapered plate girders on the visible north side to truss rafters above the acoustic ceiling.

Along the centreline of the Competition and Diving Pools, a ridge box truss connects the main ribs, and supports intermediate plate girder ribs spanning to the north side. The roof structure is completed on the south side by long span beams between the main ribs. To allow air flow to the underside of the roof lining, the purlins are spaced off the liner using discontinuous profiled T-sections welded to the purlins.

To avoid bracing to the lower plane of the roof elements, restraint to the bottom chords is provided by the roof purlins through U-frame action - achieved for the plate girders by site welding the CHS purlin elements to the webs, which were then stiffened to the bottom chord level. These stiffeners were also used to disguise the joints in the web plate to maintain a clean crisp structure. Most of the site welding was done at ground level and the main ribs then lifted in complete pairs.

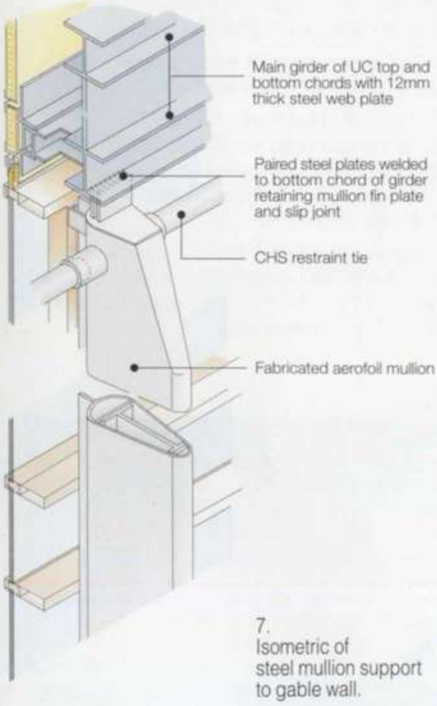
An in situ concrete frame and thrust blocks support and stabilise the roof structure. This frame carries the changing area, spectator seating, upper level fitness facilities, and the leisure pool, which is partly suspended.

The late addition of the basement training pool meant the removal of a planned line of columns and the introduction of long-span beams.

There are no movement joints within the main roof and concrete structures. Instead, thermal / shrinkage control joints are provided around all the one-piece concrete pool tanks which are cast on slip membranes.

6.
Flume access stair.

8.
The diving pool.



7.
Isometric of
steel mullion support
to gable wall.

All pool tanks were designed as water-retaining structures and were cast to a specific design sequence to avoid early thermal shrinkage cracking. The profile of each pool tank is punctuated by recesses for the submersible booms, water supply trenches, windows, and ladders.

To permit the thermal and deflection movements of the semi-arch shaped roof, the glazed gable walls are supported from aerofoil mullions restrained laterally at their head. The connection allows both vertical and horizontal movement with the plane of the mullions stabilised by the CHS tie element which follows the roof profile. Under longitudinal thermal movements the glazed wall simply moves out of plumb. The mullions also provide support for the external cleaning walkways.

Most of the publicly visible reinforced concrete elements are concealed by finishes; however, the diving boards and flume stair dominate the internal gables of the arena. At the west gable the flume access stair rises from the poolside slab to the top landing platform. The main C-section structural column is all the more dramatic as it is supported from a poolside transfer structure bridging the plant space below.

The diving boards are a development of those used at Ponds Forge and include one of the world's first 3m wide, 10m boards, to permit synchronised diving events.

Acoustics

Nick Boulter Raj Patel

Pools inevitably have a long reverberation time because of the hard surfaces and large volume. Here, the scope to incorporate acoustic treatment was limited, and so the absorptive surfaces had to be very effective. The team decided to use the roof deck for acoustic absorption. By perforating the inner liner sheet, the mineral wool for thermal insulation could also be made to absorb sound. Doing this, however, reduced the liner sheet's structural strength, which limited how much perforation could be accommodated.

The design team undertook a series of acoustic tests to determine how effective the perforations would be, and these showed that additional absorption would be required.

Previous experience indicated that the international standard for acoustic tests could over-estimate performance, and so these tests were conducted using a method that better reflected the actual installation. These demonstrated that the real performance would be significantly less than published data indicated. The shortfall was made up with baffles hung over the seating area. The Centre is close to some student residences and it was important that noise from the complex did not disturb them. A noise survey ascertained existing external levels around the building, but whilst this was useful in setting limits for noise generated by the pool activities and associated plant, it was important also to allow for the effect the pool structure would have on the noise climate. The building envelope would screen the noise of traffic, etc, behind the pool, so it would be much lower than measured during the survey. The effects of this were taken into account when setting criteria for noise leaving the pool complex.

Although noise from the services was the primary concern, the potential for noise breakout from cheering crowds and from music used in the aerobics facility were also considered.

Voice alarm

To comply with building control requirements, the voice alarm (VA) system is fully integrated with the fire detection systems. The VA system loudspeakers are also utilised for public address purposes. In the Competition Pool, coverage is by nine co-entrant high directivity horn loudspeakers mounted from the central roof gantry. Co-entrant horns have an extended frequency range that delivers highly directed and natural-sounding, intelligible speech for emergency broadcasts. The extended low frequency response ensures that the system is also suitable for music - important during competition events such as synchronised swimming, as well as for crowd entertainment during breaks in events.

As well as these loudspeakers, connection points are provided along the poolside wall for underwater loudspeakers, which are weighted and dropped into the pool (one loudspeaker at each end) for specific events.

Headworn radio microphones with a single earpiece are provided, which allow a commentator or announcer to be anywhere in the pool area and talk at normal speaking volume without feedback in the system.

This is useful for training purposes, allowing coaches to walk up and down the poolside providing instruction on training technique. The system is replicated in the training pool.

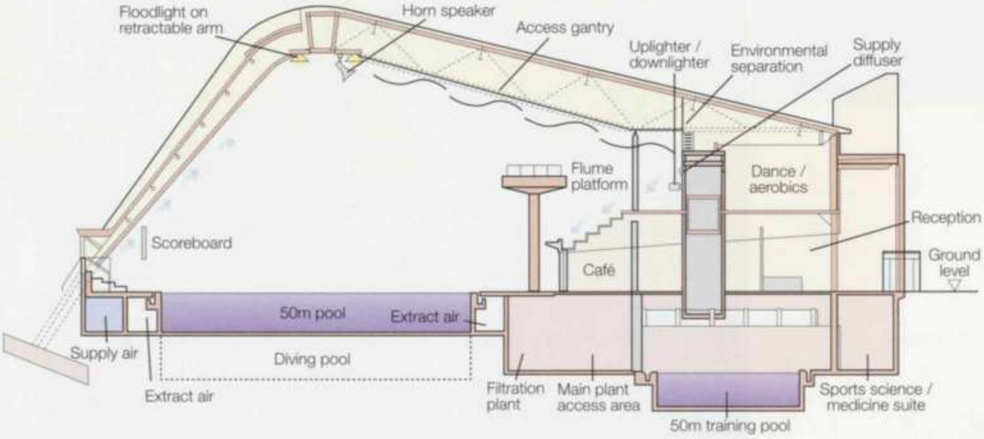
9.
Acoustic baffles over the main pool.

The Competition Pool has an independent fixed lifeguard microphone.

The VA system can isolated via a key switch on the main fire panel. When in isolated mode, in the event of a first-stage alarm a coded message goes to all areas of the building, before any automatic emergency messages are broadcast to public areas.

This ensures that staff respond and take up predetermined evacuation locations, and allows a response period for the location of the emergency event to be checked.

The 'event' manager (ie Chief Fire Officer) decides when to evacuate and whether to do this via pre-recorded messages or by live broadcast via the fireman's microphone.



10 left:
Cross-section through main pool.

Environmental engineering

The primary challenge for the mechanical engineer in the pool design was providing ventilation to control evaporation from the pools and protect the building fabric, whilst ensuring satisfactory conditions for the wet bathers.The trend for warmer water temperatures and consequent warmer air temperatures (1°C > water temperature) results in increasing evaporation rates.

With water temperatures of 29°C, the calculated evaporation rate at maximum bather activity for all the pools is approaching 0.5 tonne / hour!

Another serious issue is the durability of materials in pool environments, given their potentially corrosive nature. To address these issues, Arup developed the successful integrated engineering approach used previously on the Ponds Forge Project, utilising builderswork ducts to provide air distribution routes to and from the main pool hall. Warm dry air is delivered up the building envelope fabric and return air is pulled from low level at the point of maximum contaminants through the deck level grating. CFD analysis was used to check that air temperature and velocity distributions in the pool hall were within acceptable limits.

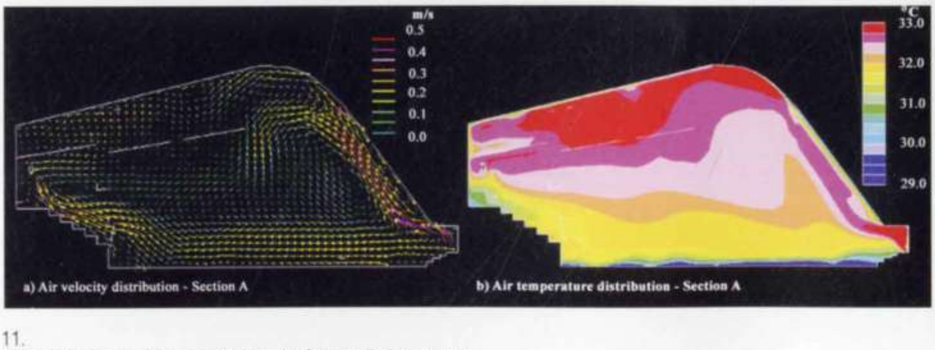
To remove evaporated moisture from the pool hall, the plant was sized (for 'fail-safe' reasons) to achieve this by utilising full fresh air. This, however, is not an economic solution and desiccant dryers were incorporated to maximise the volume of recirculated air with adjustable minimum fresh air rates to suit bather density via CO_2 sensors.

A small-scale CHP (combined heat/power) unit) is installed to reduce running costs. The building's performance was modelled utilising the BEANS programs to identify a suitably sized unit to operate 365 days/year. A packaged 300kW(e), 410kW (th) was selected and incorporated in a dedicated acoustic enclosure. The CHP installation was an early target for value engineering, and the client decided to lease the equipment rather than purchase it as originally envisaged.

The unit operates as the 'lead' heat generator, supplemented as necessary by the boilers.

The basement plantrooms contain the main mechanical and water treatment plant. One criterion in the layout of this area was that a 3m x 3m corridor had to be provided to allow removal or replacement of filter vessels if necessary.

The training pool effectively splits the basement into east and west zones, with a linking 'corridor' housing some of the filter vessels and principal services distribution routes.



a) Air velocity distribution - Section A

b) Air temperature distribution - Section A

11.
CFD analysis of winter conditions with full ventilation system.

Fire safety design

George Faller

From the fire safety perspective this is a 'public assembly' building, accommodating a significant number of people, mainly spectators, beneath a sealed roof enclosure. There is prescriptive guidance that covers a generic 'public assembly' building, but none that recognises the distribution of fire loads and public areas to be found in such a pool arena. The 'public assembly' code was thus used for guidance, but the actual nature and use of the building was taken into account in developing a rational fire safety design.

The principal benefits of using a fire engineering design approach were as follows:

- The fire safety design had to take into account that during the Games there will be many more people than normal using the pool arena.

  Instead of designing the fire safety systems to cope with this one-off situation, the large population will be accommodated by a package of temporary measures, some only available for the duration of the Games.
- An extended evacuation time (reduced escape widths) was agreed, based on the low risk of fire developing, and the large building compartment volume.
- The large compartment volume - more than recommended in the Approved Document (AD) 'B' - was appropriate in view of the low fire risk within the enclosed space.
- Compartmentation between the plant area and the public pool area was eliminated by adopting special precautions to control the spread of fire from high-risk areas. This assisted the mechanical design by negating the need for fire dampers which would have been subjected to the pool environment and consequent corrosion / failure.
- The large natural smoke reservoir created by the roof volume enclosure was shown to be sufficient to maintain the smoke above head height for significantly longer than the calculated evacuation time.
- Due to the small fire load in the plantroom and the restrictions imposed by site boundaries, it was agreed with Building Control that the area of natural ventilation to the basement could be less than that recommended by AD 'B'.
- The 'fire break' afforded by the pool between areas of fire load and external façade made it possible to reduce the recommended separation distances between the complex and surrounding buildings without having to protect façade openings.

Electrical engineering

The complex is served by a 6.6kV dual supply intake connecting to a single 1250kVA rated cast resin insulated transformer. Maximum demand is around 1100kVA, which is also supported by the CHP set synchronised with the mains supply at low voltage. The containment for all distribution in the pool environment uses uPVC and GRP high impact heavy duty material to prevent risk of corrosion.

Lighting pools poses its own problems. Great care must be taken to minimise glare, whilst the components need to be suitably selected to withstand the warm and potentially corrosive environment. In the pool hall 64 units cater for both major events and everyday local community use. The leisure pool, Competition Pool, and Diving Pool areas are illuminated to the required levels by 1000W metal halide and 400W SON floodlight units mounted on a central overhead gantry, positioned to avoid specular reflection off the water from the light sources. Avoiding reflection is important to the safe operation of the pool, ensuring good visibility to all areas of the pool floor by life-guards and optimising spectator viewing. The main metal halide floodlights are fitted with toughened diffused glass lens units to control glare - a design consideration for backstroke swimmers. Each floodlight is mounted on a specially designed purpose-made retractable arm bracket which allows easy lamp replacement from the gantry. Switching patterns can be controlled to pre-set levels to meet FINA requirements.

12.
Floodlighting in the main pool.

Supplementary temporary floodlighting will be required for TV filming, and structural support has been incorporated to facilitate this during the 2002 Games and any other TV-covered events.

Feature lighting is provided by metal halide floodlight units, fitted with filters and located on the gantry to wash parts of the roof structure with colour. The leisure pool area is also fitted with clusters of basin-mounted submersible SELV 12V dichroic light sources operating within a specially designed outer casement which allows water movement to maintain low surface 'touch' temperature for bathers.

General lighting to the training pool comprises low glare recessed fluorescent IP-rated luminaires integrated into a waved ceiling, and perimeter wall-mounted metal halide uplighters aimed to spread light onto the waved ceiling before reflecting onto the pool surface. Lighting control allows for 300lux and 600lux average lighting levels, the upper level being a recommendation from an adviser to Manchester City Council for specialist training pools. Replacement of lamps is from the floating floor or traversable boom.

To control glare from direct sunlight and daylight into the pool hall, integral sealed window blinds are provided on the north, west, and east façades. Each blind system is operated by IP-rated motorised control units linked to master controller stations strategically located around the pool hall. The rooflights are on the north side of the roof and are opaque.

External feature lighting creates a significant impact. The north roof is washed with blue, whilst the front elevation uses encapsulated fluorescent tubes to bathe the entrance area façade in green. Feature external street lighting and several wall wash lights highlighting the sandstone elements, complete the visual welcome to Manchester's new state-of-the-art aquatic facility.

Reference

(1) BROWN, M *et al.* Ponds Forge International Sports Centre. *The Arup Journal, 26*(2), pp3-9, Summer 1991.

Credits

Client:
Manchester City Council Special Projects Group, in conjunction with Manchester University, UMIST and Manchester Metropolitan University

Architect:
FaulknerBrowns*

Engineering design:
Arup Nick Boulter, Mark Brown, Mike Buckingham, Sarah Clemmetsen, Jane Collins, Alan Dunlop, George Faller, Graham Gedge, John Gregory, Dennis Harrison, Nigel Harrison, Yasmeen Harrison, John Hopkinson, Richard Morris, Gordon Mungall, Raj Patel, Colin Peart, Steve Shaw, Craig Taylor, Pat Thorpe, John Waite, Gary White, Andrew Woodhouse, Darren Woolf

External works contractor:
MEDC

Quantity surveyor:
Tozer Capita (pre-contract)

Pool water treatment,
and movable floors and booms:
FES

Planning supervisor:
Dobson House Consultants

Main contractor:
Laing Ltd

Illustrations:
1, 6, 8, 9, 12-14: Ian Lawson
4: FaulknerBrowns*
2, 3, 7, 10: Claire Noble
5: © Laing Ltd
11: Darren Woolf

13 and 14.
External lighting on three façades.

Osaka International Convention Centre

Shigeru Hikone
Isao Kanayama
Tatsuo Kiuchi
Joop Paul
Jin Sasaki

1.
Aerial view of OICC against Osaka City centre.

Introduction

The Osaka International Convention Centre (OICC) in Nakanoshima, Osaka, Japan, opened to the public in March 2000. The building comprises five major facilities - a plaza, an event exhibition hall, an auditorium, a circular conference hall, and a variety of medium and small conference halls.

Due to the area restrictions of the site, these various components were planned vertically rather than horizontally. For a complex of this type, such a design solution is extremely unusual, and perhaps unique. As a result, the final design comprised six supporting structural cores, one at each corner and one at the midpoints of the long sides, with a total height of 104m.

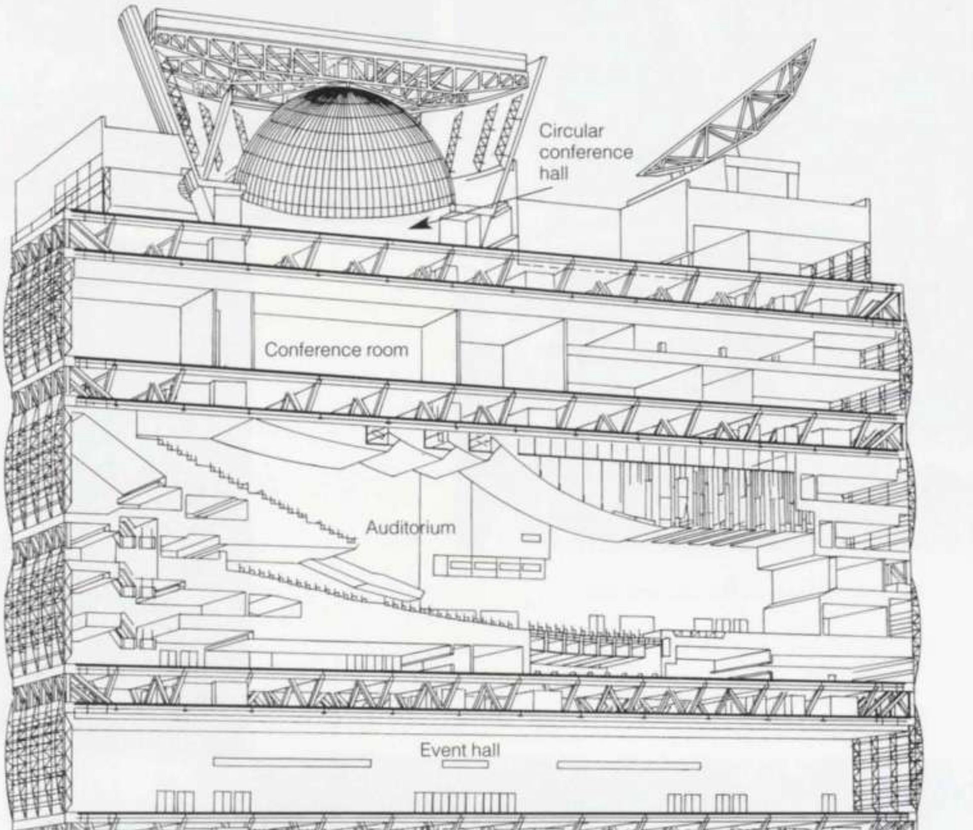
There are 13 levels, and spaces within the single-storey deep supertrusses at every third level are used for the mechanical, electrical, and public health installations. The building is rectangular in plan, 95m x 59m, and has a plot area of 6756m^2 and a total floor area of 67 545m^2. The budget was around US$500M.

The project originated from an architectural design competition held in 1994 and won by the Kurokawa Epstein Arup Consortium, comprising Kisho Kurokawa Architect & Associates, A Epstein & Sons International, and Arup in Japan as structural and seismic engineering designer.

For the project, Arup drew on its 'seamless' design approach. Various parts of the firm worldwide supported the Japanese office, including members from Hong Kong, London, and Birmingham, embracing structural, seismic, and geotechnical expertise. The structural and seismic design was reviewed by the Building Centre of Japan (BCJ) and approved by the Ministry of Construction - as is standard practice for Japanese buildings over 60m tall.

The OICC was the first Arup Japanese project to receive BCJ's technical appraisal for high buildings.

Arup's Japanese office supervised the site from the commencement of construction in November 1997. The project was built by a joint venture of 10 companies, led by Takenaka Corporation, Osaka.



2.
Schematic section through OICC showing principal internal spaces.

The building

The ground floor extends upwards for two of the 13 levels, and is a virtually column-free space; it includes a public open plaza with a 15.5m high ceiling and a circular stage 9m in diameter.

The event exhibition hall, from the third to the fifth levels, has a floor area of 2600m², which can be partitioned into two or three sections. Here, the floor loading intensity is 10kPa (1 tonne/m²), and the ceiling height is 9.4m.

Above this, the auditorium, accommodated within the sixth to ninth levels, is a theatre-type, multi-purpose hall, seating 2754. Its movable stage can be arranged in an end or centre configuration, and the entire auditorium can be partitioned into two.

On the 10th floor are conference rooms including one seating 600, though combinations can be made that accommodate up to 1000 people, thus creating a space suitable for use by international conferences.

Above again is the circular conference hall on the 12th floor; this is about 23m in diameter, with an area of 393m². Its domed ceiling rises from 4.6m to 16.8m. This spacious hall accommodates up to 550 people and features some of the most advanced, state-of-the art conference amenities and equipment. Finally, there is a heliport on the roof above this hall.

