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Front cover:
Exhibition Hall at the New South Wales Royal Agricultural Society Showground, Sydney
(Photo: Patrick Bingham-Hall)

Back cover:
Interior space above the rotunda, No 1 Poultry, City of London
(Photo: Peter Mackinven)

Number 1 Poultry

Mike Booth
Philip Dilley
Robert Pugh

Introduction

Standing opposite the Bank of England, at the very heart of the City of London, Number 1 Poultry has one of the world's most prestigious addresses. Designed by the late Sir James Stirling, the striking high-specification stone-clad office and retail building is a worthy modern companion to its establishment neighbours.

The site is steeped in history. It was variously developed from the first Roman settlements in the mid 1st century AD, through Saxon and mediaeval times, up to the Victorian buildings still standing when the new development began. This historical background set the significant physical and legislative constraints which the planning, design, and construction of Number 1 Poultry had to overcome, a lengthy process with a history of its own.

Planning

Lord Peter Palumbo's father became involved with the site some 30 years ago, acquiring small City freeholds between Poultry and Queen Victoria Street at Bank. His objective was to complete a jigsaw, with the vision of the whole one day forming a site large enough to sustain the landmark modern building he felt the City lacked and needed to maintain rank with other international cities. This legacy was taken on by his son and first came to public prominence in the early '80s when proposals to build a tower and extensive plaza to a '30s design by Mies Van der Rohe were announced. There was much public debate and opposition to these radical proposals, and Lord Palumbo turned in 1985 to James Stirling to produce a more conservative contemporary urban design. Arup was appointed as engineering advisor.

At the heart of the debate was concern for the future of the existing Victorian buildings, principally the Grade I listed Mappin and Webb premises that used to stand at the apex of the triangular site directly overlooking Bank. Stirling at first produced designs retaining the Mappin and Webb building, but its physical deterioration was such that it was becoming uneconomic for restoration. So a subsequent design was produced for the entire site, involving complete demolition and offering greater opportunity for the landmark new building.

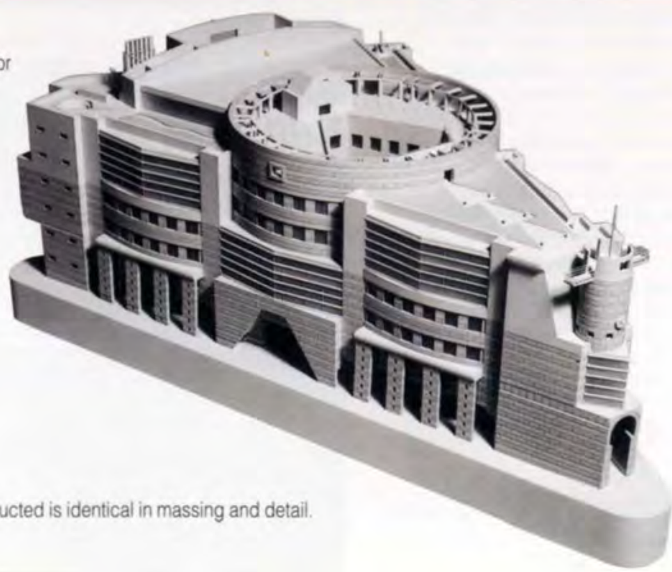
A planning application was submitted for the Stirling design, which became the subject of two public enquiries and famous through Prince Charles' reference to the proposed design as being like a '1930s' wireless set'. Permission was finally granted in 1989 by the then Secretary of State for the Environment, Sir Nicholas Ridley, on the basis that the design represented a 'potential masterpiece' which was of more importance to the nation than the retention of the listed buildings.

New beginning

Considerable legal obstacles remained, each exploited by pressure groups still intent on saving the doomed Mappin and Webb building. So it was not until 1993 that Lord Palumbo's City Acre Property Trust formed a joint venture with German financier Dieter Bock's company Advanta to develop the project, which was to be managed by Altstadtbau, part of Advanta.

After the untimely death of James Stirling his practice was continued by his former partner, Michael Wilford, and Michael Wilford and Partners were appointed by Altstadtbau as architects. Ove Arup & Partners were appointed in September 1993 as structural, geotechnical, building services, and façade engineers as well as offering traffic engineering, acoustic and fire safety consultancy, and design team co-ordination.

1.
The Grand Staircase from ground to first floor at the eastern 'prow' of the building.



2.
Architect's model.
The building as constructed is identical in massing and detail.

3.
The Mappin and Webb building, February 1994.

Planning consent for the building was due to expire in June 1994, only nine months later. Three critical conditions had to be met within this time to satisfy the consent.

It was a condition that (a) a physical start of new construction be made before this expiry date. Before that, demolition had to take place, and for that to happen it was also a condition that (b) a full building contract first be let. Additionally, an agreement (c) with English Heritage on the scope and method of archaeological works was to be in place. It was therefore imperative that a contract be let at the earliest opportunity.

Construction management forms of contract were not an option due to the planning condition. Also, since the design only existed at a planning stage, there was no time for a conventional tender. Altstadtbau decided on a guaranteed maximum price contract, tendered on the basis of scheme design information from the design team, prepared by December 1993. Tender documents were issued in January 1994 and following negotiations John Laing Construction were appointed at the beginning of April 1994. The contract signing satisfied planning condition (b).

In parallel with this, an enabling works package had been separately procured to secure the site, commence service diversions, and prepare for demolition. This package included installing a small section of permanent retaining wall in the only undeveloped part of the site - the St Benet Sherehog Churchyard graveyard, which first had to be exhumed and investigated by Museum of London archaeologists. This small section of 'permanent' construction was sufficient to satisfy planning condition (a).

After some months of tense negotiation, an agreement was reached with English Heritage on the scope of the appointment of the Museum of London Archaeology Service. This finally satisfied the outstanding condition (c) just before the planning consent expiry deadline.

Design concept

James Stirling's signature architectural style, in massing terms at least, could generally be described as consisting of the arrangement of geometrical shapes, and this is evident in the Number 1 Poultry design. The triangular site defines the base plan. This is bisected by an existing (and maintained) public thoroughfare, which manifests itself at the centre as a large alternating triangular and circular courtyard or 'rotunda' through the height of the building. The imposition of the rotunda divides the long sides of the plan into three segments, where the alternating triangular and circular shapes are mirrored at the façade line.

The multi-storey building is also a sequence of functional layers, which informed the overlapping geometry:

- a two-storey basement predominantly housing plant, storage and car parking
- a lower ground and ground floor retail area
- first to fifth floor office space
- a landscaped roof garden including a public restaurant.

Almost implicit in a James Stirling building is the quality, colour, and patina of the finishes - samples

4.
Number 1 Poultry in the heart of the City of London.

and representation of which were held as evidence in the planning enquiry and ultimately as examples as a condition for consent. These geometric, functional, and quality features were enshrined in the planning consent, and strictly maintaining them was very much a constraint for the design development, documentation, and construction, to ensure that all the planning conditions were properly satisfied.

Physical site constraints

The City location and historical context brought a number of significant physical constraints that had an impact on the design and the construction:

Location

The site was effectively an island isolated by two heavily trafficked city roads, Poultry to the north and Queen Victoria Street to the south, meeting at a major intersection at the site's apex. A narrow street to the west, at the base of the triangle, separated the site from adjacent existing buildings. This meant that there was no free site area and no opportunity for construction traffic to stop on the roads. Consequently, the structure had to be designed and staged so as to accommodate construction traffic within the building plan.

5.
Façade detail.

Façade engineering

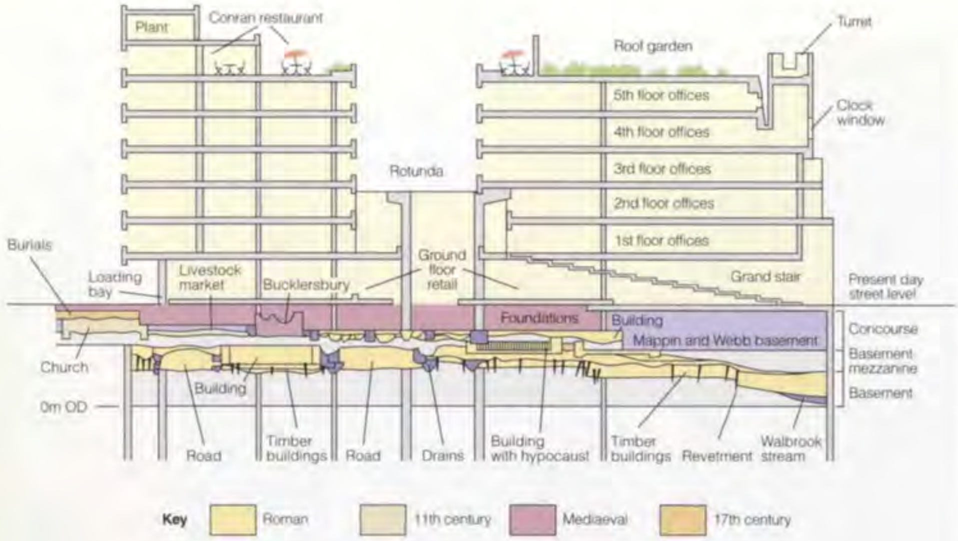
David Anderson

Number 1 Poultry was the biggest commission to date for the then very small Arup Façade Engineering (AFE) group. The brief was to develop with the architect a system supporting the stonework and to assist in detailing the interfaces with windows, doors, shopfronts, and insulated render, including thermal insulation, waterproofing, and the complicated roof garden finishes.

Apart from preparing tender drawings and specifications, AFE were extensively involved with selecting the two types of stone used. Working closely with the Australian and South African offices, arrangements were made for the architect to visit quarries in these countries. The Australian beige sandstone 'Helidon' was finally selected after extensive research and testing both in Australia and in the UK. Interesting enough, it proved cheaper to ship beige sandstone from Australia that to procure a British equivalent! The red sandstone 'Wilderness Red' comes from Gloucestershire.

AFE also had significant involvement in removing and reinstating four 19th century terracotta friezes, formerly part of the Mappin and Webb façade. The terracotta panels have been refurbished, and are now on the Poultry (north) façade. Each frieze is approximately 5m long by 1m high and formed of nine or 10 individual pieces of terracotta cleverly jointed to create a seamless image depicting a scene from historic London.

6.
Friezes rescued from Mappin and Webb façade.



7 left:
Long section.

Road closures and public thoroughfare

A narrow street crossing the site was closed and removed to accommodate the development, but only on condition that 24-hour pedestrian access was maintained on a similar axis throughout construction and in the permanent design. The impact of this was that the site was effectively divided in two at ground level. This had a major effect on the method and sequencing of demolitions, basement construction works, and staging of the superstructure.

Services diversions

As fortune would have it, the road to be closed carried one of the main arteries of the City's telecommunications, the 'life blood' of financial institution operations. Despite commencing this as an early enabling work, the timescale for carrying out the intricate diversion around the site was significant and exacerbated the separation of the site into two segments.

Existing buildings on site

The existing buildings, 4-6 storeys high with 1-2 storey basements, were generally Victorian though some modern refurbishments had been carried out, including areas with piled foundations. Following heritage artefact removal and asbestos removal, demolition had to be carried out in a controlled sequence due to the confined urban location - in the first instance only down to ground floor level due to basement construction and archaeological issues.

St Benet Sherehog Churchyard graveyard

This ancient graveyard occupied part of the site and had to be exhumed prior to archaeological examination and subsequent excavation.

Adjacent buildings

The site being an island, there was only one very close building for which basement construction needed to take significant account. However, all the buildings within a certain radius had to be taken into account, impact assessed, and movements and condition monitored. In particular the nearby Mansion House had already been subject to effects from the new underground construction of the Docklands Light Rail Station at Bank.

Adjacent Underground tunnels

The site is bounded by London Underground railway tunnels typically only 2m-3m from the boundary. The Central Line runs to the north under Poultry, and the Waterloo and City Line to the south under Queen Victoria Street (including the pedestrian *Trav-o-lator* tunnel connecting the platform to the Bank Station underground concourse, at the apex of the site). These tunnels were up to 100 years old, typically in bolted segmental cast iron construction, and with very limited operational clearances. They were potentially extremely sensitive to any distortions caused by ground movement, which was very likely as the project had a proposed three-storey basement. The design and method of basement construction were thus significantly bound by the requirement to minimise ground movement. Additionally, railway vibrations were determined as being a concern for the office areas and so isolation had to be incorporated into the design.

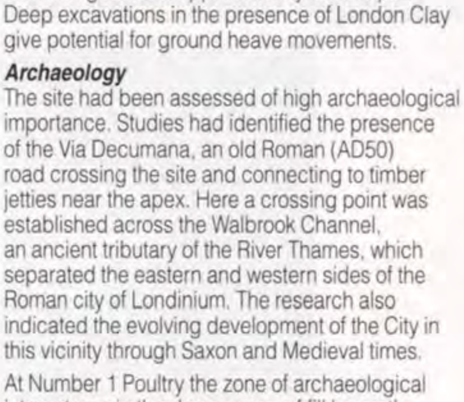
Site geology

Typical of central London ground conditions, the general sequence of soils was 8m-10m of fill/sands and gravels overlying London Clay with Woolwich & Reading Beds at approximately 60m depth. Deep excavations in the presence of London Clay give potential for ground heave movements.

Archaeology

The site had been assessed of high archaeological importance. Studies had identified the presence of the Via Decumana, an old Roman (AD50) road crossing the site and connecting to timber jetties near the apex. Here a crossing point was established across the Walbrook Channel, an ancient tributary of the River Thames, which separated the eastern and western sides of the Roman city of Londinium. The research also indicated the evolving development of the City in this vicinity through Saxon and Medieval times.

At Number 1 Poultry the zone of archaeological interest was in the deeper area of fill beneath the existing Victorian basements. The depth of this excavation, the programme objectives of the developer, and the requirement to minimise disturbance to adjacent tunnels, meant that open excavation was not a viable option. Top-down basement design and construction was therefore adopted, and the project eventually involved the UK's largest archaeological investigation, by the Museum of London, within the top-down method.



8.
Top-down construction under way in the basement, October 1996.

Substructure construction

The substructure is a three-storey framed structure on piled foundations within a secant pile wall retaining structure. A fundamental requirement of its design was to control ground movement to avoid adverse effects on the adjacent Underground tunnels. A detailed analysis of stage-by-stage predictions of movement effects had to be submitted to London Underground as a condition for permission to develop so close to their properties. The conclusions were that the order of magnitude of distortions, and therefore stresses, would not be greater than previously experienced during the initial construction or under existing conditions, and on that basis they were acceptable. Theory is one thing, so a system of on-site movement monitoring was established to provide a practical control to compare with predictions at the various stages.

The construction sequence adopted was:

(1) Demolish existing buildings to first basement level and establish working platform. A protected pedestrian walkway across the site had to be maintained at all times.

(2) Remove obstructions below basement at retaining wall and pile locations by trial pitting and blind boring. Assessed by the archaeologists as a 6% loss of potential site exploration area, this was accepted as an integral part of the process.

(3) Install perimeter secant pile wall, and main foundation piles (together with 'plunge' columns to support superstructure construction). The logistics of associated heavy plant manoeuvering on such a confined site, made more awkward by the dividing road diversion and pedestrian walkway, were particularly onerous.

(4) Construct ground floor slab to prop retaining walls and initiate construction above.

(5) Excavate to remove remaining basement obstructions to enable archaeological excavation to proceed beneath the ground slab level.

(6) Progress with the construction of five of six superstructure storeys during the time made available for archaeological and final basement excavation.

(7) Complete roof and basement slabs.

As described, this sequence was controlled by a system of ground movement monitoring, which comprised:

- inclinometers installed in secant pile retaining walls to measure lateral ground movements at the site perimeter
- tunnel gauge surveys to measure diametric distortions
- Automatic electronic surveys to measure machinery (the *Trav-0-Lator*) distortion
- Surface monitoring by survey studs in pavements to measure ground settlements at the site perimeter and environs
- Building monitoring by survey target prisms to measure adjacent building settlements.

The range of predictions was from up to 30mm in the long term at the retaining wall, approximately 10mm for tunnel distortions, and less than 5mm for building settlements. The monitoring process adequately demonstrated that the construction was indeed behaving as predicted in controlling ground movements, hence safeguarding the adjacent properties.

Superstructure

This design was dominated by geometrical constraints and the fact that the building was to be predominantly clad in open-jointed stonework. This, acting as a rainscreen, required a continuous lining wall behind, structurally able to support (a cavity width away) heavy stone panels. The geometry and the general lack of repetition led to the conclusion that a reinforced concrete wall would be most suitable, so an in situ frame was adopted, comprising ribbed floor slabs supported on a limited number of internal columns and structural walls at the perimeter, rotunda, and additionally at the cores.

The articulation of the façade, with alternating geometries, and the overlap of office and retail floor plates, required the careful addition of non-imposing transfer structures to preserve the building profiles. The concrete walls were useful in this respect as, despite their frequent openings for windows, they could form multi-bay or multi-storey 'Vierendeel' panels capable of spanning over column-free or set back building lines below. The walls also provide the building's primary stability.

On the down side, the geometry and setting-out of walls,where they provided the backing to articulated stone cladding, required carefully co-ordinated detailing - making the structure more complex. This would not suit a typical commercial building development program that would generally dictate a separate simpler structural frame followed by panel cladding. However, the finished product is distinguished by a subtle enhancement of solidity and permanence through integration.

As noted earlier, there was a requirement to isolate the offices from ground-borne vibrations from the adjacent railway tunnels. A vibration isolation joint, comprising resilient rubber bearings with suitable lateral restraint, failsafe, and fireproofing details, was therefore provided beneath the first floor structure - the lowest office level. For economy, and perhaps unusually, only two-thirds of the building plan was isolated - only those areas within the vibration zone of influence. Bearings were designed with low load settlement characteristics and located to avoid any concerns of differential movement effects within the building structure.

At the top of the building the roof slab was designed to support heavy landscape loads from the Garden and its public restaurant which, due to its prime location, is sure to become another 'City Institution' and perhaps tourist attraction.

9. South façade of rotunda.

10. Main lift lobby.

11. Concourse-level shops.

Building services

Mark Walsh-Cooke

• The offices were designed to have a 'category A fit-out' complete with ceilings, air- conditioning systems, and light fittings, leaving tenants to install the floors, underfloor services, and any special fit-out needs. The retail spaces and rooftop restaurant were designed as serviced shells to be fitted out fully by the tenants.

• The offices are conditioned with a variable air volume system, served from air- handling units at basement level. Air is supplied at 15°C - 17°C and terminal reheat is provided by either heater batteries in the supply air ductwork or radiant heater panels below the glazing. The radiant panels are recessed into the façade and are profiled to follow the curve of the cladding around the atrium drum.

• Solar gain and glare control is provided by motorised mid-pane blinds within the triple glazing. The degree of control varies from automatic control of a complete length of the façade in the open plan areas to individual room control with user adjustment in each prow office.

• Planning restrictions limiting the area available for louvres on the façade meant that fresh air had to be drawn down lined shafts from the roof garden level. The air-handling units in the basement connect to these shafts via insulated ductwork plenums. Exhaust air is discharged above the street level arcades.

• Generally the acoustic rating for the offices is NR35. However the special quality prow offices were designed to achieve NR30.

• The retail units at ground and concourse levels are provided with a tempered fresh air connection, toilet extract and a commissioned chilled water loop, all for future extension by the tenant during the fit-out. Additional space is provided in the basement and at roof level for a future chiller and cooling tower. This was sized to provide additional cooling for financial dealer areas on a part of each office floor.

