Osaka Maritime Museum

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

Introduction

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

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

Project history and design team organisation

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

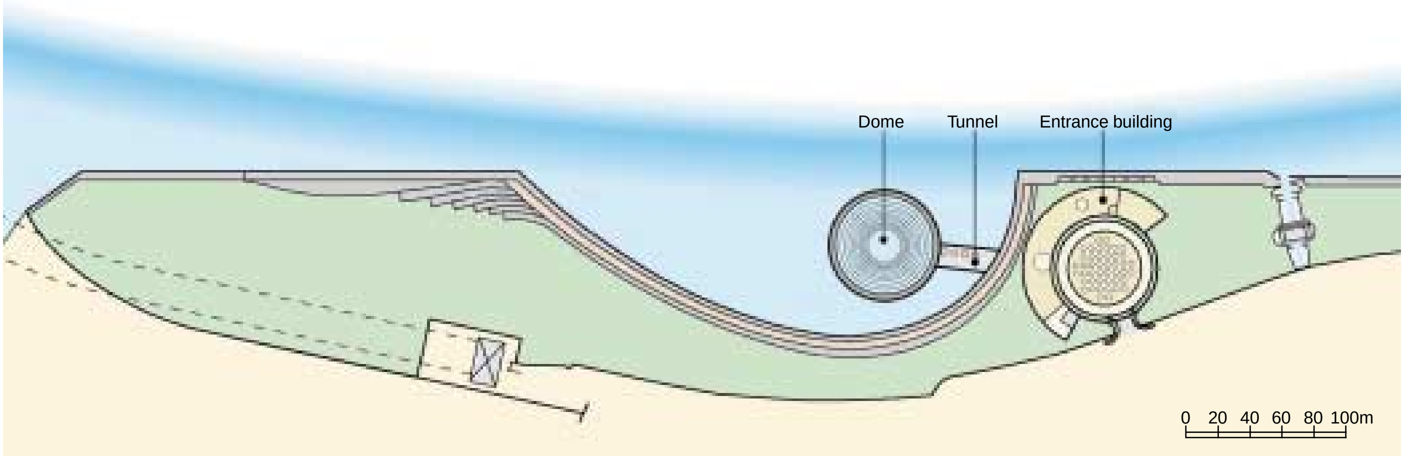
The centre of activity moved to Japan, where the architect set up a project office and Arup Japan provided the engineering services.

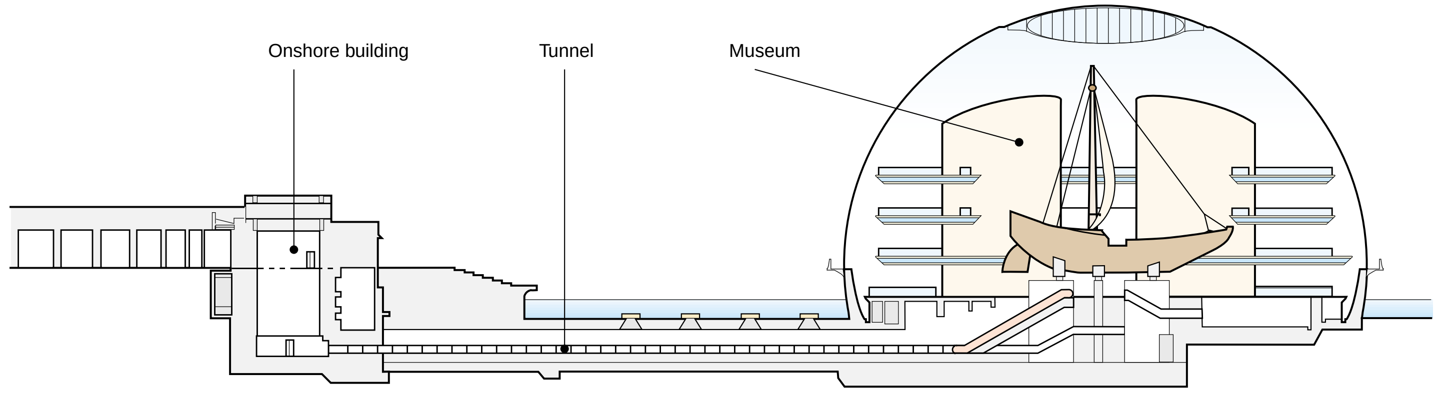
Responsibilities were clearly defined during each phase. Arup's structural commission included the glazed dome and the superstructure of the building inside. Tohata was responsible for the entrance building, the tunnel, the basement of the dome, and the piled foundations of the three buildings.