The structure

The six 14m x 12m structural cores at the corners and the midpoints on the long sides have concrete walls up to the first floor, 1.5m above ground.

The main frame of the superstructure consists of 1.2m x 1.2m steel H-section columns, with flanges and webs up to a maximum thickness of 80mm. The high strength, heat-treated (quenched and tempered) steel has a tensile strength of 590N/mm². The steel of the beams and the one-storey deep 'supertrusses' has 520N/ mm² tensile strength.

At every third level, these supertrusses span between the cores, with intermediate floors either hung or propped from them to create column-free spaces. The structure utilises 'unbonded braces', a system of passive seismic energy absorbing devices developed by Nippon Steel Corporation. These provide hysteretic damping and limit the force levels generated in non-sacrificial structural elements.

Each of the six structural cores consists of columns, beams and unbonded braces. The cores are connected to each other by more sets of 20m long unbonded braces, spanning two floors and providing horizontal resistance.

The total weight of steelwork, including secondary steel, is approximately 34 000 tonnes.

3.
The completed building from the north east.

5.
The plaza at night.

6 below:
The auditorium.

4.
The event exhibition hall.

7.
The auditorium stage.

Kobe earthquake 1995

The Asia-Pacific region has high seismic activity; Japan is on the eastern edge of the European tectonic plate and bounded to the east and the south by the Pacific and Philippine plates.

The Kobe earthquake of 17 January 1995 had its epicentre on the north side of Awaji Island, only about 60km from the city, with a magnitude measuring M=7.2. The peak ground accelerations were large both horizontally and vertically, with a duration shaking of 10-15 seconds. The peak ground acceleration measured at Kobe Meteorological Observatory was 818gal (cm/sec^2) or 0.8g.

Damage to steel structures from brittle fracture was reported, with the main source of the damage observed to be large inelastic deformations concentrated in column and beam ends, as well as cracks in or near welding sites.

At that time designers generally assumed that, in an earthquake, plastic hinges form in beams and thereby dissipate energy. This assumption became dubious, however, after results from the Kobe earthquake were examined. In many instances, connections did not behave in a ductile manner, and fractured unexpectedly.

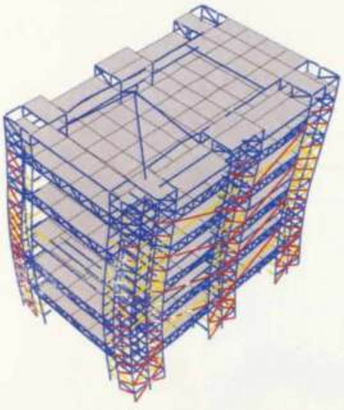
The ductility of materials is expressed as a yield ratio, a ratio of displacement at ultimate tensile strength to yield strength. However, no consideration had been given to material fracture toughness, and in the context of an earthquake, materials must have both a good yield ratio and fracture toughness to ensure ductile behaviour.

Arup's challenge in the seismic design of the main structural frame of the OICC was to achieve both damage control and ductile behaviour, whilst avoiding brittle fracture of connections.

Seismic performance-based design

In Japan, the basic seismic performance criteria for designing buildings which exceed 60m in height are outlined in a guidance paper issued in 1986 by the High Rise Building Appraisal section of BCJ[1].

Two seismic events, commonly referred to as 'Level 1' and 'Level 2', must be considered. The specific intensity of these events varies with geographical location, but qualitatively, 'Level 1' represents an event which may occur more than once in the lifetime of the building, while 'Level 2' represents the maximum intensity of seismic event which has occurred at the site in the past or which may possibly occur in the future. In turn, the performance of the structure under a Level 1 event is limited such that '... *the building shall not be damaged and the main structure shall behave within its elastic limit...*' while for a Level 2 event '... *the building shall not collapse, or cladding fall, etc, such that there is a threat to human life.*'



8.
LS-DYNA 3D model
showing OICC's seismic performance.

However, in the aftermath to the damage observed at Kobe, the performance criteria were redefined, together with the inclusion of two additional design events, 'Level 3 earthquake' and 'active fault effect', as follows:

'The building should be fully operational under a Level 1 event, represented by an earthquake with a peak ground velocity of 20kine (cm/sec):

- *no damage to structural elements*
- *plasticity only to be permitted in the unbonded braces*
- *no damage to non-structural elements*
- *storey drifts limited to less than 1/200* ['storey drift' is the relative horizontal displacement between the upper floor and the floor of each storey.]

The building should remain operational under a Level 2 event, represented by an earthquake with a peak ground velocity of 40kine (cm/sec):

- *damage to be light, requiring minor repair*
- *beams permitted to form plastic hinges*
- *no plastic hinges permitted in columns*
- *storey drifts limited to less 1/100*
- *storey displacement ductility limited to less than* $\mu_\Delta = 2.0$.

(μ_Δ = *the ratio of storey ultimate displacement to storey yield displacement)*

Following a 'Level 3' earthquake, defined by a peak ground velocity of 60kine (cm/sec), the building should ensure the life safety of its occupants:

- *damage to be moderate, requiring repair*
- *some building systems to be protected.*

Under the 'near active fault' phenomenon, characterised by a single impulse with a peak ground velocity of 80kine (cm/sec), collapse prevention should be achieved:

- *structural collapse should be prevented*
- *non-structural elements may fail.'*

3D non-linear finite element time history analysis

To simulate the performance of the building during a large earthquake, Arup carried out several three-dimensional finite element time history analyses using LS-DYNA 3D. This advanced software is more commonly used to model highly complex non-linear behaviour, such as collisions in the automotive industry and virtual prototyping of fuel flasks in the nuclear industry.

The OICC project, however, represented the first major civil engineering application of LS-DYNA 3D. Another program, NASTRAN, was utilised for all linear design check analyses, while an LS-DYNA model, incorporating 10 000 non-linear elements to capture the potential inelastic behaviour of all structural members, was developed in parallel to validate the non-linear seismic performance of the building. Ground motions, comprising horizontal and vertical components with standardised peak ground velocities of 20, 40, and 60kine, together with a pulse signal representing the potential near fault phenomena of the active Uemachi Fault in Osaka city, constituted the suite of input time histories for validation of the seismic performance.

Part of this suite included the Fukushima (N-S) signal, recorded in the free field close to the site during the 1995 Kobe earthquake. However, to assess the significant soil / structure interaction in the deep piled basement, input signals for the time history analyses were applied at the base of the piles. To ensure consistency with the Fukushima free field site response, it was necessary to deconvolve this signal to the base of piles level. These site responses were assessed by Arup geotechnical specialists in Hong Kong using the program SIREN, which analyses the response of a one-dimensional soil column when subjected to an earthquake motion input.

'Damage-tolerant' design

'Unbonded braces' are passive devices which absorb seismic energy efficiently during an earthquake. In the 'damage-tolerant' approach to design adopted for the OICC, these braces are sacrificial elements designed to leave the rest of the building with little damage from an earthquake. Inside the unbonded braces are flat or cross-shaped steel braces, covered with debonding chemicals, that can stretch and shrink freely under seismic loads but will not buckle, since lateral support is provided by concrete filled tubes surrounding the braces. The steel grade used for the braces has a minimum yield point of 235N/mm^2, and tensile strength of 400-510N/mm^2. To control the seismic energy-absorbing performance of steel braces, an upper boundary of 295N/mm^2 to the yield point was additionally specified. The maximum steel brace dimensions are 40mm x 700mm, inside a concrete-filled 800mm x 650mm steel casing. The unbonded braces can absorb 40% to 75% of the total seismic energy through the time history analysis, effectively reducing the energy input to the building.

9.
An unbonded brace before erection.

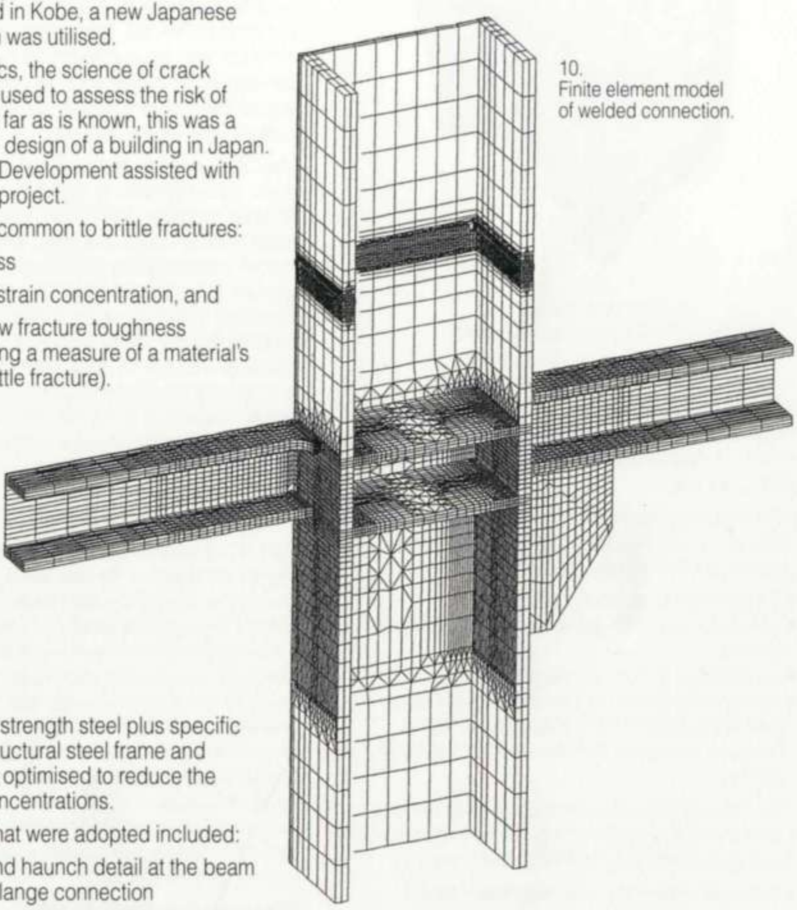
Ductility and fracture toughness

To control damage to the main superstructure and ensure that the steel behaved in a ductile manner without developing the brittle fractures that had been encountered in Kobe, a new Japanese steel specification was utilised.

Fracture mechanics, the science of crack propagation, was used to assess the risk of brittle fracture. As far as is known, this was a first in the seismic design of a building in Japan. Arup Research & Development assisted with this aspect of the project.

Three factors are common to brittle fractures:

- high tensile stress
- points of stress/strain concentration, and
- materials with low fracture toughness ('toughness' being a measure of a material's resistance to brittle fracture).



10.
Finite element model of welded connection.

The use of higher strength steel plus specific detailing of the structural steel frame and connections were optimised to reduce the effect of stress concentrations.

Specific details that were adopted included:

- the use of a round haunch detail at the beam flange / column flange connection
- removal of run on / run off tabs (these had previously been left in place)
- prohibition of temporary attachments.

Brittle fractures had initiated from both of the latter details in the Kobe earthquake.

The required fracture toughness was established using the principles described in *PD6493*[2] and *WES2805*[3], which both describe methods for assessing the acceptability of flaws in welded structures. The input requirements for a fracture assessment include:

- flaw geometry, size, and location
- stresses, primary and secondary
- material properties.

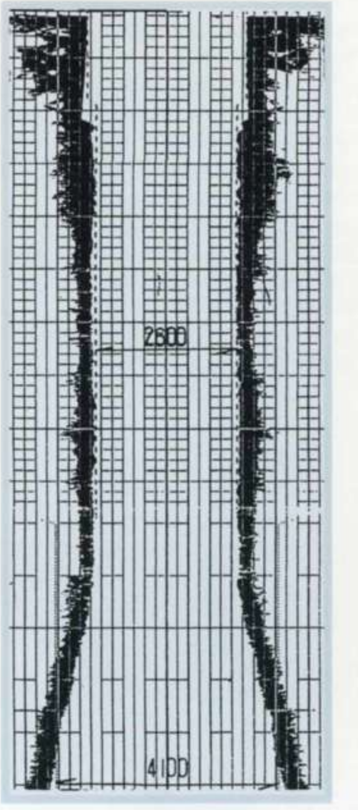
To assess toughness requirements, an assumed flaw geometry was adopted[4]. The stress condition for a typical supertruss column connection was established using a 3D non-linear finite element time history analysis. This was validated using a full-scale mock-up, which was also used to establish residual stress levels and prove the welding procedure.

Toughness requirements were specified in terms of both Crack Tip Opening Displacement (CTOD) and Charpy impact energy. Material properties were specified for both parent and weld metals.

Soils and foundations

The topsoil, alluvial sand, and clay lie within 29m depth from ground level (GL-29m. The diluvial sand, with SPT (standard penetration test) readings of 34-60, and clay with SPT of 13-20, lie alternately below GL-29m to GL-76m. The typical groundwater levels were reported to be around GL-8m.

The foundations consist of cast in situ concrete bored piles with under-reams bearing on the diluvial gravel at GL-53m. In the seismic design of the piling for OICC, non-linear pile / ground interaction studies were carried out by Arup geotechnical specialists in the Hong Kong office.



11.
Scan of Koden borehole test.

The piles typically have a 2.6m diameter shaft with a 4.0m diameter under-ream. A proprietary *Koden* ultrasonic wave test scanned and checked the bored hole before the concrete was poured. For the first time in Japan, the quality of the cast in situ concrete piles was inspected by the pile integrity test, which measures the velocity of an ultrasonic wave transmitted from two probes inside pile concrete.

The excavation extended to a depth of 18.5m, and this resulted in the strata beneath heaving, due to the release of pressure from above. It was assumed that granular strata would heave immediately but that the heave in the clay strata would continue for some time; thus, after the basement was built, the slab would be subject both to uplift forces from water pressure and heave-generated pressure from the soil. An alternative to allowing this soil pressure to reach the slab was to construct the slab on a collapsible material with the following properties:

- It must be able to support the weight of the concrete slab before it hardens.
- It must collapse at a known pressure.
- It must continue to collapse until the remaining heave is complete.
- It must not degrade in a manner that produces dangerous gases such as methane.

To calculate the extent of the 'rebound', the heave was analysed using the program VDISP, with collaboration from Arup geotechnical specialists in the UK. If the space beneath the slab was filled with appropriate collapsible material, the analysis indicated that it should be able to accommodate the heave. Collapsible boards with the required properties were therefore placed under the basement slabs.

The retaining wall to the basement was the composite basement 'TSP' wall developed by Takenaka Corporation. During the excavation, soil-cement pile walls were used as earth retaining walls, with H-section steel beams - which are usually buried after construction completion - forming temporary reinforcing beams for them. The basement exterior walls consist of vertically installed H-section beams with studs that embedded within the concrete walls. The composite action thus developed between the H-section and reinforced concrete wall effectively reduced the overall thickness, resulting in a more efficient use of the site.

Top-down construction sequence

This procedure, which allowed excavation of the basement and erection of the steelwork for the superstructure simultaneously, was implemented in view of the fact that not only was the schedule tight, but it involved both a time-consuming deep excavation and limited space for site storage.

The 'soil mixing' (soil, cement and bentonite) retaining wall was constructed first, and then the piles placed from ground level downward. A borehole was constructed using the bentonite and a drilling bucket with steel casing on the borehole top. The under-ream was installed using an 'earthdrill' machine, and the concrete placed using tremie pipe. A basement steel section encased in SRC column, known as 'Koshinchu', which transfers the construction loading to the pile foundation during steel erection, was pushed into a pile top from ground level as soon as the concrete casting was completed. Excavation of the basement and erection of the steel superstructure were carried out after completion of the ground floor slabs.

Soil rebound was monitored and continuously compared with predictions from analysis throughout the duration of construction.

This monitoring was done using a measurement system set in the bored holes, installed before commencement of construction.

Site steel erection

This was done in the following sequence, using a 35 tonne capacity tower crane in each of the four corner cores and a 20 tonne crane in each of the two cores midway on the long sides:

(1) The steel cores were erected.

(2) The longitudinal supertrusses were assembled at ground level or at a lower supertruss floor level, and lifted up by tower crane.

(3) The unbonded braces spanning two floors were lifted and connected to their respective pairs of cores.

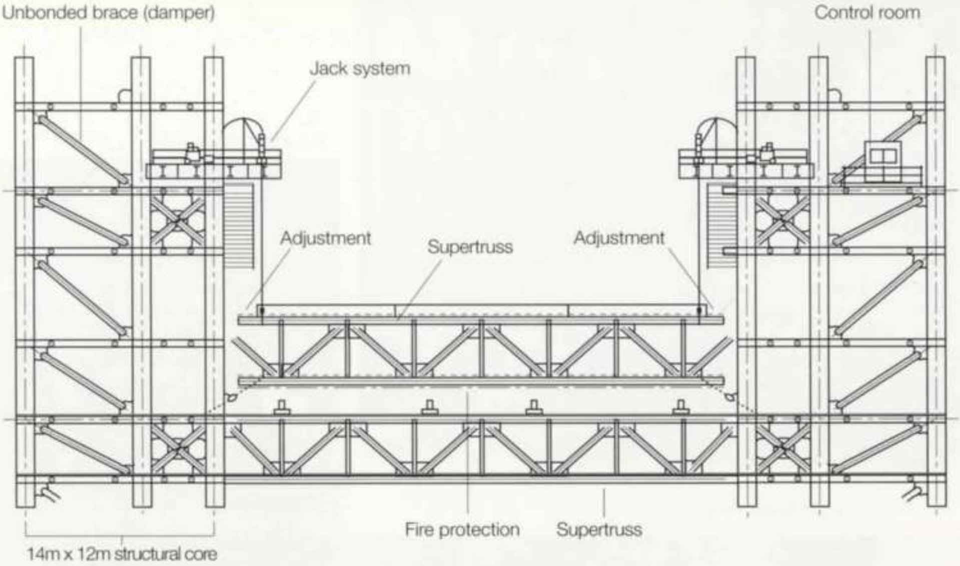
(4) A 34m x 95m supertruss floor, consisting of 15 transverse supertrusses plus secondary beams, divided into two or three parts, was assembled at ground level or a lower supertruss floor level.

(5) The metal decks with fire protection were constructed, and the mechanical, electrical, and public health facilities installed.

(6) Each resulting floor block, with a maximum weight of approximately 840 tonnes, was jacked up from the upper supertruss level. The lifting speed averaged 2m - 3m/hour.

(7) The joints for the columns within the cores were temporarily connected during jacking. To control the column axial forces to meet the design criteria, these were released once and then connected again after the jacking.

During construction pre-erection analyses were carried out to check the structural stability. The axial forces acting on the columns were also gauged.



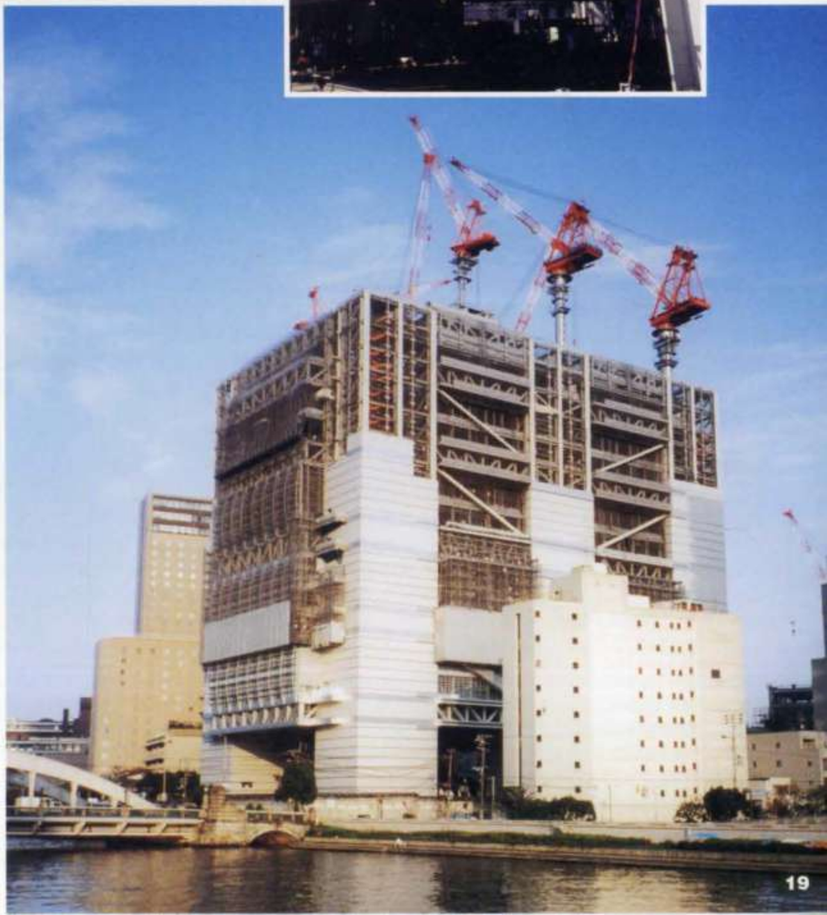
12 below left:
OICC under construction from north west, August 1998.

13 above:
Construction sequence for lifting a supertruss.

14 below centre:
CO_2 gas shielded metal arc welding of a super column.

15 right:
Lifting a supertruss.

16 bottom right:
Construction progress by November 1998.

