THE ARUP JOURNAL

1/2002

ARUP

THE ARUP JOURNAL

Vol 37 No 1 (1/2002), Editor: David J Brown
Art Editor and Designer: Desmond Wyeth FCSD; Deputy Editor: Karen Svensson
Editorial: Tel: +44 (0)20 7755 3828 Fax: +44 (0)20 7755 3716

Published by Arup, 13 Fitzroy Street, London W1T 4BQ, UK Tel: +44 (0)20 7636 1531 Fax: +44 (0)20 7580 3924 e-mail: corporate@arup.com **www.arup.com**

Arup is a global organisation of designers. It has a constantly evolving skills base, and works for local and international clients throughout the world.

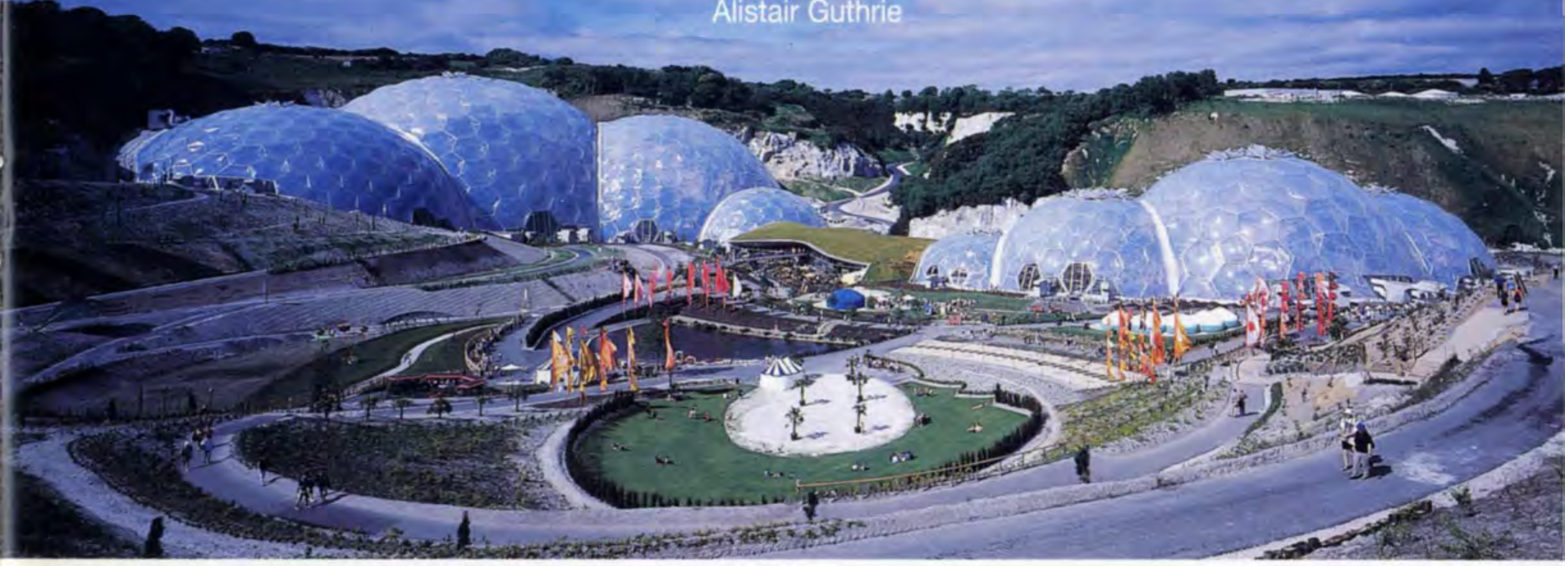
We shape a better world

Front cover: The Eden Project (pp3-12) Photo: Graham Gaunt

Back cover: Miller Park stadium (pp 24-33) Photo: Tim Griffiths

Creating the Eden environment

Chris Barrett
Andy Bascombe
Mark Bostock
Hugh Collis
Geoff Farnham
Alistair Guthrie



1.
Eden: showing the grass-roofed restaurant linking the Humid Tropics Biome (left) with the Warm Temperate Biome (right).

How it began

Early in 1995 Arup was approached by Tim Smit, the renewer of Cornwall's 'Lost Gardens of Heligan', and Jonathan Ball, the Cornish architect, to help them realise their ideas for a spectacular enclosed botanical environment in that relatively remote English county, recreating major global habitats, from desert to tropical, on a huge scale for education and research.

The firm's initial role was to advise on the indoor climate, with Nicholas Grimshaw & Partners as architect and Anthony Hunt as structural engineer. Early statements were made that this was to be 'the biggest greenhouse in the world'.

A hill tip of china clay spoil had first been considered as the site, but the design team soon realised that this would not be stable structurally, and the orientation would not give sufficient sun to heat the spaces.

Instead, a 60m deep china clay pit close to St Austell was chosen. It had significant south-facing rock slopes, and its concealed, almost hidden, approach would add to the drama for visitors.

Then began the complex process of realising the vision, with Arup playing a significant role in many areas. Initially Arup was involved in the design ideas for the project, including the climate control and water management. Later we contributed significantly to the economic assessment and business case, planning, environmental statements, traffic analysis, materials selection, and fire and communications engineering.

Key concepts

Very quickly the initial design ideas developed. The prime driver for the climate and water control was to create the correct environment for growth using minimum water and energy resources. Four key ideas were developed:

- *to wrap the enclosures around the south-facing rock face so maximum use could be made of its heat storage capability*
- *to make the enclosure as efficient as possible, maximising light and sun transmission for plant growth and minimising heat loss through the fabric*

For this, it was decided to use the transparent film material ethylene tetrafluroethylene co-polymer (ETFE): three layers enclosed in a frame and pressurised with clean dry air to form a cushion - ideal for this type of enclosure.

- *to control the indoor climate to match the growing needs of the plants, matching temperature and humidity with available light*

This required close working with the horticulturists, producing a series of graphs of minimum and maximum temperature varying with seasons and time of day.

- *to use, recycle, and treat the rainwater and groundwater at the pit, minimising use of new water from outside.*

The immediate necessity, however, was to produce a viable scheme that could be costed and presented with the business case to the Millennium Commission and other potential funders.

'The story of Eden is a remarkable journey, much of it through uncharted and complicated territory. The breathtaking spectacle now nestling in Cornwall owes as much to those meeting the challenges behind the scenes as it does to the more obvious panache of the architects and plantsmen.

Arup was there every step of the way with unrivalled expertise and innovative thinking in economics and planning, as environmental, fire, and water engineers, and as communications and traffic specialists. As much as anyone they helped make the vision a reality.' - The Eden Project

Business case

From mid-1995 Arup became engaged in identifying the strategy to deliver the Eden Project. This involved working with Eden co-founders Tim Smit and Jonathan Ball to determine the nature, character, and location that would make it bankable and establish the public interest element. On the basis of this, applications could be made to the UK's Millennium Commission for National Lottery monies (£30M), and then to the European Union's Regional Funds (£10M): funds necessary to be put in place as part of the public / private financing of what was going to be an £80M investment in a major visitor, educational, and research facility in a life-expired clay pit. All this was a challenge as far-reaching and as significant as the creativity needed in delivering the appropriate design within the capital spending limits imposed by the business case.

The role of Arup in this upfront service is generously acknowledged in Tim Smit's book *'Eden'*[1].

Project Creation is one of Arup's great skills, but creating and delivering an investment on this scale is no mean feat. Cornwall, however - though far away in the south-west from England's main centres of population, and having few national man-made visitor attractions like the Tower of London or Madame Tussaud's - nonetheless has outstanding natural tourism assets attracting several million visitors annually. While there are no major investments like Alton Towers, the county has a huge tradition of horticulture and gardening - reflecting its benign weather. So it didn't take long to conclude that a visitor destination, of which part would be covered, would be attractive to holiday visitors as well as Cornish residents.

Hence the proposition that such a market would provide the basis on which Tim Smit's ambitions in education and research could be fulfilled.

In his book, Smit described the first business case as 'a good first stab, considering that he [Mark Bostock] was herding cats'. It provided the basis for the development of the Project in terms of its funding, planning, design, and subsequent delivery. The first Eden Project business case was based on creating, as a significant national asset, a destination suitable for broadly 1.5M visitors a year by 2009. In general terms, it balanced various prognoses through several years for visitor ticket receipts plus extra spending, together with anticipated grants from the Millennium Commission amongst others, against different scenarios for the capital cost of the project.

With the business case approved and the Millennium Commission and most other Funders on board, the next challenge was to obtain planning permission. The most sensitive public issue was the high increase in traffic that Eden would bring to the area and its environmental impact on the Cornish countryside. Arup was appointed as planning consultant for traffic consultancy and to prepare the Environmental Statement.

Planning, and environmental impact

Eden's innovative and pioneering approach was evident throughout its planning process. 'Sustainability' was a key theme from the outset, long before its widespread use as a design concept in other schemes.

This was emphasised in the opening of the Environmental Statement – the project aimed 'to provide as far as possible, a sustainable environment maximising the use of renewable energy'. This broad aim meant that a key objective of the design was to accommodate environmental concerns such that adverse effects were appropriately mitigated, with opportunities grasped to maximise local environmental benefits from the scheme.

Eden's environmental effects were analysed and presented in three separate studies – Environmental Statement, Traffic Impact Assessment, and Planning Supporting Statement – that led not only towards obtaining planning permission, but also documented a baseline of environmental factors against which the project could be audited in future to evaluate and confirm its green credentials.

2.
Site plan.

Specialist studies - of water resources, geology, ecology, landscape, noise, air quality, cultural heritage, socio-economics, construction impact, and traffic - were carried out by Arup, and the findings of these were brought together in the Environmental Statement in December 1996. The proposed design fully addressed and mitigated the project's adverse impacts and was set to achieve net beneficial environmental effects overall.

Eden's key local benefit was its anticipated boost to the local economy. It was expected that the project would lead to the creation of around 1000 man years of construction work over a three and a half year period, employment opportunities for local businesses during the construction phase, and approximately 290 full-time or full-time equivalent staff on opening. Further revenue was expected to be generated by new visitors to Devon and Cornwall, attracted as a result of Eden's existence, achieving literally incalculable benefits through additional expenditure and the creation of new jobs in the wider economy.

In the years since the environmental case was made, Arup has maintained a close working relationship with Eden and continue to provide specialist environmental services relative to specific ongoing projects as appropriate.

3.
The grass-roofed restaurant.

4 below:
Restaurant interior.