• The building is supplied at 11 000V from a unit protected LEB ring. Landlords HV switchgear and transformers give a load capacity of 2500kVA from which the supplies to all the tenant units are individually sub-metered.

14.
Chiller room.

• A landlord's standby generator supplies all the essential loads in the event of power failure and includes the firefighting lifts, sprinkler pumps, staircase pressurisation fans, and basement smoke extract fans. Facility has been allowed for the office tenants to add further generators to give 100 % standby capacity for the building.

• The fire alarm system incorporates phased evacuation by means of a voice alarm system and interfaces with all the tenants' alarm panels and the London Underground Bank Station system.

• The office floors are illuminated by category 2 recessed circular down-lighters carefully integrated with the triangular ceiling panels. A lighting control system is provided to minimise the rewiring necessary during fit-out of the open plan areas and as an energy-saving feature.

• A door access system is provided to secure the landlord's areas from the tenants' areas and CCTV cameras cover the building extensively.

12.
Roof Garden, looking west across top of rotunda.

15.
View through 2.5m diameter clock on the (east) front of the building.

16. The clock turret.

13.
Conran roof restaurant.

17. The building at twilight.

Conclusion

Practical completion was achieved in February 1998, when tenant fit-out of the retail units commenced.

This included the *Coq D'Argent* – the rooftop Conran restaurant, and shops by Austin Reed, Gap, Toni & Guy, Boots Opticians, Seattle Coffee Co, and Crabtree & Evelyn.

Arup was retained by several of the tenants to design their fit-out work, or in some cases to modify the base building installations.

The firm also designed the particular works for dealing rooms and executive offices for General Accident who now occupy the third floor as their corporate headquarters.

Credits

Client:
City Acre Property Trust (Lord Peter Palumbo) / Advanta joint venture

Project manager:
Altstadtbau

Architect:
Michael Wilford & Partners (Sir James Stirling)

Consulting engineers:
Ove Arup & Partners

Main contractor:
John Laing Construction

Illustrations:
1, 3, 6, 9-17: Peter Mackinven
2: John Donat. 4, 7: Catherine Flack
5, 8: Peter Ross

Whitney Museum of American Art, New York City

Raymond Quinn

Introduction

A sculpted granite monolith, Marcel Breuer's 1966 architectural landmark stands on Madison Avenue in New York City's Upper East Side Landmark District. It was built to house the Whitney Museum of American Art which, since its founding by Gertrude Vanderbilt Whitney in 1922, had outgrown two previous buildings in Manhattan. By 1994 the Museum decided that its next expansion would embrace adjacent townhouses it had acquired on Madison Avenue and the contiguous north side of East 74th Street. In 1994 Gluckman Mayner Architects was hired to design and execute the renovation and expansion. In 1995 Arup's New York office was appointed for full engineering design services.
A two-phase project was conceived.

Phase 1

This involved the complete renovation and expansion - to form the Museum's offices and library - of three of the newly-acquired townhouses. This part of the project presented no special engineering challenges, other than to design a new infill structure to connect them to the Museum building. This included the stair towers and elevators necessary to make the renovated buildings meet code requirements, as well as the main mechanical systems and vertical distribution.

The main challenge here was the co-ordination needed to connect four adjacent existing buildings with differing structural systems and varying floor-to-floor heights.

Phase 2

Phase 2 transformed the Museum's existing fifth floor offices and fourth floor mezzanine library into new gallery space. To maximise this, the fifth floor occupied area was extended out to the one-storey high parapet wall by roofing the terraces with a new steel frame and metal deck roof. A primary architectural element of the design was the inclusion of five large steel-framed skylights in the new roof to bring natural light to the new galleries below. The skylights use laminated translucent glass with interlayer UV filters and have external fixed blade-type shading devices. All skylights are raised 4ft-6ft (1.2m-1.8m) above roof level so that, although the shading devices allow morning and evening direct sunlight onto the glass, it is diffused by the skylight and further reflected by its walls.

1 top.
Marcel Breuer's Whitney Museum of American Art.

2.
New library reading room.

3 below.
Rooftop air-handling concept.

Mechanical services

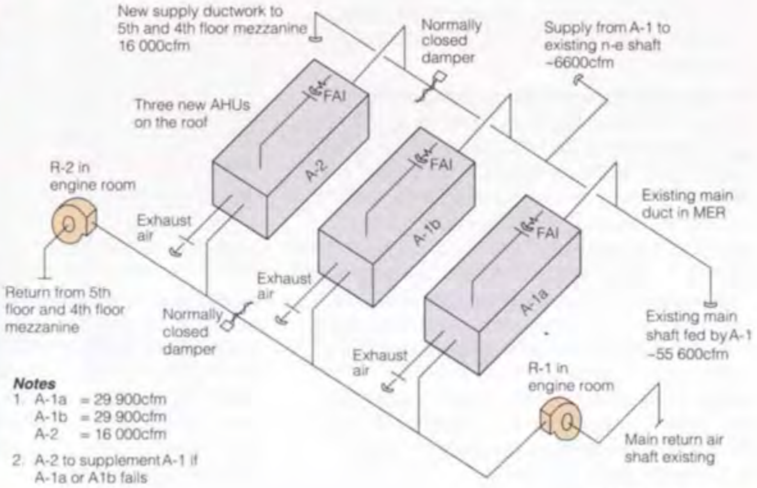
Phase 2 had two main mechanical systems design issues: to replace the existing air-handling units (AHUs), and to provide adequate air distribution to the galleries, all while meeting the following criteria:

- Maintain close control of air conditions in the new gallery spaces.
- Give one of the new galleries enough cooling capacity to accommodate a high lighting level (6W/ft^2 / 65W/m^2) combined with a high allowance for equipment heat output (4W/ft^2 / 43W/m^2).
- Provide air distribution in one of the new galleries compatible with displaying the Alexander Calder mobiles to be suspended from the ceiling.
- Replace the existing single, 35-year-old AHU serving the lower six floors (including basements) of the building and make provision to add gas phase filtration to all air-handling systems serving exhibition and art storage areas.
- Provide redundancy in the new mechanical systems and make provisions for additional future redundancy.
- Ensure all modifications were compatible with any future upgrades of zone temperature and humidity controls on the lower, original gallery floors.
- Do the work without closing the Museum and without significant downtime for the mechanical systems.
- Execute the project cost-effectively.

Air-handling systems replacement

In Breuer's original design the building's single chiller cooling tower and two main AHUs fully occupied the mechanical (sixth) floor (the 'engine room'). One AHU served the original fifth floor offices and the second, a field-built, 65 000ft^3/m (30m^3/s) unit, served the other six floors. The initial problem was to provide the new air-handling equipment for the new galleries and replace the collapsing larger AHU within the space limitations of the engine room while meeting the criterion of no Museum/system downtime. During preliminary studies the decision was made to replace both existing AHUs with three new separate units, for several reasons:

- The construction schedule would benefit from as much off-site prefabrication of mechanical systems as possible to limit any potential downtime, and to complete the construction while winter free cooling by outside air was available.
- New York City Labor Union rules require all AHUs with capacity of 30 000cfm (c14m^3/s) or greater to have field-built casings, often resulting in poor quality at high cost. However, factory-built units were preferred (for the high level of interior unit finish needed to achieve museum space air quality), so units of less than 30 000cfm (14m^3/s) were required.
- Three units could be arranged to provide a more secure service to the building should any one unit or component fail.



4.
New north gallery.

5 right.
New fifth floor entrance gallery.

These preliminary studies showed that the new AHUs could not be installed in the engine room: space constraints would have compromised their operation, hampered long-term maintenance, and not created space for future redundant equipment. Thus although this scheme had less impact on the original building design, it would not have realised all the Museum's goals. Also, the additional no-value expenditure on the temporary systems needed while the engine room was being reconstructed made the scheme financially unattractive.

A second series of studies investigated building the permanent air-handling equipment on the roof. The design concept was to extend the existing shafts up one level and rapidly (the initial estimate was two weeks) reconnect them to the new units directly above. By keeping the existing equipment running and using temporary connections, service to the Museum would be largely maintained during switchover.

Three rooftop air-handling configurations (see concept Fig 3), were investigated:

(1) Use three outdoor AHUs.

(2) Use three indoor AHUs with a new lightweight metal panel building as a protective enclosure.

(3) combine AHUs and lightweight metal panel building into one by using a factory-fabricated rooftop air-handling penthouse.

The latter was deemed the best compromise between minimising the impact of the new air-handling equipment on the roofscape and engine room below, the capital cost, maintenance access, and long-term quality of service in New York's extreme climate.

The penthouse compactness and its general appearance on the roof were particularly important for the scheme's approval by the NYC Landmark Commission. Following submission of preliminary plan and elevation dimensions, the scheme was eventually accepted with unit dimensions of 45ft x 35ft (13.7m x 10.7m) in plan and a height restriction of 12ft 6in (3.8m) - a critical factor in the design.

Penthouse design and construction

Success implementing the scheme depended on using outdoor air to cool the gallery spaces during construction, as the chilled water system would be decommissioned. To exploit the November-March weather conditions, the mechanical systems' design and construction had to be completed in six months. To meet this schedule, and because of the complexities in designing and constructing the penthouse, a manufacturer was preselected from competitive bidding on preliminary drawings and outline specifications. They were involved in the design process and developed all the fabrication and detail drawings while Arup developed the technical requirements and design criteria for the penthouse.

The air-handling penthouse had several design complexities:

(1) The unit casing had to be built so that thermal bridging would not cause humidified air to condense inside. AHU casings for museum applications typically have double wall construction to maintain air quality. In this case the internal wall also had to be a vapour barrier to prevent interstitial condensation.

(2) Heat gain to the penthouse itself had to be minimised, so that this, together with the increase in the overall building size and higher gallery cooling loads, did not exceed the capacity of the existing chiller. (Existing building in-use cooling loads were estimated from study of the Building Management System records.)

(3) The best position for the penthouse air intake, given the location of the building shafts and the direction of airflow through the penthouse, would have been close to the cooling tower discharge.

For safety reasons, the penthouse needed to incorporate an attic arrangement that ducted outdoor air from the end of the unit furthest from the cooling tower.

The penthouse contains three adjacent air-handling chambers, each with 29 900fm (14.1m^3/s) capacity and an access vestibule on one side. The vestibule and the air-intake attic wrap around the air chambers forming buffer zones to them and reducing the chiller load developed by the penthouse itself.

All the piped and electrical services from the engine room below enter the penthouse in the vestibule, which also houses the unit's main electrical panels, a raceway for power distribution, fan motor variable frequency drives (vfd) and DDC control panels. All piping and electrical and controls wiring from the unit to the vestibule was completed and tested in the factory.Two air chambers supply air to the existing VAV distribution system serving the lower floors. The third supplies the new galleries which use a constant volume air distribution system with zone reheat and humidification for temperature and relative humidity control.

The new galleries require only 16 000cfm (7.55m^3/s) of the 29 900cfm (14.1m^3/s) available from the third air chamber, but it was decided to have all chambers of equal size to give some spare capacity. The third chamber therefore had to deliver 16 000cfm (7.55m^3/s) under normal circumstances but also be able to supply the full 29 900cfm (14.1m^3/s) should either of the others fail. Maintaining stable air conditions over this flow range required the use of split coils, multiple control valves per coil, chilled water diverting valves, and a variable impeller width centrifugal plenum fan with a vfd. The new ductwork arrangement allows interconnection of the two air distribution systems, giving a reduced level of service to all areas of the building during a failure. In this situation the third unit can deliver the higher volume with distribution of the extra air controlled using modulating dampers in the two systems' two main ducts. Static pressure sensors and duct-mounted volume flow measuring devices are used to control these dampers, ensuring priority to the control of space conditions on the fifth floor and fourth floor mezzanine.

Structural modifications

A composite concrete slab and steel beam construction supports the penthouse, which was built in five separate pieces - each sized to fill a standard flatbed truck - to reduce trucking, rigging, and setting-in-place costs. The five-piece decision followed exhaustive investigations which concluded that the configuration of AHU components could not allow the section splits to line up with the existing structure. Steel tubes were therefore laid on the roof to transfer the load onto existing steel beams, themselves reinforced to cope with the increased load and to allow the necessary roof penetrations. This transfer scheme proved least expensive but marginally exceeded the 12ft 6in (3.8m) height restriction. A contractor change, after shop drawing review, was to enlarge the transfer steel tubes to a more readily available size. This proved fortuitous as some of the penthouse sections weighed significantly more than the manufacturer's earlier estimates.

(a)

(c)

(b)

(d)

(e)

6.

(a) Penthouse sections arrive by truck.

(b) Section is lifted onto roof.

(c) Fan section is set in place (note air intake, fan controls, and roof modifications).

(d) Second section is set in place.

(e) Completed penthouse.

Penthouse installation

The specification included inspecting and pressure testing the penthouse at the factory. Initially there were problems with the complex construction of the casing's inner walls and remedial work delayed shipment by two weeks. Although final delivery to site was smooth, and rigging and setting-in-place were completed in a few hours, completion was delayed by assembly and sealing problems.These, coupled with unseasonably warm weather, required temporary air-handling equipment to be rented to air-condition the building for the opening event and the following few weeks. After final connection and commissioning, the penthouse became the primary, and then only, air-handling system for all areas of the Museum.

New gallery air distribution

One aim was to maximise the new galleries' ceiling heights within existing slab-to-slab dimensions. To achieve this a system of double-walls was developed to act as permanent gallery partitions and provide distribution routes for all building services, thus keeping ceilings free of major distribution routes. The double-walls also form return air plenums, with air entering via slots in the plate bronze lining of the portals between galleries. Services access these double walls from horizontal distribution in the deep fourth floor ceiling void below. Air supply to the fifth floor galleries is from sidewall slots where the double walls meet the ceiling structure. Conventional diffusers are not used; the air is supplied from simple sheet metal air plenum boxes connected to slots in the exhibit walls. A simple mock-up of the air plenum and slot configuration, tested during construction to check slot dimensions, allowed them to be further reduced. The plenum configuration was tested for various positions of inlet balancing dampers to ensure the design noise criteria would be met by the final assembly. The tests were done by Arup Acoustics from Arup's New York office, using the underfloor air supply system as a quiet test air source.

The air distribution requirements for the fourth floor mezzanine provided an interesting paradox. This low-ceilinged space needed a high air change rate to deal with the 10W/ft^2 (108W/m^2) lighting and equipment heat gain criterion, and yet this had to be provided in a way that accommodated display of the Calder mobiles; space air velocities had to be low enough not to cause significant movement of them.

A ventilated ceiling air distribution system, more commonly used in manufacturing clean room facilities and operating theatres, was adopted. Supply air from the double walls is ducted to each of the voids formed by having the ceiling tight to the underside of the beams. A recessed trough in each void both conceals the lighting track and provides perforated metal surfaces through which air from the pressurised ceiling supply plenum is introduced to the space at velocities less than 75fpm (0.4m/s). Detailed analysis of the space heating requirements showed the heating need to be minimal and consistent with using a very low velocity, high level supply air system. The ceiling void was sealed to create the pressurised plenum and fully insulated to eliminate impact of the slab's thermal inertia on the space temperature control.

Exhibit design

Two components of the exhibit design specifically required an engineered solution: the enclosure for the Calder 'Circus' and a vitrine to house the 'Brass Family'.

The Calder 'Circus' was to be mounted on a circular dais and enclosed by three curved glass panels, each 11ft (3.35m) tall and cantilevered from a moveable base which also stabilises the panels and counterbalances them when they are moved. For maximum visual clarity the panels are made from two layers of curved, low iron content, float glass. The vitrines use similar, but tempered, glass clamped into an end frame and supported from heavy steel tubes designed to minimise deflections.

Phase 1 of the project was completed in December 1995 and Phase 2 opened in April 1998. Renovation work is continuing in other parts of the Museum.

7.
Calder Gallery: exhibit casework and ventilated ceiling.

Credits

Owner:
Whitney Museum of American Art

Owner's representative:
Zubatkin Associates

Architect:
Gluckman Mayner Architects

Consulting engineer:
Ove Arup & Partners Leo Argiris, Louis Arzano, John Beckwith-Smith, Dan Bonardi, Richard Bussell, Caroline Fitzgerald, Lui King, Igor Kitaygorodsky, Mike McEntee, Ian McNally, Swan Foo Meng, John Miller, Liam O'Hanlon, Raymond Quinn, Ashok Raiji, Mahadev Raman, Joel Ramos, Finola Reid, Joe Savarino, Anatoly Schleyer, Tom Smith, Richmond So, Marina Solovchuk, Adam Trojanowski, Margarita Vanguelova, Seth Wolfe

Exhibit designer:
Ralph Applebaum Associates

Construction manager:
AJ Contracting (Phase 1), York Hunter (Phase 2)

Code consultant:
JAM Consultants

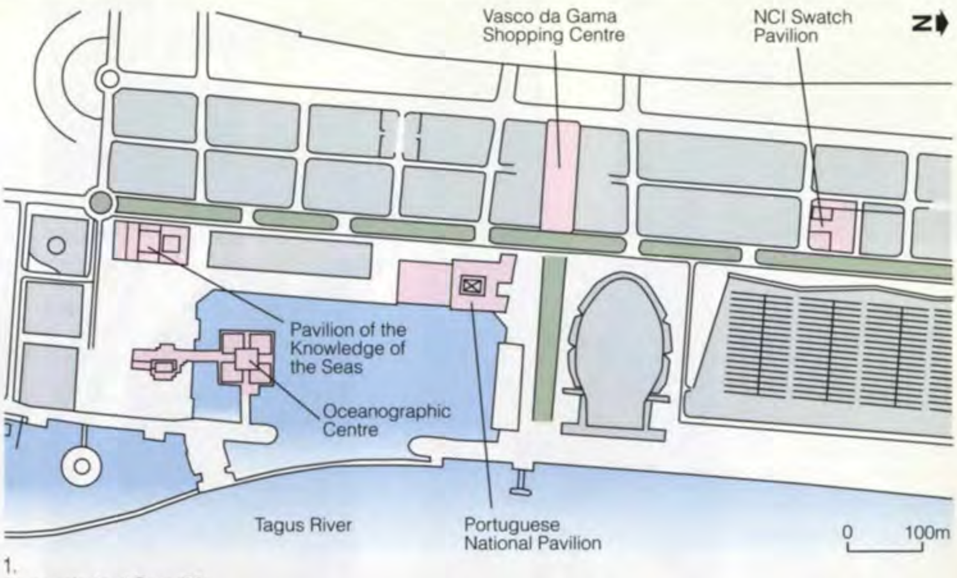
Illustrations:
1, 2, 4, 7: Paul Warchol Photography
3: Emine Tolga
5: Bernstein Associates
6a-d: Raymond Quinn
6e: Adam Trojanowski

EXPO '98, Lisbon

The 1998 Lisbon World Exposition was held to celebrate the 500th anniversary of Vasco da Gama's famous voyage of 1497-99 round the Cape of Good Hope to India - the first European to do so. It accordingly took as its theme 'The Oceans, a Heritage of the Future'. It ran from 22 May to 30 September 1998, and was, measured by the number of participating countries, the largest world exposition yet.

It covered a 60ha site in eastern Lisbon, stretching for some 5km along the west bank of the River Tagus. Arup worldwide made major contributions to five of Expo '98's buildings:

- Oceanographic Centre (pp12-15)
- Portugese National Pavilion (15-18)
- Pavilion of Knowledge of the Seas (19-21)
- Vasco da Gama Shopping Centre (22-24)
- Swatch Pavilion (24-25).