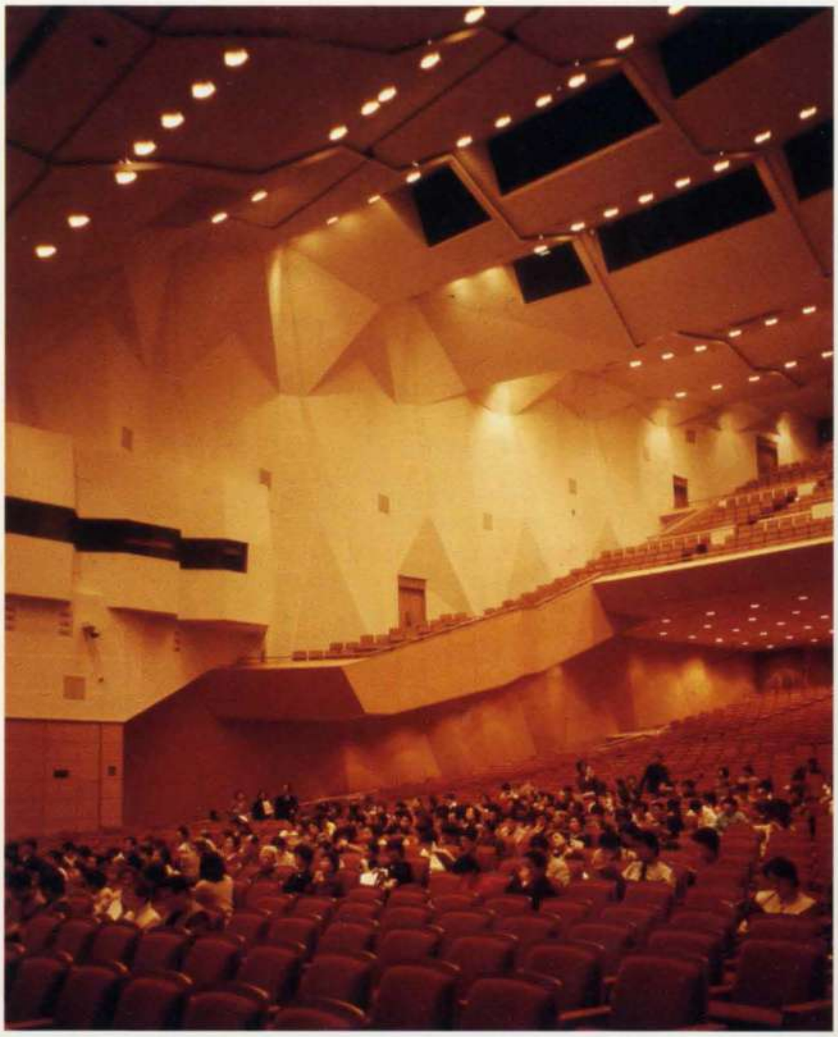


17.
The auditorium under construction.

18.
Oil cylinder for fuse system.

19.
Tuned mass dampers.

20.
The auditorium in use.



Fuse system and tuned mass dampers for the auditorium

The auditorium structure had to fulfil two conflicting requirements.

- It had to be flexible enough to accommodate 'storey drift' of the main superframe whilst transferring seismic shear forces from the auditorium to the main frame during an earthquake.
- It had either to be stiff enough to limit vibrations under people load, or be highly damped.

To minimise the stress concentration from the sloping concrete slabs of the auditorium through the diaphragm action caused by the imposed storey drift of the main superframe in an earthquake, a unique system was adopted.

A slide system with seismic sensors and oil cylinders at the cantilevered tip of the second auditorium level (2F) was used as the electrical fuse system. When the sensors detect a seismic wave, the sliding system at 2F is automatically released to avoid the stress concentration - and the system is designed to recover after an earthquake. The 1F structure has longitudinal slits on the concrete slabs, which can provide in-plane stiffness reduction.

Also, tuned mass dampers (TMDs) are used to reduce vertical response resulting from audience movement during rock concerts. Special studies were made to improve performance of the structure against vibration from audience activities, various dynamic inputs being modelled and compared with criteria in published literature researched by Arup's Advanced Technology Group (ATG).

The dynamic response of the main auditorium structure under audience load from various activities - dancing, bouncing, jumping - was analysed by ATG; the maximum allowable acceleration from these was based both on a literature study and experience, and set to 10% of gravity acceleration (0.1g). For the upper structure, eight 3.5 tonne TMD units were needed at the cantilever tip next to the grid line and four 3 tonne TMD units at the back span. For the lower structure, 16TMD units of 2.5 tonnes to 3 tonnes were needed. Using TMDs reduced the response of the upper and lower structures from a maximum 0.4g to about the target 0.1g. Performance tests under cyclic load by impact machines and 50 persons confirmed that by using TMDs the vertical response was reduced by 30- 60% as opposed to that of not using TMDs.

Conclusion

OICC was a great challenge to Arup Japan, and proved a successful collaboration between various parts of Arup worldwide and the other design team members. The building was the first major project in Japan for Arup since Kansai International Airport^5, and demonstrated the firm's capability in advanced seismic design.

The Centre has been used not only for international and domestic conventions but also for musical concerts, art and flower arrangement exhibitions, academic symposiums, commercial exhibitions, etc, since March 2000, and has been dubbed 'Grand Cube' as a symbol of Osaka. Sadly, the city did not host the G8 Summit Meeting 2000 (OICC was designed to be its venue), but Osaka is now in the running for the 2008 Olympics.

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(3) WES2805, Method of assessment for flaws in fusion welded joints with respect to brittle fracture and fatigue crack growth.

(4) HIKONE, S *and* KANAYAMA, I. Steel Design and Fracture Mechanics Assessment for Osaka International Convention Centre, The Arup Partnerships International Seismic Seminar, Osaka, Japan, October, 1998.

(5) DILLEY, P *and* GUTHRIE, A. Kansai International Airport Terminal Building. *The Arup Journal, 30*(1), pp14-23, 1/1995.

Credits

Client:
Osaka Prefecture

Design team:
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A.Epstein & Sons International

Arup John Batchelor, Simon Cardwell, Chris Carroll, Tim Chapman, Kayo Cooper, Martin Cooper, Philip Dilley, Sam Hatch, Shigeru Hikone, Isao Kanayama, Tatsuo Kiuchi, Mark Little, Tim McCall, Daryl McClure, John Miles, Hideki Nishizawa, Arata Oguri, James Packer, Jack Pappin, Joop Paul, Ted Piepenbrock, Jin Sasaki, Bailey Shelley, Ikuhide Shibata, David Storer, Jeremy Tandy, John Tingray, Michael Willford

Main contractor:
JV led by Takenaka Corporation

Illustrations:
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2: Fred English
5, 9, 14-15, 20: Tatsuo Kiuchi
8, 10-11, 17-19: Arup
12: Jin Sasaki
13: Jonothan Carver

Osaka Maritime Museum

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Mark Facer
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1.
Approaching the Museum complex, with the dome visible behind the entrance building.

Introduction

In 1993 Osaka City's Port and Harbour Bureau approached Paul Andreu Architects (PAA) of Paris for advice on a maritime museum project. The architect suggested locating the building at sea, and showed the client some conceptual sketches of a spherical dome floating in the mouth of Osaka Bay. This led to Osaka Maritime Museum being positioned off reclaimed land on the edge of the Bay. Over the last decade, this land had been developed with high-rise offices and an exhibition centre, but a vast area remained unused. The intention was that the Museum should become a landmark building attracting people from the city centre.

Now complete, the Museum is a spectacular sight in the waters of Osaka Bay. Its 70m diameter, fully-glazed steel dome is connected via a 60m long submerged tunnel to an entrance building on land; this building incorporates a circular front court, also 70m in diameter. The dome encloses three annular exhibition floors surrounding the *higaki kaisen*, a reconstructed timber trading boat from the Edo period of the 17th to 19th centuries. The site area is 33 443m^2 and the gross floor area 20 699m^2, 70% of which is inside the dome.

Project history and design team organisation

Following their appointment by Osaka City to carry out the feasibility study, PAA asked Arup in London for structural and services input. Subsequently, the commission extended to basic design with the engineering jointly carried out by Arup and Tohata, one of Japan's leading architectural and engineering consultants. The basic design was done in Paris, London, and Osaka, and was completed in spring 1996. In early 1997, the same team was commissioned to undertake detailed design.

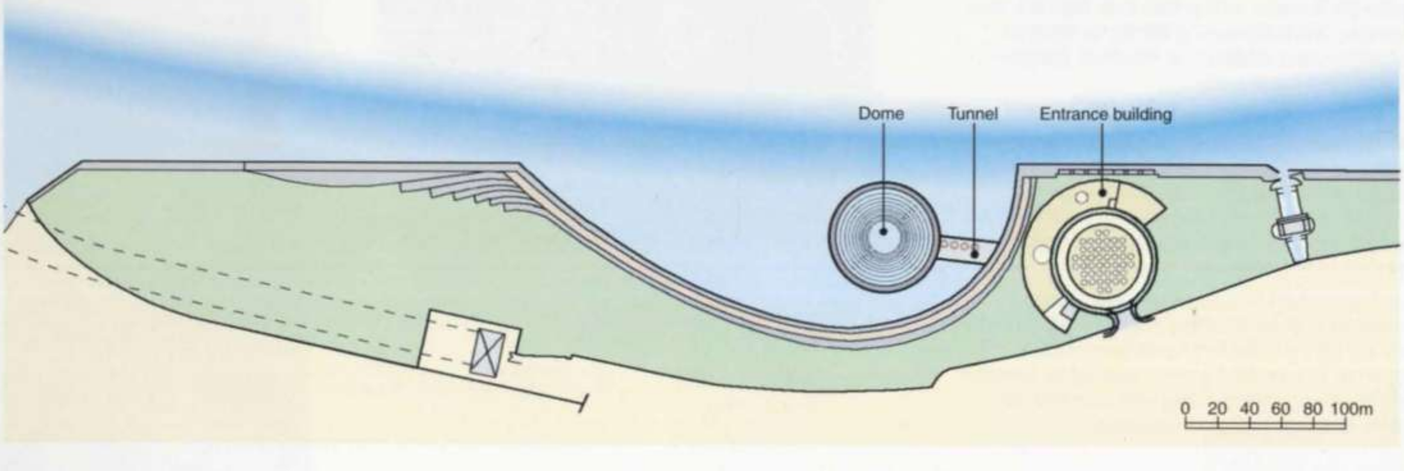
The centre of activity moved to Japan, where the architect set up a project office and Arup Japan provided the engineering services.

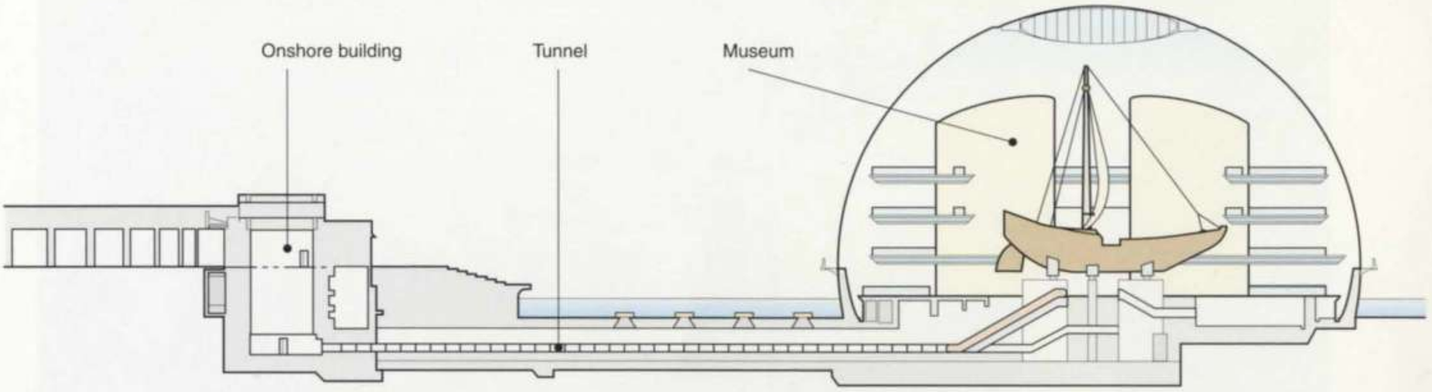
Responsibilities were clearly defined during each phase. Arup's structural commission included the glazed dome and the superstructure of the building inside. Tohata was responsible for the entrance building, the tunnel, the basement of the dome, and the piled foundations of the three buildings.

Arup designed the mechanical systems within the dome including exhibition spaces and air-handling plantrooms, whilst Tohata took care of the remaining spaces including the tunnel and the plantrooms in the entrance building.

Electrical and fire engineering were included in Tohata's scope. Engineers from both firms, appointed separately by the architect to undertake design up to tender and site supervision, worked closely to achieve the client's and architect's design aims.

2.
Plan of the Museum complex showing the onshore and offshore buildings and the linking tunnel.





3.
Section through the Museum.

Structure

The dome

The dome is a hemispherical single layer grid shell fixed at its 'equator' level to a circular reinforced concrete wall. The choice of geometry for the arrangement of structural members was an important early design decision made jointly by the architect and Arup engineers. The spherical surface is approximated by a series of squarish planes with maximum repetition. The glazing system uses flat glass, without panel bending or warping or any noticeable steps between panels. To achieve this the top two sides of the glass panels are slightly shorter than the two lower sides and the size of the panels decreases with height.

The dome structure is a diagrid of straight tubular members, 190.7mm in diameter and 6-12mm thick, butt-welded to cast steel nodes and braced by high strength rods 25-36mm in diameter. The rods are prestressed so that none goes slack under any design load combination. Near the top of the dome, the diagrid connects to a ring beam, a 3.3m wide vierendeel truss fabricated from steel plate.

There are 25 nodes between the 'equator' and the outer edge of the ring beam, and 48 nodes around the circumference.

The 21m diameter glass 'cap' within the ring beam is supported by an orthogonal array of cable trusses at 1.5m centres, with a maximum depth at the apex of 4.7m.

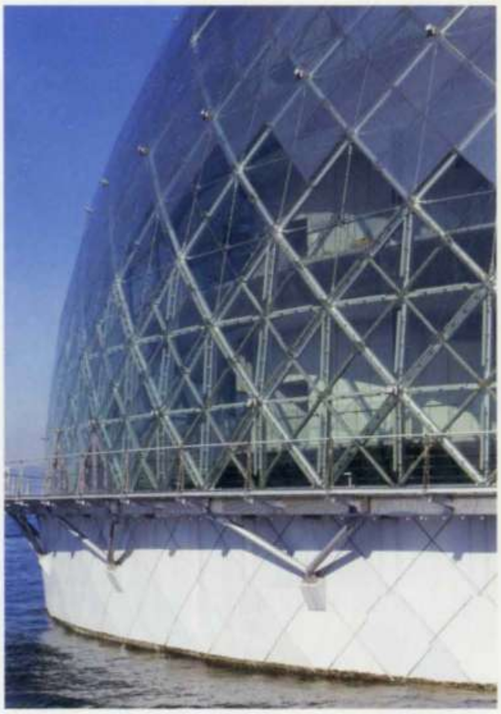
Seismic and wave loads were considered in addition to dead and wind loads. With reference to the base shear reactions from preliminary time-history analyses (using the Oasys LS-Dyna3D program with different real seismic records as input), the design seismic load for static analysis was taken to be either 1.0G horizontally combined with 0.3G vertically, or 0.4G horizontally with 0.7G vertically.

Professor Oda of Osaka City University investigated wave impact loading on the dome structure under typhoon and high tide conditions, using physical experiments and theoretical analysis to determine design wave loads. These indicated that under the most onerous conditions (water level at 500mm below the 'equator' with waves 4.4m high at 6.6sec intervals), the bottom 5m of the dome could be subject to wave loads with a maximum pressure of 100kPa at the 'equator'.

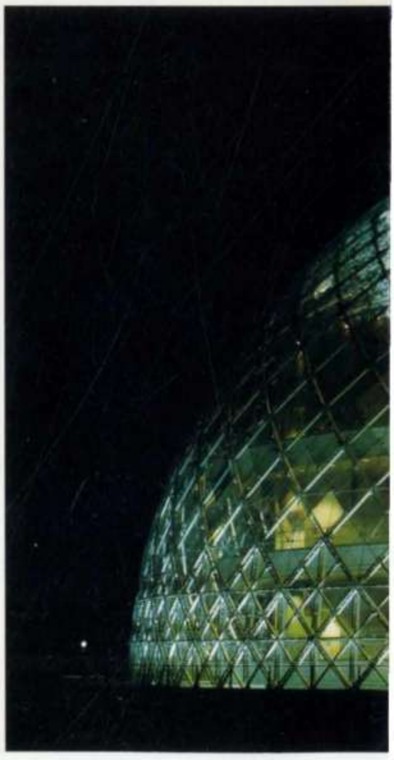
For the structural analysis, a half model was constructed using the GSA program, and both static and dynamic analyses were performed with geometric stiffness (P-delta) effects taken into account. Buckling analyses were also carried out for each load combination to account for any magnification of stresses.

The prestressed rods effectively fully triangulate the dome in plane, resulting in a fairly stiff structure with the period of the first mode being around 0.3 seconds. The moment-connected diagrid, together with the shape and relatively light weight of the dome, aids in resisting earthquakes.

4.
Interior of the entrance building: the glazed lift riser, leading to the tunnel, is on the left.



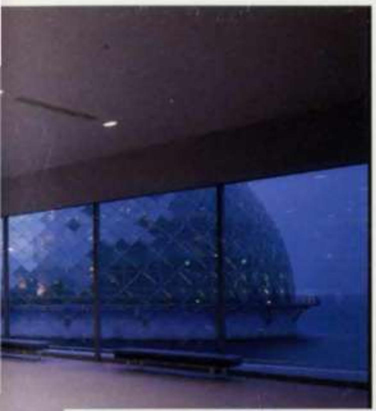
5.
The escape deck at the dome's 'equator'; behind the glass are the structural T-sections, designed for resistance to wave impact.



6.
At night, the illuminated dome seems to float on the water.

Analyses using the Fablon program, including both material and geometrical non-linearity, were carried out to ensure that the dome remains stable under excess loading.

Point-fixed glazing is used throughout, including the top 'cap' within the ring beam which is double glazed to control heat gain. In the five levels of the shell just below the ring beam, a single pane of glass (maximum 1.5m x 1.5m) covers each unit of the diagrid. The glazing of the levels below is divided into four panes (maximum 1.7m x 1.7m), with the centre point positioned where the tension rods cross. The rod tension stiffness is used to support the glazing out of plane. Lower down, where the glazing is subject to the wave load, thicker glass is used with backing T-sections running along both the perimeter and the diagonal to provide line support against positive pressure.



7.
Looking into the submerged tunnel from the entrance building.

The internal building and its substructure

The three annular floors are supported by steel truss beams about 900mm deep, fabricated from small H, T, and angle sections. In situ reinforced concrete slabs were cast onto the bottom chords. The finished floor level is 150mm above the top chord, the floor being either metal decking with a mortar topping or a free-access raised floor system for future maintenance. This arrangement provides a continuous plenum within the floor to supply fresh air and air-conditioning for the exhibition spaces, as well as a route for other services.

The vertical loading of the annular floors transfers to the substructure via steel tubular columns, typically 355.6mm diameter and 9.5mm to 30mm thick. The columns, which the architects wanted visible, are in 'FR (fire-resistant) steel', which needs no fire protection according to local regulations.

Three 7.4m diameter reinforced concrete cylinders with cast-in steel frames penetrate the floors and provide lateral resistance against earthquakes. These cylinders are located on plan so as to avoid horizontal eccentricity of stiffness. They enclose 'double spiral' staircases for vertical escape routes.

The site consists of roughly 25m depth of reclaimed land over 15m of alluvial clay, so piles were founded to the diluvial gravel at around -40m depth. Because of the possibility of liquefaction under earthquake, precast concrete piles with steel encasement were used for the top 10m. Asphalt compound was applied to the top 20m to eliminate negative friction due to settlement. The pile caps were cast monolithically with the 1.6m to 2.5m thick mat slab, which provides the weight to balance buoyancy forces. Given the highly corrosive environment, epoxy-coated reinforcing bars were specified for the mat slab and for the perimeter circular walls.

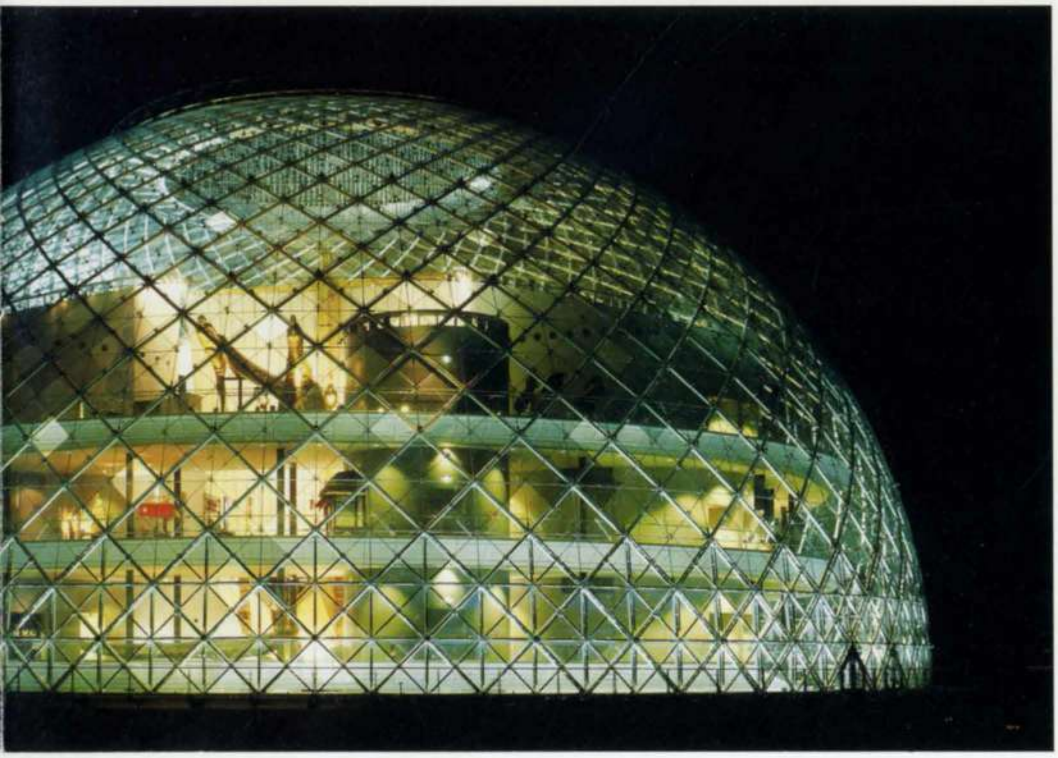
The entrance building and submerged tunnel

The semi-circular entrance building contains the entrance hall and offices at ground level and storage and plant rooms in the two basement levels.