Eden facts & figures

Project site: 50ha
Area of pit: 15ha
Project value: £80M

- 85 000 tonnes of soil manufactured from clay risings
- 1.8M tonnes of earth moved to reshape the pit
- 43M litres of water pumped off site during in December - February of the first winter on site

Humid Tropics Biome

Area: 1.5ha; *Volume:* 330 110m^3;
Maximum height: 55m;
Maximum width: 110m; *Length:* 240m

Warm Temperate Biome

Area: 0.65ha; *Volume:* 85 620m^3;
Maximum height: 35m;
Maximum width: 65m; *Length:* 135m

Awards

British Construction Industry Awards 2001: Major Project Award: Winner

The Inaugural Fire Safety Engineering Design Award

Hot Dip Galvanising Awards 2001: Overall Winner

RIBA South West Regional Award Winner

Concrete Society Building Award: Certificate of Excellence

American Institute of Architects Excellence in Design: Architecture: Joint Winner

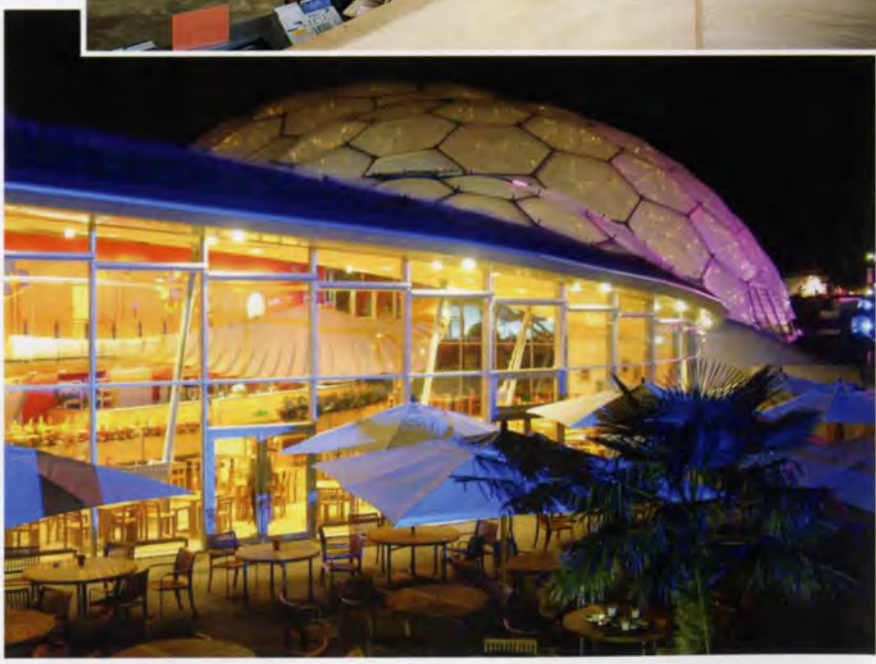
BCSA Structural Steel Design Awards: Architecture: Joint Winner

Business Commitment to the Environment Awards: Winner

IPR Cream Awards: Best Consumer Campaign: Winner

Accountancy Age Awards: Winner

British Institute of Architectural Technologists: Technical Excellence: First Prize



5.
The restaurant at night, lit up for the 'Last Night of the Proms' 2001.

Traffic

A particular environmental challenge was traffic impact, both of access and transport to the site during construction, and from visitors after Eden opened. With a projected target of 1M visitors per year from 2002 onwards, clearly substantial new traffic would be generated on the existing roads. Detailed assessments of the necessary road improvements, and the environmental impact of these on local resources, were carried out. Again, a key objective was to provide the necessary improvements - including identification of appropriate access routes to the site from the local road network - whilst minimising the environmental impact in accordance with the project's overall design philosophy. Arup identified the optimal solution now in place.

The chosen site was not close to main roads, and could not be served easily by rail. In transport terms it was much more difficult than the earlier hilltop site. This had been close to both the A30, the main access road to and through Cornwall, and the Par to Newquay railway line. The chosen site, by contrast, is about 10km south of the A30, whilst the nearest principal road, the A390, is about 1.5km further south. This single carriageway, running through many small towns and villages is thus sensitive to increased traffic flows.

The first analysis was to determine how much traffic would visit the site, when it would come, and from which directions. The volume was assessed based on an initial 1M visitors pa, compared with the 800 000 figure used in the business case, as the access arrangements had to be able to cope if visitor numbers were higher than predicted.

To assess daily variations, statistics for other visitor attractions were examined, the Lost Gardens of Heligan being the most relevant. Visitor attractions vary, with 'peak days' between 1.0% and 1.3% of the annual total. As Eden would be less weather-dependent than most, the lower figure was chosen, and 10 000 visitors assumed on the peak day (Bank Holiday Monday). On normal weekdays, arrivals would be after the local morning peak period, and departures mainly before the evening peak, so Eden was not expected to cause significant congestion on the main road network. The arrival and departure profiles of a Cornish leisure park were used as a guide. With about 80% of visitors expected to arrive by car, and an average of 2.5 to 3 visitors per car, some 3000 cars were anticipated on peak day. The remainder would mainly come by coach, although bus, cycle, and pedestrian access was also planned. To aid understanding, comparisons were made with St Austell's Asda food superstore, which generated about 50% more car trips on a normal Friday than Eden would on Bank Holiday Monday, and about three times as many in a year.

To determine where visitors would come from, Arup examined Tourist Board figures for how many stay in each part of Devon and Cornwall, and for distribution of traffic in proportion to use of tourist accommodation. This showed that a good route from the A30 could best accommodate most trips.

Next to be looked at were the road options.

Clearly the existing lanes were inadequate, as they would bring unacceptable traffic into nearby villages and hamlets, and were too narrow for the many buses and coaches expected. So various options for new access were examined. Widening the local lanes, with new sections to avoid narrow or built-up locations, proved unsatisfactory. 'Park and ride' was also rejected, as it would only relocate the traffic pressures, make visitor access more difficult, and cost more. After examining several options it was agreed with the County Council that a new road should be constructed from the A391 in the west; although most visitors overall would be coming from the east, this gave the best route from the A30, via the A391 St Austell link road.

Much of the new road would follow the line of a quarry haul route owned by English China Clays plc. From that route to the site there were two options, one to widen existing roads and the other to create a new road through open fields. The latter was chosen; it was easier to negotiate purchase of the land required, and fewer hedgerows of nature conservation value would be disturbed.

6 above:
Location plan.

In terms of environmental impact, this access road was far more significant than Eden itself. The Project would be invisible beyond the boundary of its quarry location, which would also contain any noise generated, whilst careful design of water recycling and treatment, and provision of balance for stormwater in the lake, satisfied the Environment Agency about water pollution and flooding concerns. And the quarry itself had no ecological interest by virtue of its previous use. The new road, however, posed questions. As parts of English China Clays' landholding had not been cultivated, and were held for future china clay extraction, there were some concerns about disturbance to flora. The route, therefore, and the site access, were aligned to minimise impact on ancient hedgerows, whilst the new road's boundaries were designed with earth banks to develop new habitats for hedge species and to blend with the existing field and road boundaries. The road, indeed, gave considerable environmental improvements, as land previously scarred by mineral extraction was regenerated, with drainage and planting undertaken to ensure that any damage to the natural environment was more than outweighed by positive habitat creation.

Though the new road protects most nearby communities from additional traffic, the team recognised that traffic would increase in other places, and the Eden Trust made funds available to the County Council to mitigate adverse impacts. Encouragement of non-car travel modes was integral to the transport planning.

Local bus, coach, and train operators were keen to participate, and Eden guaranteed, as a planning obligation, to provide an approximately hourly bus service to St Austell railway and bus station to connect with mainline trains. Bus services for staff outside opening hours were also provided.

7 below:
Eden is invisible beyond the boundary of its quarry location.

Within the site, footpaths, cycle routes and bridleways have been established outside the area for which admission is charged, to improve the connectivity of these networks, and a contribution agreed to the County Council to assist in funding these routes outside Eden's land ownership.

Access for coach operators is encouraged through direct marketing, group travel discounts, and provision of facilities for coach drivers - all building on the successful Heligan experience. Also, two other group travel prospects, it is hoped, will increase the numbers of visitors arriving by coach, and benefit Cornwall's tourism economy. Newquay Airport can handle large passenger aircraft, and so can receive charter tours with a particular interest in gardening and botany. Eden's international profile is the catalyst for attracting such tours, which could include other botanical attractions in Cornwall. Cornwall is also well placed to accommodate cruise liner calls, on the way between Spain or Portugal and London or Dover. Eden - which would be attractive to many choosing cruise holidays - makes it possible to market Cornwall to cruise operators.

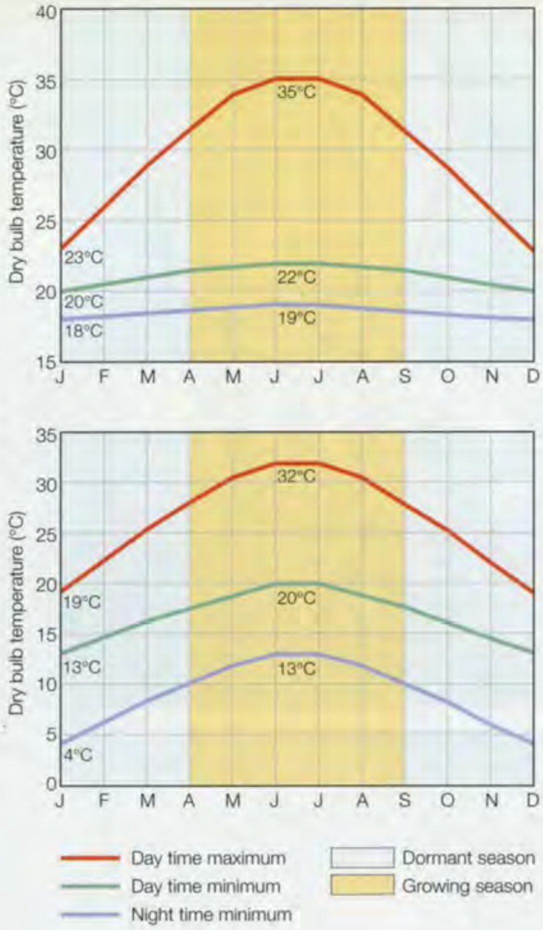
Imaginative thinking on transport opportunities was part of the project planning.

8.
Air outlets in the Warm Temperate Biome.

9.
Interior of Humid Tropics Biome.

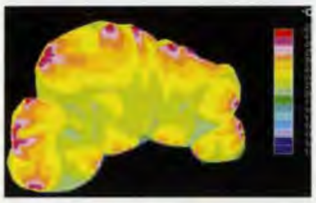
a)

b)

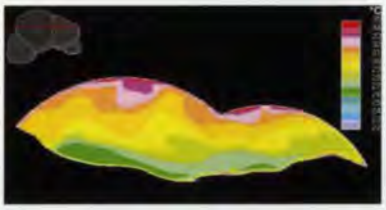


10 a) & b).
Temperature criteria:
a) Humid Tropics Biome
b) Warm Temperature Biome.