1.
Arup projects at Expo '98

The Lisbon Oceanographic Centre

Graham Beardwell   Erik Dirdal   Peter Hartigan   Tim McCaul   Martin Walton

2.
View into 'open ocean' tank.

Theme and concept

The Lisbon Oceanographic Centre, also called Lisbon Aquarium, was a major feature of Expo '98, drawing on and contributing to Expo's overall oceanic theme. When completed it was the largest aquarium in Europe and the second largest in the world, containing 250 000 specimens of more than 200 species of marine life. Intended to attract tourists well beyond the life of the exposition itself, it has now been handed over to the City authorities. During Expo it attracted up to 50 000 visitors a day (equivalent to 18M per year).

The American architectural practice Cambridge Seven Associates was appointed by Parque Expo to lead the design; as lead architect, Peter Chermayeff was already renowned for his success with aquaria around the world. Working with Arup, the architects developed the building design concept of an imaginary ship. Within Arup, Building Group 2 in London were involved with structural, mechanical, electrical, public health, fire safety, façade, and geotechnical design.

A major purpose behind Expo was to regenerate a derelict strip of land along the Tagus estuary. As part of this, the Aquarium was sited in a disused dock. It comprises two separate buildings: the support building, which is located on dry land next to the dock, houses the ticket office, Aquarium shop, temporary displays, and administrative offices. The Aquarium itself, characterised by its irregular profile, lies out in the midst of the dock, like a ship at berth, in a building designed to accommodate all of the aquatic displays, laboratories, water storage, and the crucial water treatment facilities. The two buildings are linked by a pedestrian footbridge, whilst a causeway at dock level provides vehicular access.

Internally the exhibition space was designed to display aquatic environments from all corners of the globe. The key concept was to have a central 'open ocean' tank measuring 38m x 38m x 7m deep. This would be the centrepiece of the building and allow many different species of fish to be exhibited in an open environment, giving almost uninterrupted views into the tank. The volume of water contained is equivalent to that in four Olympic-sized swimming pools.

Surrounding the central tank are four separate and very individual exhibits that reflect the different oceans of the world and allow animals to be viewed in both a submarine and terrestrial manner:

- The Southern Ocean
- A coral reef in the Indian Ocean (tropical)
- A rocky Pacific coast (temperate)
- The Azores coast in the Atlantic Ocean (Northern Ocean).

Great care was taken in arranging the internal artificial rocks and artificial corals so that no viewing window would show any other window, thereby reinforcing the ocean experience.

3.
Non-public area above open ocean tank.

4.
Detail of roof structure.

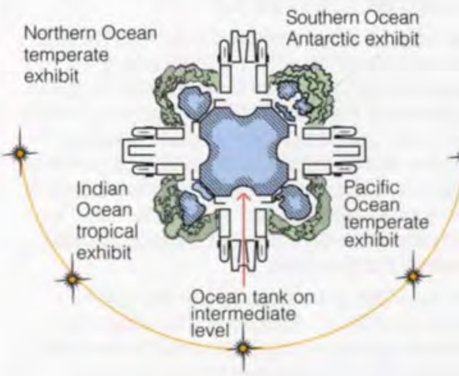
The structure

The structural design of the Aquarium necessarily evolved from the demanding architecture and the local environment. The dock was originally tidal, and had silted up with mud from the river. In places this was up to 8m deep, and was not stiff enough to support the Aquarium or to provide adequate lateral stability. The gravity loads of the building are therefore supported by piles founded in the stiff soils beneath the mud. The potential of low lateral stiffness was overcome by dredging the mud and replacing it with imported fill, which was then compacted by vibroflotation.

The main structural frame is of reinforced concrete. Lisbon lies in a zone of high seismic activity, so careful consideration had to be given to the resistance of forces generated by the large masses of water in the main tanks; to compound the issue, these tanks were some 10m above the water level in the dock. Seismic stability is provided by a system of shear walls designed to transmit the loads down to the foundations. These also form the cores containing lifts and services, which are placed at the midpoint of each side of the plan and are orientated so that pairs of cores act in tandem in each major axis. From the top of the cores the masts supporting the roof emerge.

The substantial plant required for the building's environmental control is on the ground floor (ie dock water level) beneath the main exhibition tanks. The suspended slab supporting the 7m deep open ocean tank is 500mm deep, spanning between wide beams linking into the shear walls. These in turn are held up by 1.1m square columns.

Each of the four habitat zones extends beyond the peripheral line of columns to oversail the dock. The loading generated by the water, rock, and soil features required cantilevers 1.5m deep, the size of which is disguised by transverse and ring beams which produce a coffering effect over the water.



5.
Key plan showing four 'corner' exhibits with 'open ocean' tank beneath.

The tanks are viewed through c200mm thick acrylic panels. Careful attention was paid to the details supporting these panels to avoid the possibility of leakages. Various loadcases were analysed to allow the tanks to be full or empty in any combination. Within the tanks are a number of 'rock' features which are in fact constructed from concrete sprayed onto a mesh of steel reinforcement around a polystyrene core, to reduce weight. The realistic rocklike finish was achieved by carving and colouring the concrete.

The roof is of glass, suspended from a lattice of curved tubular steel members. These cantilever out from above the central tank over each corner habitat and reflect the design's nautical theme.

An arrangement of steel rods and tubular steel masts provides additional support.

The bridge, a bit like a 'gangplank,' links the Aquarium to the support building, and in order to accommodate the enormous numbers of visitors during Expo it was built on two storeys.

Visitors embark at the upper level, circulate around the habitats, then drop down a level to view the underwater scenery before disembarking at the lower level.

A deep truss was used to bridge the 50m span.

6.
The Aquarium from the north-west. Its isolation within the dock tends to mask the scale of the building.

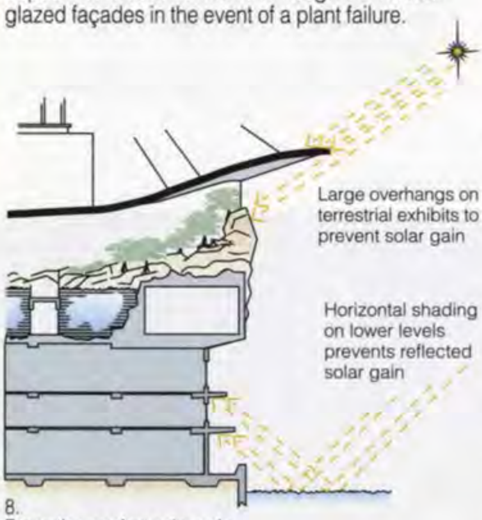
7.
The tropical habitat.

Mechanical services

The approach to design of all engineering services was totally driven by the need to understand and develop a series of suitable environments for the animals that would live in the building.

The central 'open ocean' tank is maintained at 21°C throughout the year to provide a best average water condition and maximise the number of species that can inhabit the tank.

Each of the four habitat zones was carefully evaluated to determine the most suitable living conditions for the animals. The influence of the orientation of the building, local seasonal temperature profiles and breezes, characteristics of the façade, and roof performances were all studied to enable best conditions to be achieved with the minimum amount of artificial control systems. Each habitat operates at different temperature and fresh air levels. All the exhibits are capable of natural ventilation through the vertical glazed façades in the event of a plant failure.



8.
Protection against solar gain.

The Southern Ocean exhibit houses both seals and penguins in separate tanks, each having a volume of 230m^3. The internal conditions are required to be maintained between 6°C -18°C on a seasonal basis, though the preferred maximum temperature for the birds is 14°C. The water temperature is required to be maintained at 10°C and 15°C respectively for the two exhibits throughout the year. The Southern Ocean exhibit is oriented to the north-east to reduce the effect of solar radiation. Overall shading coefficients are 0.5 for the walls and 0.25 for the roof.

The Northern Ocean exhibit contains marine animals and puffins. As for the Southern Ocean the internal conditions are required to be maintained between 6°C-18°C on a seasonal basis; here the preferred maximum temperature for the birds is 14°C-16°C. The tank volume is 640m^3 and is required to be maintained at 16°C all year. Again to reduce effect of solar radiation, orientation of this exhibit is north-west. Overall shading coefficients are 0.5 for the walls and 0.25 for the roof.

The Temperate Ocean's inhabitants are sea otters in a 400m^3 tank. Once more the internal conditions are at 6°C-18°C seasonally, and water temperature is maintained at 18°C. The overall shading coefficients are 1.0 for the walls and 0.39 for the roof.

Finally, the Indian Ocean exhibit contains marine animals in a 640m^3 tank. Here, the internal conditions have to be maintained between 20°C and 32°C seasonally, with the water temperature at 24°C. The overall shading coefficients are 1.0 for the walls and 0.39 for the roof.

The orientation was assessed to achieve the best possible daylight level for natural planting, and protection from unwanted solar radiation. To guard the terrestrial areas against the high solar intensities, a 4m wide glazed roof overhang was provided - and this also contributed to the building's particular character. The roof glazing itself is varied to provide the required average shading coefficient, and to give different levels of daylight in particular areas to reflect planting zones.

The top of the open ocean tank is not open to visitors and has no daylighting. This allows the artificial lighting not only to be varied to meet the requirements of the animals but also to create 'theatrical' effects like artificial storms.

The Expo site had a central CHP source, which was capable of providing the Aquarium with both heating and chilled water. However, the building's construction programme was unfortunately in advance of the rest of the site and the need to have it fully operational with secure energy supplies was critical to it being stocked with the animals prior to Expo opening. The Aquarium therefore has its own energy sources and standby electrical power in the event of a power failure.

Security of electricity, cooling and heating is critical to the creatures' well-being; any plant failure for more than a few hours can result in them becoming distressed or worse.

With the life support systems having such high water turn-over rates (15 minutes for the small tanks to one hour for the main exhibits), high pumping energy loads require all the water treatment systems serving the exhibits to operate for 24 hours a day to provide for the continuous cooling requirement.

The building is ventilated by 11 air-handling units (AHUs), five of them dedicated to each of the main exhibition areas. The supply air to these areas is delivered by high-level jet diffusers to encourage low-level air movement and distribute air over the glazed roofs and walls to reduce condensation. AHUs serving the Southern and Northern Oceans were both capable of housing high efficiency air filters to allow airborne particles related to bird diseases such as aspurgellosis to be removed.

The Northern and Southern Oceans are both pressurised to reduce air infiltration from other parts of the building, though flexibility was required as birds - in particular penguins - can be very smelly. The quantity of fresh air to all parts of the building is high and typically equates to a minimum percentage of 25-35% of the total supply air volume. All the ventilation units with these fresh air rates were fitted with thermal wheels between the fresh air intakes and the exhausts.

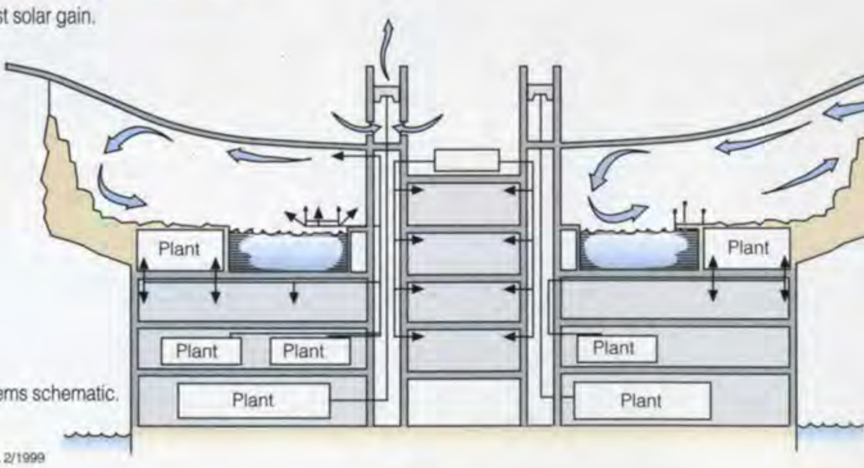
Chilled water is generated by three roof-mounted air-cooled chillers, each rated at 680kW, serving a chilled water system operating at 7°C-13°C. Heating is from gas-fired boilers and distributed by a conventional water circuit.

The mechanical plant's location made maximum use of the large plant areas underneath the exhibition levels and the four towers that separate the exhibition areas. This cruciform shape allows discrete vertical distribution of all the services fed from a perimeter services ring at ground floor level.

The support building on the quayside is serviced totally independently, with its own heating, cooling, and ventilation plant. The environment of the link bridge is sheltered and shaded but not treated, which is acceptable given the climate in Lisbon.

Electrical services

The Aquarium building power supply is provided at high voltage (10kV) from the Expo utility ring main system. Cables are routed via the underside of the access bridge from the dock. Maximum electrical demand was approximately 3MVA and was served from three 1250kVA cast resin transformers. The main switchboard arrangement was such that one transformer outage could be tolerated by the closing of bus couplers and some load shedding. The transformers were provided with fan-assisted cooling to maximise their capacity during such an outage.



9.
Mechanical systems schematic.

10.
View from the west.

11.
Aquarium: close up view from the north-west.

A significant portion of the electrical load was attributable to the Aquarium tanks' life support systems, where high pumping requirements consumed power and caused heating of the water. Additional cooling was necessary to compensate for this heating effect. Other significant loads included the exhibit lighting, which in some areas exceeded 100W/m^2 and the building HVAC load.

As continuous operation of some of the life support systems was essential, especially small exhibits with less inertia, a standby generator was provided. Sized at 1800kVA, this enabled the various exhibit life support systems and other statutory loads to be maintained during a power outage. It was not intended, however, that the Aquarium would remain open to the public during a power failure.

Lighting of the main exhibit tanks and habitats was provided mainly from tungsten and metal halide projectors located outside the building at roof level. These were arranged to light via transparent roofing panels enabling a more naturalistic lighting effect. A strand dimming/control system was provided, such that lighting could be controlled automatically to simulate a natural daylighting sequence.

Generally there was sufficient spill lighting from the exhibit tanks to light the visitor circulation routes around the exhibits. Where additional lighting was required, this was provided from dimmable tungsten downlighters which were located to avoid causing reflections in the exhibit acrylic window.

Particular care was needed in the location and control of exit signs, so that the views of the exhibits were not compromised by pictogram reflections. It was agreed with the local authorities that exit signs in exhibit areas would operate in a non-maintained mode.

One final point - if you happen to visit, you must pay a call to the sea-otters. These are now the most famous in the world!

Credits

Promoter:
Parque Expo '98/IDEA

Architect:
Cambridge Seven Associates

Structural, services, fire safety, façade, and geotechnical engineers:
Ove Arup & Partners Alistair Guthrie, Martin Walton, Tim McCaul, Erik Dirdal, Peter Hartigan, Graham Dodds, Andrew Minson, Dan Pook, Jo Massey, Paul Sloman, Maurya McClintock, Fiona Cousins, Fred Ilidio, Graham Beardwell, Rod Green, Sam Hatch, Martin Cooper, Rob Davis, Ian Robinson, Dave Carroll, Geoff Balrow, Ted Piepenbrock, Shigeru Hikone, Sergio Solera

Associate engineers:
Antonio da Fonseca (AFA)

Contractor:
Engil

Steelwork sub-contractor:
Construções Metálicas Socometal SA

Illustrations:
1, 5, 8, 9: Emine Tolga
2, 3-7, 10, 11: Peter Mackinven

The Portuguese National Pavilion

Mike Gilroy Fred Ilidio
Andrew Minson Martin Walton

Introduction

The organisers of Expo '98 intended that Portugal should be the only country to have its own independent national pavilion. This would host all formal ceremonies and functions, and also have enough exhibition space for simultaneous and diverse events. It was given pride of place adjacent to the Doca dos Olivais on the bank of the Tagus.

Like all the main Expo buildings, it was to be a permanent structure whose function would change afterwards. During the design stage, the nature of its post-Expo role was not clearly determined; possibilities ranged from 'a maritime museum' to a 'government ministry building'.

As a further complication, the type of exhibition to be housed in it during Expo was only finalised once construction was well under way, so a building adaptable with minimum effort from one function to another was required.

The architect, Alvaro Siza (Portugal's master architect), was directly appointed by Parque Expo '98. As a result of previous collaborations, he approached Arup to be multi-disciplinary engineers for the project.

Early on, the architect decided on a rectangular, low-rise structure, 65m x 110m on plan, with one level of basement below ground and a single utilisable floor above. The roof, although generally open to the elements, would house M & E equipment and be screened off by extending the building façade above roof slab level to create a 2.5m high parapet wall. The basement would provide parking space, workshop areas (during Expo), and also accommodate large and heavy M & E equipment like the sprinkler water tank. A full-height atrium would extend from ground level, completely open to provide some natural light and ventilation to the inner spaces.

To contrast with the low-rise building itself, Siza decided on a dramatic entry canopy, draped over the ceremonial plaza in front of its principal entrance.

Because Lisbon is in a zone of high seismic activity (it was almost completely destroyed by an earthquake in 1755), it was decided early in the design process that due to possible high seismic forces, the building and the canopy would be completely separate, each having its own supporting structural system.

Building structure

After various options were investigated, it was agreed that the solution for maximum internal flexibility of usage would be a reinforced concrete external structure to transfer seismic and other lateral loads to the piled foundations and provide a watertight basement in the tidal zone. Internally, steel columns supporting steel beams acting compositely with lightweight concrete on profiled steel deck provides the required flexibility.

As the floor slabs transfer internal seismic loads to the outer walls in diaphragm action, several 'permanent' floor panels had to be identified as non-removable when the building function changed. Previously, lightweight concrete had not generally been used in Portugal, and its incorporation here was seen as an advancement for the Portuguese construction industry.

The requirement for large column-free ground floor areas was achieved by suspending several of the beams supporting the first floor from steel trusses at roof level, thus avoiding a basement congested with columns, and saving the costs of additional piling.

Continued ▶

1. The Pavilion from the south-west.

2. Concept sketch for elevation.

The perimeter reinforced concrete structure comprises walls with large windows 7.5m apart plus counterforts between to give out-of-plane stability to the walls and support for external balconies. The 2m wide west balcony is a tapered reinforced concrete cantilever, anchored by a beam element in the walls which transfers the cantilever moment, as a torsion, into the counterforts.
The 3.9m wide east balcony is formed from precast planks spanning 3.75m between cantilever beams, made possible by an assured backspan in the form of permanent internal first floor beams midway between counterforts. The latter, which prevented the on-grid beams being used as backspans, were sized to support cantilevers directly, with care taken to ensure similar stiffness of the alternating different cantilevers.

Building services

As part of the design strategy to allow for the Pavilion's future significant modification, the services systems were developed so that only the basement, roof, and risers were fixed.

The basement would always be a single-storey space for plant, support areas including kitchens, etc, and car parking, but most first level floors would be able to be removed or introduced.

After much deliberation the perimeter external wall was made double-skin to contain all services risers, including ventilation ducts, and be the final distribution point wherever possible.

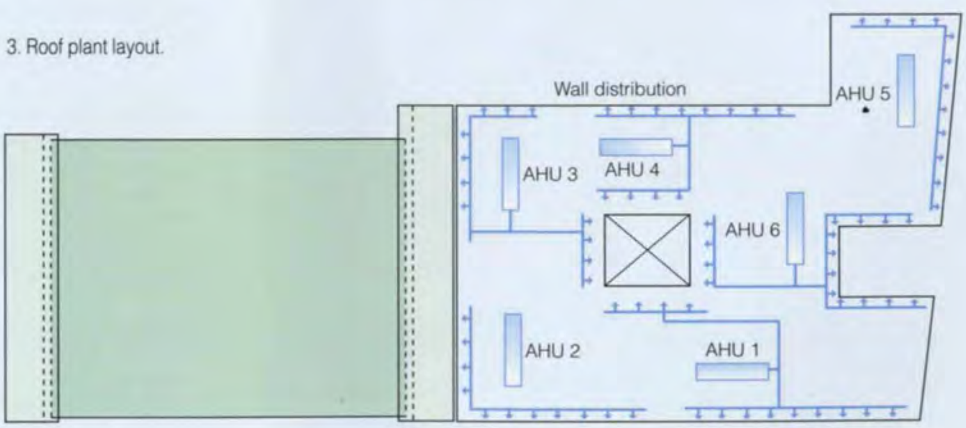
Electrically, any future changes of internal layout and use would generally require amending the service installation back to the main riser.