Via glazed risers, visitors are led to the submerged corridor, a 60m long, 15m wide reinforced concrete tunnel which takes them to the centre of the dome underneath the reconstructed boat. The tunnel structure is in two parts: the 'land side' half has steel-encased precast piled foundations and is buried in the ground. The 'dome side' half is submerged into the seabed without piles, as its weight just balances its buoyancy. These two tunnels, the dome and entrance buildings are connected via water-tight movement joints.

8.
Visitors emerge from the tunnel beneath the reconstructed *higaki kaisen* timber ship.

9.
The main staircase connecting the annular floors, viewed from the first floor.



10.
The third floor, showing the three core structures, the transparent riser, and the ring beam above.

Dome services

The architects' concept of a glass bubble in the sea provides both a spectacular home for a traditional trading boat and a strong link to the maritime environment. The site is on latitude 34°N (like Cyprus, Los Angeles, and Atlanta), resulting in summer and winter design temperatures of 35°C and -1°C respectively. The services challenge is to maintain the transparency suggested by the concept whilst achieving satisfactory internal conditions for both occupants and exhibits. Most museum exhibits are much more sensitive to changes in temperature and humidity than people.

Services design development

The design of the building services and the cladding had to be co-ordinated to provide comfortable conditions in sunny marine surroundings.

To achieve acceptable internal daytime conditions, the skin of the dome reduces ambient levels of both light and solar heat. At the same time, day and night views in and out are maintained and top lighting achieves an appropriate internal character.

An important related factor is the varying altitude of the sun, peaking at 79° in summer and just 36° in winter. Many shading arrangements were considered during design development.

One - an external device rotating around the dome, positioned always in the sun's direction - would have been both effective and a reminder of the importance of the sun's position to early navigators. It was eventually ruled out for cost reasons.

The glazing for the diagrid shell area, supplied by Asahi Glass, is special in that it provides shade. The laminated glazing incorporates a sheet of perforated metal sandwiched in the interlayer, the size of the perforations controlling how much sunlight passes through the 'lamimetal' glazing.

To optimise the fixed shading, the surface of the dome was analysed in relation to the daily passage of the sun throughout the year. Banding the resulting solar gains established a series of contour lines over the surface, which in turn generated an optimum shading pattern that identified the performance requirement of each glass panel on the dome. Where solar gains are at a maximum, the lamimetal is almost opaque. Where solar gains are small, the glass is clear. Overall density of the lamimetal was chosen to give the best balance between visibility and comfort. The dome can be single-glazed because winter periods are short.

Smoke venting at the top of the dome was identified as necessary during the initial feasibility studies, but the need for opening panels in the point fixed glazing was avoided by incorporating the smoke vents into the cladding of the vierendeel ring beam.

Internal design conditions

An environment for conservation requires control of relative humidity, temperature, and chemical pollution. High relative humidities allow mould to flourish, while low humidities increase the danger of cracking in materials like wood. Following studies of other Japanese museums, appropriate standards of temperature and humidity control were achieved by providing areas for sensitive exhibits within the large circular cores, separate from the main volume of the hemisphere.

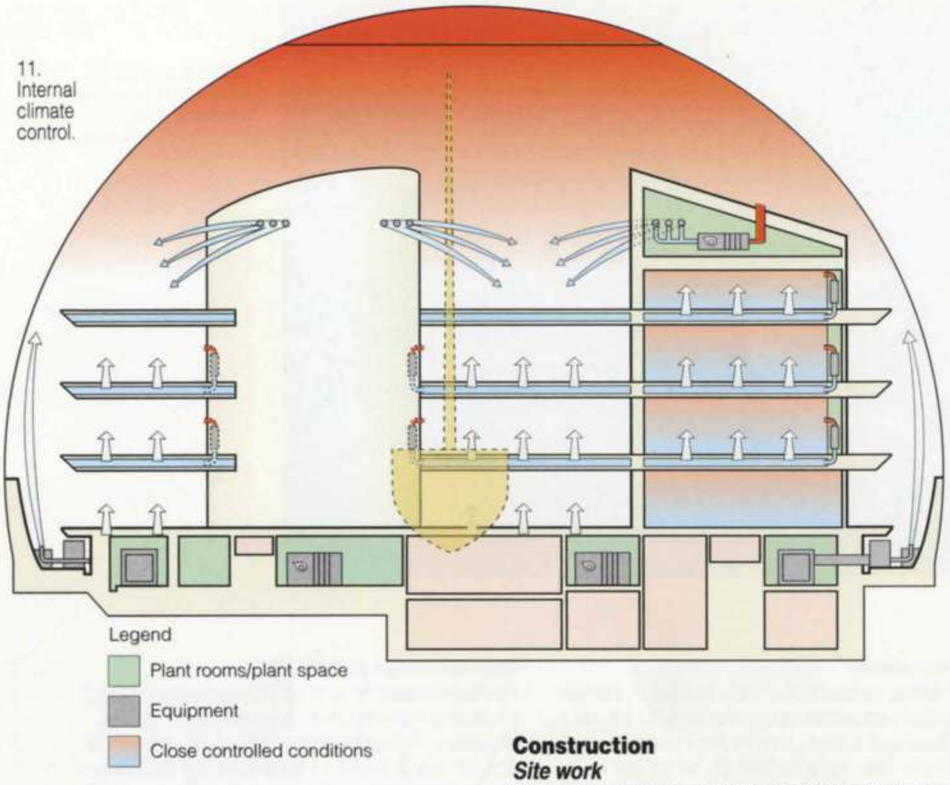
Within the dome itself, the combination of façade solar control and air-conditioning is designed to satisfy the requirements of large areas of glazing, occupant comfort, and conservation, whilst avoiding the risk of condensation.

The strategy for controlling the environment is unconventional. Radiant temperature is a major influence on occupant comfort, and in the dome, the inside surface temperature of the external glazing largely determines the mean radiant temperature. In winter, the surface temperature of the glass is cold, resulting in a low mean radiant temperature. Raising the internal air temperature compensates for this chilling effect. In summer, the glass sphere is heated directly by the sun, resulting in a high mean radiant temperature. In areas where there is a significant exposure to the glazing, the top level for example, the air temperature inside the sphere is reduced locally to compensate.

The special nature of the dome makes this strategy essential for comfort. In winter, the local air temperature is raised to 24°C, but in summer it is reduced to 19°C. This is unusual, as conventionally internal temperatures are allowed to drift up in summer and down in winter to save energy. The risk of condensation is reduced on cold winter nights by heating the sphere to about 17°C.

Using Arup in-house software, each significant zone in the dome was analysed in relation to its height and orientation, its relationships with the façade, and its use. The variation in humidity levels, resulting from the variation in temperatures within the dome, was compared with conventional museum spaces. The design of the mechanical services takes into account the need to control these zones separately throughout the year.

11.
Internal climate control.



Environmental systems

Air-conditioning of the dome and its spaces is provided by several systems serving separate zones. The dome itself has three large air-handling units (AHUs) at its base and three at high level, one on each main core. They supply heating and cooling air through nozzles around the base of the dome's perimeter, and at high level on the main cores. The six AHUs provide most of the heating and cooling needs, and encourage air movement at the top level and perimeter for improved comfort and avoidance of condensation.

Other levels in the dome incorporate underfloor air-conditioning systems. Air is supplied from small vertical AHUs in core walls, through a floor void, to floor grilles. This arrangement keeps the overall floor depths to 1.2m and minimises the need for ceiling accessibility, both key architectural design requirements. The floor void also provides a flexible distribution route for other services.

The spaces within the cores for sensitive exhibits are air-conditioned to museum standards by similar vertical close control AHUs in core walls, again supplying air through grilles in the raised floor.

At the base of the sphere, below the occupied floor, is a plant space incorporating the three large perimeter AHUs, two AHUs for two large simulator machines, a single unit providing air for the control of the environment close to the main boat exhibit and two serving the lowest public floor level.

The air handling plant is provided with conditioned fresh air, heating water and chilled water from a plantroom in the entrance building on the shore. Services are routed through the underwater tunnel.

Construction

Site work

Site work commenced in March 1998, with Arup responsible for supervising construction of the glazed dome and its internal superstructure. The construction sequence for the dome building on site can be summarised as follows:

(1) piling and retaining wall structure

(2) excavation within the dome building

(3) construction of mat slab and basement structure

(4) erection of Internal superstructure

(5) boat installation

(6) dome installation

(7) excavation of surrounding area to let in sea water.

Of all the work for the project the dome installation was the most critical and significant.

Dome fabrication and installation

The short, 25-month, construction programme meant that erecting the dome after completion of the internal structure (or vice versa) would not be possible. Fortunately, the dome being positioned only 15m from the shoreline, together with sufficient depth of water, made an innovative approach possible: fabricate the complete dome offsite and then install it over the completed internal building using a large floating crane.

The Harima works of Kawasaki Heavy Industry (KHI) was chosen to fabricate the dome, not only for its capability but also for its convenient location only 33km across Osaka Bay from the site; Harima is near Awaji Island - famous as the epicentre of the 1995 Kobe earthquake.

As well as allowing fabrication to proceed in parallel with site work, it could be constructed to factory standards of accuracy and safety, and the structure could be painted and glazed (except where the temporary lifting beams had to be attached), prior to installation. The installation date was selected based on anticipated weather and marine traffic conditions, as well as the desire to complete as much work as possible on site beforehand. 7 November 1999 was chosen, with only one week's leeway for postponement.

Dome fabrication began in late 1998, after extensive quality testing of the cast steel nodes for the diagrid structure. The hemisphere was divided into 12 large units, each being assembled on purpose-made jigs. The jigs, weighing almost as much as the dome itself, were designed to give the fabricated units precise geometry and to act as propping structures during erection.

After completing prestressing of the rods, the units were erected onto a temporary central support to form the complete shape. The ring beam was fabricated separately and installed, complete with tensioned cable net and clad with glass and smoke-extract panels, on top of the diagrid units. The remaining rods in the areas between the units were then prestressed. The dome was now ready for Asahi Glass to install the glazing panels.

12.
The core structures contain exhibition areas; note air-supply grilles on the floor.

13 above:.
Inside the dome perimeter, showing the space between the dome and the internal floors..

14.
Close up of ring beam and core structure (note ventilation ducts on the wall)

16.
The *higaki kaisen* surrounded by the annular floors.
The ship sits on reinforced concrete columns with seismic isolators.

15.
The diagrid shell and the ring beam.

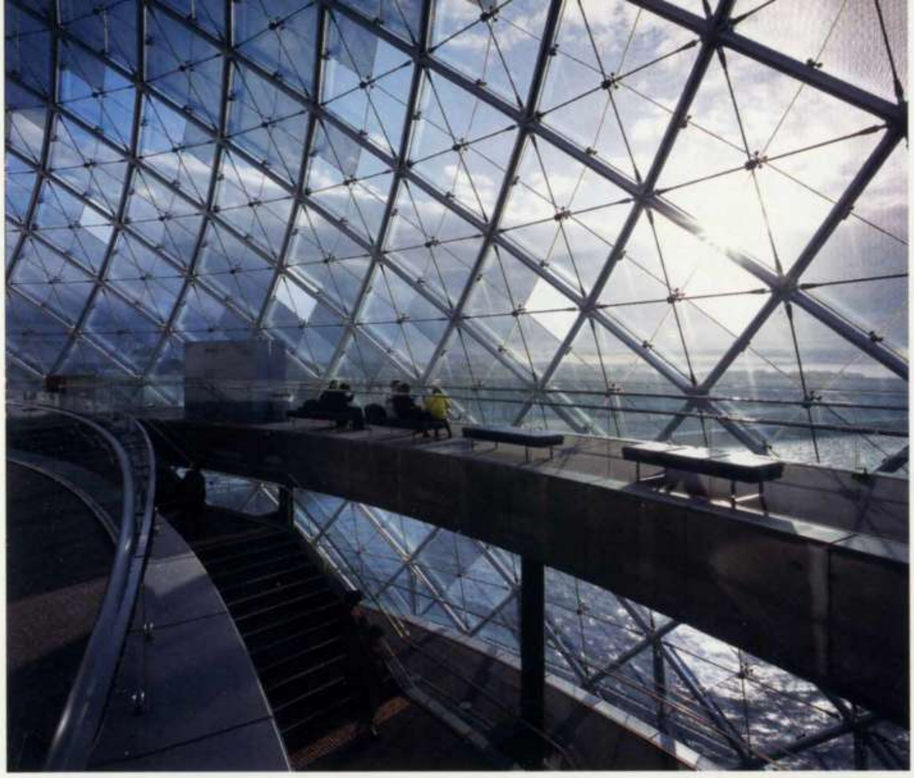
Installation

17. (a) - (f)

(a)
Lifting the 1200 tonne dome from the propping jigs.

(b)
Lowering the dome onto the barge.

(c).
En route in Osaka Bay.
In the background is the Akashi-Kaikyo bridge, the longest suspended span in the world.



18.
Looking out through the dome from the third floor.

Meanwhile, work on site had proceeded to programme and in October 1999, on completion of the internal structure, the timber boat was installed using a floating crane.

Several key issues influenced the installation of the dome, including:

- Level differences between the bottom nodes at 'equator' level were measured precisely beforehand and reflected in the levels of the base plates cast on top of the circular concrete walls on site.
- There was very little clearance between the internal structure and the dome - about 1.5m. KHI carried out a wind tunnel test and concluded that the maximum tolerable wind speed during lifting would be 7m/s.
- To ensure the dome was placed precisely, several pencil-shaped guide poles were attached to the substructure.
- An impact analysis by KHI indicated that the metal-to-metal impact of the dome hitting cast-in base plates could damage glazing panels. Sandbags were placed between the base plates to minimise the impact.

3 November 1999:
A 4100 tonne capacity floating crane lifted the dome at the Harima works, leaving the propping jigs on the ground. The dome complete with most of its glazing panels weighed 1200 tonnes, including the lifting ring and temporary lifting and stabilising trusses. The dome was placed on a barge and towed out into Osaka Bay.

5 November 1999:
The spectacular voyage of the barge took place, followed by a number of news helicopters.
The 33km trip went smoothly and took six hours.

7 November 1999:
After a day of safety checks in Osaka Bay, the giant floating crane lifted the dome again and approached the site. Thanks to wonderful weather, with almost no breeze, the whole operation ran smoothly to programme. The dome was in place and anchored to the substructure by lunchtime.

Conclusion

The total cost, including building services but excluding the exhibition package, was 12.8bn Yen, or approximately £80M. Construction was completed at the end of May 2000, followed by intensive exhibition works. The Mayor of Osaka City officially opened the Museum on 14 July 2000, with the leaders of the design teams in attendance, and it enjoyed its first summer in full operation with record high temperatures. At the time of writing, Osaka Maritime Museum has already attracted more than 100 000 visitors, fulfilling the project's initial purpose.

Following Kansai International Airport Passenger Terminal Building, Osaka Maritime Museum is the second major project in Japan for which Arup was commissioned to undertake the multi-disciplinary design. Though this did not encompass all design aspects of this particular project, the unique approach introduced to integrate all the engineering disciplines has already made a significant impact on the local architectural scene. It will thus certainly be a landmark for Arup in Japan.

Credits

Client:
Osaka Port and Harbour Bureau

Architect:
Paul Andreu Architects
Japan Design Office

Engineering design:
Arup Robert Baker, Jo da Silva, Pat Dallard, Mark Facer, Andre Gibbs, Scott Groves, Shigeru Hikone, Ryoichi Hirose, Martin Manning, Arata Oguri, Dan Phillips, Jin Sasaki
Tohata Architects and Engineers

Lighting consultant:
Lighting Planners
Associates

Building contractor:
Taisei + Fudo
+ Toyo Joint Venture

Mechanical contractor:
Taiki + Seiken
Joint Venture

Electrical contractor:
Toenek + Sanpo
Joint Venture

Plumbing contractor:
Daidan + Nissetsu
Joint Venture

Lift contractor:
Mitsubishi
Electric Corporation

Timber boat contractor:
Hitachi Zosen
Corporation

Illustrations:
1, 4-10, 12-16, 17a, 17c-f, 18:
Katsuhisa Kida
2, 3, 11: Penny Rees
17b: Arata Oguri
19: Jonothan Carver

19.
Route map of voyage of the dome, towed to its final site on Nankou Island in Osaka Bay.

(d)
The dome lifted from the barge.

(e) & (f)
Placing the dome in its final position over the Museum structure.

Melbourne Museum

Peter Bowtell Erik Guldager-Nielsen Peter Haworth Brendan McNamee Neil Paynter

History

For almost 100 years the State Library and the Museum of Victoria shared buildings on the Melbourne city block bounded by Russell, La Trobe, Swanston, and Little Lonsdale Streets. Over that period both organisations grew in holdings and staff numbers, and it became obvious in the 1980s that each required extra space to display its collections adequately and to fulfil efficiently its research obligations. As a result it was decided that the Museum should move and the State Library facilities be rationalised and expanded on the existing site. Arup was appointed as structural engineer for the Library rationalisation project, ongoing throughout the 1990s.

After some political debate, the decision was made to build a new Museum close to the Royal Exhibition Building - a wonderfully graceful domed building constructed in 1880 in one of Melbourne's famed city parks, and with particular significance for Australia in that the country's first Federal Parliament met there in 1901. Two utilitarian annexes had been built to the north as overflow space from the main building, but construction of the new Melbourne Exhibition Building by the Yarra River (another Arup project) enabled these to be demolished. The new Museum could thus occupy this liberated land, with no encroachment on the gardens and with all perimeter trees carefully protected.

The 1994 architectural competition was won by the Melbourne firm Denton Corker Marshall. Arup assisted them with the winning entry and, following their appointment, was engaged as civil, structural, and traffic engineer for the A$290M project.

Museum layout

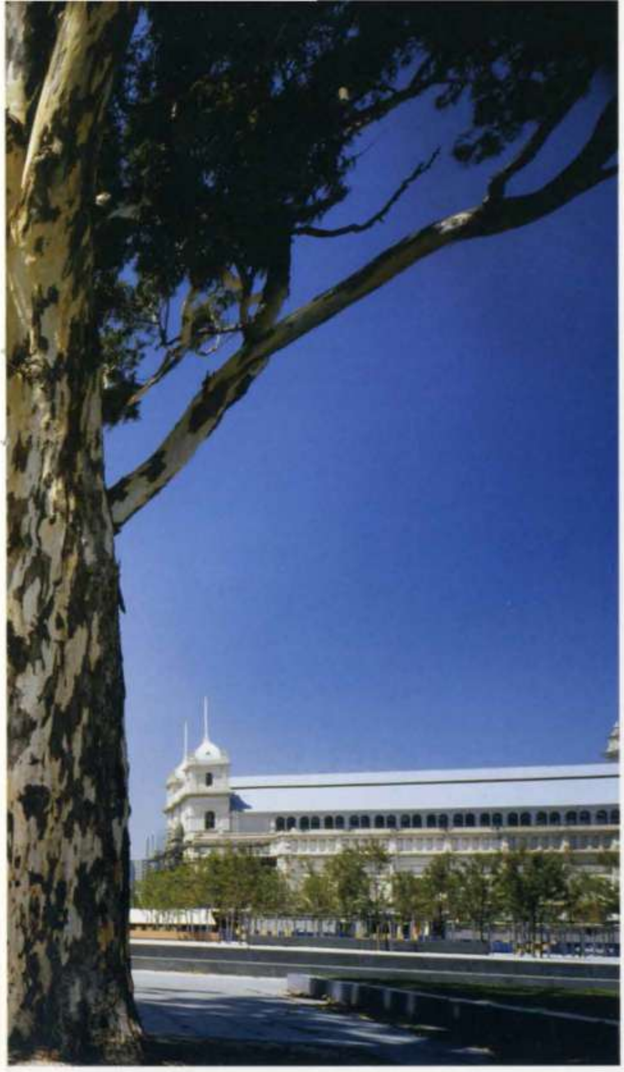
The architectural scheme essentially forms a campus of individual buildings for specific use, connected by clearly signed, enclosed, public pedestrian ways. A new 900-space, two-level underground car park between the Royal Exhibition Building and its new Museum neighbour has on its roof the Events Plaza, a large public space running east / west. Access to the Museum's main entrance is from this, via a 20m high glazed wall leading to the foyer and thence to the 'Orientation Galleria', also laid out east / west. Immediately north of the main entrance are the public areas - the museum shop, restaurant, lecture theatre, and meeting rooms - in two lower levels. Above them is the Central Facilities Area: collection storage, research, preparation, and administrative departments. At this point the structure has seven levels, flanked at each end by two major 'book-end' buildings - an IMAX theatre to the west and the Touring Exhibition Hall to the east.