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

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

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





3.
Section through the Museum.

Structure

The dome

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

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

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

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

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

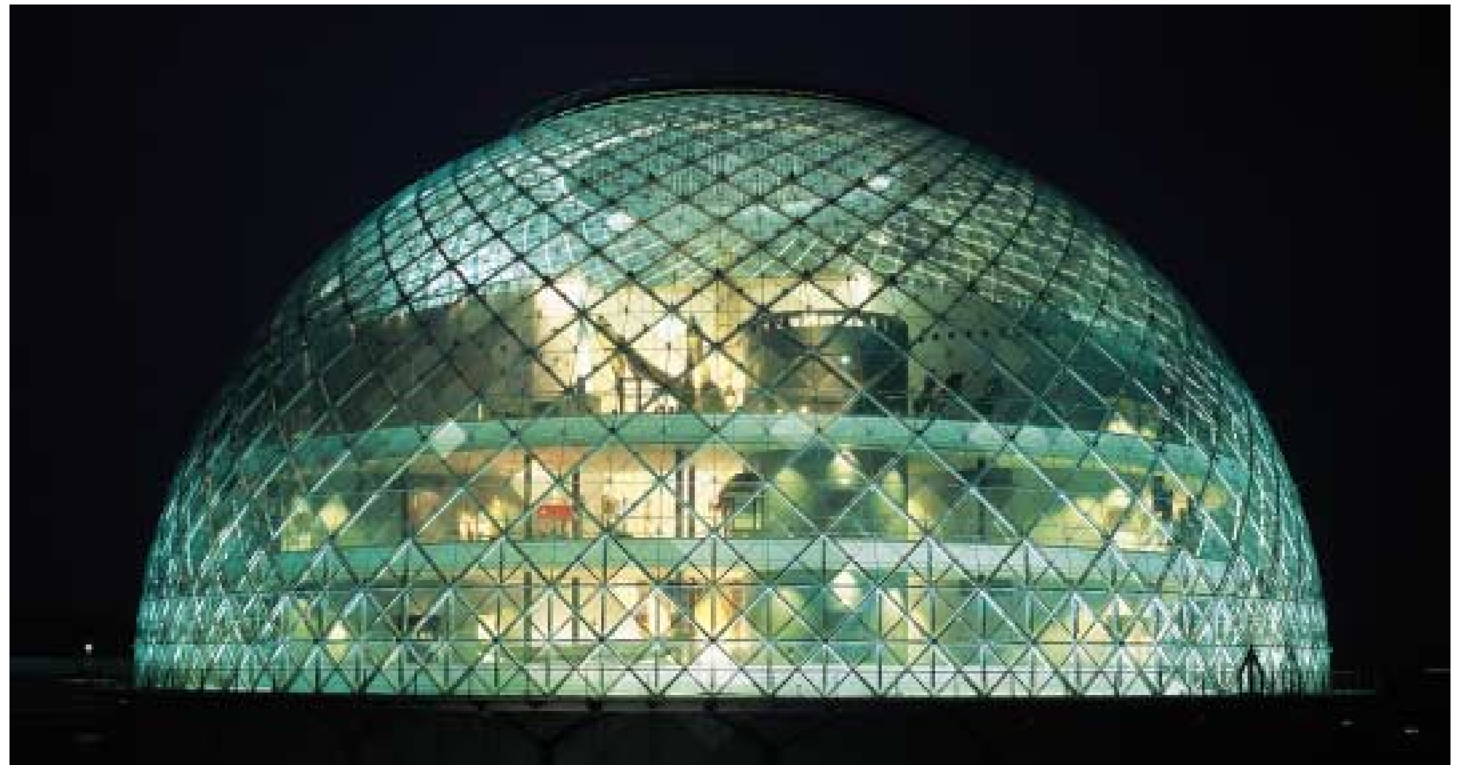
Professor Oda of Osaka City University investigated wave impact loading on the dome structure under typhoon and high tide conditions, using physical experiments and theoretical analysis to determine design wave loads. These indicated that under the most onerous conditions (water level at 500mm below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