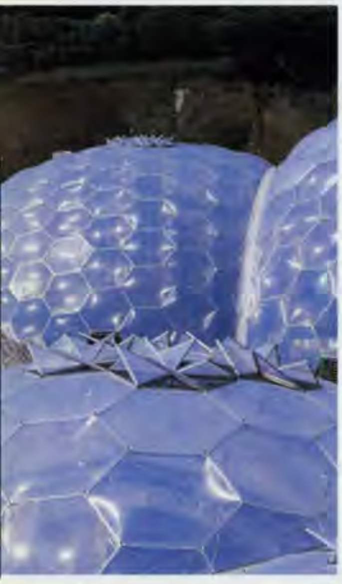
12.
Summer air flow patterns in the Humid Tropics Biome.



13.
Winter warm air distribution in the Humid Tropics Biome.



14.
Summer warm air distribution in the Humid Tropics Biome.



11.
Air outlets open in the Warm Temperate Biome (foreground) and Humid Tropics Biome (rear).

The Biomes

The environmental and transport plans were now in place, but the funders were not prepared to proceed with such a risky and innovatory project without a commitment to a firm price from a contractor. After a tender process involving protracted negotiations, many design changes including the deletion of a third (desert) habitat and the complete redesign of the visitor centre and link building between the habitats, and several intensive value-engineering exercises, a joint venture between Sir Robert McAlpine Ltd and Alfred McAlpine plc was appointed to construct the project. The design team was novated to this consortium and the 'real design' began, three years after the first discussions.

Most of the original concepts had survived the planning and financial hurdles. The scheme would comprise a series of Buckminster Fuller-type 'Biomes', constructed from hexagonal panels of tubular steel joined with Mero systems.

This geometry allows the domes to merge into each other and to follow the uneven contours of the edge of the clay pit. Where the domes merge together, there is a supporting arch of steel. The structures are founded on a concrete ringbeam which follows the pit contours. Considerable work was required by the geotechnical engineers and contractors to stabilise the rock faces and to deal with the numerous underground springs that surfaced during construction.

The Biome environment

The rock faces are an important part of the climate control strategy in the Biomes. When the sun shines on the enclosure it heats both the space directly and the rock behind it. This creates a natural collection and storage system, reducing daytime overheating but providing heat back into the space from the rock as the enclosure cools overnight. The critical factor in making the most of this is the Biome skin's performance.

ETFE has a light transmission for a single sheet of around 95%, depending upon its thickness. It is light in weight and its ability to cover hexagons up to 11m across means that the structural obstructions are minimised. Maximising the light is essential if as near natural as possible growth conditions are to be achieved, but with three layers of material and this structure the light transmission compares favourably with that of a normal greenhouse.

The triple layers of the ETFE have a combined U value of 1.4 W/(m^2 °K) - better than double-glazing. This reduces the heat loss at night, and in winter improves the performance of the rock storage, reducing the amount of additional heating energy required. It has the added advantage of considerably reducing the length of time condensation occurs on the inside of the enclosure.

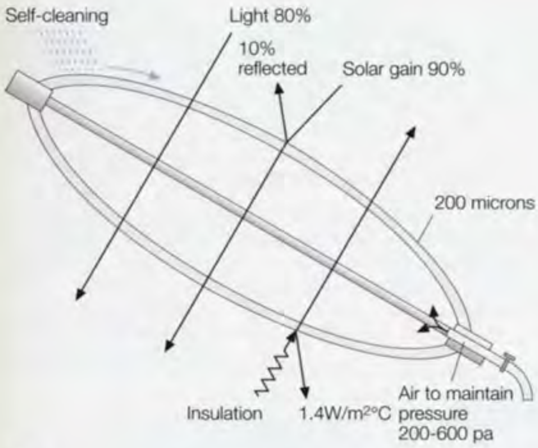
With this clear strategy for the enclosure, the horticultural team was consulted to find out the environmental conditions required in each Biome. What were the optimum highest and lowest temperature and humidity for the plants, and what were the maximum and minimum they could withstand? How did these figures vary between the growing and dormant seasons? How much day-to-night variation was acceptable? All this discussion resulted in a temperature and humidity chart for each Biome showing the acceptable variations. With these decisions made and the geometry of the enclosures fixed, a large computer model was built to predict the thermal performance of the spaces, taking into account the changing weather and the requirements of the plants, to determine how the maximum natural energy could be captured and the heating bill kept to a minimum. Several schemes were considered early in the design for the additional heat. These ranged from combined-heat-and-power (CHP), to active solar collectors, to biomass boilers. In the end, however, funding considerations drove the decision towards gas.

When heating is needed, large fans blow jets of warm air up to 50m across the space from the edge of the Biomes. These jets also blow upwards across the internal surfaces, keeping them warm and inducing large air circulation currents throughout to maintain the temperature. There is no other heating in the space, thus giving maximum flexibility for planting. The fans are supplied with hot water from Eden's energy centre by an underground heating main.

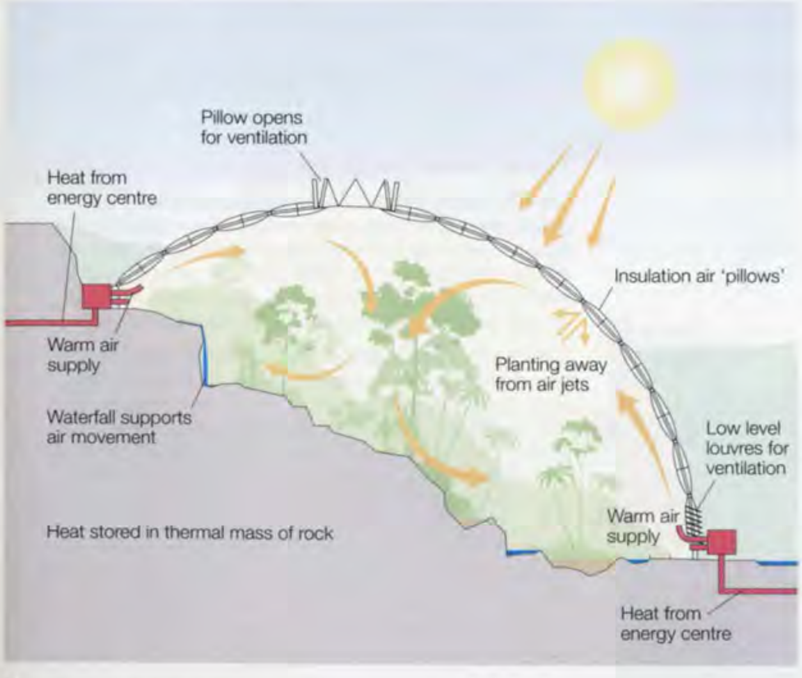
To engineer correct positions for the jets within the Biomes' irregular shapes, a computer analysis predicted and visualised the airflows and air temperatures throughout the space. Computational fluid dynamics (CFD) produced three-dimensional representations of the speed and direction of the air movement, and the temperature distribution. With this, the air jets and fans were positioned and adjusted for direction and speed to give even temperature distribution and to check that the airflow would give some movement to the plants without creating undue draughts.

The team also had to consider what would happen in summer when strong sun could make the enclosures overheat. To neutralise this, automatically controlled openings at the top and bottom of the Biomes open in stages, letting the hot air out at the top and drawing replacement cooler air in at the bottom. The areas and locations for these were designed using the CFD model in summer mode. Plants give out moisture as they grow and the ventilation system is controlled to reduce this moisture build-up if it gets too high. On the other hand, in the Humid Tropics Biome, it is often necessary to increase the humidity by fine spray misters.

The automatic control has to ensure that all these systems work together to achieve the right temperature and humidity. Unlike normal air-conditioned buildings these conditions vary continually. For example, when there is no sun in winter the temperature is allowed to drop to a daytime minimum before the heating jets are turned on. Conversely, when the sun comes out the temperature is allowed to rise, storing heat in the rockface until the maximum temperature for the season is reached, and then the ventilation openings are activated. Since the relative humidity depends on the temperature, the misters need to respond to changing conditions to keep the humidity within the right band. All this is to give the best conditions to the plants with minimum energy consumption.



15.
Performance of an ETFE cushion.

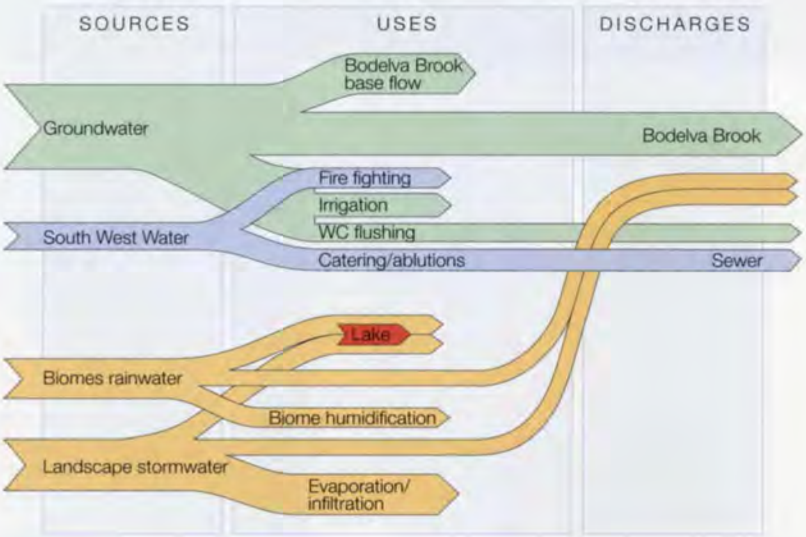


16.
Section through typical biome showing environmental strategy.

Water strategy

Water conservation is a big issue at Eden. The clay pit has copious quantities of water derived from rainfall on the pit area and from groundwater and natural spring sources. All these are more than adequate for all the Project's horticultural requirements including irrigation and humidification, with a sufficient margin to service the fire hydrant system for small fires and for flushing toilets and urinals. The only water not provided from natural on-site sources is the potable supply for drinking, catering and ablutions.

A water strategy was devised with the civil engineers for a collection and disposal system, plus collection and distribution systems for 're-used' water. The water extracted from groundwater and springs is collected and stored in a large underground tank before being pumped into the water distribution system via a filtration and ultraviolet disinfection plant; water for toilet and urinal flushing is subjected to secondary disinfection by silver ionisation treatment. Excess groundwater overflows into the site surface water disposal system. The re-used water mains network also supplies fire hydrants throughout the site, though these can also be served from the local mains water supply via onsite fire pumps in the event of a groundwater shortage or a major fire.



17.
Water strategy.

Budget-impelled value engineering exercises necessitated combining the grey water and fire mains into a single combined system. Pumps at the bottom of the pit provide the grey water and normal fire supply, whilst emergency fire pumps at the top supply the requirements for a major fire. The 60m height difference between the top and bottom of the pit made pressure control of the ring main network an important factor. A duplex design was adopted with one ring main serving the top areas and another the lower regions; pressure-reducing valves maintain the design pressures in each of the main areas and the Humid Tropical and Warm Temperate Biomes.

The re-use of rainwater is of particular interest.