Further north are the main exhibition areas. To the east is the Mind and Body Gallery above the Science and Life Gallery, while to the west the Australia Gallery lies over the Aboriginal Centre 'Bunjilaka'. These pairs of major public galleries flank the central and dominant feature, the Forest Gallery, a soaring 40m high space beneath a high sloping steel canopy or 'blade'. This representation of an eastern Victorian forest contains mature trees, plants, animals, birds, and water features - all within a stainless steel mesh enclosure. Again to the north are more, double-height, spaces, the Evolution Gallery and the Te Pasifika Gallery, for particularly large and tall exhibits. Both are enclosed by curving, raked walls.

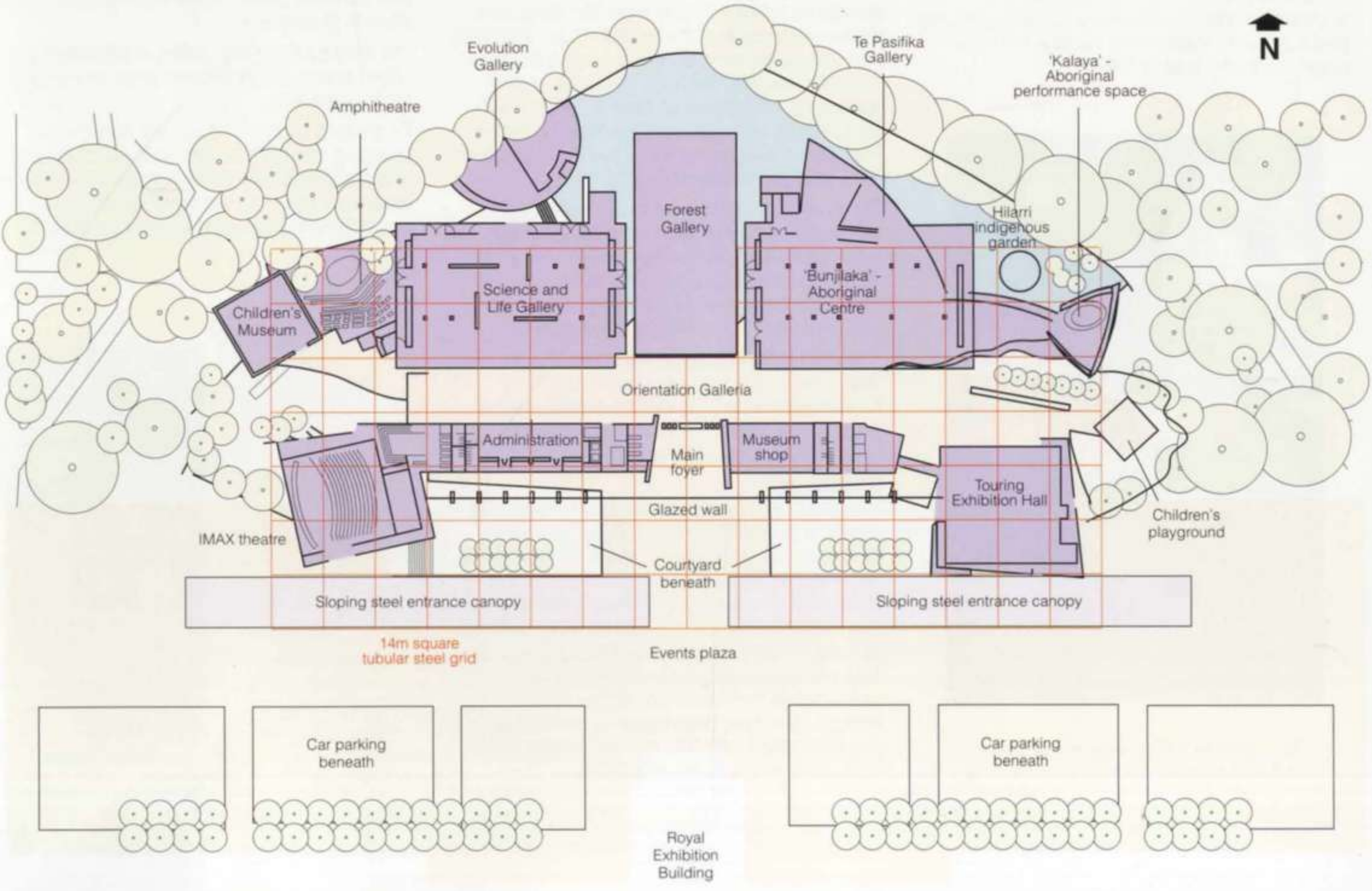
West of this main gallery complex is the Children's Museum - a big box rotated about both major axes. To the east and set in its own gardens is the Aboriginal performance space 'Kalaya'. This complex building contains a steel and timber ramp from which visitors can view Aboriginal dance performances in a central area.

Denton Corker Marshall positioned the Museum's main entrance between two major sloping steel canopies, each with a 23m cantilever at its east or west extremity. The entire building campus is then visually contained within a 14m square grid of tubular steel beams (250mm square in section) supported by similar columns. Only the canopy above the Forest Gallery bursts through this artificial 'ceiling'.

1 top.
The western 23m cantilever of the steel entrance canopy to Melbourne Museum, within the 14m square steel grid. The IMAX theatre is on the left; the Royal Exhibition Building is on the right.



2 above:
Aerial view of Melbourne Museum under construction, showing its relationship to the Royal Exhibition Building and Carlton Gardens.



3.
Site plan.

Traffic planning

Arup was engaged to determine the Museum's traffic demands and their effects on the surrounding road system. The team made recommendations for vehicular access and egress, and advised on planning such areas as the back-of-house delivery spaces below ground beneath the Bunjilaka Aboriginal Gallery. Later assistance was provided in negotiations with the relevant authorities.

Geotechnical conditions

Melbourne's Central Business District - the Museum site is on its north-eastern extremity - has reasonably well-known subsurface geological conditions. The western part of the city has erratic basalt flows above Silurian mudstone bedrock; the eastern area has no basalt. The outcropping Silurian mudstone or siltstone layer is usually highly weathered at the surface but quickly increases in strength with depth.

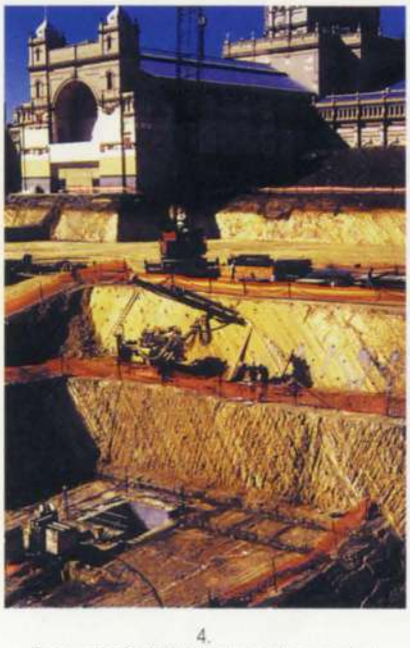
Detailed geotechnical investigation confirmed these expected conditions. Minimal groundwater seepage was anticipated. Possible soil contamination was also investigated, as initial planning suggested that much excavated material would have to be removed to tips.

An upper level of fill was shown to contain excessive levels of phenols, whilst the upper portion of the Silurian layer displayed high levels of naturally occurring arsenic. Tipping contaminated soils is expensive, so every effort was made to maximise the use of the soil - in buried areas - on the site.

Contract commencement

A previous contract between the Museum and the IMAX theatre operator required an early works contract to be let for demolishing the existing annexes and other buildings on the site and for the bulk excavation. The latter included installing ground-anchored piled perimeter walls round the 20m deep excavation for the IMAX theatre.

Tenders for the main contract were called in September 1996. Construction was delayed slightly by the ground contamination matters, but work began in earnest in early 1997.



4.
Excavation for IMAX theatre and car park at south-east end near Royal Exhibition Building.

Detailed design

The car park

This is in two parts - 65m x 105m in the east and 70m x 140m in the west. An optimum column grid for parking, 8.3m x 10.4m, was chosen. The structural system for the suspended slabs includes shallow band beams spanning the 10.4m with a one-way slab between these beams.

A pedestrian tunnel links the Museum and the Royal Exhibition Building beneath the lower parking floor. These buildings were sufficiently far apart to allow the car park to be built in open cut. Along most of its northern edge, the car park opens directly to the public landscaped space of the sunken plaza beneath the Main Entry level, so the lateral pressure on the southern basement wall could not be resisted by passive pressure on the north wall. This necessitated buttresses or internal frames to resist the loads.

The Events Plaza above had to be landscaped, so the lower floor of the eastern car park extends further south than the upper floor. Prestressing was chosen for the band beams. The offset retaining walls on the south side introduced restraint, preventing rational prestressing of the slabs, so they are conventionally reinforced. This constraint did not apply to the western car park whose slabs are post-tensioned. For the prestressing to behave as intended, a system of joints around the car park perimeter allow for elastic and long-term creep and shrinkage movements. The jointing was somewhat complicated, having to coincide with landscaping and paving patterns.

Central Facilities and Orientation Gallery

The two buildings housing the Central Facilities Area are each about 85m long and up to 30m wide, arranged symmetrically about the 28m wide main entrance. From the lower level, tapering inclined columns rise to support the facilities floors above.

The structure is in reinforced concrete except for the roof which is partly steel-framed. Collection storage occupies a double-level 15m deep area for the entire length of the two buildings - effectively a double-height concrete box providing four-hour fire rating, security, and internal climate control assistance, and carried on internal columns with the sidewalls acting as deep loadbearing beams. The floors, designed for 10kPa live loads, comprise band beams and one-way slabs.

The structure was checked for both wind and seismic loads - the latter proving dominant due to the heavy loads at the upper levels. The location of transverse walls positioned the shear centre well away from the centre of the applied lateral load - with the shear centre differing between floors.

The effect on individual frames and walls was determined using a series of two-dimensional frame analyses, and the intuitive impression that the structure was robust enough to resist the seismic loads was confirmed.

Directorate

The Directorate, containing the senior managerial offices, is on a bridge: three parallel steel portal frames spanning the 28m between the two Central Facilities buildings. The available depth for the portal members was tight - limited by the floor-to-floor height. Because the Central Facilities buildings can each move independently, the bridge could not be restrained by the adjacent concrete supports, so the portals frames are tied at floor level with high strength steel rods, prestressed to compensate for part of the dead load. This allowed slender beams to be used, and reduced deflections.

Touring Exhibition Hall

This eastern 'bookend' is effectively a 30m square, 9m high, concrete box, whose slab-and-beam roof supports part of the three upper storeys of the Central Facilities building above, plus mechanical plant. A major 30m spanning post-tensioned beam, constructed in lower and then upper halves to reduce propping costs, transfers the loads.

A feature of this hall is its external cladding - planar surfaces in a non-orthogonal arrangement, necessitating an intricate system of steel-framed supports bracketed back to the basic concrete box.

IMAX theatre

Here, a prime requirement was for 23m clear height and, as the architect had located the theatre beneath the Central Facilities storage area, a 20m deep excavation was needed, shored with intermittent ground-anchored bored piles.

The building is essentially an irregular concrete-walled box, but steel rather than concrete was chosen for the main roof members because of the great height of scaffold required for any in situ concrete construction.

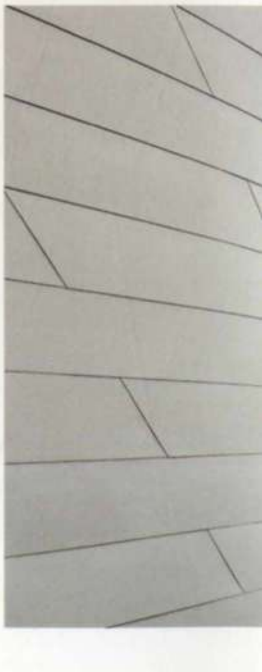
Major trusses were fabricated and assembled off site, transferred in one piece, and hoisted into position. These act as transfer members supporting parts of the Central Facilities building above, as well as the complex audio and mechanical units which serve the theatre, which opened for business some two years before the Museum proper.

Main exhibition areas

The two-storey high galleries each side of the Forest Gallery are basically large boxes, their walls formed generally from full-height loadbearing precast black pigmented concrete panels, 225mm thick, cast in South Australia. In the east galleries, some external panels were 150mm thick, and have to be supported from internal 225mm thick reinforced concrete walls acting as deep beams spanning over the lower gallery where walls cannot continue down to ground level.

The walls by the Forest Gallery are stepped at the upper level to accommodate ramps alongside this landscaped area.

Floors are typically 1.1m to 1.4m deep beams spanning 14m north / south, spaced 7m apart and supporting 250mm thick slabs. The exhibition areas were generally designed for a 5kPa live load plus 0.3kPa allowance for suspended objects.



5.
The cube of the Children's Museum: on the left is the north-west corner of the Science and Life Gallery.

The latter was accommodated by casting a series of 10kN capacity ferrules into the slab soffits on a 3.5m grid.

The floor beams include large penetrations for service ducts, etc, whilst the slabs contain cast-in conduits up to 80mm diameter, distributing to floor access boxes every 3.5m.

At the upper level, the floor beams cantilever to the south some 6m over the gallery space, necessitating some post-tensioning to control deflections.

The roof structure is 2.6m deep downstand / upstand beams spanning 14m at similar centres, with secondary 1.4m deep upstand beams spanning across the main beams and supporting services equipment platforms. The roof slab is typically 150mm thick with allowance for panels to be knocked out to accommodate possible future services inclusion.

A sheet-metal roof covers the concrete, fitting between the protruding parallel beam upstands.

Evolution Gallery and Te Pasifika Gallery

Both these tall feature galleries have a main curved wall, taken from a cylinder slice and then rotated about two axes. The reinforced concrete walls span vertically onto a steel-framed roof and contain several large penetrations, the size and number of which precluded treating these structures as shells.

Each feature gallery has a mezzanine level.

The Te Pasifika Gallery is part-supported from transfer walls over the back-of-house facilities area. The 400mm thick curved wall spans 20m vertically and contains almost full-height slot windows.

The 300mm thick and 34m long straight southern wall contains a 23m long triangular opening.

The Evolution Gallery's northern straight wall is 40m long. Its eastern half has no vertical continuity down to its foundations, requiring it to span 20m horizontally. Wind loading thus essentially adds to the dead load horizontal component, due to the inclination of the wall and the normal vertical load.

Children's Museum

This 21m-sided cube, rotated about two axes, is steel-framed, with wall columns on a 4.2m grid and roof beams spanning north / south across its width. A 2.4m deep services trench runs around the perimeter of the building and acts as the wall foundation. The building is clad in panelised fibre cement sheeting with each external side of the cube subdivided into individual differently painted squares.

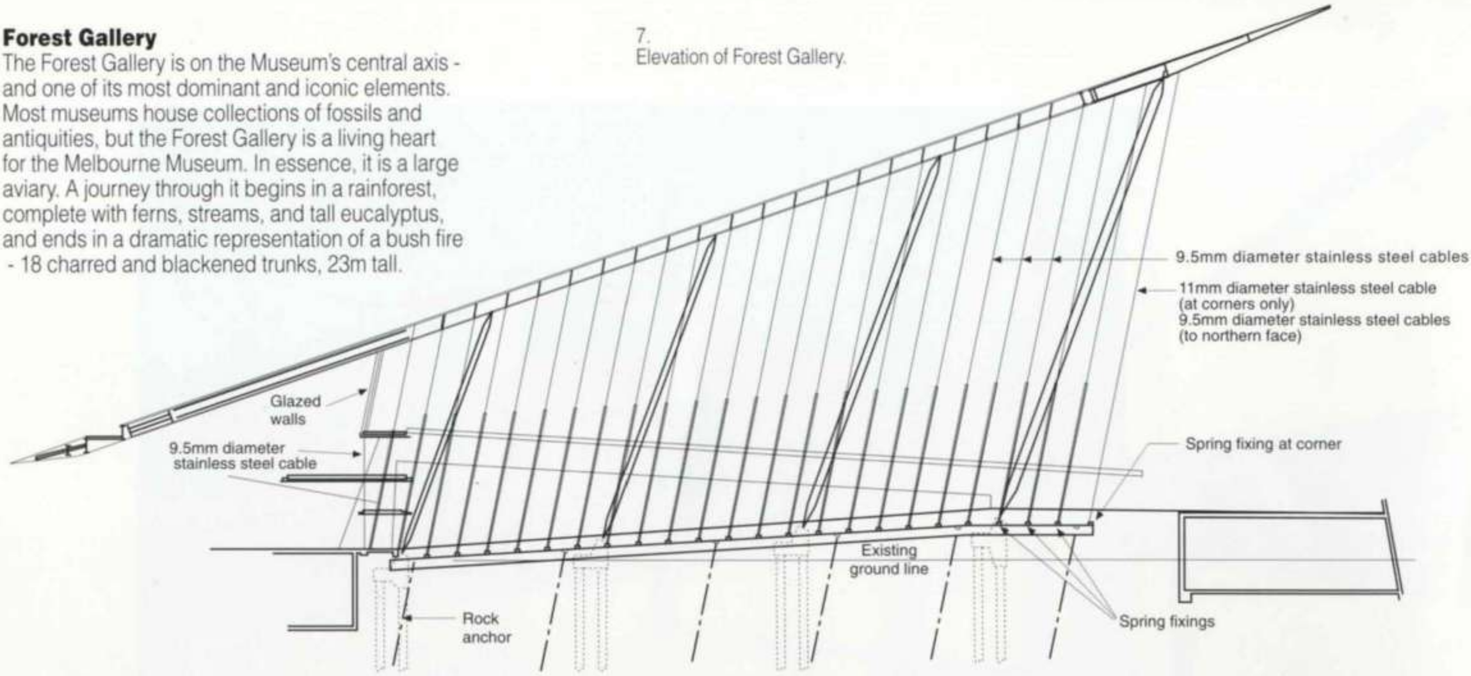
Aboriginal Cultural Centre - 'Kalaya'

This building is small but structurally complex; triangular in general plan shape, all its walls are curved in plan. It is steel-framed, requiring curved structural girts which cantilever beyond the plan outline to produce wing walls. The timber-clad, steel-framed ramp makes two turns of a helix from ground to first floor levels, forming the viewing gallery to the dance display area enclosed by the ramp. The Centre is clad in panels of *Cor-ten* weathering steel.

6.
The Bunjilaka Aboriginal Centre is in 'organic' contrast to the rectilinear style of the rest of the Museum.

Forest Gallery

The Forest Gallery is on the Museum's central axis - and one of its most dominant and iconic elements. Most museums house collections of fossils and antiquities, but the Forest Gallery is a living heart for the Melbourne Museum. In essence, it is a large aviary. A journey through it begins in a rainforest, complete with ferns, streams, and tall eucalyptus, and ends in a dramatic representation of a bush fire - 18 charred and blackened trunks, 23m tall.



7.
Elevation of Forest Gallery.

The prime elements of the blade roof that soars above are two 1.2m deep primary steel beams running full length along each side. These support the mesh side walls, together with transverse louvre trusses across the width of the space at 3m centres. Each beam is supported on four columns, inclined 18° to the vertical, and varying from 350mm to 800mm in diameter. At the high point, the roof floats over 40m above ground. To counter the natural tendency for the inclined columns to fall, the roof is anchored to the primary concrete buildings at the south end.

At the northern end, the roof becomes solid, cantilevering some 15m from the last column support. The mesh enclosure was one of the fundamental drivers of the roof system.

To achieve the architect's vision of the planar walls, the concept of a tensioned mesh 'curtain' was developed. Using the mesh as the sole load-resisting element was considered, but it was decided to provide primary support on a series of stainless steel cables to allow for ease of future mesh replacement.

The mesh support cables are 12mm diameter, stainless steel, 19-strand rope at 2.4m centres, inclined at 12°. To control thermal variation and still maintain tension to the cable, each rope anchors into a spring box cast into a ground beam.

Cables are prestressed to 10kN, but loads of up to 50kN per cable are generated under full wind load.

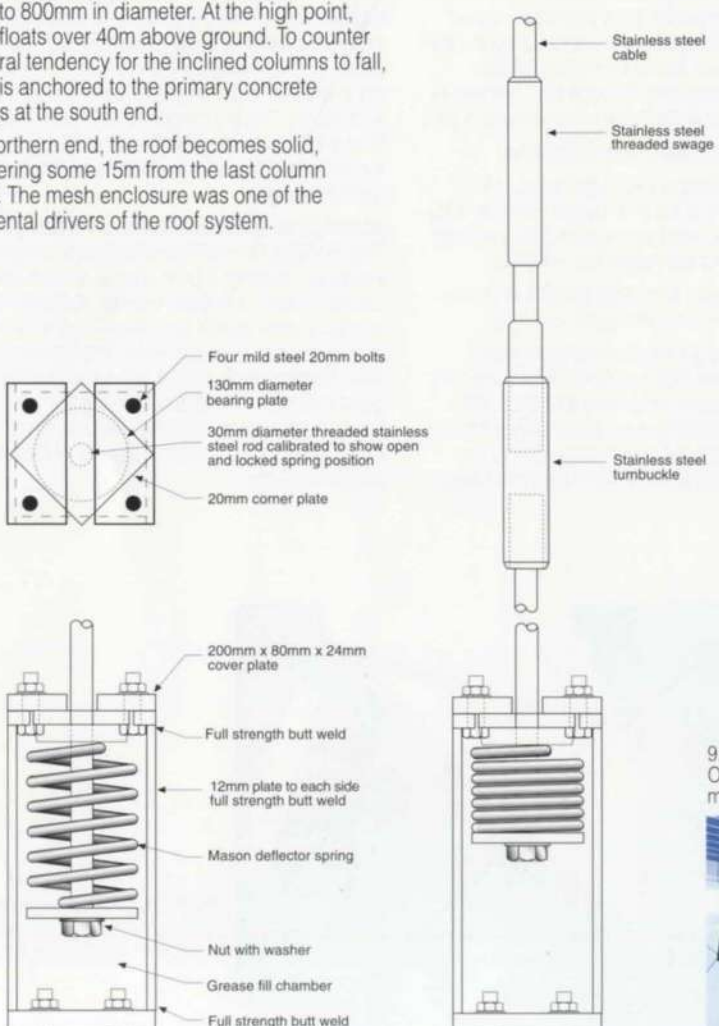
Maximum lateral out-of-plane movements have been controlled to under 1m.