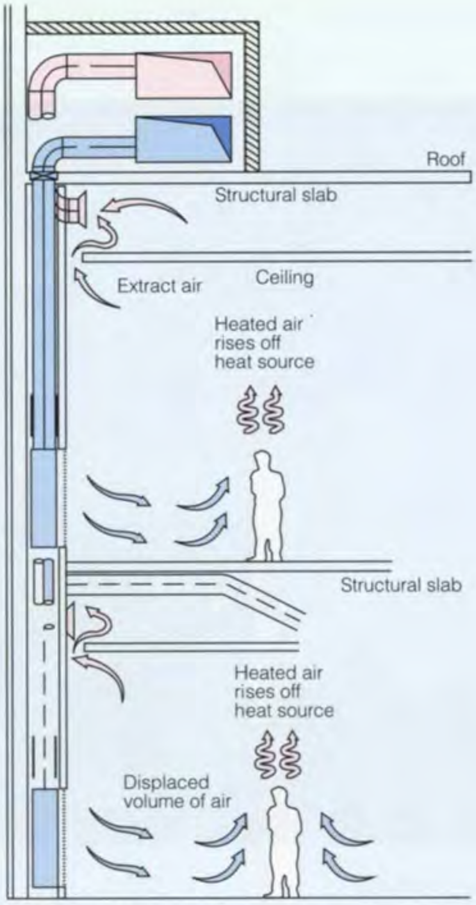
Mechanical

Expo being in summer, air-conditioning was needed for most of the visitor spaces, particularly since it was the primary VIP guest pavilion. Heating and cooling provision was simplified by the Expo' 98 Committee's choice of site-wide CHP. Heating water was provided at 50°C and chilled water at 8.5°C with an agreed minimum pressure differential of between 0.5 and 1.0 bar. This energy was then transferred by the building's own water circuits through plate heat exchangers.

Air-conditioning was from a displacement system with each riser in the two-storey building having a terminal volume control at roof level. The initial installation provided a manual control damper with the option of installing motorised volume control dampers as part of a future fit-out. This type of system would give the required temperature control to all the occupied areas.

3. Roof plant layout.





5. Cross-section of wall air-handling strategy.

The main exhibition and visitors areas were air-conditioned by seven roof-mounted air handling units each rated 7m²/s - 9m²/s serving the vertical zones below. The displacement units were selected to meet the Pavilion's maximum occupied depth - up to 18m - the typical duty of each being between 150l/s and 350l/s. Toilets, kitchens, car parks, and other ancillary spaces were all treated separately by local systems.

To minimise air-conditioning loads, and allow the building to interact with the surrounding Expo as well as enhance views across the river, the external walls were developed to provide maximum possible solar protection. On the long elevations the 3m thin windows were recessed to the back of the external double-skin walls, giving significant solar shading. The river elevation was also given external balconies forming a visitor's terrace, as well as providing shade.

The double-skin walls thus acted as risers, principal shading element, and structure, and gave a high external mass to the perimeter to reduce the effects of strong solar loads. The façade windows were all designed to accommodate external shutters to further reduce solar gains and avoid affecting the natural air distribution patterns from the displacement wall-mounted supply units.

Electrical

The 10kV electrical supply was came from Expo's local high voltage network. A 1000kVA capacity transformer was provided, and local voltages of 400\230V supplied sub-distribution boards and motor control centre panels throughout the building. Exhibition areas were serviced via underfloor trunking co-ordinated with the exhibit locations, and a small standby diesel engine generator was installed for standby power supplies to hosereel booster pumps, sump pumps, and car park smoke extract fans. Extra low-voltage systems, including an analogue addressable fire detection and voice alarm system, security, and CCTV, were included.

Acoustic advice was provided on airborne sound insulation, impact noise control, and room acoustics.

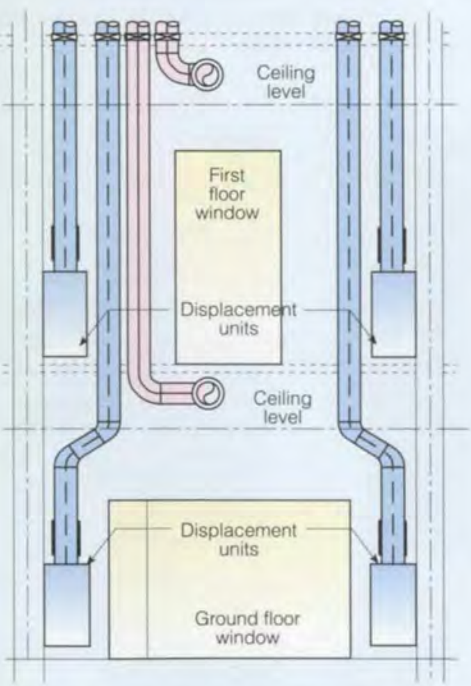
Canopy structure

The simplicity and lightness of the canopy structure over the ceremonial plaza, contrasting with the massiveness of the Pavilion itself, was a notable Expo feature.

The canopy is of reinforced concrete, with a clear span of 67.5m between supports. It is cast in a catenary profile with a maximum sag of 3m, and is supported by cables within its depth (Fig 7 overleaf shows the construction sequence).

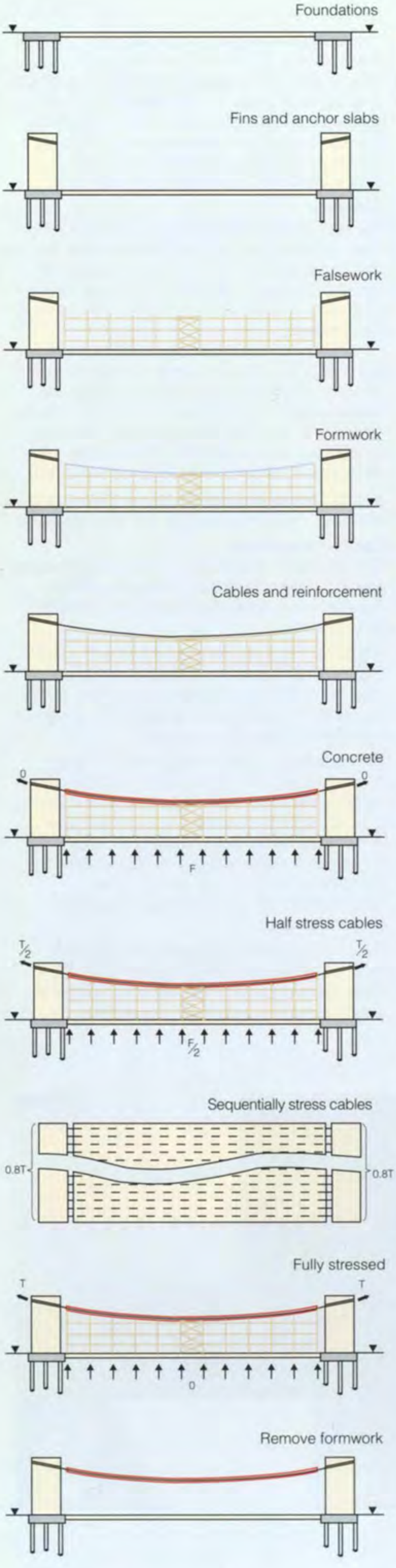
The mass of concrete and slightness of drape induced large forces in the cables, anchored at either end in slabs which, together with cantilever walls, form porticoes at each side of the square. A 'cut' between the membrane and porticoes introduces shafts of light and creates striated shadows on the porticoes, lightening the atmosphere in the square beneath the expanse of concrete above.

The porticoes are supported on pile caps held apart by compression struts beneath the square; these also ensure that under seismic loading the porticoes move in phase with one another.



4. Elevation of wall air-distribution strategy.

6. North side of building.



7. Canopy construction sequence.

8. Beneath the canopy.

The canopy structure is separate from the Pavilion building to permit relative movement under seismic loading. This separation is expressed as a large, discrete gap in keeping with the building's scale.

The canopy is only required to support itself and remain 'uncracked', which for a soffit 10m above ground was agreed with the architect to mean a maximum crack width of 0.15mm. It was assumed, and later proved, that this requirement could be met without prestressing the concrete, allowing the pure catenary suspended profile to be adopted.

The minimum concrete membrane thickness, determined by reinforcement, suspending cables, and cover requirements, was 200mm. The cables are housed in greased ducts, free to slide within the canopy to minimise tension in the concrete. Seismic analysis determined the ultimate cable capacities, the critical case being the vertical component of seismic loading, which induced cable tensions 20% higher than the static ultimate loadcase. Uplift is resisted by the mass of concrete, any local peak uplifts being resisted by minor local deformations and redistribution of dead loads.

Given the critical constraint that the soffit must not crack, canopy deformations under service loading were analysed to assess flexural and thermal (global) cracks. Other crack-inducing effects include concrete shrinkage, cable tensioning, and through-thickness thermal differences, but analysis indicated that the 0.15mm criterion would be met.

The canopy was cast in the catenary profile in its final position, thus forming the architecturally required monolithic element. Once the concrete was cured, the 100 cables were sequentially and uniformly stressed. When all were at working stress, the falsework had become fully unloaded and was removed, revealing the unique concrete catenary canopy.

9. Cable attachment of canopy.

Credits

Client:
Parque Expo '98

Architect:
Alvaro Siza Vieira

Consulting engineers:
Ove Arup & Partners
Cecil Balmond, Graham Beardwell, Andrew Gardiner, Rod Green, Fred Ilidio, Brian Lieberman, Erin McConaghy, Andrew Minson, Bob Venning, Martin Walton, Malcolm Wright

Local engineering consultants:
Segadaes Tavares & Associados

Illustrations:
1, 8: Peter Mackinven
2: Cecil Balmond
3-5, 7: Emine Tolga
6, 9: Andrew Minson

Pavilion of Knowledge of the Seas

Graham Beardwell
Fred Ilidio
Andrew Minson
Martin Walton

Introduction

The architectural commission for this pavilion was a direct appointment to João Luis Carrilho da Graça, the well-known Portuguese architect, who in turn appointed Arup as engineers. From the outset, the Pavilion of Knowledge of the Seas was intended to be a permanent structure, the venue for a maritime exhibition during Expo '98 and subsequently a maritime museum. It was central, near the Portuguese National Pavilion and the Aquarium, close to the Doca dos Olivais.

The building was designed with its structural form clearly visible, the form itself creating a sculpture. It is monolithic, with strong rectilinear orthogonal lines and large external elevations with few penetrations. Natural lighting penetrates the internal spaces through hidden folds in the roof plates.

The building consists primarily of three accessible levels:

- a below-ground car parking level which also houses the principal services plant
- a ground level incorporating exhibition spaces, services facilities, and equipment area
- a first floor level providing exhibition spaces and service facilities.

A central tower links all three, and projects above the roof to provide a maritime 'sailing ship' metaphor for the building from the side.

The overall plan dimensions are 110m x 55m. The roof height varies but is generally about 14m above ground level, except for the tower which climbs to 40m. The large external walls do not extend below first floor level, except centrally in the tower area, thereby creating an impression that the building 'floats' above the ground (extending the maritime metaphor).

1 top:
Pavilion of Knowledge of the Seas from the south-west.

Structure

The fact that Lisbon is in a zone of high seismic activity influenced the structural design of this as much as other pavilions. The early decision to use reinforced concrete as the principal structural material was not only for architectural and aesthetic reasons but also to transfer the large seismic forces (estimated by hand calculations and confirmed via computer modelling) to the piled foundations into the riverbank.

To minimise these large seismic forces, lightweight concrete was used in the roof slabs, which were constructed on profiled steel decks and act compositely with the supporting structural steel beam framework underneath. In common with the Portuguese National Pavilion, this rare use of lightweight concrete in Portugal has been viewed as an advancement for the Portuguese construction industry.

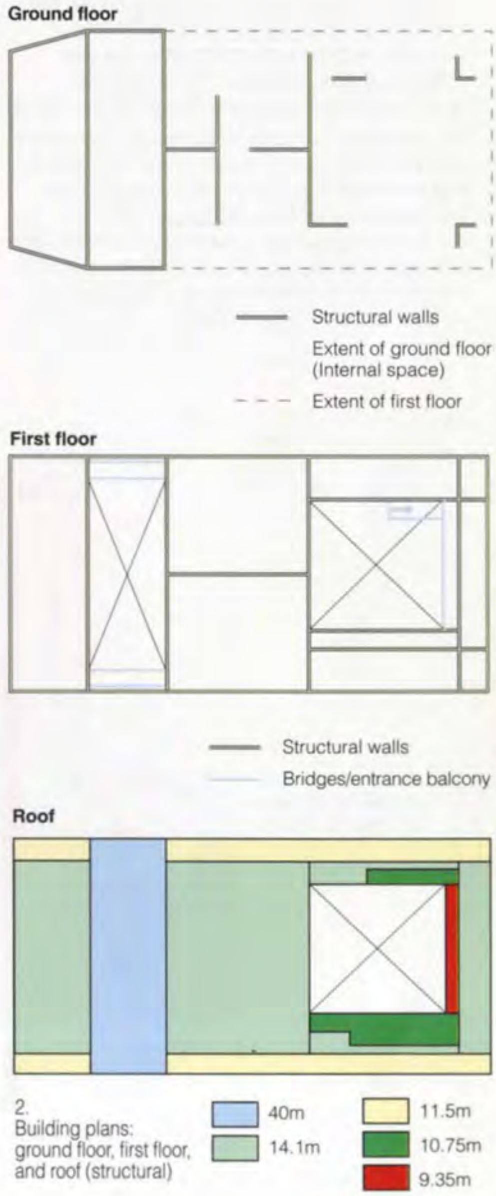
Large uninterrupted exhibition spaces were achieved by using composite acting lightweight trusses spanning up to 18m. In addition, above the central galleries, two 3m deep upstand plate girders span 33m.

Folds in the roof plate, designed to allow natural lighting without the need for visible penetrations, make use of 2.6m deep vierendeel trusses.

All the external visible building surfaces are unclad structural walls. Creating such large areas of externally unclad reinforced concrete in white cement presented interesting structural challenges, both in design and in construction, since limitation of crack widths on visible surfaces to an acceptable size was, of course, an important factor. It was agreed that a clean crack of 0.2mm or less would not be visible except under close inspection, so this was accepted as the permitted limit under service conditions on visible surfaces.

Any cracking in excess of this under abnormal loading (for example, a seismic event) was deemed to be acceptable and repairable provided it did not compromise the structural integrity or safety of the building.

To maintain an acceptable environment in the internal spaces, insulation was applied internally to wall and floor slabs and externally to roof slabs.



2.
Building plans: ground floor, first floor, and roof (structural)

The external perimeter walls - not extending to ground level - are supported by orthogonal walls that cantilever to the building perimeter. By the entrance area, the latter only extend to the ground for a fraction of their length, forming two L-shaped supports. Apart from these, the entrance square is free of ground floor structure on three sides.

The stability of the building, which is symmetrical about its longitudinal centre-line, is achieved principally by longitudinal and transverse walls extending from roof to foundation levels. The first floor slab transfers loads to these from the walls that only commence at first floor.

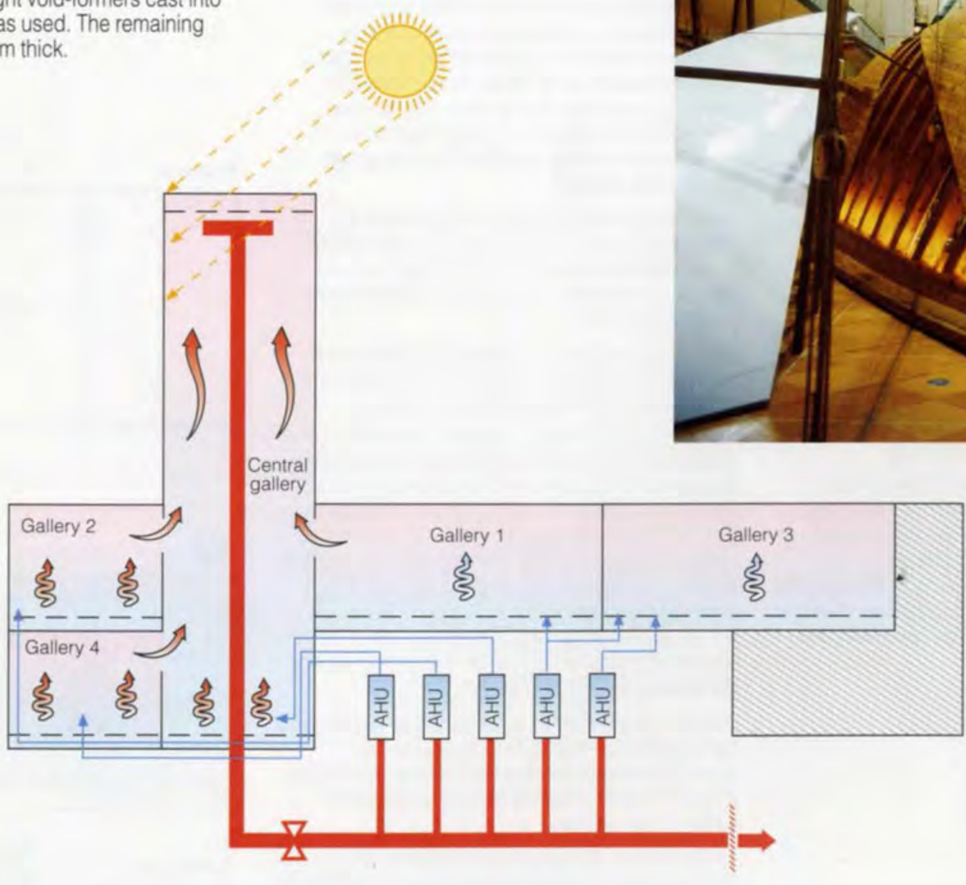
The foundations were piled, and designed to account for a 4m-6m thickness of hydraulically-placed fill which has little structural strength and a slight possibility of liquefaction under seismic loading. Attention was given to minimising differential settlement to avoid stressing and cracking exposed concrete walls. Because of the building's proximity to the river and the relatively high water table (tidal), all usable substructure areas were constructed in monolithic cast in situ normal-weight reinforced concrete.

3.
Entrance area.

4 right:
The SN Gallery in the tower.

As the thermal range in Lisbon can be rather large, a thermal model was analysed in addition to the normal gravity and seismic models to ensure that all the above structural serviceability criteria were met. Also, a construction sequence was determined and followed on site to minimise cracking from shrinkage and differential settlement.

The superstructure (except for the roof slab areas) is of cast in situ normal-weight reinforced concrete. The tower walls are 600mm thick and solid from foundations to roof level. Above roof level, to minimise structural mass, a cellular wall construction with permanent lightweight void-formers cast into the centre of the walls was used. The remaining walls are 250mm - 400mm thick.