The horticulturists wanted the purest possible water to be used for humidification in the Humid Tropical Biome, water purity being very important to prevent deposition of minerals on plant surfaces. The best source for this water was considered to be rain from the surface run-off of the Biomes. The rainwater is collected at the base of each Biome using a proprietary enclosed channel drainage system linked to hoppers at the base of each of the Biome main gutters. These, due to their impressive scale, contribute very effectively to the collection system.

Water strategy text concludes at foot of page 11 ▶

Fire engineering strategy

Andy Passingham

18.
Interior of Humid Tropics Biome, showing distances involved for escape in case of fire.

From the outset, it was clear that a prescriptive code approach would be of limited value. This would have classified the building as an assembly type occupancy, but if Eden had been designed to fit the recommendations of assembly codes (as in *Approved Document B* and *BS5588: Part 6*), the design team would have been faced with trying to make the building conform to guidance and limitations derived from safety measures intended for theatres, stadia, and other more conventional public buildings. The relevance of this guidance was clearly limited for this project – there was no 'rule book' to follow.

It was therefore proposed that the fire safety be based on a 'first principles' approach, or performance-based design. Early in the process, this was discussed and agreed with the client and the Cornish local authorities. This allowed Arup to continue the design with the help and support of the Restormel Building Control and the Fire Service.

The fire hazards in a building like this are very different from those typically encountered in conventional buildings. The vegetation clearly constitutes a fire load, potentially an extremely large one, so at an early stage the potential for a forest fire type scenario was discussed.

The team carried out a qualitative hazard analysis of the risk, in terms of frequency and consequences, of a vegetation fire in the building, but this showed such a fire to be of sufficiently low probability that it was an impractical design parameter.

The examination of fire loading therefore turned to items other than the vegetation. In both Biomes, huts known as 'shambas' are provided as information points for visitors. These are built of timber, with thatched roofs, and also have electrical power. Scenarios involving a fire in a shamba were therefore developed as the basis for the fire safety design.

Large visitor populations are expected in a high profile building like Eden, and their safe and efficient evacuation is a key part of the fire strategy. The circulation - and hence evacuation - routes are far from conventional; visitors walk around the Biomes on winding pathways linked to exits around the perimeter, and as the Biomes are cut into the quarry side, pathway elevations vary considerably. A major challenge for Arup was to address the scale of the building, reflected in the length of the travel routes. If code escape distance recommendations were to be met, then escape from the upper parts of the Biomes would need tunnels cut through the side of the quarry, an extremely expensive solution. Also, these tunnels would probably need to be pressurised, as they would be at the upper levels of the Biomes near potential smoke layers.

Arup therefore proposed that evacuation be based on time taken rather than distance travelled, so that in the event of a fire the occupants would walk extended distances to lower level exits rather than use exits at the top of the Biomes. This was also preferred as it encouraged the population to move away from the upper levels where smoke would gather. It was considered preferable for occupants to be walking down, away from the smoke layer, rather than queuing at a high level tunnel entrance where they would be more likely to be affected by smoke. While this would result in evacuation distances of up to 150m, these were considered acceptable due to the overall low level of hazard and large size of the space.

To justify this proposed strategy, combined smoke and evacuation modelling was carried out with SIMULEX software. This allows the actual geometry from the architectural drawing plans to be dynamically modelled, plus the examination of various scenarios such as the effect on evacuation times of discounting various exits.

Due to the structure's unique geometry, conventional smoke modelling software packages were unsuitable for calculating the rate of smoke fill in the Biome - these assume rectangular 'box' enclosures. Project-specific spreadsheets were therefore developed which allowed for the geometry of the Biomes, using the 3D model of the structure developed by Nicholas Grimshaw & Partners.

From the model, it was possible to determine accurately the cross-sectional plan area of the Biome at various heights, and hence assess smoke filling rates using design fire scenarios agreed with the local authorities.

The evacuation modelling showed that the Biomes would be cleared in five to six minutes, whilst the smoke modelling indicated that a smoke layer would not descend to levels where it would impede evacuation for 15-25 minutes (depending on the fire scenario). The team therefore concluded that the escape distances could be safely extended and that evacuation conditions would be acceptable under the conservative scenarios studied.

Many fire safety systems conventionally associated with public assembly spaces were unsuitable, particularly in the Biomes. Detection methods including optical and aspirated smoke detection were found to be ineffective, due to the potential for smoke stratification to delay detection at high level, and plants obscuring optical detection sight lines.

Although the Eden buildings are essentially low fire hazard spaces, the fire safety strategy had to be developed from a common sense, first principles point of view. The recognition that there was little relevant guidance for the project, and that adherence to conventional codes would result in unnecessary, costly, and ineffective measures, unlocked the design process. Close collaboration with Nicholas Grimshaw & Partners, Restormel Building Control and the Fire Service, allowed each team member to fully participate in developing the design and clearly understand the thought processes and reasoning behind the proposed strategy.

The result is a simple, robust, and cost-effective strategy that provides a high level of fire safety for the occupants and users of the Eden Project.

19.
Misting in the Humid Tropics Biome.

Communications

Jim Read

21st century visitor expectations are such that the facilities at Eden would not be commercially attractive without the application of multi-media technology to provide information and interaction throughout the venue.

At the same time, Internet-based services are central to attracting, informing, and educating potential visitors before they arrive at the site and as a means of maintaining and updating interest in the future.

IT users in Eden

The operator

Management:
Project Director, Finance Director, Operations Director, Marketing Director, Corporate Affairs Director, facilities management, day visitor catering, Education and Interpretation Director, HR Director, Eden Botanical Institute (EBI) Director, Living Collection Director, facilities management

Administration:
Accounts staff, sales staff, Living Collection, education staff, EBI staff, hot desks

Support staff:
Retail and catering, ticketing, guide, and Information points, gardening and horticulture, shops, restaurant, café, technical support, cleaning

Visitors

Tourists, locals, families, day trippers, specialists and enthusiasts, education and school groups, the virtual visitor

Academics

Students and technicians, professors, teachers and lecturers, guests and other research establishments, club members and associations

Miscellaneous users

Media, corporate partners, conferences, special events of local, national or international importance

Arup was asked to write a communications masterplan to assess the impact of information and communications technology (ICT) on the project, and to analyse requirements for telecommunications infrastructure and the systems and applications to support research activities, the Visitor Centre, administration tasks, and sales and marketing activities, now and in the future. A key feature was to propose a site-wide ICT infrastructure that would accommodate requirements for equipment and cabling space, identify a suitable cabling architecture, and give requirements for IT networks to support all technology applications.

Another aspect explored in the Masterplan was the opportunity for using new media techniques including e-commerce for ticketing and retail applications. Perhaps the most exciting idea was the development of a 'Virtual Eden' that would allow distribution of digital content from the Eden Project, thus opening up the Eden experience to the virtual visitor.

The project has also been keen to attract technology sponsors and partners, and Arup Communications helped evaluate the marketplace to bring on board partners to create and implement the range of systems and electronic tools necessary for the site's operation.

All the site-based systems proposed in the masterplan have been implemented, including the extensive duct network for telecommunications cabling - designed from the outset to cater for the future expansion of Eden.

Some of the multi-media systems, and the proposals for the Virtual Eden, have not yet been realised due to budget constraints, but at the time of writing discussions are ongoing with the creative director and marketing team about how, through these leading edge technologies, Eden can be even more successful in the future.

20.
Typical rainwater collection point.

▼ *Water strategy conclusion:*

After collection, the rainwater flows by gravity through a Hydropad settlement unit to capture settleable solids, floatables, and oils from the run-off. Following settlement, the water is discharged to underground buffer tanks before being pumped via fine filters into three existing concrete china clay slurry tanks with a combined capacity of 1.67M litres. These tanks were extensively refurbished and covered, and provide enough storage capacity to cover the maximum calculated drought period for the area of eight weeks.

The tanks are at the top of the pit and provide sufficient static head to pressurise the distribution system serving the Humid Tropical Biome without recourse to additional pumping. The distribution system serves this Biome, where it is used to maintain the required humidity via the high-pressure misting system.

The bacterial cleanliness of the re-used rainwater is also vitally important. It is being misted into atmosphere and so must not contain anything that would constitute a health hazard. To ensure that the misting water contains no bacteria, it is treated in the bulk storage tanks by silver ionisation disinfection.

This system is configured to treat the stored water after initial collection to ensure that it remains uncontaminated, and again before final distribution. The silver ion levels are monitored during both these processes.

Eden's total projected annual water requirement was calculated in round figures at approximately 62M litres. However, of that, only 13M litres (around 21%) is sourced from the mains water supply. 37M litres of groundwater is used for irrigation and toilet flushing and 12M litres of re-used rainwater for humidification.

21.
Bottom ventilation opening with climate control unit on left, partially obscured by vegetation.

The Eden Experience

Eden has been lauded by the press worldwide as the success story of the Millennium projects. Following the 'soft' opening of the Visitor Centre on 15 May 2000, 0.5M people visited the project to see the ongoing construction. Since the main opening on 14 March 2001, visitor numbers soared above all predictions and the facilities have been hard pressed to cope. However, the conditions in the Biomes have been met and the plants have thrived.

Energy consumption is less than predicted, demonstrating the efficiency with which the solar energy is captured and maintained in the space. Eden is clearly one of the most successful Millennium Lottery-funded projects in the UK. In its first 12 months of operation (year ending 31 March 2002), it is forecast to reach 2M visitors, out-performing Arup's initial business case and far in excess of the plans finally adopted!

Reference

(1) SMIT, T. Eden. Bantam Press, 2001.

21.
Inside the Humid Tropics Biome.

Credits

Client:
Eden Project Ltd.

Project manager:
Davis Langdon Management

Quantity surveyor:
Davis Langdon and Everest

Architect:
Nicholas Grimshaw and Partners Ltd

Planning supervisor:
Aspen Burrow Crocker

Economic, environmental, building services, transportation, fire, and communications consultant:
Arup Chris Barrett, Bob Barton, Andy Bascombe, Phil Bellinger, Mark Bostock, Michael Bull, Mark Busuttil, Hugh Collis, Gavin Davies, Brian de Mellor, Rob Evison, Geoff Farnham, Diane Gilchrist, Jake Goh, Alistair Guthrie, Michael Holmes, Alan Iles, Paul Lander, Leroy Le Lacheur, Andrew Long, David Mills, Tony Moore, Richard Owen, Mike Pang, John Papworth, Andy Passingham, Barbara Payne, Howard Porter, John Pullen, Jim Read, Dorothee Richter, Dermot Scanlon, Clare Smith, Mark Smith, Lorna Walker, Paul Whitehouse, Colin Whyte, Liz Wood-Griffiths, Darren Woolf, Rainer Zimmann

Structural engineer:
Anthony Hunt Associates

Project supervisor:
Land Architects Ltd

Landscape architects:
Land Use Consultants

Constructor:
Sir Robert McAlpine Ltd / Alfred McAlpine plc

MEP sub-contractor:
MJN Colston Ltd

Biome sub-contractor:
Mero (UK) plc

Foil sub-contractor:
Vector Special Projects

Plant physiology:
Silsoe Research Institute

Horticultural Management System:
VanVliet Automation Ltd

Illustrations:
1, 3, 4, 7-9, 11, 20-22: © Arup / Graham Gaunt
2: Penny Rees & Sean McDermott
5: Alistair Guthrie
6: Steve Capper & Sean McDermott
10, 15-17: Martin Hall
12-14: Arup
18: Andy Passingham
19: NGP / Perry Hooper

BT 'Workstyle', Brentwood, Essex

Alastair Hughes
Declan O'Carroll
Eugene Uys

1 (above).
Main entrance from the main gate.