The mesh is fixed to the support cables by purpose-designed, stainless steel clamp fixings. As the mesh is not tensioned, other than by its own self-weight, a woven steel fabric was selected to avoid problems from local distortions and the potential fatigue associated with welded wire meshes.

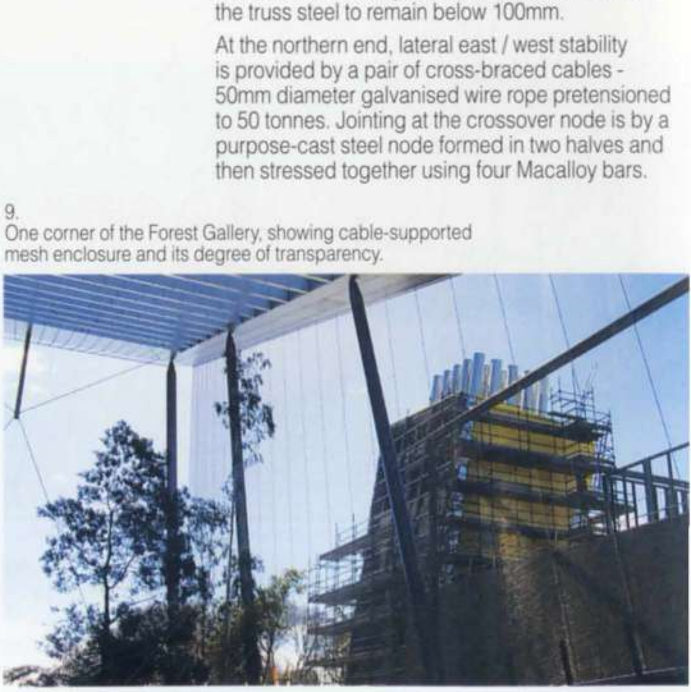
The top surface of the roof is also clad with mesh between louvre trusses - in this case supported on cables at 900mm centres running the roof's full length. The cables also provide lateral restraint to the trusses, enabling the maximum dimension of the truss steel to remain below 100mm.

At the northern end, lateral east / west stability is provided by a pair of cross-braced cables - 50mm diameter galvanised wire rope pretensioned to 50 tonnes. Jointing at the crossover node is by a purpose-cast steel node formed in two halves and then stressed together using four Macalloy bars.

8 below:
Spring boxes for wall cables in Forest Gallery.

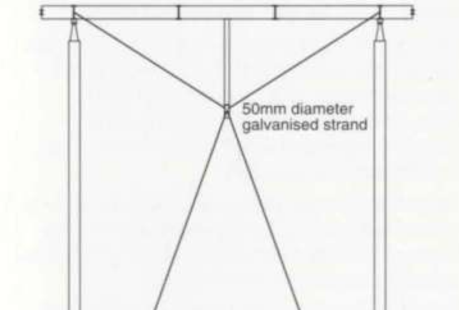


9.
One corner of the Forest Gallery, showing cable-supported mesh enclosure and its degree of transparency.



10.
The Forest Gallery is the living heart of the Museum.

11.
Cable-braced north wall of Forest Gallery.



Grid frame and entrance canopies

This 14m square grid, some 18m high, extends over the entire complex, and was designed to support the main entry canopies and the banks of louvres screening and shading areas below. For cost reasons, the louvres have not yet been installed, but provision has been made for this at some future stage.

Though it looks to be continuous, the grid is actually split into three distinct sections. The east and west portions of the frame measure 98m square, independently braced back in plan to fixing points on the Central Facilities roof. The central portion of the grid 'floats' independently from the adjacent fixed grids, with lateral movement restrained by springs housed in the expansion joints. This controls the frame's thermal expansion, and simultaneously allows for the lateral loads due to wind to be passed across the joints and into the bracing system.

Two large canopies are located at the front of the building and slope down at 5° towards the entrance, visibly directing visitors to the central arrival point. Clad in perforated aluminium on the underside, and transparent acrylic on top, the canopies provide both shelter and protection from the elements.

The leading angle of the canopy cantilevers some 23m from the grid frame. The plane of the canopy is supported from above by a pair of 1.2m deep welded beams, each sitting on rotational bearings to avoid any transfer of moment into either the crossbeams or the grid itself. The roof plane is fully braced in plan and lateral loads are transferred through three sets of triangulated rods to the bracing in the top surface of the grid.

Glass wall

To allow views into the Museum, and to link visually with the Royal Exhibition Building across the plaza, the south wall is enclosed by a full length planar glass wall, over 140m long and up to 22m tall at its highest point. The east and west portions of the wall are supported on steel mullions (250 x 150mm), supported at floor level and propped back to the Central Facilities building at approximately 3/4 height from the base of the wall. Deflection at the top of the wall varies from 130mm inwards to 50mm outwards, requiring a special detail for sealing the top of the wall to the roof above.

In the central portion of the wall near the main entrance, the buildings behind disappear, making it impossible to continue the same system of bracing. To simulate the same propping condition, a series of portal frames were constructed around the entrance gallery to support the glass at intermediate mullion locations. Cable trusses connect to the adjacent mullions, giving both lateral and vertical support to the glazing in this area.

13.
Internal view of the 22m high glass wall to the foyer.

Back-of-house and north boundary

The back-of-house facilities are below ground beneath the eastern exhibition galleries. Semi-trailers have to turn within the loading dock area, so the columns supporting the 21m high walls of the Pasifika Gallery are on the base 14m square grid. Within the northern perimeter walls of the back-of-house is an office and curatorial area with windows onto Carlton Gardens. The perimeter wall of this area, half a storey below ground, was originally designed to be of precast concrete panels to avoid disturbance to the existing trees in the Gardens, but at the contractor's request it was changed to a soldier pile and concrete wall having precast load-bearing panels above ground level. The latter support the northern terrace, which is covered with up to 2m of soil landscaping.

12.
The spectacular main entrance of Melbourne Museum at night.

Civil engineering

The design of drainage from downpipes and external areas was complex, primarily due to the multi-level nature of the development and limitations on outlets. Authority requirements dictated that all stormwater runoff had to be apportioned between one of two outlets, replicating the previously existing flow regime. Both outlets had limited capacity and levels were relatively high, which meant that falls had to be kept to a minimum. A temporary drainage system was required to service the IMAX theatre until installation of the final system.

Site restrictions forced much of the stormwater drainage under the floors of the building, threading between structural elements and other services. A major length had to be stepped down to twin high-density polyethylene pipes to overcome height restrictions. Positioning of access pits took into account architectural requirements and future accessibility, and many pit lids were designed with bolt-down covers to resist hydraulic pressures during extreme storms.

Precast trench drainage systems were used extensively throughout the significant areas of open paving, and several styles of grate were specified for aesthetic reasons, including brick slot drains to 'hide' the drain. The paved areas themselves are predominantly slab-on-ground but also traverse suspended slabs.

The architect specified a stretcher bond paving pattern comprising individual 0.7m x 2.4m units. Arup developed a steel fibre reinforced concrete solution to improve construction productivity, accommodate varying support conditions, and give construction traffic access much sooner. Slabs nominally 8.4m square were saw cut to shallow depth to imitate precast pavers, and include black oxide colouring.

Paving also extended to the base of a heritage-listed *Eucalyptus Cladocalyx* with a broad but shallow root system. An innovative design was developed for this area to minimise disturbance; it incorporates a series of treatments to allow continued interchange of air and water around the root system whilst minimising compaction.

Construction

Excavation

An early works package included the bulk site excavation, and the soldier pile wall for the deep IMAX theatre excavation. The soldiers were reinforced concrete, and permanently ground-anchored back as excavation proceeded. Rather more groundwater seepage than envisaged was encountered at the base level, needing extra permanent pumps to drain the cavity between the anchored wall and the architectural wall in front.

Sequence

The first structures to be started were the IMAX theatre concrete shell and the west car park. However, excavations confirmed ground contamination from naturally occurring arsenic in the mudstone, and resolving the disposal of this took nearly three months. As much as possible was retained to be buried under concrete structures. The main Museum buildings then commenced under the control of the appointed contractor for the main works, who also took over the IMAX early works. As the buildings are separate, construction proceeded on about five main fronts across the 350m x 200m site.

Central Facilities

This building was constructed using standard formwork. Some of the lower columns are double storey height and inclined and had to be supported off props until they were attached several storeys higher. Additionally, one level was hung from the floor above.

Parts of the Central Facilities buildings are supported from the roof structure of the IMAX theatre and the Touring Exhibition Hall. The IMAX theatre's two east-west, 3.4m deep, 29m steel trusses - plus two 12m cross-trusses - were fabricated in Geelong about 50km away and trucked to the site in one piece. The longer trusses were around 58 tonnes and lifted into position using a single mobile crane.

15.
IMAX theatre transfer truss ST3 being lowered into position.

16.
Cantilevered tip of Forest Gallery canopy being dual crane lifted into position.

The Central Facilities building over the Touring Exhibition Hall is supported from concrete beams, one of them 3m deep by 1m wide prestressed concrete, the other a two-storey, 400mm thick wall with partial prestress. Both beams span about 30m east / west.

Exhibition galleries

The panels around the perimeter of the exhibition galleries were erected with two levels of raking props (with pockets through the intermediate floor slab level). The panels formed a backshutter to form the integral columns. The slabs and beams were constructed with conventional formwork.

Because of its complex geometry the Te Pasifika Gallery was constructed using a single-sided (internal) shutter. After concrete had been sprayed onto it and had achieved sufficient strength, the shutter was lifted to the next level and the process repeated.

Tension anchorage plates were incorporated in the curved wall, and as it progressed upwards, the inclined dead load component and any wind load were tied back to the base structure.

The Evolution Gallery was in an area which the builder was maintaining for access to the Forest Gallery. As time constraints crept in, he decided to construct the concrete shell by erecting steel falsework and then erecting concrete precast panels with reinforcement protruding to enable full moment stitches between the panels to be made. The exception was the 20m opening on the inclined north wall, where the lower 3.5m was poured in situ on cast-in steel props to provide support for the precast panels above.

14.
The Orientation Galleria - a central circulation space within Melbourne Museum - features a pygmy Blue Whale skeleton.

Forest Gallery

The Forest Gallery canopy was assembled in five parts underneath its final location. The first stage, at the south end, was assembled in the air at the same time as the steelwork for the Central Facilities roof. The mobile crane used weighed 160 tonnes, which imposed significant surcharge loading to the surrounding basement walls. The other sections of the canopy were lifted using two cranes with the booms almost vertical to obtain the necessary load capacity. Bolts were inserted in the splices from 40m high boom lifts; the heaviest lift was about 60 tonnes. The last nose section of the canopy had to be erected with strongback frames, as it cantilevered from the canopy and did not have sufficient bending strength to span between cranes.

Assembling the Forest Gallery canopy influenced the landscaping, as there was only a short time window to transplant the mature trees (up to 23m tall). Their size and the volume of soil needed required mobile cranes to be brought in from the north gardens. In the event, delays in steel erection pushed the landscaping out by 12 months.

Children's Museum

The Children's Museum was erected with the steel frame parallel to the building's skewed axis - and the builder was notified by members of the public that they believed there had been a collapse!

Once the building was clad, many people entering felt disorientated by the inclination of the steelwork. Even fully fitted-out, the floor appears to rise significantly across the building.

Opening

The Melbourne Museum was formally opened on Saturday 21 October 2000 by the State Premier of Victoria, the Hon Steve Bracks MP, in a ceremony which coincided with the start of the city's annual Arts Festival.

The opening ceremony was broadcast live on the internet in Australia's largest ever webcast. Accessed around the world, this was one of the most watched broadcasts internationally to date. The Premier praised the architects and their team, as well as the Museum itself, for creating a 'major world class attraction'.

Almost 65 000 people visited the Museum on 21-22 October, which is believed to be an international record for the opening of a facility of this type. Since then, visitor volumes have been as high as 7000 per day, and reactions have been extremely favourable.

Credits

Client:
Office of Major Projects acting on behalf of Victorian State Government

Architect:
Denton Corker Marshall Pty Ltd

Civil, structural, and traffic engineer:
Arup Edward Aquilina, Peter Bowtell, Tim Cottrell, Joseph Correnza, Adam Cox, Peter Duggan, Eugene Golshtein, Erik Guldager-Nielsen, Peter Haworth, Andrew Heath, Andrew Henry, Greg Hopkins, Paul Janssen, John Legge-Wilkinson, David Marinucci, Neil Paynter, Charles Spiteri, John Violi, Debbie West

Quantity surveyor:
Rider Hunt, Melbourne

Building services engineers:
Lincolne Scott Australia Pty. Ltd

Building surveyor:
Peter Luzinat & Associates

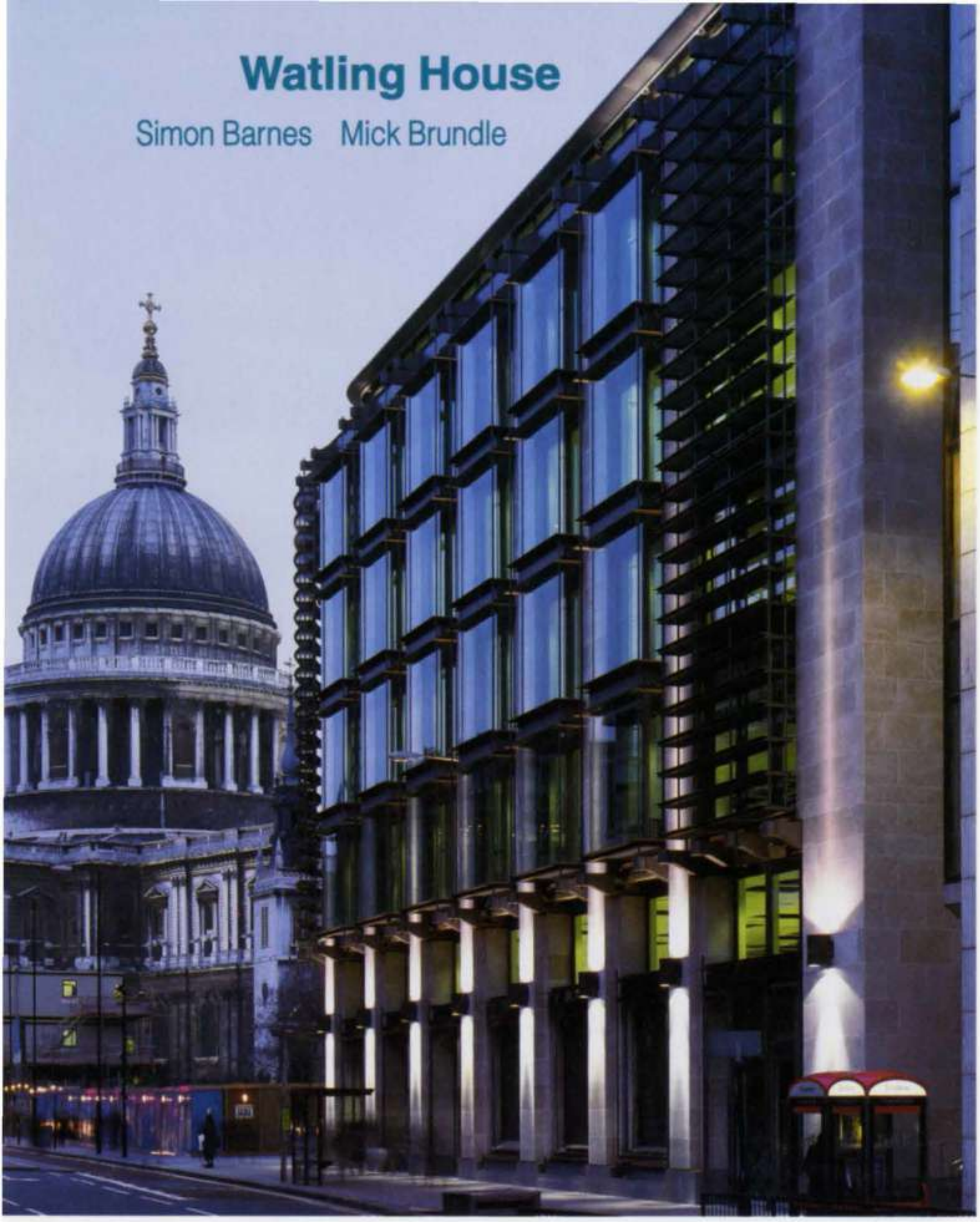
Main contractor:
Baulderstone Hornibrook Pty. Ltd

Illustrations:
1, 2, 5, 6, 9, 12,-14, 17: Gollings Photography
3, 7, 8, 11: Jonothan Carver
4, 10, 15, 16: Arup

17.
The beautiful Hilarri indigenous garden, part of the living Melbourne Museum.

Watling House

Simon Barnes   Mick Brundle



Origins

The gestation of Watling House spanned more than a decade, the design of the building evolving as the financial equations of the London commercial office market changed and the approach to what was permissible architecturally, two blocks away from St Paul's Cathedral, became less reactionary. There has been a history of disappointment in attempting to design anything in the environs of St Paul's, particularly for architects of a Modernist persuasion. For example, Arup Associates' competition-winning urban masterplan of 1992 for the Paternoster area became a high profile casualty in a latter-day 'battle of the styles'.

Watling House was originally commissioned by Stanhope in 1988 at a peak of bullish activity in the City of London commercial office market; detailed planning approval for a building was granted in 1991, only to be shelved when the property market collapsed. Revived in 1994 with a brief to maximise site potential by omitting the atrium, the design for a second scheme was granted detailed planning permission in 1995. British Land ultimately became the client, and the building was further refined into a third and final planning application in 1997 - the design that was built. Work started in March 1997, with a handover in December 1998 to allow fit-out works by an anchor financial services tenant to commence in January 1999.

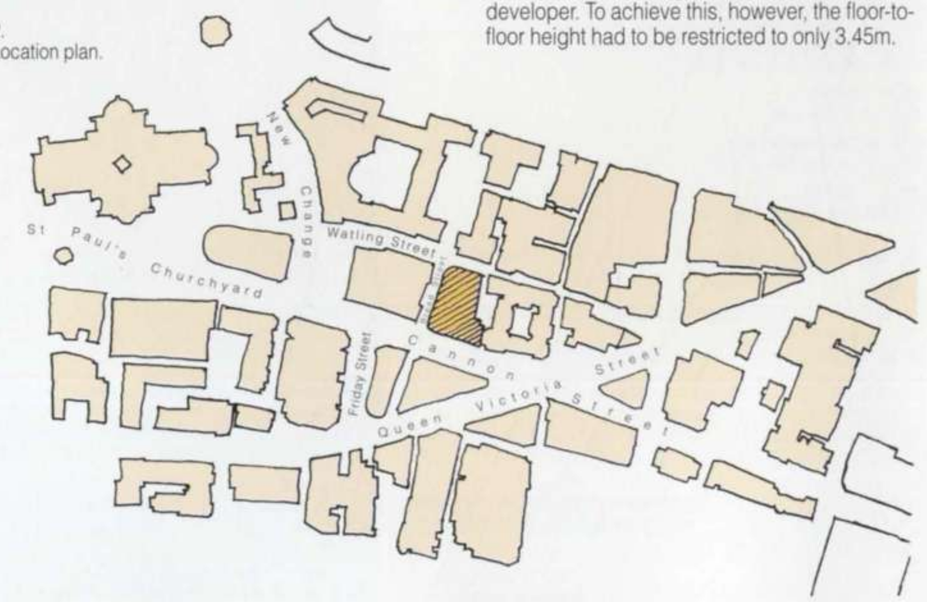
1 top:
Watling House: Cannon Street façade.

The site

The Watling House site is just east of St Paul's (Fig 1), surrounded by roads on three sides and a service courtyard on the fourth.

The main east / west vehicular thoroughfare, Cannon Street, is to the south, with the narrower but more engaging Watling Street to the north. The undistinguished Bread Street forms the north / south edge between Watling Street and Cannon Street (Fig 2).

2.
Location plan.



3.
Watling Street in the Blitz, 1941: the site of the new building is on the left.

The character of the three main streets ranges from the big-city scale of Cannon Street, with its wide thoroughfare and buildings covering entire city blocks, to the finer grain of Watling Street, its 19th century warehouse and retail mix, and its iconic view of St Paul's, immortalised in 1941 by a photograph of a postman trying to find an address amid the lingering smoke and chaos of Watling Street the morning after an air raid (Fig 3).

Since the War, the area has been a preferred location for the financial services and legal market, and the previous, post-War, Watling House was leased to a well-known firm of City lawyers. The site forms the south-west corner of Bow Lane Conservation Area - rich in archaeological material from Roman times. It also falls within a strategic aerial grid known as 'St Paul's Heights', which strictly limits the height of development within the City and maintains views of the cathedral's towers and dome. The restrictions in height imposed by St Paul's, the influence on architectural expression and materials implied by its location within the Conservation Area and proximity to the cathedral, and the high value given to the unexcavated archaeological resource, were the main drivers in the process. These, set against the desire to maximise the site area potential, suggested several key ideas which forged the basis of the design.