5.
Long section showing air-handling strategy.

6. The Pavilion from the north.

Services

The Pavilion is divided into five main exhibition areas with the central gallery in the tower (the SN Gallery) being over 40m high and capable of housing a tall sailing ship. The other four galleries are 5m high and used for a mixture of artefacts and electronic exhibits. Each gallery has a 600mm false floor to provide an unobtrusive primary distribution route for all the services systems.

Mechanical

Only the central gallery is intended to be daylit, having a substantially glazed roof with temporary internal sails to act as shades if required. Only the central gallery thus has any potential solar gain problem, and its orientation and height mean that any incident direct radiation can be absorbed before it reaches lower occupied levels. The high external structural mass was used to moderate the effect of solar gains onto the internal spaces.

The air-conditioning system design had to be highly flexible as none of the exhibits were defined at the design stage, though it was confirmed that none would be 'sensitive' and only occupant comfort conditions would be required. With this in mind, the mechanical design was developed as a displacement system with all the air-handling units in a central ground floor plantroom, able to feed directly into the 600mm false floor zone of each gallery. Each gallery has its own AHU rated from ≥2m/s to ≥5.5m/s.

The connections between the galleries all had to be fitted with motorised smoke dampers to maintain the integrity of each space and allow safe evacuation of the occupants from the building in an emergency condition.

To maximise the benefits of the displacement system and the high level solar gains in the central gallery, all the other galleries connect to it, with all the extract being drawn from the top of its space. The return air path back to the ground floor plantroom was via two double-skin walls, allowing ductwork to be avoided in the gallery spaces and providing an access route to the top of the pavilion. This allowed the maximum temperature differential to be achieved as well as energy to be recirculated when appropriate to all the galleries.

The basement level parking and entrance and office areas all had separate ventilation plant or fan coil units.

The site-wide CHP provided heating and chilled water to this pavilion. Heating water was at 50°C and chilled water at 8.5°C with an agreed minimum pressure differential of 0.5 - 1.0 bar. This energy was then transferred to the building's own water circuits by plate heat exchangers in each system.

Electrical

The incoming electrical supply was provided from the Expo utility ring main at 10kV. A substation integral to the building and incorporating a cast resin transformer SF6 ring main unit served the estimated maximum load of 550kVA. Standby power for the fire protection systems came from a diesel generator on the roof. Fire detection is fully automatic: an analogue addressable system designed to provide full coverage (type L1). This operates on a two-stage basis, using a voice alarm system. It is also possible to page and broadcast other messages using the voice alarm system.

In the galleries, 150lux of background lighting is generally provided by freestanding uplighters that wash the white painted soffits with light. A compact fluorescent source was selected for good colour stability, flexibility of control, and superior lamp life. The freestanding uplighters also serve as enclosures for the (self-contained) emergency lighting units and the voice alarm system loudspeakers.

Incoming power / wiring was provided via the raised floor zone below. Dedicated power supplies were also provided to facilitate specialist display lighting by others.

Credits

Client:
Expo '98

Architect:
João Carrilho de Graça

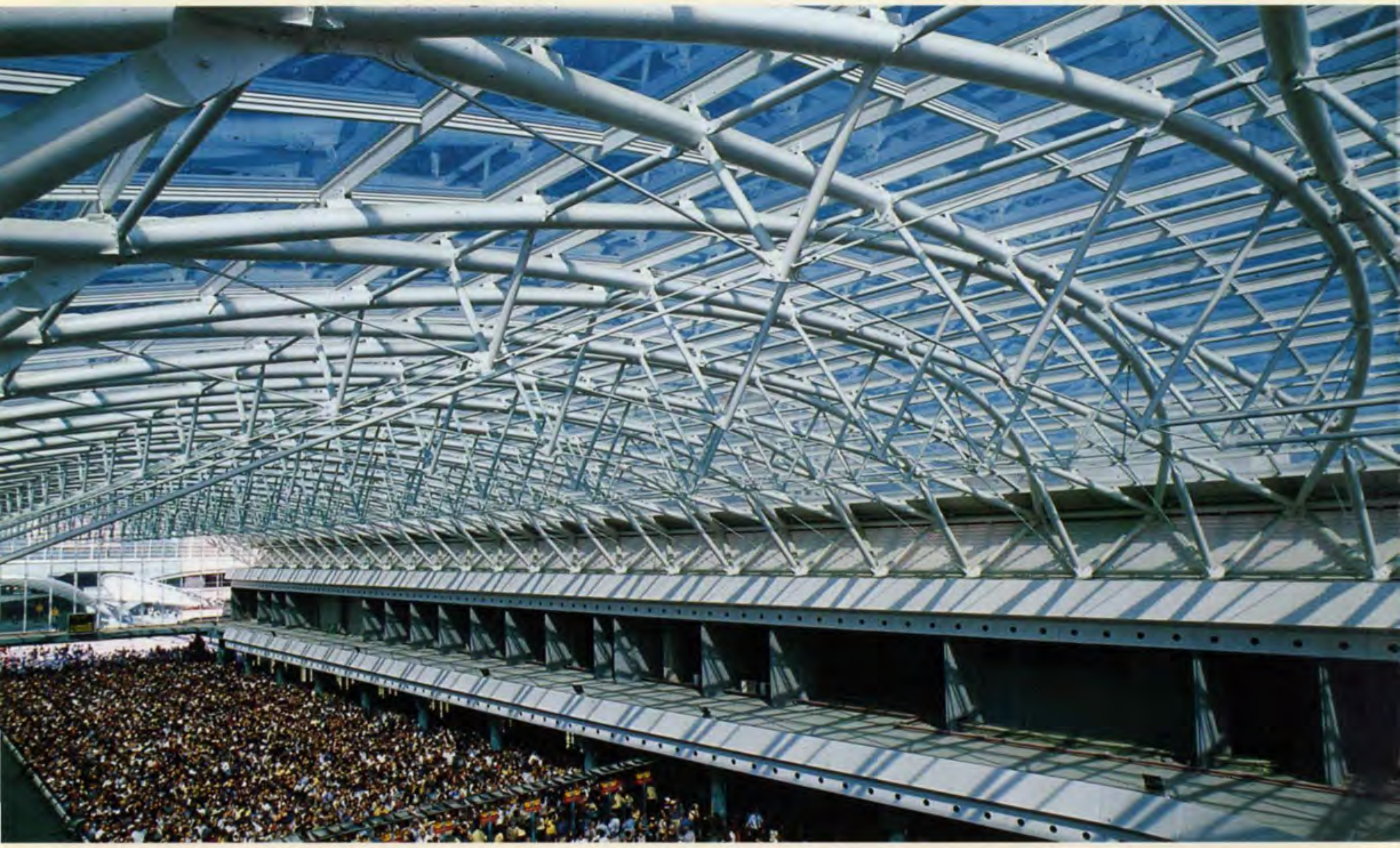
Consulting engineers:
Ove Arup & Partners Cecil Balmond, Erik Dirdal, Mike Gilroy, Rod Green, Fred Ilidio, Erin McConaghy, Andrew Minson, Bob Venning, Martin Walton, Malcolm Wright

Local engineering consultants:
Adao Fonseca & Associados

Illustrations:
1, 3, 6: Peter Mackinven
4: Andrew Minson
2, 5: Emine Tolga

The Vasco da Gama Centre roof

John Abbott Neil MacLeod Craig Thompson



1. Expo '98 crowds beneath the Vasco da Gama Centre roof.

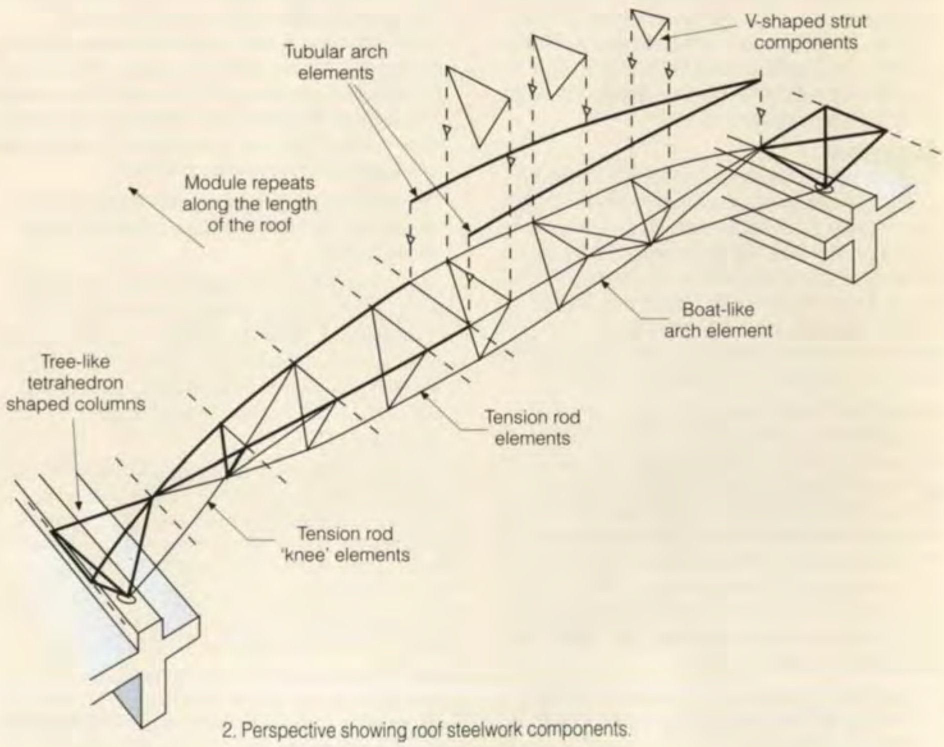
Introduction

Shortly before Christmas 1996, Arup (Pty) Ltd, Johannesburg, was approached by Revalvi, a long-standing contractor client in Portugal, to prepare a tender design for a 140m x 35m barrel-vaulted steel and glass roof over the atrium of the Vasco da Gama Shopping Centre, one of Expo '98's central buildings. An attractive aspect of this was that it would cover Expo's main entrance, next to the Oriente Station, designed by Calatrava.

Arup's task was to design the structural steelwork and to work with Revalvi's in-house designer GJM Design to develop the glazing system. It was decided to base the tender on an alternative steelwork design which in appearance closely followed the architectural concept of inclined steel arches and tie rods, but changed the structural form for greater efficiency and to suit the proposed fabrication methods. This resulted in a non-linear tied arch structure that could be fabricated in South Africa and shipped in small pieces to Lisbon for erection. An important aspect was the early involvement of Girder Naco (Pty) Ltd, the proposed steelwork contractor, in development of the details.

The structure

The structure is formed by a repeating pattern of arches, curved in cross-section and in plan, which gives rise to interesting three-dimensional forms while maintaining structural order and simplicity. Pairs of these arches, inclined away from each other by 4m at mid-span, are joined at their ends and tied with longitudinal Macalloy tension rods to form boat-shaped elements covering the central part of the span. These 'boats' in turn are supported on the tips of tree-like tetrahedron structures which reach inwards from each side of the roof, thus reducing the effective span of the arches and the weight of the 'boats'. The roof is braced against sway by additional tension rods.



2. Perspective showing roof steelwork components.

This pattern of repeating elements forms the 'building blocks' of the entire roof. All compression steelwork is tubular in cross-section, 273mm and 89mm in diameter, with the tension rods being Macalloy bars. At the ends of the building, the steelwork roof cantilevers forward to form dramatic 'visors' or 'peak cap' shapes above the entrance doors. Lastly, a 25m long x 15m wide structural steel pedestrian bridge with a glass floor is hung from the steelwork roof at one end.

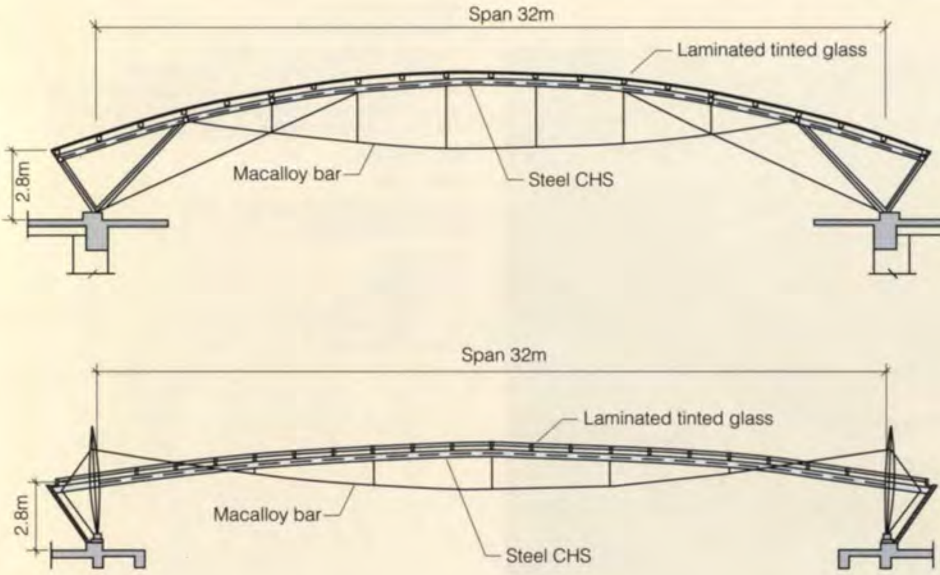
The design in the tender documents showed the client's desire for a dramatic, aesthetically pleasing structure, with appearance clearly more important than minimising cost. The alternative design, conceptualised and designed by Arup and fabricated and erected by Girder Naco, responded to these high aesthetic demands in an innovative, practical, and cost-effective way. At 240 tonnes it was substantially lighter than the original tender design, and thus considerably cheaper.

Great care was taken to achieve aesthetically pleasing connections fabricated from plate and rolled sections instead of the costly and heavy castings required in the tender design. Extensive use of physical models enabled aesthetic and structural requirements of key connections to be resolved.

Complex three-dimensional non-linear computer modelling, using OASYS FABLON, allowed the designers to design a structure that did not require pretensioning of rod components on site. Intensive conceptual design and pricing sessions with the steelwork contractor in a short tender period were strong contributing factors to Arup winning the tender. The project is a fine example of the benefits of close co-operation between designers and steel fabricators. Girder Naco was very much part of the design team, contributing to the design process with good practice fabrication ideas.

As all steelwork for the roof was fabricated in Girder Naco's works in Wadeville, Germiston, and shipped to Lisbon for erection, a reliable, repeatable industrialised production assembly line approach had to be developed if the components were to fit into containers and also fit together on site without difficulty. Girder Naco achieved this by trial fitting prototype primary components to resolve fabrication details and improve fit. Once problem connections had been resolved, prototype components were used by Girder Naco to form jigs which were then used for the repeated production of the steelwork components. The complex three-dimensional geometry of the roof was effortlessly resolved by Girder Naco's high quality workshop details and template production personnel and prototype components generally showed remarkable accuracy and fit at trial assembly.

As a final check prior to shipping, two full bays of the roof were assembled in Girder Naco's yard to ensure compatibility of fit between the tetrahedron-shaped column 'trees' and the 'boat'-shaped arches. Erection methodology and potential tolerance problems were identified and resolved by the fabricator and designers.



3. Typical cross-sections: Tender enquiry design (below); Arup's alternative design (above).

4.
Tetrahedron units being erected on site.

5.
Junction of Macalloy bar and tensioned rod components.

Glazing

The project also included glazing end walls, curved in plan and up to 12m high, using tempered glass with countersunk bolted fixings attached to bowstring trusses. After Expo '98, the project was to be completed with the installation of four more footbridges across the atrium, all with glass panel floors. The specified glass was 12mm thick laminated, tempered, body-tinted green glass, supplied by Viracon in the USA. Although thicker than the minimum required structurally, this gave the desired degree of solar control and robustness.

The aluminium framing was developed specifically for this project, and included condensation drains as well as a complete, sealed, back-up drainage system, designed to cope with substantial defects in the primary external silicone. This design condition arose from experience on a previous glass roof in Portugal, where the local seagulls delighted in pecking out lengths of the sealant. Great care was taken to co-ordinate the aluminium design with the steelwork, in order to minimise overall sizes and to avoid duplication of framing members.

Conclusion

The contract for the roof was won against stiff international competition. The project as realised testifies to the high level of design and fabrication expertise in the South African steel industry, which continues to deploy this expertise successfully in the global market.

Credits:

Client:
Sonae Imobiliaria

Architectural concept:
José M Quintela

Delivery architect:
Promontorio Architects

Structural and façade engineers:
Arup (Pty) Ltd, Johannesburg, South Africa
John Abbott, Keith Baker, Hansie Buys, Bradley Geldenhuys, Damane Hlalele, Dave Jackson, Neil MacLeod, Gary Noca, Beatriz Padhila, Radivoj Sendic, Errol Shak, Craig Thompson

Main contractor:
Revalvi Lda

Steel fabricators and erectors:
Girder Naco (Pty) Ltd

Illustrations:
1: John Abbott
2, 3: Emine Tolga
4, 5: Craig Thompson
6: Peter Mackinven

6. Interior of Vasco da Gama Centre.

The Swatch Pavilion

Bruce Danziger Tom Watson

Introduction

In 1996 Arup designed a fully demountable pavilion at the Atlanta Olympics for the Swatch watch company[1]. The building, of translucent polycarbonate panels on a framework, was designed to evoke Swatch technology and be portable. It helped to sell a record number of products during the Olympics, and because of this tremendous success the same team including Arup was invited by Swatch to design a new structure for Lisbon.

Concept

Expo '98's theme of 'The Oceans, a Heritage for the Future' embraced future technology serving exploration and preservation, allowing Swatch to communicate to the many visitors the message of their precise reliable technology. At the same time, they wanted to offer a provocative, fun experience.

At Atlanta, Swatch featured their timing technology at all venues where precision reliability was represented. At Lisbon, where timing didn't play into the overall theme of the event, they emphasised their pioneering entry control technology - Swatch Access. Swatch offered every visitor the opportunity to purchase an Access watch as an integral part of the ticketing / entry technology. Each watch stored information to allow visitors to come and go throughout their visit. Also, it gave those who chose to enter the event this way a special level of interaction with exhibits in the Swatch Pavilion. The overall navigation theme led to the pavilion experience being termed 'Swatch Navigator' - each visitor negotiating a journey of exploration and discovery.

1. The Swatch Tower.

2. The Swatch Pavilion at night.

The initial choice was between two design concepts, the 'vessel' and the 'island', the former conceived as a vehicle for learning about new things - venturing forth to discover and explore a new world. The 'island', on the other hand, made the pavilion a destination, the navigators arriving there to experience new cultures, technologies, and places. This was the scheme selected.

Like the Swatch watch and the Atlanta pavilion, the Expo 98 'Island' was designed with a transparent shell (in this case glass - plastic was used in Atlanta) for the building envelope. The shell was designed to be penetrable to all the parts of its workings, revealing and celebrating the creativity of its conception.

Recyclability was an important feature. Swatch - in both pavilion projects and in its corporate mission - is committed to thorough use of resources and does not discard materials needlessly at a project's close. In Atlanta, extra effort was made to ensure recyclability despite resistance from standardised construction practice. Where possible, materials were rented, reused, or resold to partially reclaim their value, and similar principles were applied at Expo 98. Exhibits were designed for reuse with reusable packaging containers. Pavilion assembly and erection were also completed locally, minimising the environmental impact of shipping non-native materials to the site. The design originally included reusable aluminum trussing elements, but for cost reasons steel was substituted.

The building

The project was fast track with design and construction in nine months - a further incentive to include reusable and recyclable ready-made systems. The design team sought innovative technical solutions designed for simplicity, and like the Swatch watch, the pavilion represented a fully integrated building solution.