Introduction

In January 1997, BT Property appointed Arup Associates to design their new offices in Brentwood, Essex, England, as one of the coming generation of 'Workstyle' buildings. BT's aspiration is that these will provide social hubs for their people to meet and exchange ideas, with all the facilities needed by the knowledge-based workers of the future. The buildings are linked to BT's Corporate Network, enabling individuals to work remotely from wherever is most efficient at the time.

BT wanted a comfortable, energy-efficient environment to stimulate and motivate the building's users, not least by giving them control over their own environment, and for Arup Associates to achieve this required a holistic approach to the design of the entire office environment. Integration of the following issues was fundamental to the building's success:

- a coherent and clear office layout
- good air supply, controlled by the occupants
- good lighting, from both daylight and artificial sources
- a feeling of spaciousness, with views out of the building and contact with nature
- a stimulating environment to promote interaction between occupants.

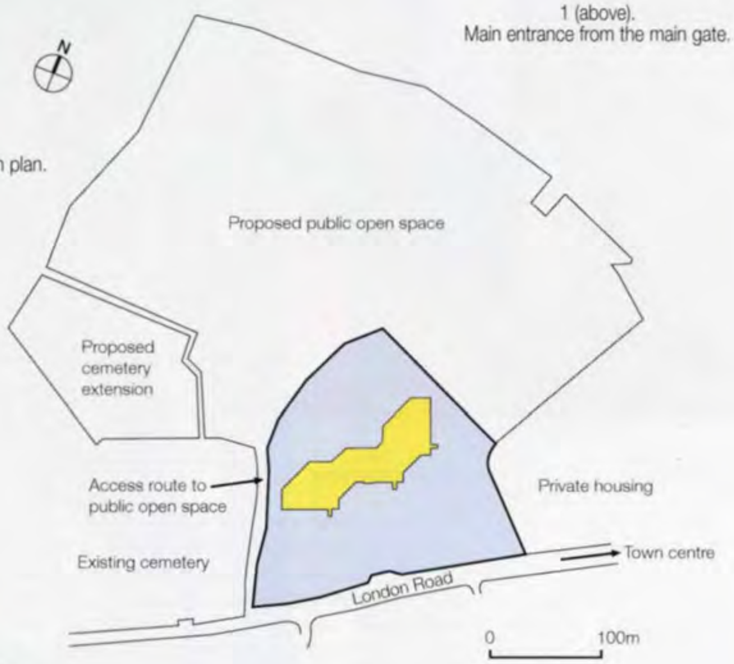
The Brentwood building is based on a briefing document prepared by Stanhope plc, BT's consultant developer, which adapted the generic 'Workstyle' brief both to the site and to the wider property market. The building is a unique and bespoke home for BT, but also provides commercial flexibility with potential subdivision of tenancies and a future proofing of servicing strategies that satisfies a wide range of institutional standards, to give BT a viable exit strategy.

The site

The redundant St Faith's Hospital occupied 22ha off London Road, Brentwood, on the western edge of the town centre 3km from Junction 28 of the M25 London orbital motorway. Acquired by BT, the site now divides into the building area itself occupied by BT (5.7ha), open green belt land to the north (14.7ha) leased to Brentwood Borough Council and accessible to the public, and an area reserved for a future extension of the adjoining cemetery (1.6ha). Bounded by open meadowland to the north, the cemetery to the west, London Road to the south and private housing to the east, the site generally slopes away from Brentwood town centre. It has been re-contoured to provide a platform for the new building and car parks, as well as to screen the parking from adjoining properties and views into the site.

The varied ground conditions and high water table required piled foundations. Continuous flight auger piles were chosen rather than driven precast displacement piles for noise reasons, whilst not incurring a significant cost penalty. High rates of productivity were achieved during the installation of 468 piles with a single rig.

2.
Location plan.



3.
Site plan.

4.
Reception area.

Town planning

The new building is south of an existing line of trees running southwest / northeast across the site. This allows it to sit with the landscape and not dominate the neighbouring open countryside. Brentwood Borough Council required it to be no higher than the hospital had been and to sit within the footprint of its buildings. As well as maintaining existing trees and shrub planting on the site, particularly along the London Road edge, they also insisted on conserving the maximum number of Tree Preservation Order protected trees. The major landscaping challenge was to accommodate the 800 cars required by the client's brief within these demanding conditions. The finest trees were retained and allowed to interrupt the grain of the parking where this was unavoidable, with a generous number of semi-mature specimens transplanted to complement them. Arup Associates developed the concept with landscape architects Charles Funke Associates to establish an impression of 'cars in a landscape' as opposed to 'trees in a car park'. To the same end, substantial belts of planting screen the cores at the boundaries with the main road and neighbouring properties. Significant cut-and-fill operations were also undertaken to minimise the impact of the parking.

Building anatomy

The building contains three floors of offices, totalling around 15 000m^2 net including roof-level plant, and is split into three zones. A restaurant space and two 'winter garden' conservatories, all three-storey high volumes on the perimeter, provide north-facing views to the landscape. The three major core zones are positioned to allow for potential tenancy sub-division and efficient distribution of services. An undercroft plant area, beneath the main entrance's vehicle drop-off, accommodates electrical plant, incoming frame rooms, water storage, and the refuse store.

In response to the brief's requirements for flexibility of future tenancy sub-division, a single main entrance and two secondary entrances were provided. On entering the site from London Road, the main entrance - used by both staff and visitors - is central on the south elevation. Its importance is visually established by the composition of the double-height glazed entrance screen, the projecting canopy, and the pedestrian bridge which links through to the reception area.

The secondary entrances to east and west are used by staff only, and distinguished by the diagonal linear routes from the site entrance. These entrances are identified by the full height stair towers that act as markers in the landscape. The internal primary circulation routes link these entrances with their respective cores.

5.
Section through site.

'... probably the best BT building...'
building user

Internal planning

The main entrance hall is strategically positioned at mid-level and reached via the bridge from outside into a double height space, rectangular in plan. To its rear a high-level bridge links the east and west wings and frames the view of the dining hall and the landscape beyond. West of this reception area is the main lift lobby, overlooking the triple height dining space, and adjacent there is a grand glass and steel circulation stair within the dining hall's volume to connect all three levels of the building.

Putting the restaurant centrally between the east and west wings of the office space made a natural social focus for the office community, and their use of this space for meetings is a clear sign of its success, and a freedom from inhibition on what 'meeting space' is. The glazed wall beyond to the north gives unobstructed views onto a private terrace overlooking the natural exterior.

The service bay is at ground level, directly under the main entrance bridge. From this low level, dedicated internal distribution routes link the 'back-of-house' facilities to the minor east and west cores, a strategy which ensures that all delivery and waste disposal access is entirely discrete from the offices themselves. The main fixed service cores (vertical circulation, washrooms, service rooms, and risers) are located centrally allowing for future anticipated tenancy division, and thus provide a natural framework for the building's primary circulation.

The minor cores, on the building's perimeter, contain secondary stairs and service risers and are positioned to satisfy means-of-escape requirements. In the southern façade these are articulated as independent stair towers, creating a more structured appearance that relates to the formal landscaping of the car park area. In the north the three stair cores are behind the uninterrupted free-flowing glazed wall that addresses the natural landscape beyond.

Structure

Whilst the building has three entrances, three functional cores, and three sets of most building systems, there are only two structural cores, with the structure split by a movement joint at the obvious halfway point. The central core of lifts and toilets is part of the west wing but its structural contribution is vestigial, a single wall acting as part of the lateral stability system.
The design team decided that the complexity, risks, and expense involved in movement joints meant the advantages of minimising their number outweighed any tidy-minded desire for the potential subdivision of occupancy to be reflected directly by the structure. Each of the two main structural cores forms a box around the washrooms as well as the lifts and stairs, sufficient to allow all the lateral forces and twisting effects to be resisted without recourse to perimeter frame action, allowing all columns to be designed as braced, reducing the amount of reinforcement in them.

Façade design

Duncan Richards

Specialists from Arup Façade Engineering joined the team early in the detailed design phase, when the visual intent and project cost plan were established for the building's external glazed wall. Early workshops established the design intent of a simple extruded aluminium mullion-transom stick system, with turned stainless steel buttons that restrain monolithic toughened glass panels in the joints between units. A flush transparent aesthetic was achieved without the need to drill and countersink any glass, whilst employing the simplest of fixings which were consequently cheap to produce. The desired visual intent was achieved using simple manufacturing techniques to produce a glazed wall bespoke to the project without the over-specification of an essentially simple concept. Industry 'buy-in' sessions were held with likely tenderers using detailed information in a well-advanced state of development. Glazing contractors confirmed a willingness to progress to design, and advised suitable budget rates that were referred back to the cost plan. As a result, when the project was tendered, the industry priced 'user friendly' information which had been previously reviewed and agreed in principle, was well developed and thorough, clearly addressing problem issues like tolerance, movements, interfaces, and giving consideration to their preferred manufacturing and installation techniques.

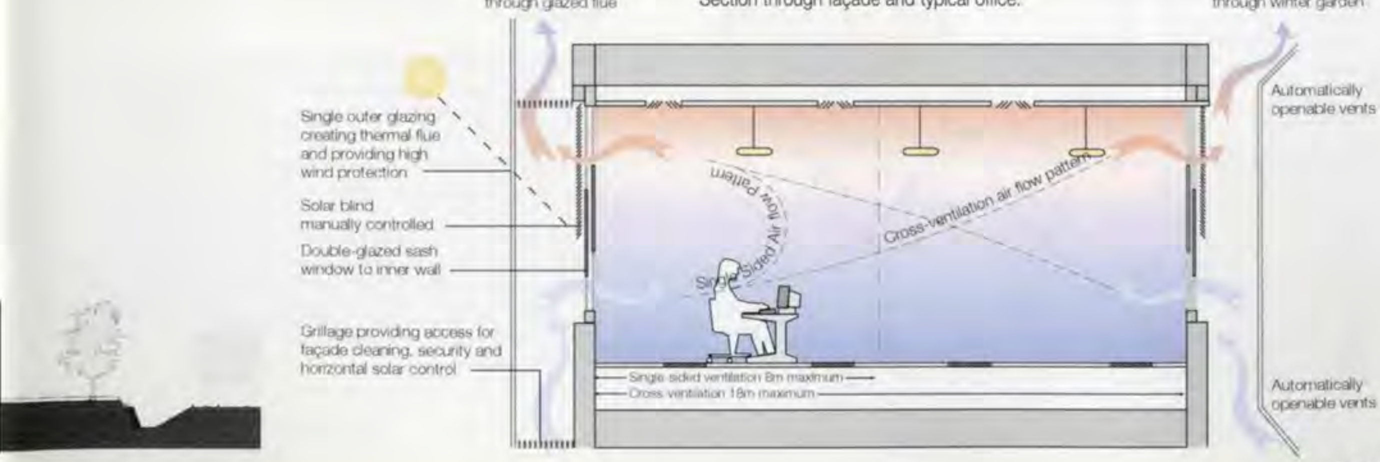
6.
Cladding detail.