The commercial equation

The site contours slope from north to south between Watling Street and Cannon Street by 1.2m. By establishing the ground floor at the lowest level of the site coincident with the pavement level along Cannon Street, entrances at grade for the main entrance to the office and retail could be established on the preferred Cannon Street address.

From the start, the design team realised that six floors rather than five - but still within the constraints of St Paul's Heights - would make the scheme commercially attractive. It was decided to make this a part of the design brief and offer it to the developer. To achieve this, however, the floor-to-floor height had to be restricted to only 3.45m.

The main challenge with regard to the building's anatomy was thus to deliver a fully air-conditioned speculative building for the financial services and legal market, at the extremely tight 3.45m floor-to-floor height, whilst maintaining a clear floor-to-ceiling height of 2.65m: the minimum requirement acceptable to most City tenants for office buildings of this size.

Omitting the atrium early in the design process changed the planning arrangement of the floor plate to a compact central core containing all the vertical circulation escape staircases and services risers, with a smaller satellite services riser on the gable with the adjacent building in Cannon Street. Having established the fundamental parameters of the floor-to-floor height and building footprint, the team developed the detail design.

The solution combines structural, servicing, and architectural strategies quietly but effectively. The proposal was to provide a reinforced concrete frame with a predominantly 6m x 6m structural column grid (together with some 7.5m spanning bays) that would enable the flat concrete slab depth to be kept down to a trim 225mm.

Conditioned air from the central basement plantroom is delivered to the office space via vertical risers into a 300mm suspended floor zone, designed as a combined air plenum and cable-way. The conditioned air enters the office space via moveable air grilles flush with the floor, returning via the office luminaires into a plenum and sprinkler zone within the ceiling void of 275mm, and returning to the basement central plant via the central core (Figs 4 & 5).

The façade design formed an essential part of the integrated solution by maintaining environmental comfort at the building perimeter through effective solar control, balancing of well-insulated solid components with full-height glazing, and provision of a triple-glazed thermal flue. The perimeter zone was additionally provided with fan-coil units within the relatively constrained floor void, providing a tempered air supply at each window opening.

To maintain a maximum building envelope height it was essential to locate the central plant within the basement area and thereby minimise projections above the roof level - a process complicated by the fact that the original basement profile, constructed in the 1950s, had to be retained.

Only the cooling towers and boilers were located at roof level, on the one small corner of the building without St Paul's Heights; the boilers were moved up quite late in the design. Nevertheless, despite these restrictions, the principles of air intake at roof level, and up to100% outside air for cooling without refrigeration when outside temperature conditions were favourable, were successfully adopted, providing a healthy and comfortable internal environment for the building's occupants.

The new basement slab was constructed as a raft and stitched into the existing retaining walls following demolition and breaking out of the original basement slab. This process retained nothing of the original substructure barring the retaining walls themselves, and so required substantial temporary steel propping prior to the new basement being constructed.

The resulting mis-match between the profile of the new building above ground level and the existing basement profile was reconciled by supporting the overlapping edges of the ground floor slab and perimeter superstructure on mini-piles, whilst supporting the coincident perimeter on existing retaining walls. Using mini-piles gave the double advantage of minimising disruption to whatever Roman antiquities might be present outside the basement profile and eliminate the vibrations associated with more conventional piling solutions.

The building and its setting

Given the contexts of the Bow Lane Conservation Area and St Paul's, the new building within touches on special City sensitivities with regard to the resolution of its massing and appropriateness of façade. St Paul's forms an exceptional backdrop to the views towards the west down both Cannon Street and Watling Street.

The new building's boundaries were pushed to encompass the existing building line and the lowest section of St Paul's Heights. The resulting volume exceeded the old post-War Watling House massing which was configured as the low podium and T-shaped multi-storey office plan common at the time, and provided a well-lit, naturally ventilated office environment, though at a low density.
As there was concern over the impact of the new volume on views of St Paul's particularly down Cannon Street, the top floor of the building was set back. This opened up the view of the dome at high level and, when repeated in the narrower Watling Street, created the impression of a lower building more compatible with the existing streetscape of 19th century architecture.

This top floor set back had many precedents in Cannon Street, where the device of lowering the inferred top of the building by a cornice or set back, was freely used (particularly on the now-demolished adjacent Bank building), and whose antecedents can be found in many historic building types.

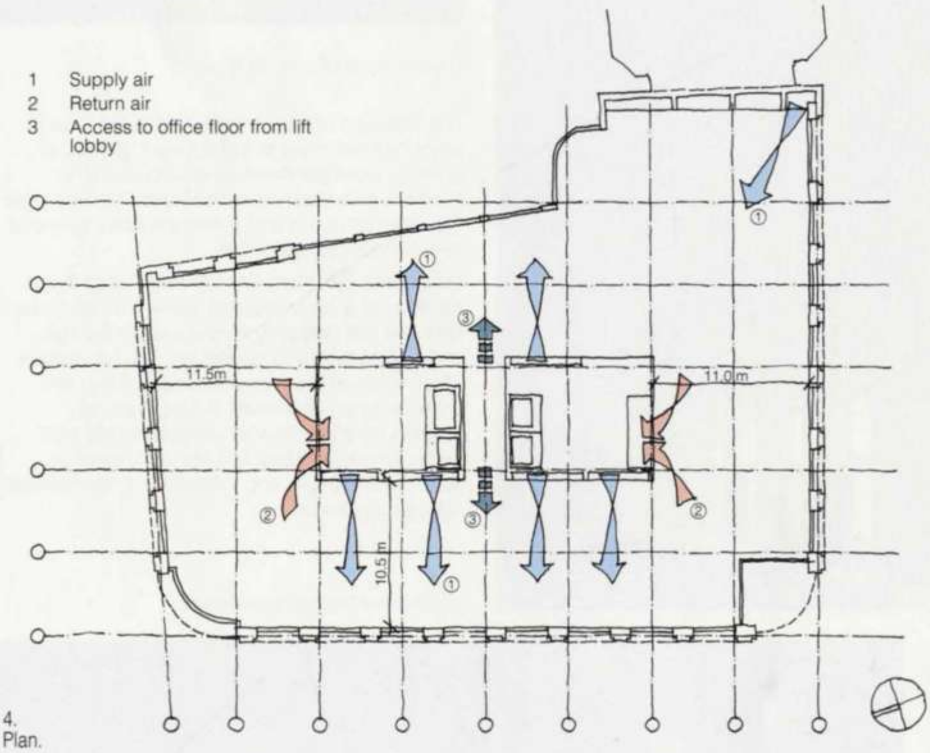
The elevational resolution

The façade textures of the surrounding buildings vary between the coarse grain of Cannon Street with its late 20th century buildings and the finer grain of the Conservation Area of Watling Street.

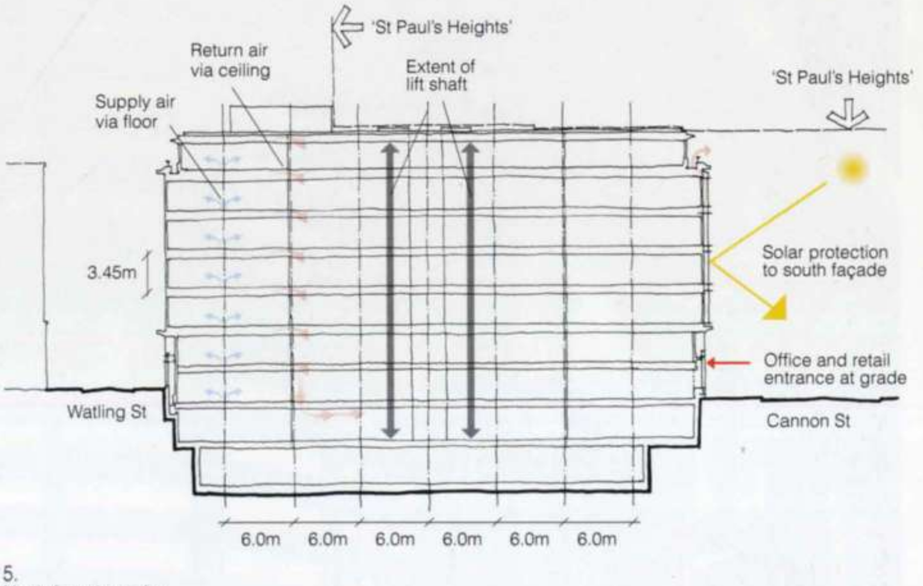
The effect of pitching the ground floor level with the pavement in Cannon Street meant that in Watling Street the ground floor was below pavement level, which - as its purpose was to become a new City 'watering hole' - was acceptable.

Although the plan structural grid was 6m x 6m, a façade grid of 4.5m, mediating between the extremes in scale of Watling Street and Cannon Street, was adopted.

When laid against the three main façades, this approach provided an anatomy that allowed a straightforward 'solid to void' elevation composition,



4.
Plan.



5.
North / south section.

with the ratio of the two 'solid' elements (insulated, reinforced concrete, masonry-clad piers) to void (glass cladding) satisfying the requirements of solar protection and control, the views from the office floors to outside, and the City's perception of an appropriate addition to the Conservation Area. Once the compositional principles had been established, the glazed cladding was developed as a series of triple-glazed thermal flues to the south and west office floors projecting over the building line which, coupled with solar activated blinds within the cavity, provided solar control to the glazing.

As the northern elevation in Watling Street did not require this degree of solar control, the outer glazing layer was omitted. The same inner window was retained, allowing a less 'glassy' and more 'solid' elevational perception when viewed obliquely down Watling Street towards St Paul's.

6.
Exterior view of office in daytime.

The retail and office entrance uses to the ground plane required more straightforward glazing, all of which when combined as an elevational 'kit' provided a vertical hierarchy of 'base' 'middle', and 'top' from ground to roof: a contemporary spin on a very old compositional idea.

On all three elevations the 4.5m vertical grid was made up of a 1.5m insulated, stone-clad reinforced concrete pier propping the edge of the flat slab, and a glass cladding zone of 3m. The two corners which followed the original curved building line were designed as a series of fixed, vertically stacked horizontal louvres which provided solar protection to the glassy corners, emphases to principle entrances, and 'bookends' to the modular elevational system.

Credits
Client:
The British Land Company plc
Architects, structural engineers, M&E engineers:
Arup Associates Simon Barnes, Mike Bonner, Mick Brundle, Martin Finch, Tony Hoban, Colin Jenkins, Elizabeth Kendall, Graham Ling, Terry Moody, Terry Raggett, Eugene Uys, Peter Warburton
Quantity surveyors:
Davis Langdon & Everest
Main contractor:
Kvaerner Trollope & Colls
Illustrations:
1, 7, 8: Grant Smith
2, 4, 5: Arup Associates/Jonothan Carver
3: Hulton-Deutsch Collection
6: Arcaid/David Churchill

7 left:
Night view of Watling House façade.

8.
Effect of corner lighting at night.

Schwimmsporthalle, Berlin

Nigel Annereau Mike Banfi Adam Chodorowski Clodagh Ryan David Wall Mohsen Zikri

Introduction

In 1997 *The Arup Journal* published 'Radsporthalle, Berlin'[1], an article that finished with 'Watch this space!' The time has come to tell the other half of the story. The project, conceived by the French architect Dominique Perrault, won the 1992 international competition to provide Olympic cycling and swimming facilities in support of the Berlin 2000 Olympic bid.

Arup supplied the other members of the design team and was responsible for all engineering disciplines including, as far as the building services were concerned, quantity surveying, cost control, and construction management.

With Olympic deadlines approaching, design of the overall project proceeded rapidly so that work could be under way on the Radsporthalle site when the Olympic Committee visited in June 1993.

Though the 2000 Olympic decision went to Sydney, the Berlin Senate decided to continue with the project, redesigning the Schwimmsporthalle with cost-saving measures. The concept remained basically intact, however, with a 50m Olympic Competition Pool, a 50m Training Pool, a Diving Pool, and numerous other small pools.

The complex was opened in November 1999 and has received critical acclaim from spectators and sportsmen alike.

The Radsporthalle and Schwimmhalle form a single architectural entity. Both are sunk substantially below a raised ground level to reduce their visual impact on the surroundings.

This raised platform embraces both the buildings and is planted with apple trees. Their roofs, although with different plan shapes, are both clear-spanning and have the same elevational relationship with the surrounding park.

They are also clad the same way, with stainless steel mesh. Linking both parts of the complex is a combined heat and power unit, situated in the Radsporthalle.

Structure and geotechnics

The ground conditions at the Schwimmhalle site are generally uniform, with 3m of made ground overlying about 10-12m of glacial till. Underlying this to a considerable depth is dense sand with occasional thin layers of gravel. The groundwater level is about 13m below pavement level - unusually deep for Berlin - due to the site being on a small hill. Without this, it would have been impossible to construct the necessary deep excavations.

1. top:
The Schwimmhalle in its sunken setting.

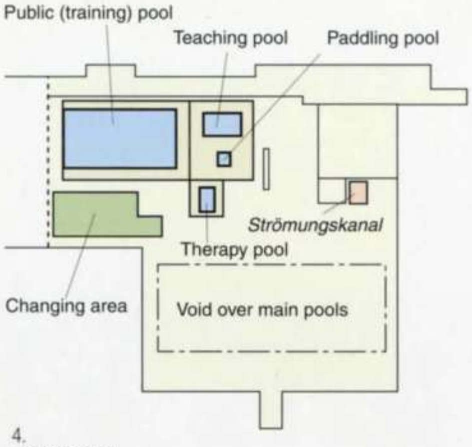
The Schwimmhalle has no continuous floors or substantial cores to provide propping action for the earth forces in the substructure, so the main retaining walls are independent structural elements. The final design is a king-post wall comprising 0.9m diameter bored piles at 2.7m centres with reinforced shotcrete panel infills. The bored piles are anchored with 2-4 levels of anchors depending on the retained height. All excavated material was taken from site by rail as fill for a disused opencast coal mine. The Schwimmhalle alone needed some 300 000m^3 of excavation.

Using permanent ground anchors for a structure like the Schwimmhalle required careful consideration. The anchors' plan extent lies within the site boundary, so they cannot be affected by present or future adjacent developments. Load cells were installed on 5% of them for regular measurements to be taken.

The excavations for the Competition and Diving Pools are 16m and 19m deep in the dense sand below ground level, and the design considered the conditions of both pools filled with water and where one or both pools is empty. The swimming pool structure is ground-bearing and designed so that when empty there is sufficient dead weight to withstand the buoyancy from external groundwater pressures. However, the Diving Pool, being substantially deeper, has a grid of bored piles beneath the base slab, which carry compression loads when it is full and act as tension piles to resist uplift when empty.

2 left:
Schwimmhalle (below);
Radsporthalle (above)

3.
Construction of the Competition Pool
and Diving Pool in waterproof concrete.



4.
+38.5m level.

The three main floors of the complex are all below existing ground level, the lowest level, +38.5m, housing the Competition and Diving Pools. The +44.5m level has the Olympic-sized Training Pool, a therapy pool, a teaching pool, and a paddling pool for toddlers.

Other spaces were set aside for specialist training activities like a trampoline area, a diving area without water (but lots of big cushions) and a *Strömungskanal* - where people stay still and the water moves.

The +44.5m level comprises the fully suspended pools mentioned above, changing and circulation areas, and the first tier of seating around the main pools below. Generally floor slabs are conventional flat slab and beam-and-slab depending on the column grid, which varied to suit the usage. Each pool, however, is completely different in form. The Training Pool (50m x 25m) is mostly above the main plantroom, its floor depth stepped to accommodate a 'floating floor'. This enables the depth at one end to be varied to suit the use - making it safe for small children if required.

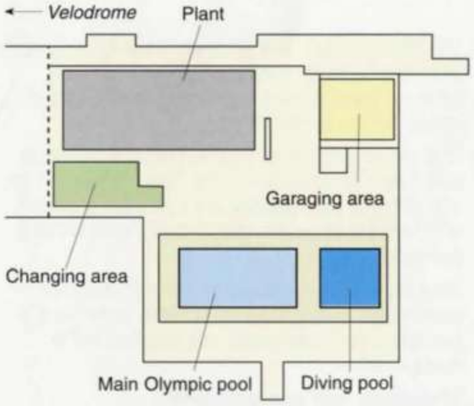
The pool bottom is a beam-and-slab construction supported by its own grid of columns rising through the plantroom. The therapy pool (9 m x 3m) has full wheelchair access, and people can be lifted in and out of the water as well as stand up above the general level of the slab. The teaching pool is shallow with a sloping bottom, allowing swimming technique to be analysed at close quarters.

Finally the paddling pool is little more than a depression in the slab to accommodate a small amount of water.

The upper level has no pools, but as well as circulation access to the top tier of seating and wet areas such as saunas and plunge pools, it does have an aerobics floor hung from the roof overlooking the Training Pool.

The Schwimmhalle's roof spans 120m x 83m. Transversely, 3.5m high trusses at 7.2m spacing span over the 58m central section with cantilevers at both sides. These trusses are supported by continuous longitudinal trusses that span 14.4m onto bridge bearings at the tops of concrete columns.

5.
+44.5m level.



At the ends of the building the roof projects 7.2m beyond the last transverse truss. As with the Radsporthalle, HD260 and 320 sections were used for the main trusses. The distance between the flanges of these sections remains constant for any section type, with heavier sections being obtained by increased flange thickness. This allowed the top and bottom chord members to be connected with diagonal and vertical struts by welding the flanges, without resorting to the use of node plates.

Space limitations, topography, excavation depths, and the presence of the pools meant that the roof structure could not be erected conventionally with cranes, so it was assembled in sections on a temporary platform at roof level on the east side of the main competition hall and launched into position with guide rails.

This took five months, two temporary longitudinal sliding beams were also installed. The heads of the concrete columns were equipped with sliding sleds at the location of the final bearings, the bottom surface of each sled made from bearings normally used for incremental launching of bridges.

Four sliding sleds were additionally equipped with horizontal guides to avoid the roof structure moving sideways during sliding. A specially developed polyurethane paint was used for the sliding beam top surface to achieve a low coefficient of friction.

The roof was slid into position using two jacks on each beam with a combined capacity of 1200 tonnes. An average friction coefficient of 3.5% was recorded from on-site measurements when the 1500 tonne steel roof was finally slid into position. Once in position the final bearings were installed and the temporary sleds removed.

The diving platform in the Schwimmhalle is the only internal feature in steel rather than concrete. It is a four-storey structure accommodating five platforms - two at 10m, one at 7.5m, and two at 5m - three fixed springboards, and one adjustable one. Access is by both lift and stairs.

The structure has moment-resisting connections to avoid bracing, and is constructed from 280mm H-sections. The critical design parameter was to meet the requirements of FINA, the governing body of international swimming, on vibration.

Mechanical systems

The Competition Pool at the Schwimmhalle is probably the first pool whose air distribution strategy is to use low-velocity air from beneath the tiered seating. Air is extracted both at high level and via overflow ducts at the edge of the pool. The pool water temperature varies between 26°C for competitions and 28°C during normal use. In spectators' areas levels of temperatures and humidities are critical. FINA Standards stipulate that spectators' areas are kept at 1K above pool water temperatures.

Significant technical issues had to be addressed, including the tendency of air to cascade from spectator areas towards the pool, causing discomfort and unpredictable water evaporation. The normally available CFD tools were unsuitable to resolve combined heat and water evaporation problems, so a series of bespoke algorithms were developed. The CFD analysis also helped test ways to prevent air cascading towards the pool. These included the introduction of a heated floor around the pool. Evaporation rates were also reduced to avoid condensation and achieve savings in heating and treating pool make-up pool water.

With spectator level air supply, substantial savings in both capital and running costs were possible. Air is supplied at 26-34°C, rather than the 18-20°C of a conventional high-level mixing system. Only the occupied zones were treated, not the whole space, so chillers and ventilation plant capacities were reduced. Further energy savings were achieved by using outside air for 'free cooling'.

6.
Partially launched Schwimmhalle roof.

7.
Launch rails and jacking point.

Electrical systems

David Deighton

The electrical supply and distribution system was largely reported in the previous *Arup Journal*[1] article. However, a significant change during completion of the project was that, although from the start the complex was considered as a single entity, in reality separate operators were selected for the Radsporthalle and the Schwimmhalle. The client asked Arup for a way to separate the energy costs for the two buildings, even though the heating, cooling, and electrical distribution systems were combined. The task was made more difficult because it is illegal to re-sell electricity in Germany, so just installing sub-meters and charging on electrical units used was not possible.

A report was prepared showing how the energy costs could be separated by the use of electrical and water flow measurement and some calculation algorithms in the building management system.

This cost was then added to the management charge of the building. The two operators implemented this and the system is now operational.

Lighting to the complex is generally by means of compact fluorescent downlighters and linear fluorescent lights. These have local switching for offices and conference rooms, etc, with centralised contactor control for all public areas using a programmable lighting control unit.

For the competition hall the lighting had to be suitable for high definition TV. This was achieved over the Competition Pool with 400W narrow beam metal halide downlighters, supplemented with 2kW floodlights at the ends of the pool to increase the vertical illumination as required to allow filming of the faster parts of the event like diving and turning.

The Diving Pool is illuminated by floodlights, with either one 2000W or two 400W metal halide lights positioned to minimise ceiling reflections for the divers. Artificially induced air bubbles to reduce reflections further break the still surface of the pool. The high speed of the divers in action is captured by the high vertical illuminance to allow the use of high definition TV cameras.

Half the luminaires in the competition hall are fitted with a hot re-strike facility to allow competitions to continue should a momentary break in the electrical supply occur.

All the luminaires have protection against the humid corrosive air collecting at high level in the hall.