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

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

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

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



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

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

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

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

The internal building and its substructure

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

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

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

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

The entrance building and submerged tunnel

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

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

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

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

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

Dome services

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

Services design development

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

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

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

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

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

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

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

Internal design conditions

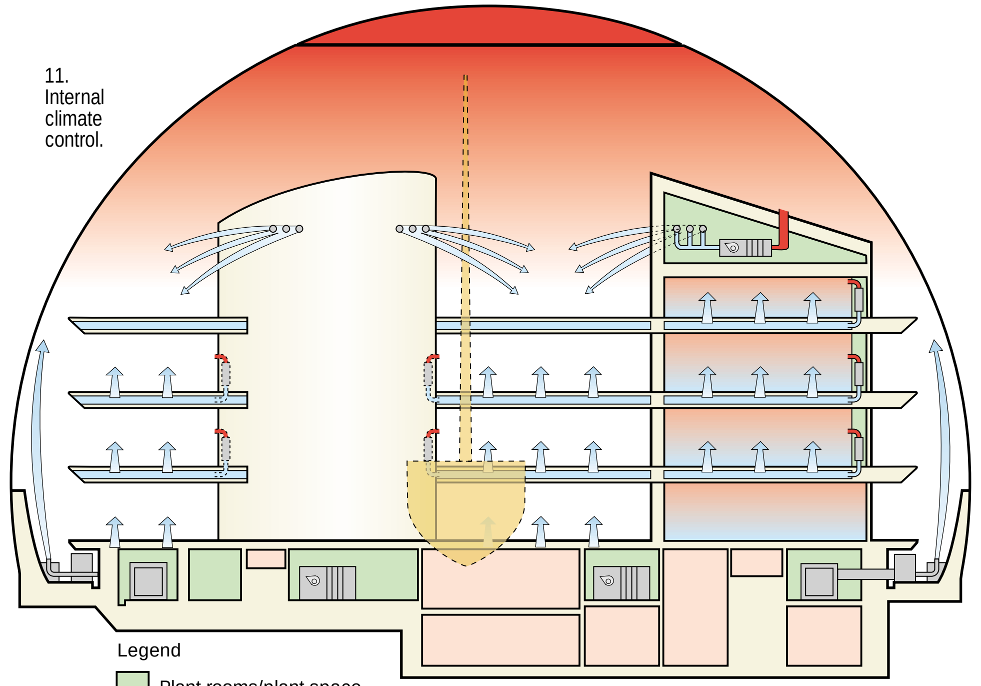
An environment for conservation requires control of relative humidity, temperature, and chemical pollution. High relative humidities allow mould to flourish, while low humidities increase the danger of cracking in materials like wood. Following studies of other Japanese museums, appropriate standards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

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

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

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

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



11.
Internal climate control.

Environmental systems

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

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

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

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

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

Construction

Site work

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

(1) piling and retaining wall structure
(2) excavation within the dome building
(3) construction of mat slab and basement structure
(4) erection of Internal superstructure
(5) boat installation
(6) dome installation
(7) excavation of surrounding area to let in sea water.