The office environment - space and light

One key to achieving the client's high aspirations for the office environment has been the choice of a generous floor-to-ceiling height of 3.1m, rather than the 2.7m in many speculative office buildings today. This allowed high levels of daylight to penetrate the building and optimised the direct and indirect artificial lighting essential to eliminate the contrast that high levels of daylight at the façade and 'dark' ceilings internally cause, typical in many office buildings. Additionally, the use of uplighting gives a desirable impression of spaciousness.

The high ceilings and continuous façade glazing also allow excellent views out of the building and a strong sense of contact with nature. Together with those issues highlighted above and the mixed mode ventilation strategy, a pleasant and comfortable office environment has been created.

The design adopted the 9x9m column grid strongly encouraged by the brief, generating an 18m wide wing of offices. Where cores occur, the building is wider, its angularity softened by 45° corners where the façade takes a diagonal line across the regular grid, the building layout responding to the lie of the land. Interior columns are circular and of painted concrete - the only concrete exposed to view. Perimeter columns, embedded in the walls to avoid interrupting the office space, are typically closely spaced at 3m, which allows them to have a compact cross-section and regularly support the modular façade.



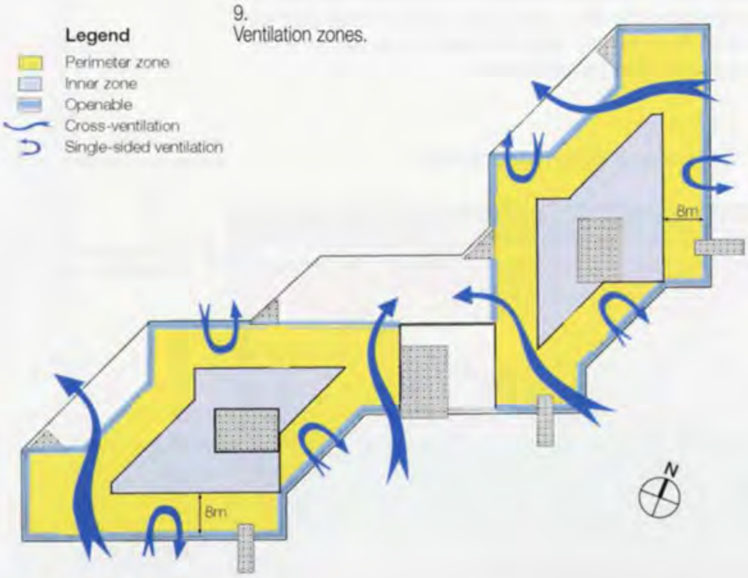
7.
Section through façade and typical office.

8.
The restaurant
viewed from reception area.

The decisions to maximise ceiling height and use a 450mm raised floor, whilst remaining within the project's commercial constraints, meant that the pressure to reduce the depth of the structural zone was significantly higher than for most three-storey buildings. Reinforced concrete was chosen as the primary structural material because steel alternatives would be economically uncompetitive in the limited depth available.

A 400mm deep ribbed slab was eventually chosen, but only after close study of an even thinner 300mm flat slab. The ribbed slab's superior payload-to-weight ratio resulted in a more economic proposition, even when handicapped with the cost of an additional 100mm strip of façade. Buildability of both these downstand-free plate floor options was compatible with the extremely short construction time demanded. The ability of the ribbed structure to accommodate service penetrations, both initially and through the life of the building, was a less tangible but nonetheless significant additional advantage, as was the reduced quantity of concrete and reinforcement.

9.
Ventilation zones.



The office environment - mixed mode ventilation

A 'mixed mode' ventilation system - natural ventilation supplemented by under-floor air supply - was used to achieve the client's energy consumption criteria, and create a comfortable office environment controlled by the occupants. This system takes advantage of both external conditions and internal heat gains rather than always treating them as problems, and allows the building to be ventilated either naturally, through the external windows, or by air supplied mechanically through floor plenums and outlets. The 3.1m ceiling height is optimal for achieving cross-ventilation across the 18m floor plate width, as well as desirable for the reasons described above. This cross-ventilation greatly assists the 'mixed mode' system, allowing a comfortable environment to be achieved but with efficient use of energy.

The system combines 'seasonal' and 'zonal' modes, ie it can operate as a naturally ventilated building for most of the year apart from hot periods in summer. This is true of most areas with the exception of inner zones far from windows, or areas needing high levels of acoustic privacy.

To achieve this Arup Associates worked closely with the client. The final solution uses a 'traffic light' system - coloured light indicators on top of the interior columns telling occupants which days windows can be opened. The building management system controls these lights. Many in-depth analyses of the ventilation systems were done to prove that these proposals would work, and they have gone on to be a great success in practice.

It was felt important to give the office's occupants control of their environment, celebrating the individual and encouraging an identity and ownership of the space. As well as having a choice of ventilation method, they can manually adjust the 'external' automatic blinds within the external glazing system, the lighting in work areas, and heating from radiators below each window.

The development of this mixed mode solution allowed BT's objectives of a low primary energy building and the brief's summer comfort criteria both to be achieved. The final result has been to create a comfortable, enjoyable and liberating office environment through a synthesis of building services, structure, and architectural form.

Roofscape

The final form of the roof and rooftop plant area needed much debate and many decisions during scheme development. Initially, three separate plant areas, corresponding to potential tenant subdivisions, were planned. However, this potentially inflexible arrangement was eventually transformed into a linear one that permitted the roof slopes to have a rational geometry. The final resolution is deceptively simple. Originally it was thought that the roof level structure would repeat the typical floor, allowing a consistent solution, a platform for rooftop plant, and thermal mass where it is most valuable. However, value engineering later determined that the perimeter zones, where the planners required screening for the plant areas, should be in lightweight steel and metal decking, creating a pitched roof. The perimeter structural frame remained as concrete through to roof level, to allow the attachment method of the façade to remain consistent. The potential difficulties of the steel-to-concrete interfaces were recognised and careful work was carried out with the contractor to pre-empt and eliminate construction difficulties.

Plant occupies a central zone bounded by 4m high concrete acoustic walls, parallel to the building edges, and extended around triangular skylights at each end. A line is scribed part way up the wall, and the roof plane slopes uniformly between this and a corresponding constant level at the perimeter, intersecting at varying angles that are a product of different wall-to-perimeter distances. The roof is flat within the plant areas, but the pitched roof promised to the planners appears to have been delivered. Only the lift motor rooms, at either end of the plant areas, are fully enclosed by the roof.

'...overall the most beautiful space I've worked in.'

These plant areas contain air-handling plant for their respective zones. It was first hoped that air could flow straight down and up ducts attached to the central cores, but it became apparent that the horizontal extent of the office spaces demanded a more dispersed pattern of risers. To mitigate the impact of this on the external envelope, the secondary risers were integrated into the escape stair cores, and fed by ducts passing through the wedge-shaped ceiling void under the pitched roof. The decision that the roof should be framed in steel facilitated this lateral air movement. Once delivered to the level needed, cool air is directed through a raised floor zone and then upward via floor diffusers into the office space. Extract at high level mirrors the pattern of supply, but in simpler form, without the physical subdivision between perimeter and interior zones necessary for the supply route.

The steel pitched roof framing is structurally expressed across the conservatory spaces. These, together with the dining hall, have tubular steel columns down to the ground. The roof's steel rafters at 3m centres cantilever over the perimeter framing to provide suspension points for the outer glazed skin, which is a true curtain wall, not touching the ground.

10.
Staircase within restaurant.

Fire strategy

The fire strategy is based on an engineered approach from Arup Fire specialists, and liaison with the local Building Control Department also benefited the project. Agreement was reached at concept stage that alternative strategies to recommendations in Approved Document B could be considered for approval. This approach liberated the design from the rigidity that would have resulted from an Approved Document compliant solution. The principal fire strategies are based on the building being treated as a single compartment with single stage evacuation, but taking into account that it may one day be divided into several tenancies. In particular, the firefighting facilities and the design of the twin skin ventilating façade benefited from this alternative approach.

The split-level car park

It was recognised early in the design stages that some form of split-level parking would be necessary to accommodate the required 800 cars. A subsurface level has been created to the west, where the geology is relatively co-operative and space permits rows of cars to be separated, allowing slots for light and air to penetrate to a lower parking deck. Semi-mature trees are planted at this lower level and emerge through the overhead slots.

Through these substantial slots along the length of the car park, a generous amount of light floods into the lower level and, together with the ramp entrance opening, they provide adequate natural ventilation to disperse exhaust omissions. From most views around the site, the existence of this extra level is very effectively concealed, further reducing the impact of parking on the site and surroundings.

The office environment - mixed mode in practice

The building has been in operation over a year and feedback from the occupants shows it to be much liked. They have become accustomed to the column-mounted coloured light indicators informing them whether it is a 'windows-open' or an 'artificial environment' day. Unlike in many 'naturally ventilated' buildings, occupants do open the windows. The sliding sash windows have been successful, making it possible to ventilate deep into the building, over the heads of the staff at the perimeter, by opening the top sash a little and keeping the bottom sash closed. The external skin is effective in reducing high wind pressures to an acceptable level, so that paper is not blown off desks, and yet allows good ventilation in light wind using the stack effect as well as wind pressure.

Occupant opinions

BT recently released the findings of a construction industry standard occupancy survey called PROBE, undertaken for the Brentwood building. Arup Research & Development have prepared the report, under licence from Building Use Studies [BUS]. The results are outstanding; for the indices on comfort, satisfaction, and summary the building was in the top 2-5% of buildings within the BUS dataset. The occupants perceived an increase of 8% in productivity due to the building - very good, compared to the national benchmarks.