The 'Island' was a large, flat, irregular roof floating above steel columns on a regular 7m grid in an overall oval or egg-shape. The columns, with moment connections to the grid, supported the roof structure of standard steel sections, its irregular perimeter form handled by steel beams cantilevered off the recessed tops of the steel columns. Isolated concrete pads supported each column, with a partial concrete slab on grade used as the floor.

The roof shielded the multiple layers and graphic skin elements from the sun's glare and heat, though with openings at certain points to allow natural light into the exhibition space. The oval 'Swatch Tower', the pavilion's main visual marker, protruded through the roof.

Since Lisbon has a temperate climate, air-conditioning was minimised. An average temperature of 27°C was anticipated throughout Expo 98, and while few of the pavilion areas were air-conditioned, most internal spaces were naturally ventilated.

The clear skies made direct solar radiation high and extensive shading of the air-conditioned Swatch Tower was achieved by the surrounding roof and its perforated aluminum panels.

Mechanical distribution ductwork in the Tower was exposed and integrated with the structural tie beam system, the duct proportions and the beam dimensions co-ordinated to allow the beam's middle section to accommodate. The conditioned areas used direct expansion refrigerant-based air-conditioning packaged units to maintain an internal 25°C when ambient temperature was 32°C. The approximate total capacity was estimated at 50kW (14 tons), 3000l/s (6300ft^2) airflow. The pavilion was served by a high voltage feeder from the Expo Park network.

The Island concept gave much outdoor space, shaded by the roof overhead. Air was driven freely through this exterior space by northerly winds, with little obstruction. Very little heat gain was trapped within the covered area and the comfort conditions were similar to other outdoor shaded areas at the site. Water feature exhibits also helped to provide some evaporative cooling.

Conclusion

Arup was commissioned in December 1996, and the concept was developed over the next two months. Detailed design was finished by May 1997. Construction began on 15 July 1997. Completion was on budget and on time in February 1998.

3. Pavilion Interior

4. Pavilion Entrance

Reference

(1) CHAMBERS, Larry. The Swatch Olympic Pavilion. *The Arup Journal*, *31*(3), pp6-7, 3/1996.

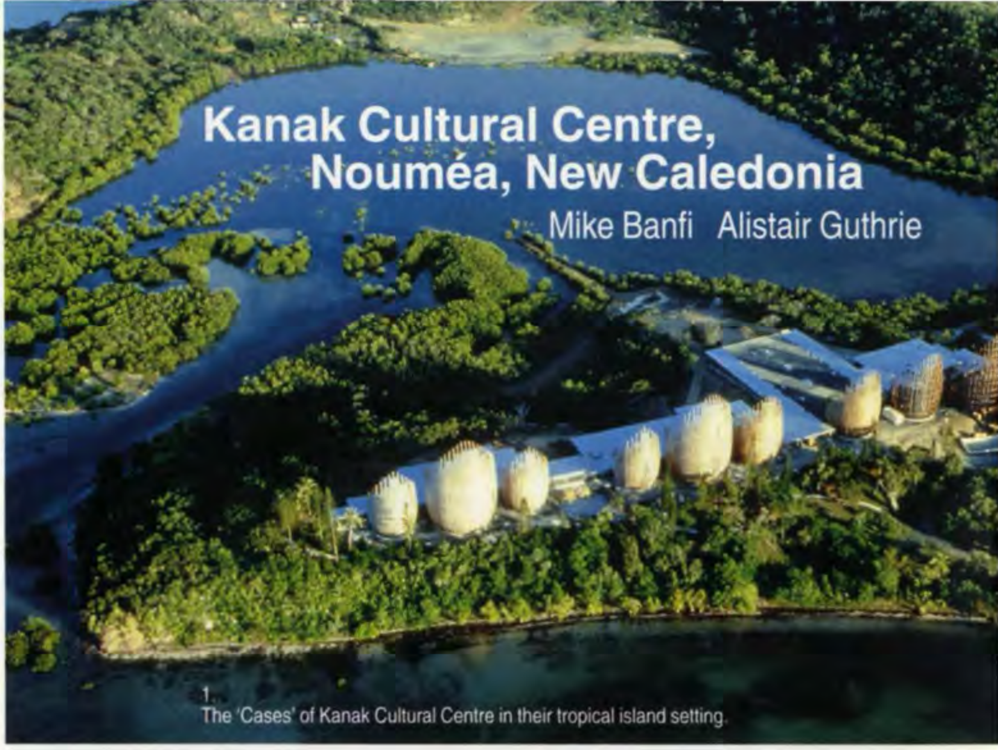
Credits

Client:
Swatch AG

Architects:
Pfau Architecture
Eyecandy

Consulting engineers:
Ove Arup & Partners California
Peter Balint, Larry Chambers, Judy Coleman, Bruce Danziger, Pompey Festejo, Michael Hoffman, Jun Lautan, Alisdair McGregor, Benedicte Riis-Duryea, Tom Watson

Illustrations:
Mark Darley/Esto



1.
The 'Cases' of Kanak Cultural Centre in their tropical island setting.

Kanak Cultural Centre, Nouméa, New Caledonia

Mike Banfi Alistair Guthrie

Introduction

New Caledonia is an island in the Pacific Ocean, some 1600km east of Australia. The Kanak Cultural Centre is situated on a thin peninsula near the island's capital, Nouméa. It celebrates the Melanesian culture of the Kanaks with its museum of living arts, and is also a memorial to Jean-Marie Tjibaou, leader of the New Caledonian independence movement, who died in 1989. It was here that Tjibaou had held the 'Melanesia 2000' festival in 1975, one of the key moments in the struggle for cultural and political recognition by France.

In 1991, an international competition was held to suggest ideas for the centre. The winning design by architect Renzo Piano, with input from Arup, employs large hut- like structures, or 'Cases', clustered together along a central spine. Housing exhibitions, study spaces and living arts, the Cases are inspired by the island's traditional construction, but employ modern technologies.

Arup was commissioned to engineer the scheme design for the whole complex and to work in detail on the structure and environmental performance of the Cases. Driving the Cases' design was the requirement for them to enhance the natural ventilation through the Centre, thus minimising the need for mechanical systems.

Climate

The climate is described as 'oceanic tropical' - generally humid throughout the year with only moderate variations in temperature from an average winter minimum of 18°C to an average summer maximum of 28°C. Relative humidity does not vary much throughout the year and is about 75% RH with average monthly maximums of 90%RH and minimums of 60% RH. To estimate the comfort conditions within the Cases, a full weather tape for a particular year was obtained from Nouméa Airport, giving details of temperature, humidity, and wind speed and direction.

Concept

The original concept was to use the giant curved structures as wind scoops, but as the design progressed it became evident that they would need to work in a variety of ways in response to the different strengths and directions of the wind.

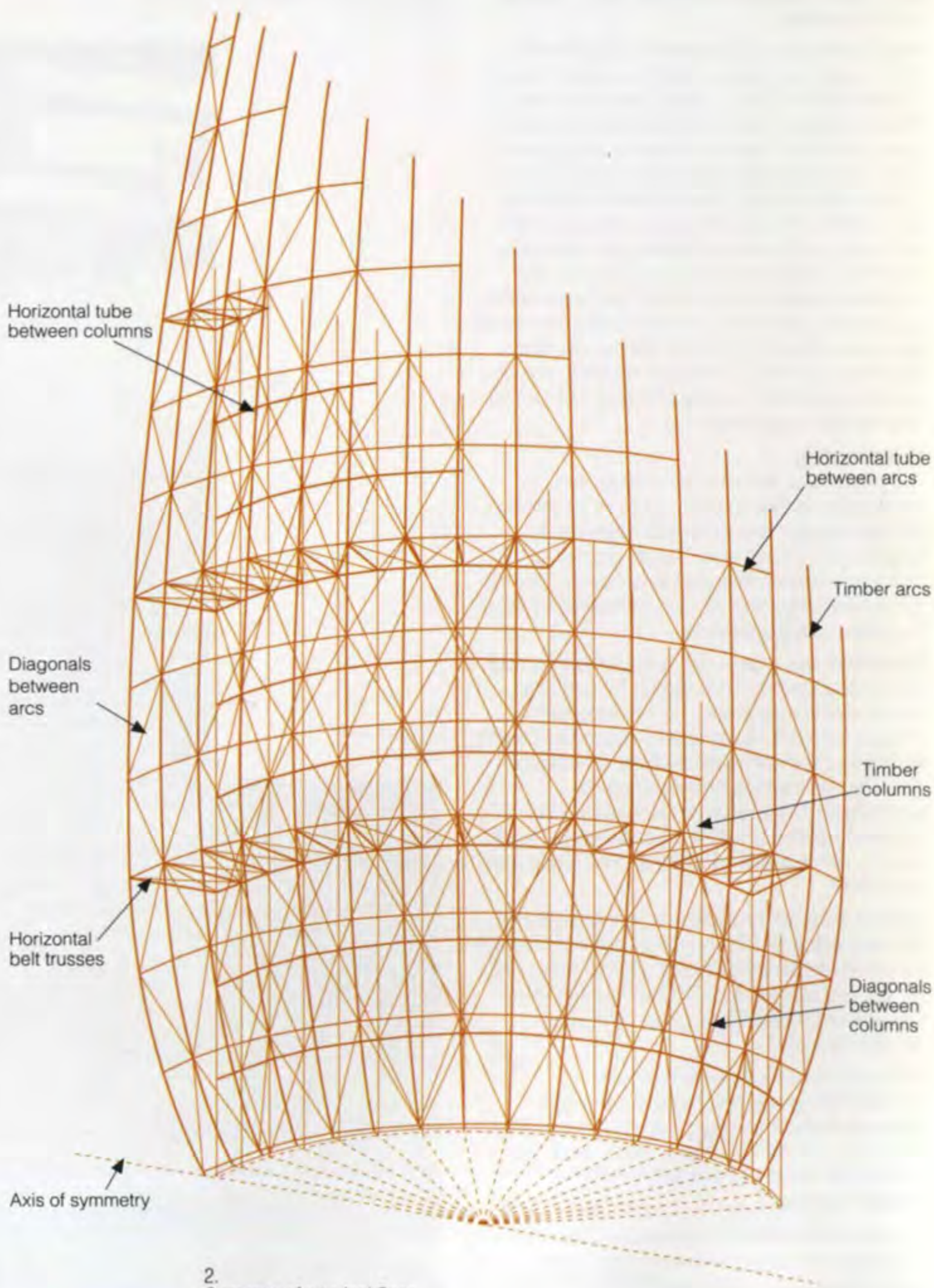
Early in the project, the client agreed that if it could be demonstrated that the spaces inside the Cases were comfortable without air-conditioning for at least 95% of the worst month of the year, then a naturally-ventilated solution should be designed. At competition stage, Arup stressed the benefits of low technology since mechanical equipment had to be imported and maintained. The challenge was to prove that natural ventilation would give adequate comfort.

Typical case geometry and modes of operation

Fig 2 shows the geometry of a typical Case, developed from the preliminary studies. The structure and cladding of the double shell is made of a renewable hardwood while the roof is an insulated panel with external shading to reduce surface temperatures.

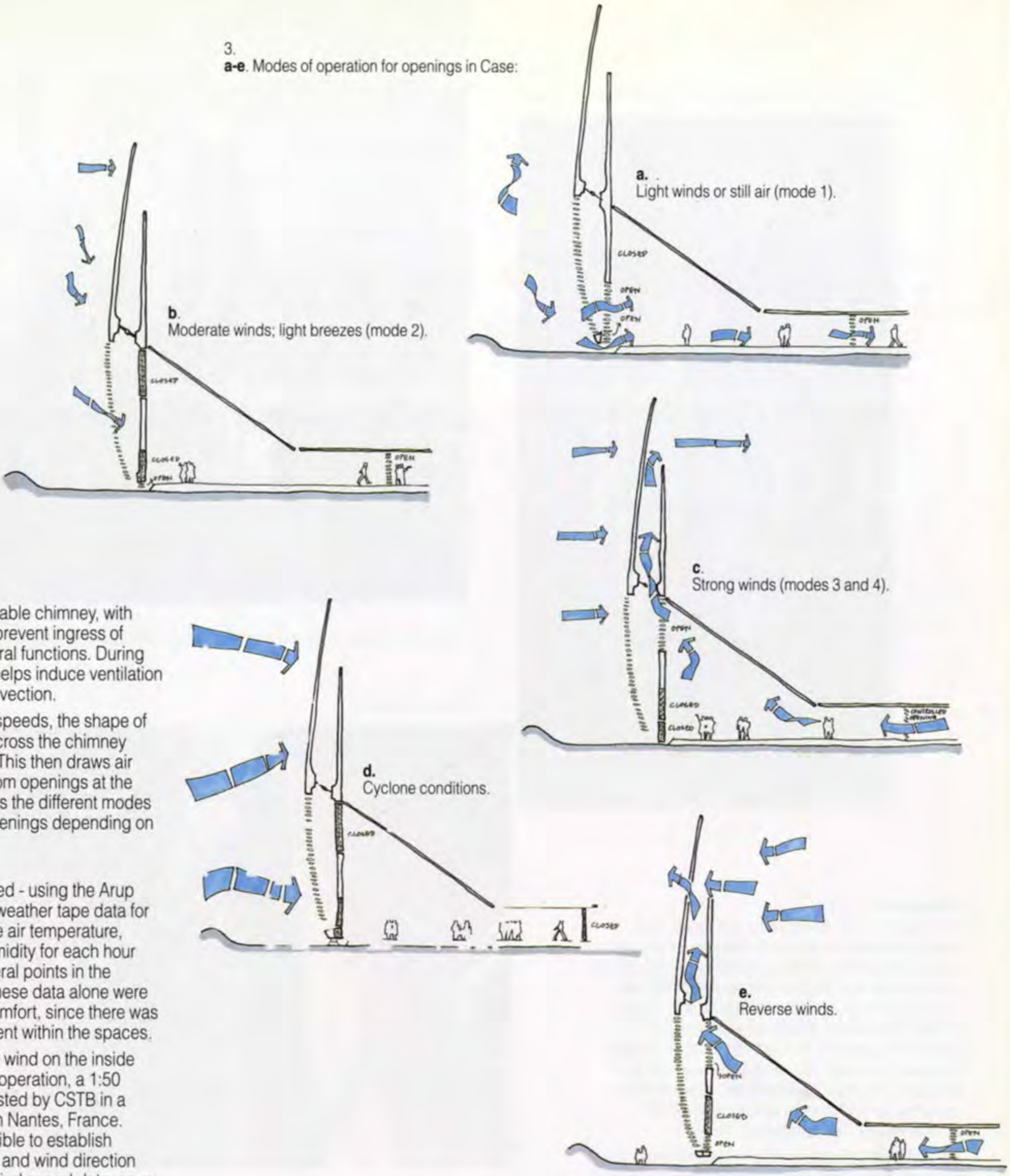
Several openings in the Case allow ventilation. Two sets are located at the front (facing prevailing winds): 2m high openable louvre windows and, at low level, 0.5m high openable louvres.

These openings are controlled automatically to either fully-open or fully-closed positions. At the back of the Case a series of openable windows allow cross-ventilation. They have three control positions and are controlled automatically to be open, closed, or half-closed. Control of the openings is based on internal air speed to maximise internal air speeds up to the limit of 1.5m/s.



2.
Geometry of a typical Case.

3.
a-e. Modes of operation for openings in Case:



a.
Light winds or still air (mode 1).

b.
Moderate winds; light breezes (mode 2).

c.
Strong winds (modes 3 and 4).

d.
Cyclone conditions.

e.
Reverse winds.

At high level there is an openable chimney, with double horizontal louvres to prevent ingress of water. The chimney has several functions. During days with little or no wind, it helps induce ventilation by stack effect or natural convection.

During periods of high wind speeds, the shape of the shell directs air up and across the chimney inducing negative pressure. This then draws air through the internal space from openings at the back of the Case. Fig 3 shows the different modes of operation for the above openings depending on wind conditions.

Comfort analysis

The typical Case was analysed - using the Arup Room program linked to the weather tape data for the sample year - to calculate air temperature, radiant temperature, and humidity for each hour every day of the year, at several points in the occupied space. However, these data alone were not sufficient to determine comfort, since there was no information on air movement within the spaces.

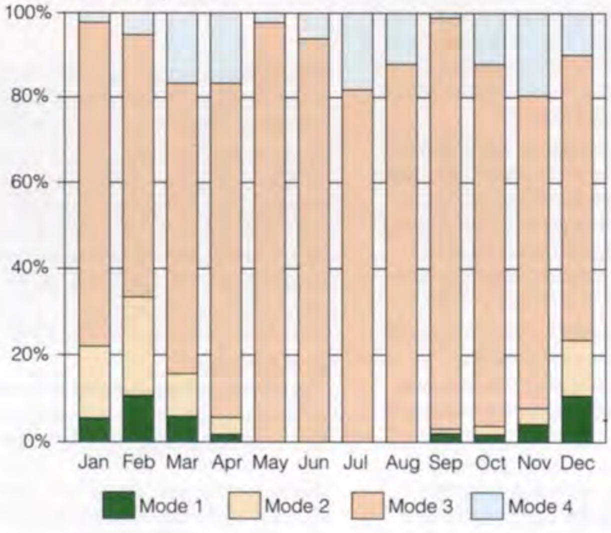
To determine the effect of the wind on the inside spaces under each mode of operation, a 1:50 scale model was built and tested by CSTB in a boundary layer wind tunnel in Nantes, France. From these tests, it was possible to establish coefficients for each location and wind direction which, when applied to the wind speed data, gave an approximation to the internal air velocity under each mode of operation.

These data were then combined with temperature and humidity calculations to arrive at a comfort index for each hour during the critical months. The resulting values were compared with both the Fanger comfort equations and the Gagge indices of effective temperature. The Gagge method was chosen, as it is the best indication for people living in naturally-ventilated conditions in a tropical climate, since it is based on experimental data from this climate type.

Comfort conclusions

The data showed that during the hottest month, February, the Gagge acceptable comfort criteria were exceeded for only 5.8% of the occupied hours. This was acceptable to the client and formed the basis of the design. Arup also calculated the percentage of time that each mode would be in operation and found that nearly all the time mode 3 would be in operation (Fig 4). Since mode 1 was hardly ever operational the openings here would be under manual operation.

4.
Comfort analysis data.



5.
Mock-up in France of part of Case structure.

7.
In this view across the sea the massive scale of the Cases is immediately evident.

6.
Detail of structure.

Structure

The design of the structure for the Cases was shared between Ove Arup & Partners, who were responsible for the concept design and the analysis up to tender, and the French firm Agibat MTI who produced the tender documentation and carried out the final design. There are three sizes of Case - the largest is 28m high and has an internal diameter of nearly 14m - and all have a similar structure. The main structural requirement was to resist the cyclonic winds which can gust up to approximately 65m/s from any direction.

The architectural concept and ventilation strategy generated the Centre's overall form, including need for an internal wall. Options for its construction were considered, and it was decided to use a similar form to the external wall. The two concentric walls are set out from a common centre and occupy about two-thirds of a circle. The main elements of both are the glue-laminated timber sections. In the outer wall the timbers are curved into arcs; for the inner wall they are vertical columns.

To provide overall wind resistance, bracing was provided in the walls to form stiff shells. After due consideration, the chosen system was to brace the timbers together with tubes at 2.25m spacing vertically, with single diagonal ties in each bay. At the base of the inner walls, half the diagonals had to be omitted to allow for opening windows.

A structure was also required to prevent the walls distorting from the circular plan geometry. This was provided by linking the inner and outer walls together with up to three levels of horizontal belt trusses.