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

Dome fabrication and installation

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

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

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

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

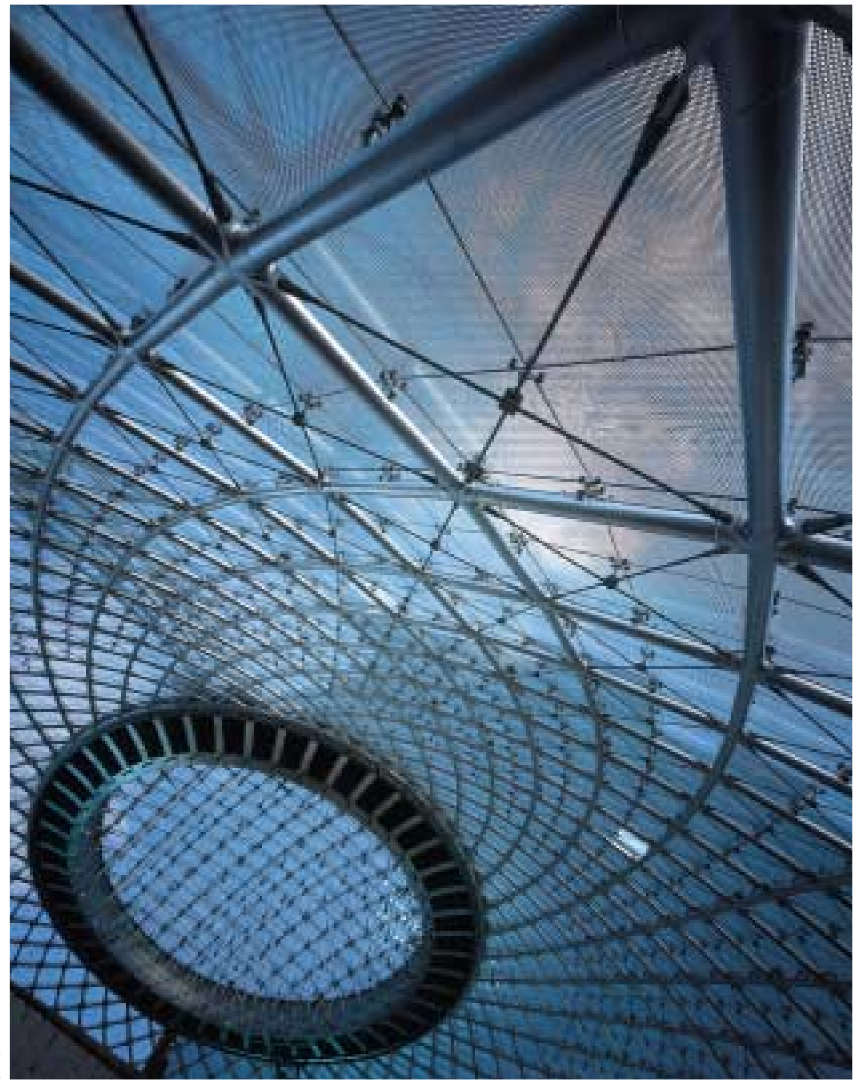
After completing prestressing of the rods, the units were erected onto a temporary central support to form the complete shape. The ring beam was fabricated separately and installed, complete with tensioned cable net and clad with glass and smoke-extract panels, on top of the diagrid units. The remaining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