The findings quoted many positive comments from occupants similar to the opinions expressed below and elsewhere in this article:

Credits

Client:
BT Building Construction and Maintenance

Promoter / Project Manager:
Stanhope plc

Designers:
Arup Associates, and Arup specialists Matthew Callander, Peter Connell, Graham Dodd, Martin Finch, Andrew Hall, John Hopkinson, Lee Hosking, Tony Hoban, Amanda Hobson, Alastair Hughes, Michael Kinney, Andrew Lawrence, Dick Lee, Declan O'Carroll, Dinesh Patel, David Pearce, Duncan Richards, Eugene Uys, Peter Warburton, Malcolm Wright

Landscape Architect:
Charles Funke Associates

Quantity surveyor:
Gardiner & Theobald

Construction manager:
Schal Construction Management Ltd

Illustrations:
2, 3, 5, 7, 9: Arup Associates
1, 6, 8, 10, 11: Richard Bryant/Arcaid
4: Grant Smith

'I really like the building design – particularly the feeling of space in the full height light areas...'

11.
Winter garden.

1.

The London Regatta Centre and powered rowing tank

2.

James McLean

Introduction

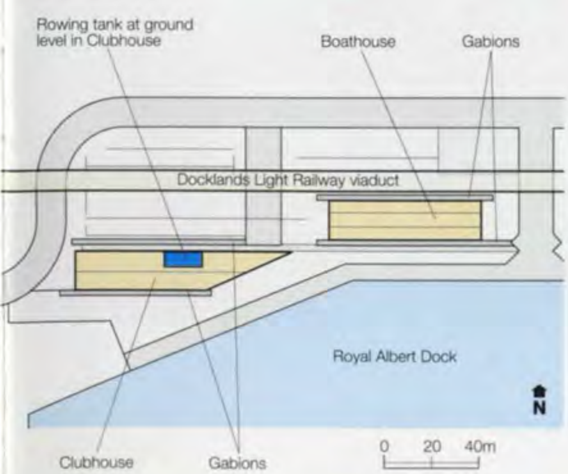
Jointly funded by the London Docklands Development Corporation (LDDC) and the Sports Council Funding Body via the National Lottery, this new centre provides permanent facilities for rowing activities organised by the Royal Albert Dock Trust. The site is at the north-west corner of the Dock in East London, near the rowing course finishing line, and on the opposite bank to City Airport. Works to extend the course to 2000m are now complete, thus providing the first Olympic-standard rowing facility in south-east England.

Following his introduction to the Trust by Mike Davis of Richard Rogers Partnership, Ian Ritchie of Ian Ritchie Architects acted as their conceptual adviser, because of his knowledge and continuing advisory role within the LDDC. At Ritchie's recommendation, the Trust approached Arup to act as engineers, one member of the team being specifically requested by the client for his rowing knowledge and expertise. Arup added input to the building grid and space planning to suit rowing needs; the passive servicing, foundation, and structural design for the boathouse resulted in overall savings, whilst the design of the powered rowing tank gave the client a unique and innovative training facility.

Layout

The Centre comprises two buildings: a boathouse to store up to 80 'Eights' with an insulated workshop space, and a clubhouse for all the necessary facilities, plus the powered rowing tank. The buildings' overall outline is defined by freestanding 3.5m high stone-filled gabion walls on strip footings along the length of the site. The boathouse is enclosed by gabion walls and a lightweight stainless steel roof, with steel mesh panels where needed for security. The clubhouse sits back from its north gabion wall, providing an access and assembly zone running the length of the building. Full length terraces on the upper level sail over the gabion to the south, providing viewing areas from the bar and restaurant for racing events.

3.
Site plan.



Gabions

The gabions are independent structures, framed with steel tees at 5.6m centres. Longitudinally, three of the four edges are trimmed with angle members and filled with 100mm+ granite fragments, retained with 5mm diameter wire mesh restrained by crossties in vertical rows at 1.4m centres. The mesh acts in catenary, and 'pillows' by around 60mm when loaded. The in-plane tension in the mesh is anchored to the main gabion frame by bolts securing an edge plate welded to the individual strands. The mesh is supported at the lines of ties by a small channel section, running vertically up the height of the gabion, to which the ties are anchored.

Boathouse

The boathouse comprises three 6m wide, 70m long bays, with metal sliding doors at each end. It is 4.5m high and the 1m slot above the gabions and doors is meshed, providing venting to the structure which reduces vertical wind loads on the roof. Small canopies down each side of the building resist high local perimeter wind pressure.

The design fulfilled a need to provide shelter economically for an area of about 1200m^2 from wind, rain, and sun, but not be completely watertight. It had to support racks for 20m long rowing boats needing level storage to prevent warping, so it was important to avoid building movement.

'Arup added input to the building grid and space planning of the London Regatta Centre to suit rowing needs...'

Boathouse text continues on page 22 ▶

4.
Main entrance, with gabion wall on right.

5.
The boathouse with its catenary roof, and racks supporting 20m boats needing level storage.

The powered rowing tank

Rowing tanks are used to teach rowing to beginners, to improve the technique of more experienced rowers, and as a training environment in bad weather. The modus operandi has been for the rowers to push the water round the tank, sitting in rowing stations fixed to concrete and using oars resembling sticks of wood. The experience is unrealistic, a chore for experienced athletes, and difficult for beginners to master, leaving them unprepared for the feel of a real boat.

An 'eight', its rowers, cox, and oars weigh about 1 tonne (1000kg). When on water, the rowers' energy is spent pulling (or pushing) themselves through the water, overcoming the drag on the shell of the boat - altogether equivalent to each rower pulling 125kg through the water. In traditional tanks, four rowers sit on the site of each channel and have to move approximately 20 tonnes of water past themselves. With normal rowing oars, this is about 40 times harder than rowing a real boat on water. The oars are torn through the water and the feel of the rowing stroke is not accurately reproduced. Also, traditional tanks are generally limited to rowing and cannot accommodate sculling. As part of the London Regatta Centre project, Arup examined these issues from first principles, and produced a revolutionary design that moves the water past the rowers, thus creating the feel of rowing in a boat on water and providing an excellent environment for teaching, developing, and training.

Water is powered by submersible electric pumps through hydraulically efficient channels, the flow adjustable electronically to simulate speeds up to 3m/sec. A rowing frame provides rowing stations that represent the layout and structure of a boat, allowing rowers to sit behind each other as they would in the boat.

6. The tank in use.

The frame is set to a chosen level above the water surface, and rocks about its longitudinal axis to enable the 'crew' to feel the balance of the boat'. Standard equipment for fitting out boats is used in the powered rowing tank, with the gearing adjusted so that conventional oars and sculls can be used.

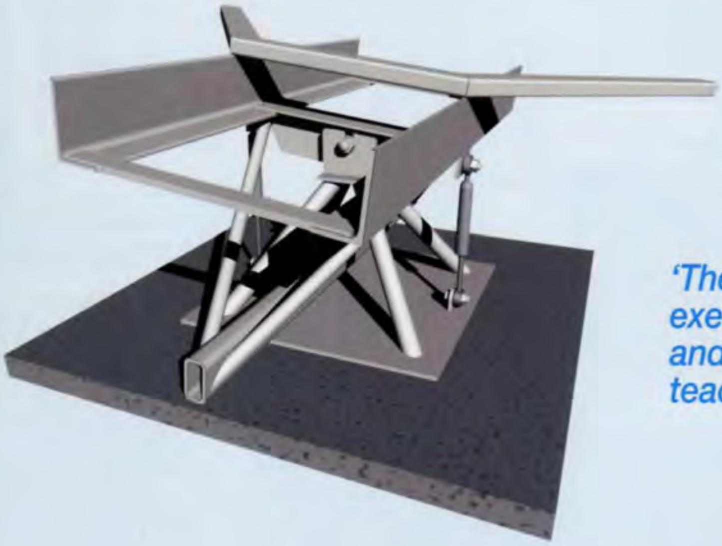
The powered rowing tank can be easily adapted for either rowing or sculling. The gearing gives a realistic feel for training intensities and for teaching beginners about the feel of the stroke.

A coxing position is also included so that coxes can be taught the control of crews and commands before taking to the water. Feedback from users of the tank now installed at the Regatta Centre has been very positive, and it is proving to be an excellent teaching facility. Arup has sold the design of a powered rowing tank to the Scottish Amateur Rowing Association (SARA) for inclusion in a facility at Strathclyde Park. This design has been developed from the Regatta Centre tank, based on operational feedback, and has been tuned to SARA's requirements. The powered rowing tank exemplifies Arup project innovation.

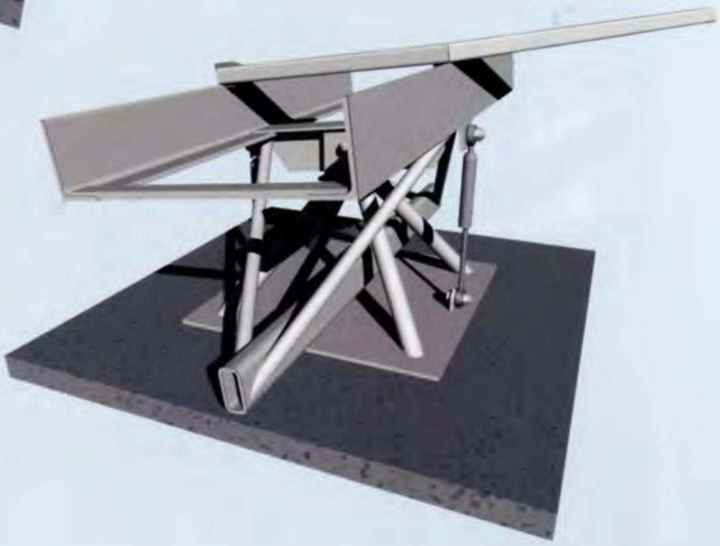
This product was designed to meet the needs of the client at the London Regatta Centre, and has the potential to be developed further and used in many more applications around the world. The specialist is now working with *Design by Arup* (the product design network within the firm) to examine this potential, looking at the development of design alternatives, methods of procurement, and advice on financing options.

A market study is under way with nearly 1000 potential clients around the world, and it is hoped that many more powered rowing tanks will be in use in the not-too-distant future. The cost of building a powered rowing tank is approximately £100 000 and would normally be incorporated in a new facility. The market for it is thus substantial: national rowing centres, clubs, or an association of clubs in one area, as well as universities.

(Arup's website on powered rowing tank design can be viewed on http://www.rowingtank.com).



'The powered rowing tank exemplifies Arup project innovation and is proving to be an excellent teaching facility....'



7 above: and 8 right:
Sections through rocking mechanism showing extreme left and right tilt.

Credits

Powered rowing tank design:
Arup James McLean

Website design:
Arup Kevin Franklin, Ray Ingles, Tristan Simmonds

Boathouse text continued from page 19 ▶

A frame and fabric roof was not considered strong and secure enough, so a robust, durable, and weathertight skin was suspended from a simple galvanised steel frame hung in catenary. The roof structure is 6m x 1.4m stainless steel sheets, 3mm thick, jointed with curved 102mm x 127mm x 11mm structural tees. These hang from 219mm diameter CHS section gridline beams running the length of the building at 6m centres. For robustness, the stainless steel sheet has been designed to span between the tees for 'people' loading, although it is able to hang in catenary from the gridline beams. The tees were designed to resist symmetrical loading by catenary action, whilst asymmetric loading and settlement of supports induce bending moments in the tees. These moments govern the tee section design. The curved form of the roof acts as large gutters, draining rainwater to the ends of the building.