An alternative would have been to use the sloping roof inside the inner wall, but it was decided to keep the roof structure as light as possible, and introduce a joint so that wall movements did not stress the roof.

A non-linear program was used to analyse the structure, including provisions for any of the ties becoming slack and to include stability effects.

Wind loading from three directions was considered, with account being taken of the varying permeability of the timber slats on the outer wall. The width of the timber arcs and columns was constant but the depth varied with height to reflect the structural requirements. The bracing tubes and diagonals are generally the same dimension for each size of Case with some variations in the diagonals near the base.

Connections

The connection between the timber arcs, horizontal struts, and diagonal ties was a major consideration. One idea was a plate slotted through the timber with steel-to-steel connections, but the geometry of the diagonals gave a large joint. Moving the ties from the centreline of the timber to the outside raised the possibility of cables with relatively simple clamped connections. However, the eccentricity at the connection had implications for the structure, and the cables on the outside would clash with the cladding. The detail chosen uses a steel casting inserted in the timber, incorporating more compact fixings for diagonal steel rods.

The connection between the timber and concrete support has a similar language, with one part of a steel casting inserted in the timber and the other forming a pinned connection to a casting bolted to the concrete.

Materials

The temperature, humidity, and proximity to the sea do not give the best conditions for the durability of materials. In selecting the timber, the possibility of termites had to be considered. The timber also had to be suitable to produce glue laminated elements in terms of its movement and suitability for gluing. Following tests carried out at the Centre Technique du Bois, the species chosen was Iroko. The steel tie rod, tubes and castings were zinc-coated.

8.
Library facilities.

Conclusion

After some delay, the project was built on site and opened in autumn 1998. It is understood that comfortable conditions have been achieved in the naturally ventilated spaces and at the time of writing further feedback is awaited.

Credits

Architect:
Renzo Piano Building Workshop, Paris

Services engineer and structural concept engineer:
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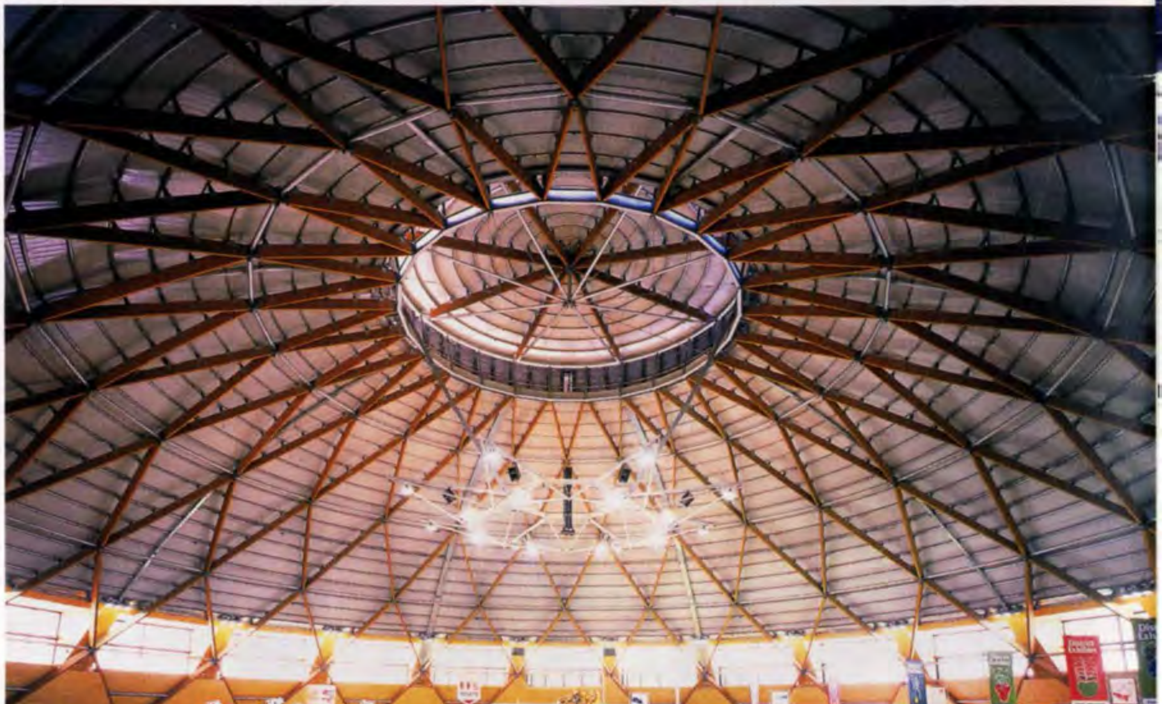
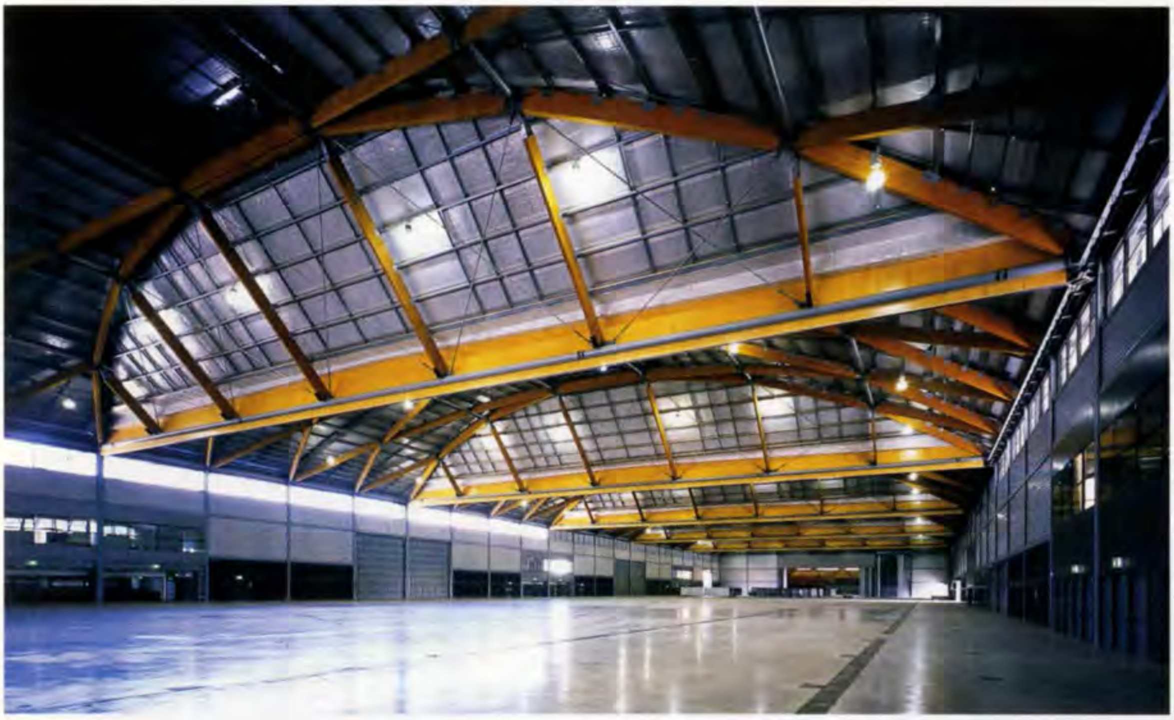
Exhibition Halls for the new Sydney Showground

Peter Bailey   Tristram Carfrae   Richard Hough   Paul Stevenson

1 above:
The Exhibition Halls in use for their first major event: the 1998 Royal Easter Show.

2.
Inside 'the Dome'. The suspended grid carries floodlights, metal halide lamps, and cabinet speakers.





3.
Circular vault roofs to the rectangular halls.

Introduction

The New South Wales Royal Agricultural Society's (RAS) chief vehicle for promoting local agricultural interests is the 100 or more events that it hosts each year on its Showground premises.

In 1989 the RAS endorsed the NSW Government's plan to relocate the Showground facilities from their historic inner-city Sydney site to Homebush Bay in the western suburbs; in due course the proposed new Showground Precinct became a key component of Sydney's successful Olympics 2000 bid in 1993.

Relocation of the facilities has now been completed at a cost of $A380M, under the control of the Olympic Co-ordination Authority (OCA), with the RAS and the Sydney Organising Committee for the Olympic Games (SOCOG) as key stakeholders. SOCOG's role was to ensure that precinct planning, trunk servicing arrangements, and the basic layout of major buildings could accommodate the requirements of an 'Olympic overlay' in due course.

The new facilities cover 30ha, and feature some of the most spectacular roofs ever designed in Australia. Prominent among them are the Exhibition Halls (Fig 1), which will serve as a key venue for the Olympic indoor sports including volleyball, handball, badminton, and rhythmic gymnastics, and for Paralympic events including basketball, handball, and volleyball. The Halls give 22 000m^2 of continuous exhibition area, also divisible into four separate spaces by operable acoustic doors. One hall, larger than the others, is roofed by a 100m diameter dome (Fig 2) that has become a landmark for Olympic Park. The three adjacent and contiguous rectangular halls, each 67m x 72m, are roofed with cylindrical vaults (Fig 3).

In early 1996, Ancher Mortlock Woolley were appointed by the OCA as architects for the Halls, with Arup supplying engineering design services across the structural, civil, mechanical, electrical, hydraulic, passive energy, and acoustics disciplines.

Environmentally, the Halls embody the Government's goal of 'the Green Olympics'. The roof structures are of plantation pine with its low embodied energy, low CO_2 generation, and high carbon fixing potential.

The efficiency of the shell-like framing ensures low material consumption. The Halls are naturally ventilated, and are partly naturally lit. The dome also has a very energy-efficient air-conditioning system, which requires substantially less cooling energy than traditional systems.

Superstructure

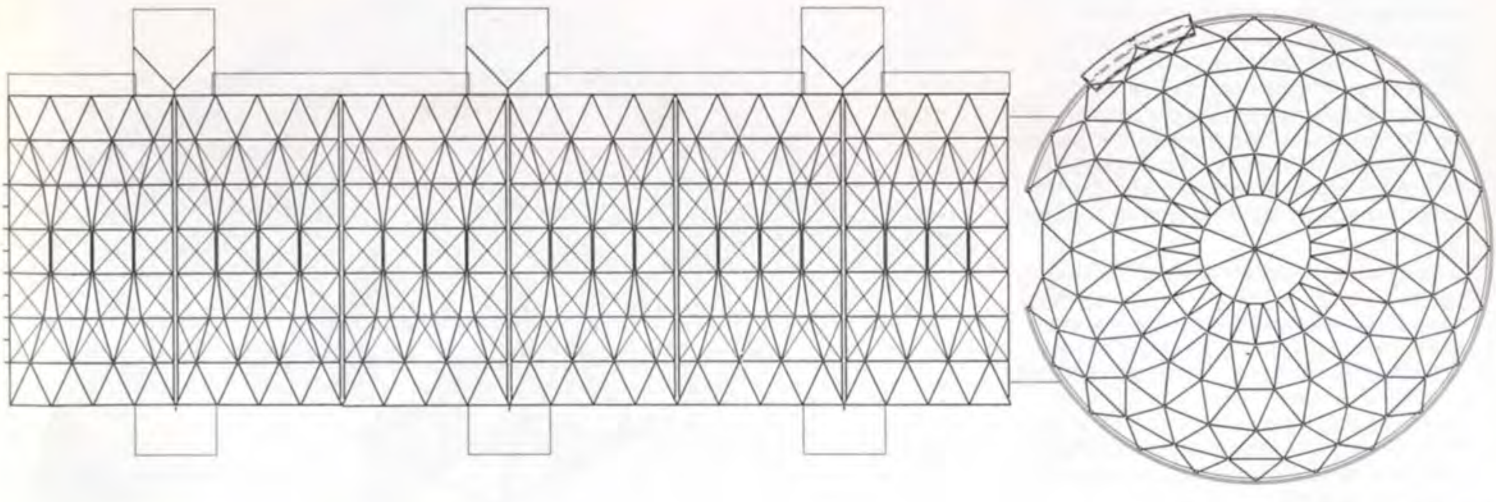
The dome

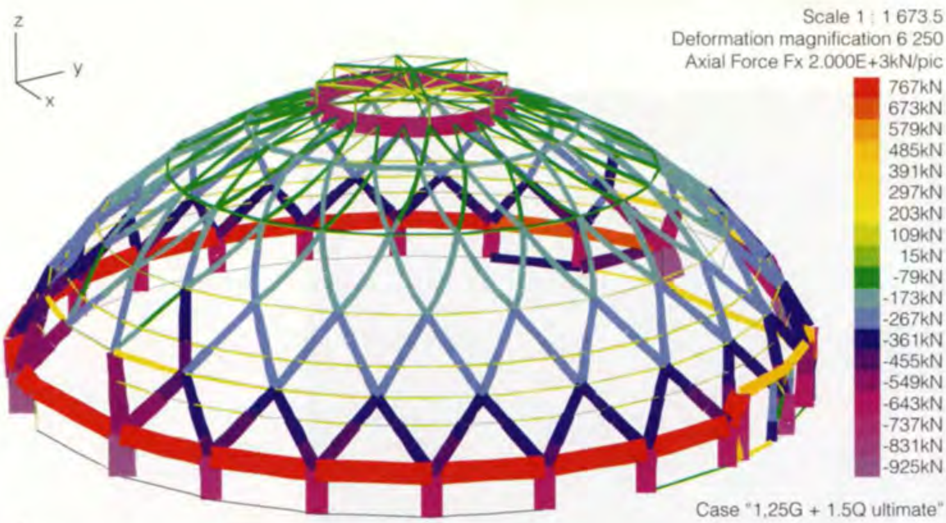
Both dome and rectangular roof vaults are single-layer reticulated shell structures (Fig 4). The choice of single-layer minimised the intrusion of structure into the Halls, thereby maximising useable volume.

The fully triangulated framing patterns maximise shear stiffness and so minimise displacements and buckling tendencies. Joints were conceived as moment-capable, to further increase stiffness and simplify fabrication.

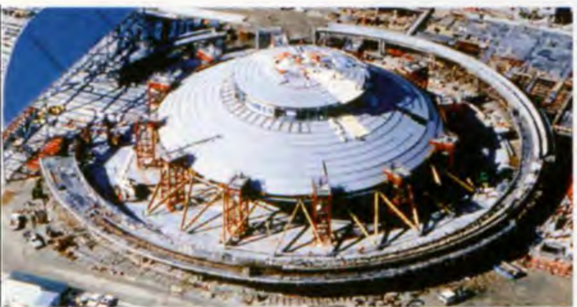
Comparative designs were carried out and 'all-steel' and 'maximum-timber' solutions costed. Although timber was expected to be marginally more expensive than all-steel, it was chosen for its environmental benefits and for its links to traditional RAS facilities.

4 below:
Fully-triangulated roof framing plan.





5.
Axial force plot for dome members.



6 left:
Dome erection: adding the third ring of members. Ring beam under construction simultaneously.

7 below:
Partly completed dome suspended from jacking towers.

Buckling modes and effective lengths for the dome structure were analysed, and checks carried out on combined stresses in both timber and steel members (Fig. 5). Continuously curved circular hollow section (CHS) steel purlins stabilise the timber sections via cleats which grip their top edges. Individual glued-laminated (glulam) timber members were tested in non-linear models to check the effectiveness of the purlins in stabilising the deep timber cross-section in torsion.
The results were interpreted in terms of effective lengths for axial compression and for negative bending (bottom edge compression), for design by code-based methods.

At major joints, circumferential CHS ties provide hoop forces to maintain the shape of the dome. The timber sections vary from 800mm x 135mm at the crown to 800mm x 280mm at openings near the ring beam; the rise from ring beam to crown is about 35m. The centre-planes of the glulam beams are set out on great circles of the spherical dome, and so intersect on a single, radial line at each node. This choice led to simple fabrication of the steel plate nodes.

The dome ring beam was kept low to avoid having a tall wall at the base, with the result that the ring beam is interrupted - to achieve extra vertical clearance - at the loading bay entry to the dome and at the opening between the dome and the adjacent rectangular halls. The ring beam forces are diverted around these openings. The ring beam itself is a large in situ reinforced concrete gutter section that collects all rainwater runoff, so it has substantial strength and stiffness for its structural functions.

In designing the timber members for tension and bending, account was taken of various published views on the benefits of lamination for the parent timber's mechanical properties, and of the risks posed by finger jointing, including laminating factor methods and methods based on shook length (length between finger joints), and characteristic finger joint strength. Permissible stress methods were used, as the Australian limit state timber code was not yet available.

Dome erection

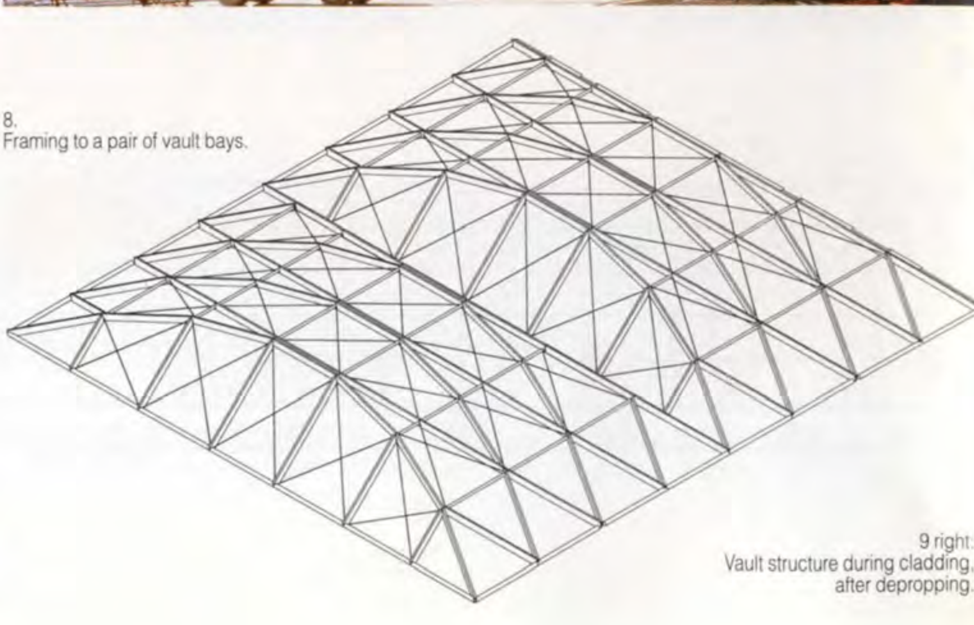
At tender, the main joints were shown with steel shoes attached to the ends of each glulam member, and split radially and circumferentially to permit any sequence of member sub-assembly and erection. Of all the methods available, that finally chosen by the contractor was unusual, but very effective. Starting with the central monitor structure propped off the slab at low level, successive rings of timber members were installed, closed with their CHS tie rings, and lifted on cables attached to 12 100-tonne centrehole jacks at the top of 12 scaffold towers (Figs 6-7).

The sequence required re-analysis of the structure to check that the circumferential members and their joints could provide the large tie force needed at each stage of lifting, a force that disappeared upon subsequent depropping onto the slab, prior to relocating the towers and jacks for the next cycle.

The method had the major attraction for the contractor of allowing the cladding system to be installed ring by ring at much lower heights than most other methods.