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

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

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

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



15.
The diagrid shell and the ring beam.

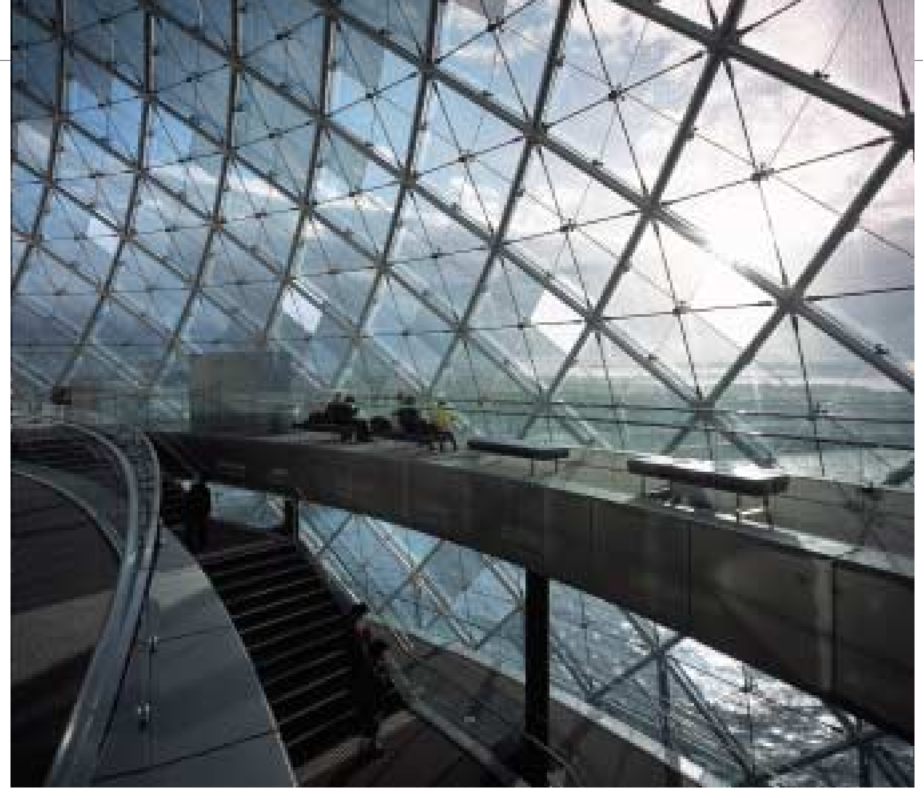
Installation

17. (a) - (f)

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

(b)
Lowering the dome onto the barge.

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



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

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

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

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

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

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

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

Conclusion

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

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

Credits

Client:
Osaka Port and Harbour Bureau

Architect:
Paul Andreu Architects
Japan Design Office

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

Lighting consultant:
Lighting Planners Associates

Building contractor:
Taisei + Fudo
+ Toyo Joint Venture

Mechanical contractor:
Taiki + Seiken
Joint Venture

Electrical contractor:
Toenek + Sanpo
Joint Venture

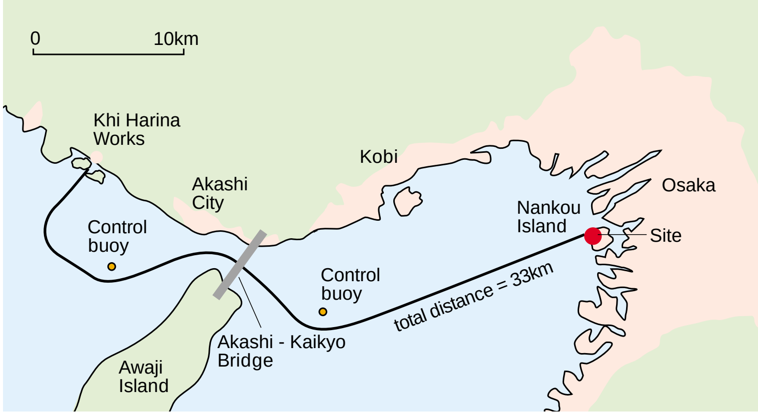
Plumbing contractor:
Daidan + Nissetsu
Joint Venture

Lift contractor:
Mitsubishi
Electric Corporation

Timber boat contractor:
Hitachi Zosen
Corporation

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

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



(d)
The dome lifted from the barge.

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