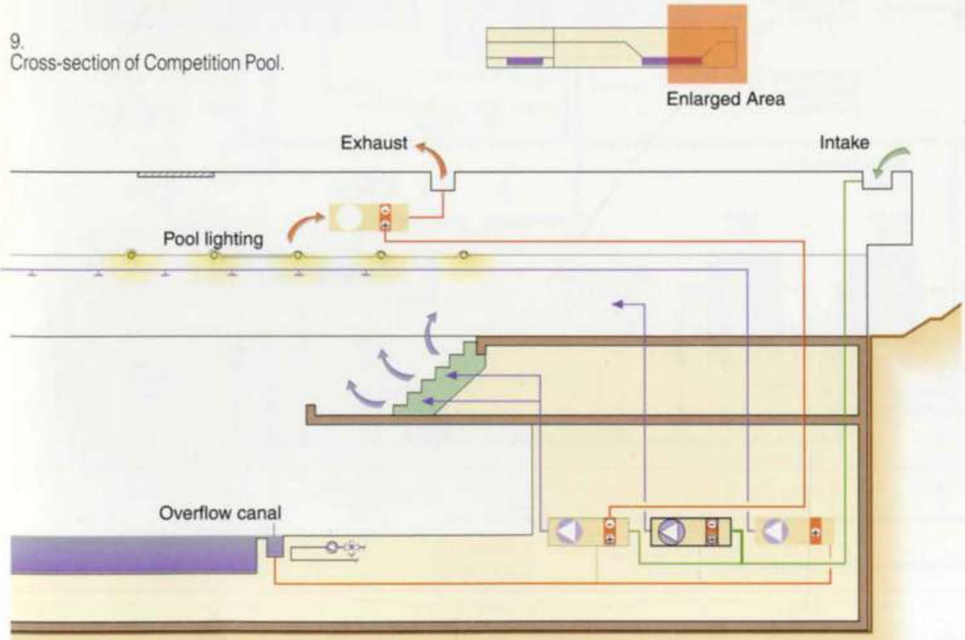
The pool basins are required by German standards to have a very high illumination; for competition purposes the requirement was 1000 lumens/m^2.

To achieve this it was necessary to install 250W metal halide underwater projectors in cast-in housings along both sides of the basin, and in the Diving Pool two layers of stacked lights were required either side. This is a specific German requirement to ensure that the lifeguards easily see swimmers in difficulty. This facility also allows for underwater filming for synchronised swimming events and water polo, and for international swimming competitions. A scene-setting lighting controller, with pre-set scenes to provide illumination for training, competition, and competition with TV filming, controls the lighting to the competition hall. The operator has the facility to pre-programme additional scenes should these be required in the future.

8.
50m Training Pool.

The risk of winter condensation is very high, so condensation on the glazed roof and façades is prevented in several ways. The Schwimmhalle's relative humidity is limited to 55%RH, whilst the cold but very dry air of Berlin is exploited to absorb the moisture-laden air of the pool halls. To achieve this economically, outside air is brought in and re-heated using reclaimed heat from exhaust air, before being introduced into the building. Internal moisture contents are controlled by sequentially increasing the proportion of dry outside air and increasing the supply air accordingly.

When the target moisture content can no longer be achieved, the supply air nearest to the glazed areas is heated further to raise the dew-point and avoid condensation.



9.
Cross-section of Competition Pool.

Large sports and leisure facilities like this must be run economically, and Arup's design reduces capital, running, and maintenance costs.

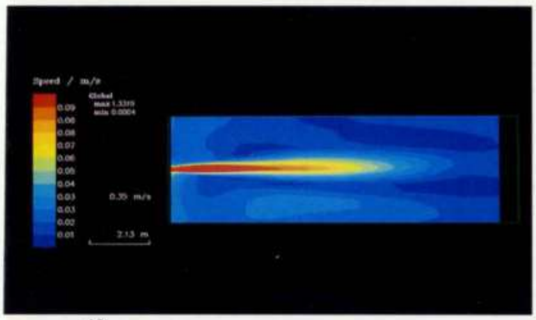
The technique adopted for air distribution gives both lower running costs and smaller air-handling plants, chillers, and boilers. Using CHP (combined heat and power) to generate on-site electricity and heat yielded further energy savings.

Pool water pre-heating for the Competition, Training, and Diving Pools is achieved by using heat rejected from the refrigeration plant, supplemented as and when necessary by the Berlin District heating system via two plate-type heat exchangers.

Heat is recovered from the showers to preheat domestic hot water.

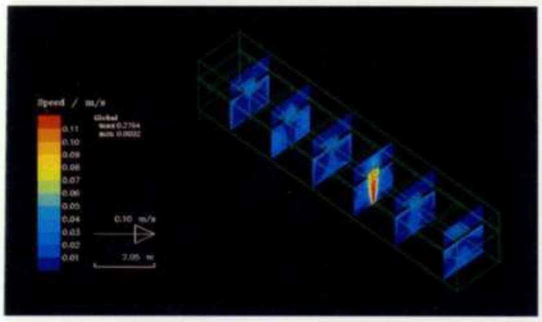
Last but not least, fabric heat losses and gains are drastically reduced, since the buildings are below ground and feature well-insulated roofs, slabs, and walls. The resulting energy savings are appreciable, given Berlin's climate; aggregate savings in plant costs are estimated at about £750 000 (DM2.376M). This does not include the cost of the space saved to accommodate otherwise larger plant. Savings in running costs of both parts of the complex are heavily dependent on use, but on average are estimated at around £230 000 pa (DM730 000).

The brief from the client was to design a world-class Olympic water sports competition venue where records could be broken. In addition to meeting the brief in terms of pool water quality, Arup's design maximises cleanliness, increases efficiencies, and reduces maintenance.



10.
CFD model: side-wall jet water outlet.

11.
CFD model (sliced version): bottom jet water outlet.



The Competition and Training Pools have onerous and sometimes conflicting requirements. Some water turbulence is needed for cleanliness, but laminar water flows must be achieved in the swimmers' zone to avoid affecting their split-second performance. This is understandable given that Olympic swimmers shave their body hair or wear body suits to reduce water drag!

CFD was used for the first time to study behaviour of water circulation through water inlet nozzles and outlets gullies, as well as to determine their optimum positions within each pool. CFD codes were rewritten, introducing bespoke algorithms for water characteristics, and performance of water inlets and outlets were modelled. CFD helped to optimise the number and location of water inlets and outlets, to provide the desired water turn-over rates, and to achieve the optimum balance between zones of water turbulence and laminar flow. Arup's studies concluded that the Competition Pool should feature 100% bottom inlets with 100% top outlets, whilst the Training Pool should have 100% top outlets and two rows of side inlets to allow a moveable floor to be added later .
The Diving Pool should have two rows of side inlets on two sides with 100% top outlets.

The water circulation regime met FINA's specific requirements for competition pools, which include water temperatures and residual chlorine levels. It should be noted that certain swimming venues, however, are favoured by competitors because they are considered to have 'fast' pools. At the design stage Arup helped the client to identify the physical and psychological factors associated with the use of 'fast' pools. At the design stage Arup helped the client to identify the physical and psychological factors associated with the use of 'fast' pools, and these were therefore introduced in the design for both Competition and Training Pools.

All pools feature a level-deck edge with full top surface overflow. This is preferred from a hygiene point of view because contaminants are removed from the water surface where pollution is greatest. In the Competition Pool there is the added advantage that the edge reflections of surface turbulence are significantly reduced, thus providing competitors with calmer water. The water treatment system provides a high standard of water clarity, colour, and sparkle, and the system is also controlled to enhance swimmers' perception of the water's smell, taste, and feel. An important feature in the Diving Pool is the creation of a cushion of air bubbles to reduce water impact and reflections, particularly during practice diving.

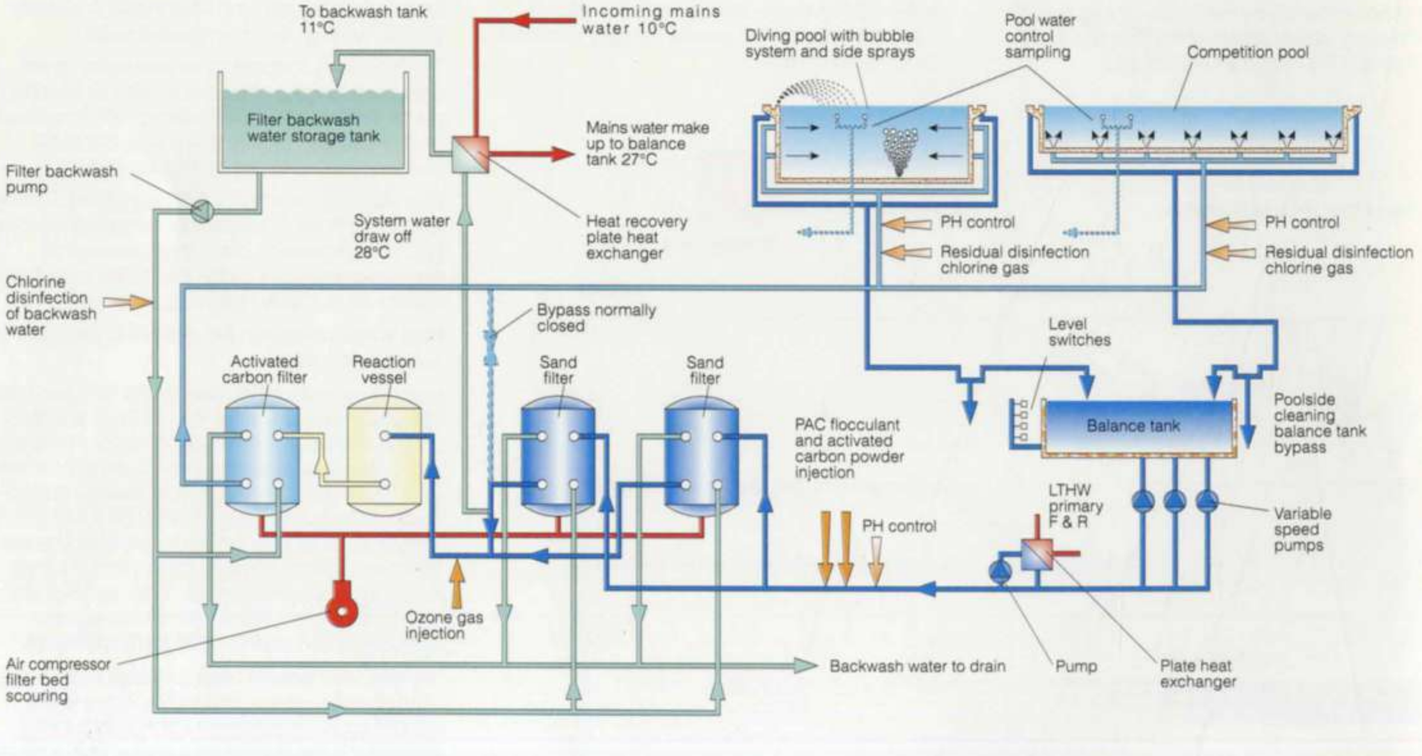
FINA's requirements for residual chlorine levels made the team opt for effective disinfection, using ozone as the only practical choice for the Competition and Training Pools. Ozone is also used as the disinfection agent for all the other pools.

Disinfection takes place outside the pools, with the advantage that there are minimal chemicals in the supply water to the pools. Chlorine gas is used for residual dosing because of accuracy of control and the cleanliness of delivery into the pool water supplies. The low residual chlorine level in the pools achieved by the use of ozone produces a less aggressive atmosphere in the pool halls with virtually no smell. The less aggressive atmosphere is very user-friendly to poolside staff, swimmers, and spectators, as well as being much less corrosive to the building fabric and mechanical equipment.

The pool water turnover times for the Competition and Training Pools are higher than those required by the DIN Standard. Arup considered the higher water flow rates to be necessary to provide the world-class venue required by the client.

Variable speed pumps were provided so that water flow rates can be reduced to the DIN levels during non-competition use.

Polyethylene, not PVC, was used for pipework and components - extensively for constructing the pool water treatment plant; at the time the installation was under way the use of PVC was prohibited by the Berlin public authorities for environmental reasons. It is standard practice in Germany for pool water distribution pipework to have an equal resistance path between the pumps and each pool water outlet nozzle to provide a measure of self balancing. This produced interesting pipework configurations in the Competition Pool , which had over 150 inlet jets.



12.
Simplified schematic of Competition Pool water circulation.

Displays, timing, and scoring systems

The Schwimmhalle hosts many types of event, including swimming, synchronised swimming, diving and water polo; competitions range from local gatherings to international championships. Each sport requires a timing or scoring system that conforms to German and international association standards for that event; equipment is only connected up when required.

The swimming timing system comprises two computerised timing units, one acting as a hot spare for the other in case of failure, located in the judges' room alongside the pool. Removable touch panels are provided for each end of the pool, to allow individual lengths to be recorded.

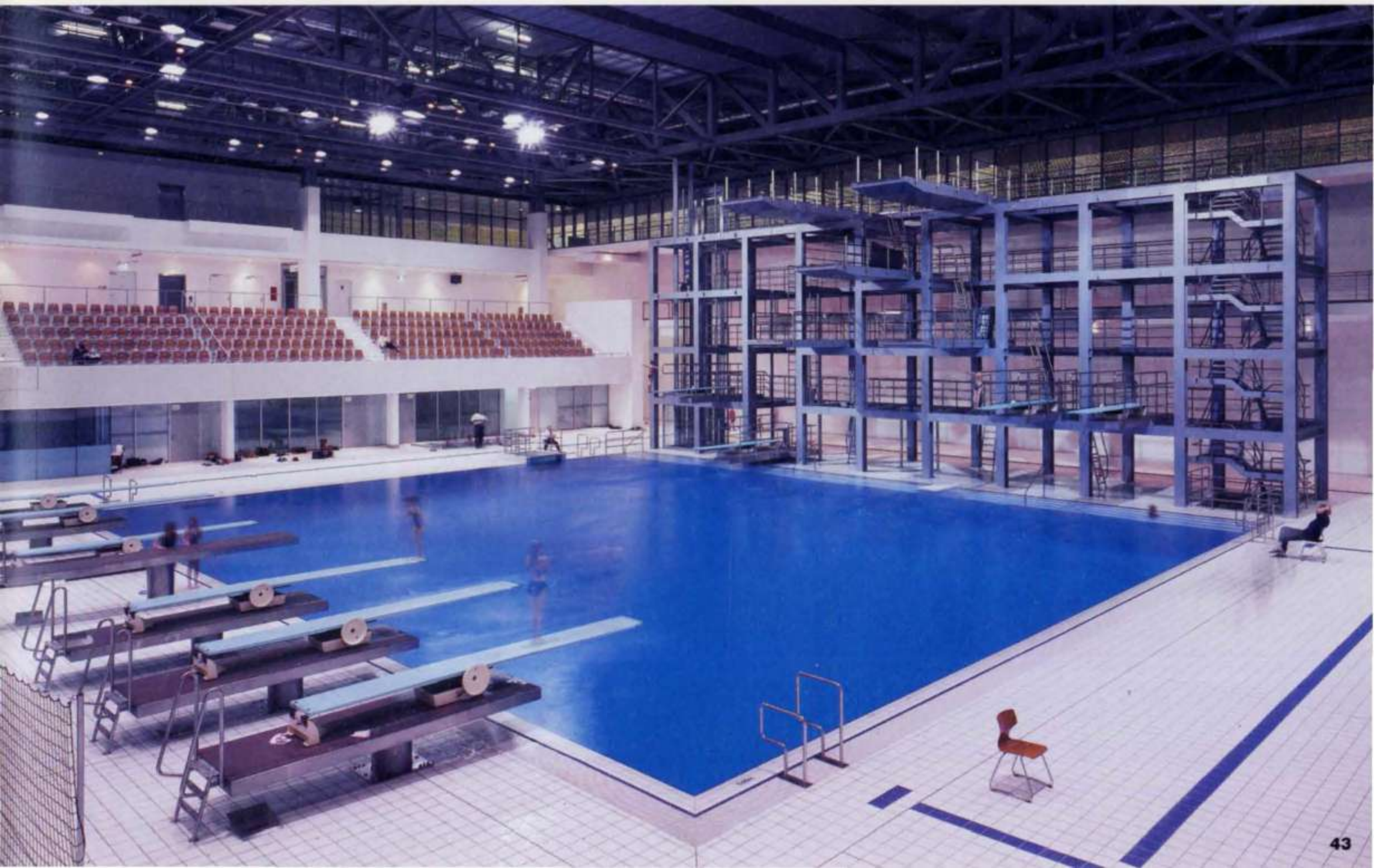
The custom starting blocks have loudspeaker and false start detection. Permanent cabling around the pool speeds up connection, and the whole system is battery powered for swimmers' safety. The timing unit provides the data for the results service, as well as the control signals that allow TV broadcasters to show timing information on-screen; these are cabled up by the broadcaster on each occasion.

One common system provides the scoring for diving and synchronised swimming, comprising a main judge's panel and seven other judges' panels, with an intercom linking them all, whilst the water polo scoring system consists of three operators' panels and two 35-second countdown displays. Permanent cabling is installed where practical to speed up preparation for events.

All three systems output data to the results computer in the judges' room. This processes the data into a form suitable for use by the LED scoreboards above the pools and to the internal house TV system, allowing results to be seen across the site. The LED displays meet FINA's stringent requirements in terms of character height and information displayed. The displays are not capable of showing video, which the pool operators hire as needed.

13.
Therapy pool.

14.
Paddling pool.



15.
Diving Pool.

16.
Competition Pool
from roof level.

Acoustics

Raj Patel

As in the case of the Radsporthalle, three key design issues were addressed to achieve the required acoustic performance:

- **Room acoustic response**
Reverberation times of the pools were analysed to ensure an appropriate room response. The geometry and acoustic performance of the finishes were studied to prevent late reflections in the natural response from the house sound system. Furthermore, the acoustic response was important to ensure that the swimming / training instructors could communicate well with swimmers. The building-wide acoustic response was analysed to meet the voice alarm system design standards.

- **Sound insulation**
The performance of the building envelope was analysed to ensure that noise break-out from the building does not result in any significant change in the environmental noise at the nearest residences.

- **Electro-acoustics**
In case of the voice alarm systems, the correct room acoustic response, coupled with the type, location, orientation, and performance characteristics of individual loudspeaker types, was essential.

The strong emphasis on training also required an electro-acoustic system that could meet the client's brief, including for synchronised swimming.

Materials used within the pool environment had to be carefully chosen both to provide the required reverberation times and be able to withstand the environmental conditions. Options for locating materials were limited, and concentrated mainly at ceiling level. In the Competition Pool a liner tray system, consisting of expanded metal mesh panels suspended directly below the ceiling with 100mm of acoustic insulation located in the tray, provides the absorption. All seating overhangs use mineral wool behind timber slatted ceilings for absorption, and this method is also used throughout the remainder of the building.

The result of using this combination is a mid-frequency reverberation time of approximately 3.5 seconds across the frequency spectrum. However, the early decay time is around 2.5 seconds from efficient utilisation of absorption incorporated in the low soffits and balcony front upstands. This avoids the common low frequency 'boom' and general reverberance associated with pool spaces, particularly when swimming events are in progress.

There are two electro-acoustic systems in the building: the site-wide voice alarm system covering all areas, and the arena bowl performance sound system. The voice alarm system design criteria ensured a speech transmission index (STI) of 0.45 in all areas of the building.

This not only required the introduction of acoustic absorption within the different building spaces but also attention had to be paid to the design of the loudspeakers.

In spaces where it was not functional or cost-effective to introduce absorption, for example in non-performance and non-public circulation areas, directional column loudspeakers were installed to optimise performance and meet the design targets. In some cases these were specifically designed to match the light fittings, as had been done in the Radsporthalle.

18 above:
Teaching pool.

The performance sound system in the pool areas consists of a fully distributed, high power, full frequency range system capable of high quality music and speech reproduction. Two different types of loudspeaker are used in the Competition Pool ceiling, arranged in a concentric arrangement covering the pool itself and the seating respectively. Underwater loudspeakers are distributed and flush-mounted into the side of the pool walls, which allows any music or training instructions to be routed under water.

This is an essential component of synchronised swimming (and is required for the pool to be eligible for Olympic events), as well as being useful for training purposes.

17.
Competition Pool.

Broadcast facilities

The site has an internal house television distribution allowing cable channels, output from broadcasters on the site, and event results to be seen across the site at bars, entrances, and so on. The system is also used to generate two channels of 'what's on' and other public information.

Each television around the site is fitted with a control box that allows a central point to be able to select the channel that monitors views, and more especially power on-off control. This saves someone having to walk round the entire site with a remote control just to turn the monitors on or off.

The Schwimmhalle design has embraced the needs of broadcasters and the temporary rigging of cables, cameras and the like. Dedicated, easily accessible cable routes exist across the building, serving commentary boxes, camera positions, and pool-side. The communications infrastructure serves the needs of radio commentators and journalists.

Conclusion

Despite having lost the 2000 Olympics to Sydney in 1993, the Berlin Senate continued with building two world-class facilities unique in their design. The Radsporthalle proved an outstanding success and the Schwimmhalle is now enjoying its first events in the world spotlight. The uncomplicated lines of the project disguise the high quality technical facilities required in a sporting landmark for the new Millennium. It is impossible to credit all the people that worked on the project but the principal participants are listed below.

Many thanks to all those others from around the world who contributed their experience in order to make this Anglo-French-German project truly 'world class'.

Reference

(1) BANFI, M et al. Radsporthalle, Berlin. *The Arup Journal*, *32*(4), pp3-10, 4/1997.

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