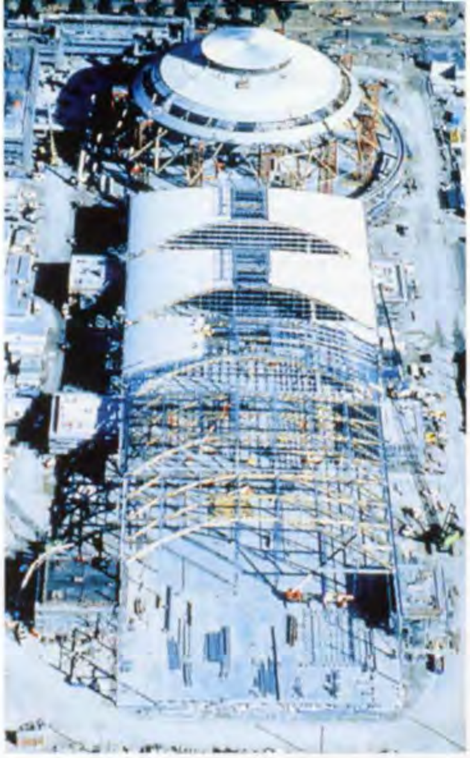
The permissible vertical differential displacement at lifting locations was also analysed, to avoid overstress from local twisting of the partly-completed dome. To monitor the actual displacements, 12 CCTV cameras were trained on measuring tapes fixed to the jacking guide rails and the signals collected at a monitoring station near the middle of the dome, alongside the centralised control for all the jacking hydraulics.

8.
Framing to a pair of vault bays.



9 right:
Vault structure during cladding, after depropping.

10 right:
Four lines of propping in place for vault erection.
Dome during final lift.



Vault structure

The vaults are of timber arches running diagonally, tied at 36m centres by horizontal CHS members with operable acoustic doors suspended at these tie locations. Arches not terminating directly on ties deliver their thrusts to the ties via the triangulation inherent in the framing pattern (Figs 8-9).
This means that most roof loads are concentrated on the four corner columns of each structural bay, although vertical wallposts are still needed for equilibrium local to the eaves.

The shear stiffness of the structural grid relies also on longitudinal CHS members, plus crossed tie-rods inserted in the trapezium-shaped bays of the grid, to complete the triangulation. As for the dome, the purlins are attached to the timber members via stiff cleats which cantilever down and stabilise the timber sections.

The deformation of the diagonal timber 'arches' in the vault is controlled by resistance of the triangulated surface in shear; the critical buckling mode has an 'effective length' of about two member lengths for major axis buckling. To increase stiffness further, the longitudinal CHS members were made continuous at joints, as were the glulam members.

A steel-framed 'monitor' structure is mounted on the crown of each vault to admit controlled daylight, to exhaust ventilation air through motorised louvres, and to provide smoke exhaust in a fire.

Along the north (sunny) wall, a fabric canopy provides both weather protection and a transition in scale from the tall wall to the adjacent pedestrian promenade. The fabric is stretched between the wall and an outer edge cable, and is drawn down to ground level in large funnel shapes which collect and discharge rainwater.

Vault erection

Initially it was intended to lift completed 67m x 36m bays, but a more piecemeal approach, with four lines of props across the 67m span, proved more flexible in terms of the delivery sequence of fabricated members (Fig 10). Again, joints were designed to be split on two axes, and this proved valuable for the chosen erection method.

The roof structure was checked for various temporary loading conditions, such as wind load on the partly-clad frame. The effect of residual stresses was also checked, given that self-weight bending of glulam beam sub-assemblies was likely to remain superimposed on the moments applying to the complete, fully de-propped structure. Temporary effects from the de-propping sequence were considered as well.

Timber procurement and fabrication

Radiata pine from plantation forests in the north west part of New Zealand's South Island was used for the vault structure, while for the dome it was mainly slash pine from Queensland, plus radiata pine from the Mt. Gambier area of South Australia.

Given the size and importance of the structure, in-grade testing of all sources was deemed necessary, and this proved a useful precaution. Production had already begun when the New Zealand radiata returned mechanical properties significantly lower than those assumed in the analysis and design. The structure was re-analysed to check for any spare capacity, and with some relocation of members, most of the production material turned out to be useable. Simultaneously, a stress grading machine was transported to the plant, and a more reliable grading regime was introduced for the remainder of production.

There was also a settling-in period to achieve the specified finger joint strength for the New Zealand radiata. An overhaul of the finger joint cutting heads and of the glueing process assisted, as did the introduction of proof bending of laminates.

During peak production, six laminating plants were involved, taking material from four mills at three sites. Machine stress grading was used for the bulk of the material, supplemented with visual grading.

In all cases, at least the outer zones of beams were subjected to some kind of proofing, for reassurance of both stock and finger-joint properties, beyond minimum SAA quality control requirements.
A percentage of beams were subjected to full-size tests, either bending or eccentric axial tension.

Joints

End-grain embedded threaded rods connect the timber members to the steel nodes, with a coupler at the timber end face to allow bolting on of the steel shoes (Fig 11).

Small-scale and full-size prototype joints were tested to destruction to understand their behaviour, particularly the groups of four embedded rods. Strain gauges indicated a delivery of load into the timber close to the coupler. Pullout and failure loads indicated load factors adequate for the anchor groups in their designed condition. During erection, the steel shoes were connected at the joint centreline by end-plate bolting, with reliance on direct bearing to transfer compression (Fig 12).

11.
Threaded couplers recessed into ends of glulam member.

12.
Typical end-plate bolted joint to vault framing.

13.
Typical transverse services tunnel beneath the exhibition floor.

Substructure and civil works

The exhibition floor is a reinforced concrete slab on ground, carefully articulated with tunnels, ducts, and trenches to distribute power, communications, emergency systems, water supply and drainage, gas, ducting for air-conditioning, and chilled water for the radiant slab zone. A 3m x 2m walkthrough tunnel along the transverse centreline of each hall feeds 300mm square in-floor trenches branching off on both sides of the tunnel at 9m centres (Fig 13).

The slab is typically 225mm thick, on a 225mm thick bonded sub-base, to cater for both construction loading and a nominal 20 tonne concentrated load during exhibitions. Maximum economy of foundations was achieved with a mixture of shallow pads and strips, and bored piles to the underlying shale, with a deep edge beam serving both as pilecap and moisture cutoff wall to zones of reactive clay.

External civil engineering works included 6000m^2 of concrete paving to various strength, durability, and aesthetic requirements, including the use of 10mm exposed aggregate finishes and black oxide coloured concrete. The catchment is drained by 300m of pipework with collection pits and pollutant traps.

Passive environmental control

As part of the client's sustainability requirements, all halls are naturally ventilated, though with air-conditioning also provided to the circular hall. In the rectangular halls, natural venting relies on low and high-level louvres, fitted with motorised dampers to moderate air flow and avoid draughts. Available breezes at roof level pass through the high-level monitor louvres and provide a drawing effect.

Computational fluid dynamics (CFD) analyses, overlaid with potential exhibition partition layouts, indicated acceptable comfort conditions and satisfactory through ventilation. Improved conditions were predicted with underfloor fresh air supply tunnels added along the longitudinal centrelines of the Halls, with the extra bonus of free cooling from the tunnel's thermal mass (Fig. 14), however, the cost of extra tunnels could not be accommodated in the budget.

The mass of the concrete floor slab, in direct contact with the ground, supplies some passive cooling, but the high volume-to-surface-area ratio of the Halls did not warrant the cost of introducing further exposed mass into the walls or roof.

All glazing is protected from direct sunlight to minimise solar gain, whether by overhangs, fins, or louvres, and the north wall is additionally shaded by the fabric canopy. To reduce radiant and conductive gains further, the roofs and external walls are insulated with 75mm of glassfibre; wool was considered, but rejected for budget reasons.

Natural light from high-level wall glazing and glazing in the monitors is available for setting up and taking down exhibits.

Air-conditioning to the dome

There are periods when natural ventilation to the dome will not maintain the comfort conditions specified, so four air-conditioning distribution systems were studied:

- overhead
- mid-level perimeter jet diffusers
- perimeter-supplied displacement system
- perimeter displacement system with supplementary chilled floor.

The fourth option was adopted for the following reasons:

- lowest operating costs - through significant reduction of supply air energy demand and by minimising conditioning of the large volume of air above head height
- smallest space demand for air-handling plant
- the highest potential for 'free cooling' during favourable ambient conditions, with the thermally stable in-ground ducts
- floor slab clear of supply air outlets, allowing full flexibility for exhibition layouts
- partial conditioning of the hall possible, or preheating by use of warmed slab alone
- reduced risk of draughts
- better air quality than methods requiring mixing of large air volumes.

Conditioned air at 19-20°C is supplied at low velocity (0.2 - 0.3m/s) through wall-mounted diffusers at the perimeter, fed by in-ground perimeter concrete ducts (Fig 15). This air is then warmed by internal heat loads (people, exhibition lighting, suspended house lighting, electronic and mechanical exhibits), and rises by buoyancy to high level where it is exhausted or returned. The rising air is then replaced by cooler air from the diffusers. This cycle lifts airborne contaminants out of the occupied zone. In winter, supply nozzles integral with the displacement diffusers provide warm air, supplied at higher velocity to increase its penetration into the space before it rises.

The chilled slab zone is in the central part of the hall for supplementary radiant cooling in summertime full occupancy mode, and to help convey the supply air all the way to the centre of the hall. The slab surface is chilled to about 18°C on hot days via embedded pipe coils . In winter mode, the slab surface can be warmed to 6°C above room air temperature.

The cooling system performance was studied extensively during the design stage using thermal modelling and CFD to demonstrate a satisfactory temperature distribution throughout the occupied space. The air is predicted to stratify with a significant gradient from bottom to top of the hall, and to provide a draught-free environment (Fig 16). This is the first application of a displacement system in an exhibition hall in Australia.

The low-level perimeter supply is well suited to Olympic mode, when seating tiers for 10 000 spectators will be erected around the edge of the hall. Cooled or heated air will be supplied to the seating undercroft, and passed out through controlled slots in the seating structure. This arrangement also allows maximum use of outside air for free cooling, a valuable bonus given the mild conditions expected for September in Sydney when the Games will be held.

Electrical and hydraulic systems

A 9m x 6m grid of outlets in the 9m-spaced in-floor service trenches delivers power and communications to the exhibitors. Each service location provides both 32A three-phase and 10A one-phase power, and a dual RJ45 communications outlet served by Cat 5 cable.

Structured communications cabling allows the outlets to serve either as voice connections or as part of a computer network extending, potentially, over all halls. A communications distributor in each transverse service tunnel interfaces to the structured cabling backbone, which includes both copper and fibre optic cabling.

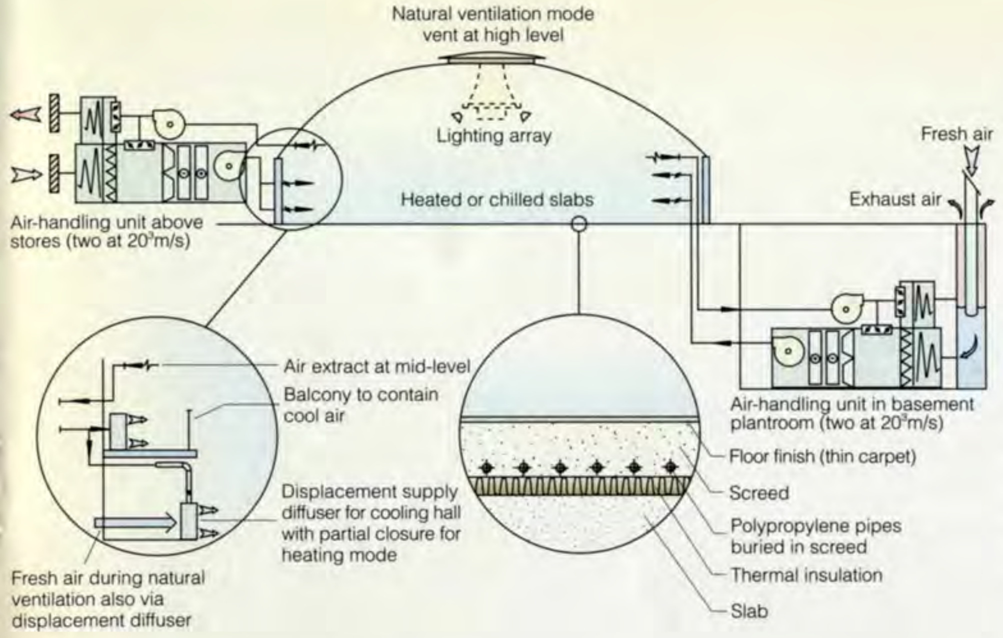
Primary electrical supply to the in-floor network is also via the transverse tunnels, using low impedance distribution busways with take-offs fitted with local protection and serving small distribution boards to limit the impact of overloads or faults.

The circular hall is lit by pairs of 400W metal halide lamps in perimeter-mounted floodlights, supplemented by a central suspended grid containing both floodlights and 1000W metal halide lamps in prismatic high bay luminaires which give some upward light as well. The rectangular halls have 1000W halide lamps in high bay luminaires. A central computerised switching system allows both central and local switching and permits several lighting levels.

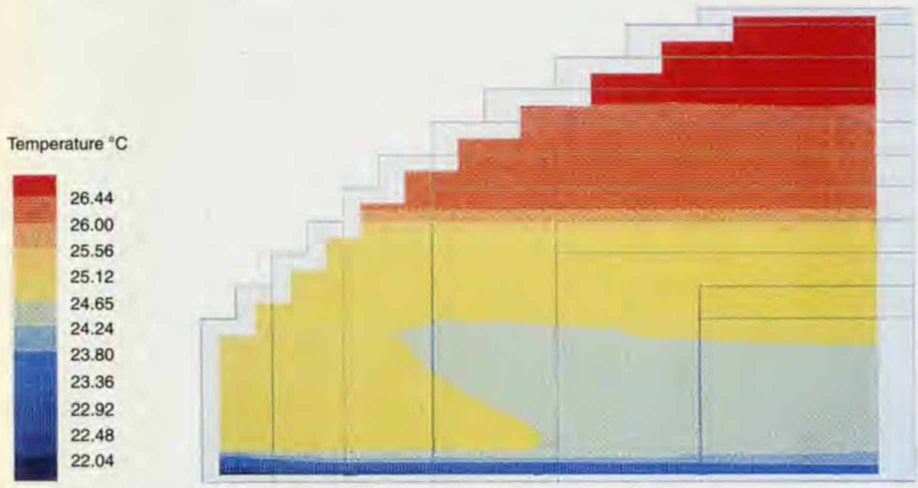
Wet exhibits are the exception rather than the rule. Water supply is available at valves along both sides of the transverse services tunnels, and is run via flexible piping down the in-floor trenches. Likewise, drainage is by temporary trench piping to the tunnels. The trenches themselves have drainage outlets and traps at the tunnels. The in-slab piping for the section of chilled slab to the circular hall is served by manifolds set in the larger trenches in that hall.

Australian Code requirements are not specific about the need for fire suppression devices such as sprinklers and water cannons in buildings of this type. Arup's fire engineering studies demonstrated that suppression was not warranted in this case.

14 left:
CFD temperature plot simulating natural ventilation to rectangular halls, with supplementary under-floor supply near middle of hall.



15.
Schematic of air-conditioning to circular hall.



16.
CFD temperature plot simulating stratification to circular hall in air-conditioning mode.

Acoustics

To minimise noise from external sources and the other halls, all hall roofs and walls needed adequate sound transmission loss and acoustic absorption. The air-conditioning system was also checked to allow specification of noise and vibration controls.

Factors determining optimum reverberation characteristics for an exhibition hall include intelligibility of the PA system, and the 'liveness' needed to reinforce the sense of space and activity without excessive noise build-up. To this end, the roof decks incorporate an inner, sound-absorbing polyester lining, with perforated timber linings over polyester insulation in the wall finishes for additional absorption. Structural members that intrude into the space, like the deep-section primary timber framing members and some of the secondary steel framing, provide some diffusion to reduce the sound-focusing risk inherent in the shape of the dome roof.

The distributed loudspeaker array in the circular hall is integrated with the centrally suspended lighting grid, and is equipped with high-powered cabinet speakers served from a central rack room. The rectangular halls have distributed loudspeaker cabinets also served from dedicated rack rooms.

Management, programme, cost

The Halls, plus the contiguous 8000m² RAS Administration Building, were designed and built in less than 24 months to a budget of $A78M. They opened in March 1998, together with numerous other major buildings in the new Showground Precinct, on time for the RAS's major annual event, the Royal Easter Show.

Construction was by Thiess, with Australia Pacific Projects as project managers and the OCA as Principal. John Holland Construction and Engineering were construction managers, appointed after the design of the Halls was well advanced. The design team was novated to Thiess from tender stage onwards after initially being under contract to OCA. The construction contract also required Thiess to accept the novation of Alfasi Constructions, the superstructure contractor, after the superstructure contract was well underway. Ensuring continuity of design intent for the unusual roof structure during the evolution of these contracting and management arrangements was a challenge for the design team, but support for the timber grid shell concept maintained momentum, and to everyone's credit the vision was kept firmly in place.

Conclusion

The Project has won numerous awards:

- Association of Consulting Engineers of Australia: Special Merit Award 1998 (the ACEA's top award) (entered as an example of well-integrated multi-disciplinary design)
- Institution of Structural Engineers (UK): Special Award 1999
- Institution of Engineers, Australia: Highly Commended Award 1998
- Master Builders' Association of NSWL Excellence in Construction Award 1998
- Lightweight Structures Association of Australia.

The close interaction between all the Arup engineering disciplines, plus the architects' keen interest and involvement in all the technical aspects of the design, ensured many examples of successful technical integration. These included the design of the reinforced concrete 'tray-in-ground' - carefully shaped and detailed to best accommodate the dense system of low-level services and air distribution on which the Halls' functioning relies - and of the superstructure envelope, which integrated various environmental control strategies with efficient structural solutions.

The direct and expressive use of engineering in the Halls is appropriate to the facility's underlying agricultural theme, and central to the design - and it has the interesting side-effect of putting the engineering itself on display in the exhibition spaces. The Halls quite literally bring engineering to the community through public architecture, in an interesting and articulate way.

Credits

Stakeholders:
Olympic Co-ordination Authority (Principal)
Royal Agricultural Society
Sydney Organising Committee for the Olympic Games

Architect:
Ancher Mortlock Woolley

Consulting engineer:
Ove Arup & Partners Mark Arkinstall, Denis Armstrong, Peter Bailey, Graeme Bardsley-Smith, Adrian Billinghurst, John Burgess, Sid Caganoff, Keith Caldwell, Tristram Carfrae, Alex Chan, Iain Clarke, Brian Cook, Harry Field, Peter Griffiths, Mark Hanson, Richard Hough, Peter Johnson, Roger Kelly, Mike King, Ingo Koernicke, Ian Kroll, Kenneth Ma, Gary Mumford, Franki Poon, Paul Raddatz, Matt Rae, Rodd Staples, Paul Stevenson, Roger Turvey, John Webster

Project manager:
Australia Pacific Projects

Construction manager:
John Holland Construction and Engineering

Main contractor:
Thiess Contractors Pty Ltd

Electrical contractor:
Heyday Electrics

Mechanical contractor:
Triple 'M' Mechanical Services Pty Ltd

Hydraulic contractor:
Map Plumbing Services Pty Ltd

Superstructure contractor:
Alfasi Constructions

Dome lifting contractor:
Austress Freyssinet

Timber supply and fabrication:
Hunter Laminates
Gunns Timber

Laboratory testing programmes:
Forest Research Institute, New Zealand
Queensland University Civil Engineering Department
CSIRO Laboratories, Victoria

Illustrations:
1-3: Patrick Bingham-Hall; © Ancher Mortlock Woolley
4, 5, 8, 13-16: Ove Arup & Partners
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