Longitudinally the building is stabilised by two bays of cross-bracing, central on each external face. The stainless steel roof sheets act as a stressed skin to provide stability to the internal rows of columns.

Lateral stability is from diagonal props at each external column position, which also restrain horizontal catenary loads in the roof. These elements are contained within the gabions that run either side of the building.

10.
Part of the line of gabions along the clubhouse.

9 below:
The boathouse exterior showing the end of the gabion wall on the left.

Foundations

As the soil is weak, the ground was surcharged with type 1 material for about a year before construction to induce predicted long-term settlements from building loads when construction began. Additional surcharge was added along the line of gabions due to the high loading imposed by them. The columns are supported on longitudinal ground-bearing strips and the gabions and perimeter columns on a combined strip footing to resist uplift from the diagonal props stabilising the roof. The column strips are tied together at column positions with concrete tie beams to ensure the base geometry is maintained.

Clubhouse structure

The 90m long, 20m wide clubhouse has two storeys: the ground floor houses the reception area, gymnasium, rowing tank, changing facilities, and plant room, whilst the first floor contains the bar / club room, restaurant, kitchen, accommodation, and caretaker's flat. Between ground and first floor a mezzanine level plantroom occupies part of the area.

11 right:
The fitness centre.

12.
Roof-mounted solar panels providing solar water heating.

'The London Regatta Centre is the first Olympic-standard rowing facility in south-east England...'

14.
First floor restaurant.

13 left:
Exterior corridor, the long gabion wall is on the left.

The external envelope of the building is a mix of contractor-designed glazing, metal-clad blockwork, and fairfaced concrete walls. The ground, first floor, and roof slabs are of concrete flat slab construction of varying thickness supported on circular concrete columns and a concrete blade wall to the north, which also provides stability in conjunction with internal shear walls. Building loads are transferred to the ground via piles of varying diameter. A deep Thames Water Authority sewer underlies one corner of the building; this limited pile spacing, and the structure therefore cantilevers over the sewer using deep beams beneath the slab.

There are balconies on the south and west faces. The south balcony is in steel and timber and cantilevers from the first floor slab, whilst a steel and glass canopy cantilevers from the north wall creating an enclosure between the building and the gabion.

The 90m concrete blade wall is fairfaced and continuous, so the concrete mix and construction method were carefully controlled to minimise shrinkage cracks.

This external wall is joined to the internal slab, so both had to be designed and reinforced to resist differential strains from temperature changes.

Clubhouse services

The services design is integrated into the architectural and structural form, with the building form and fabric used to control the internal environment and create a comfortable and energy-efficient solution. To minimise operation costs, simple, energy-efficient, heating and ventilation systems reduce heat losses in the winter and avoid the need for cooling in summer. Passive design features have been used as part of this strategy to optimise the building performance. External shading to the south-facing restaurant, bar, and gymnasium areas reduces direct solar radiation in summer, but low-angle winter sun is allowed to penetrate the building façade to directly heat areas within.

The exposed concrete soffits throughout the building help to reduce sudden temperature swings. The north elevation is virtually solid, to reduce heat loss and protect from northerly winds, with minimal glazed areas providing vision and some daylight. Gabion walls to the lower level provide further protection from the elements and help reduce unwanted infiltration losses by reducing external wind pressures. High levels of CFC-free insulation retain heat in winter, helping to lower the energy consumption of the building by reducing both maximum heat demand and the internal summer temperatures.

The primary services are fed from plantrooms in the western end of the building, running within a mezzanine spine above the 'wet areas' of the changing rooms and the multi-gym areas. Mechanical ventilation recovers heat and expels moisture from exhaust air. Perimeter heaters controlled by thermostatic radiator valves beneath the full height south façade glazing provide rapid response heating to offset fabric losses and downdraughts, while an underfloor heating system is used in the changing rooms.

Evacuated tube hot water solar collectors, mounted on the roof, provide 60% of the average annual domestic hot water (based on the estimated daily demand as recommended by solar heating design guidelines). Solar water heating pre-heats the domestic hot water calorifier that maximises the temperature difference between the solar and hot water circuits, in turn maximising the overall efficiency of the system.

Credits

Client:
Royal Albert Dock Trust

Architect:
Ian Ritchie Architects

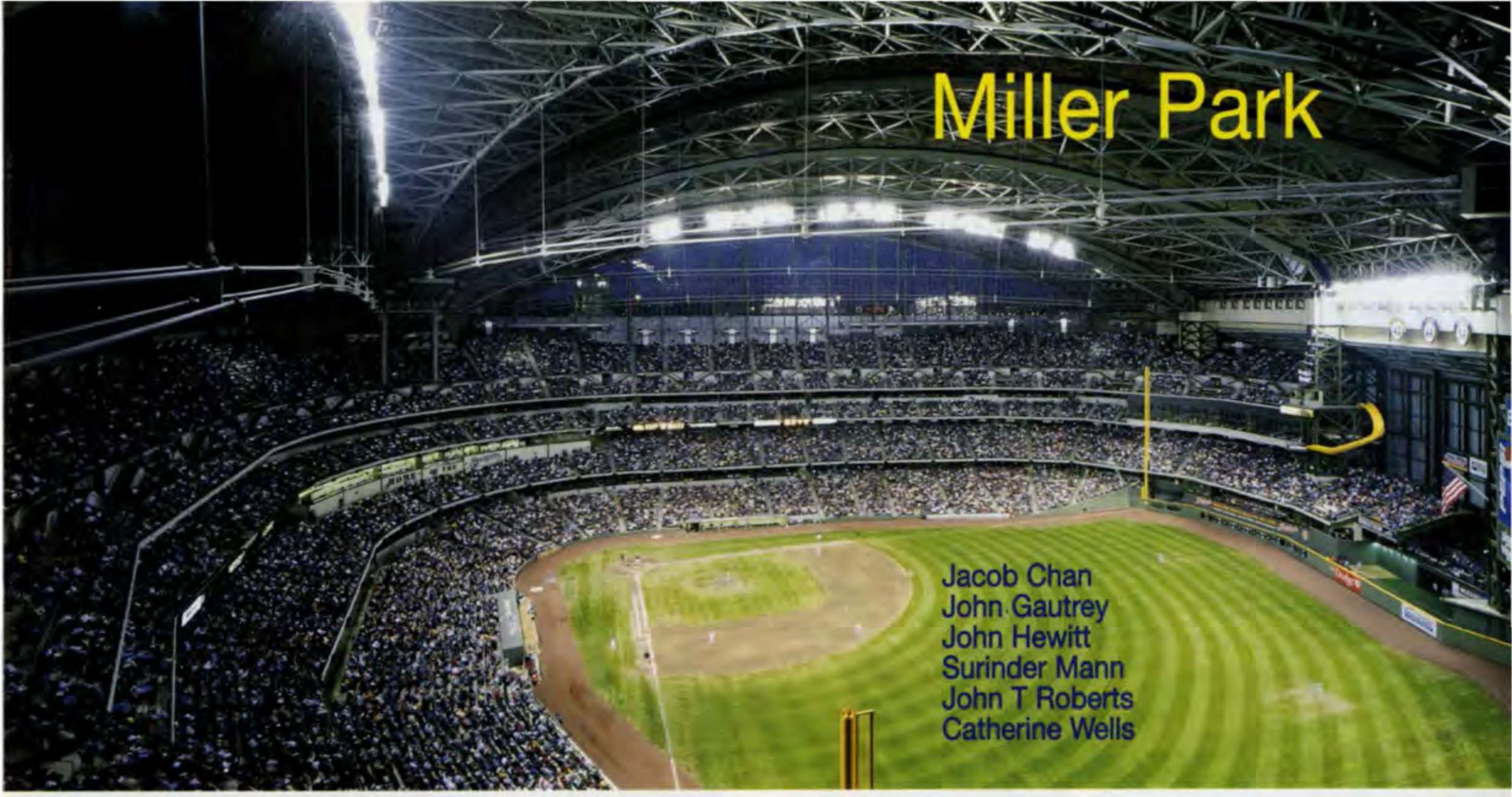
Consulting engineer:
Arup Patrick Bravery, Nick Dibben, Nick Howard, Sara McGowan, John McKenna, James McLean, Paul Sloman, John Thornton

Quantity surveyor:
Davis Langdon & Everest

Illustrations:
1: Ian Ritchie Architects
2, 4-6, 9-14: Graham Young
3: Penny Rees
7, 8: Tristan Simmonds

Miller Park

Jacob Chan
John Gautrey
John Hewitt
Surinder Mann
John T Roberts
Catherine Wells



'Miller Park is a big hit for our fans, players, and employees. It was very rewarding to hear and see the reaction from the 2.8M fans who visited during our first season. The operable roof is magnificent both functionally and aesthetically. Fans were also impressed with the comfortable environment created by the use of natural light, wide concourses, and the use of the roof in rainy or cold weather. Arup's engineers did a great job in creating a very exciting and functional design.'

Scott Jenkins,
Vice President of Stadium Operations,
Miller Park Milwaukee Brewers Baseball Club

Introduction

The weather in the Midwestern United States suffers extremes of heat and cold, with unexpected snow and rain. In Milwaukee, Wisconsin, the Brewers baseball team always had to contend with the vagaries of the local climate, often resulting in reduced attendance and lost games. From the 2001 season's opening game in April, this has no longer been a problem, since the Brewers now play at Miller Park Stadium, with its retractable roof. Miller Park is the result of many years of detailed study and planning, followed by five years' intensive design and construction.

Arup was privileged to carry out most of the engineering design, including the roof and bowl structure, foundations, electrical, plumbing, and mechanical HVAC design.

Competition Background

The Milwaukee Brewers used to play at the 48-year-old County Stadium. Increasingly, modern facilities are a major factor in the financial success of sports teams in the USA and elsewhere, and it became clear that County Stadium could no longer compete with the newest major league stadia. Additionally, fixtures lost through bad weather resulted in loss of revenue, particularly early in the season from the beginning of April, when late snowfalls are not uncommon.

The project was paid for by a local sales tax, plus funds from the baseball team and the Miller Brewing Company, and was overseen by the Southeast Wisconsin Professional Baseball Park District, a public board created for this purpose.

Competition Criteria

In the September 1995 design competition, the client's brief for a modern baseball park combined a state-of-the-art roof with a traditional architectural feel. Provision was to be made for 42 000 spectators, with associated skyboxes, concessions, catering, and other facilities. Two central client requirements were that the playing surface should be of natural grass - needing sunlight to grow - and that play should be in the open whenever possible. It was clear that any roof for bad weather shelter had to be retractable. The owner specified that:

- *It should open and close within 10 minutes.*
- *It should be typically open during the playing season.*
- *When open, the number of spectators 'in the sun' was to be maximised.*
- *It should integrate visually with the stadium, and not overhang the stadium footprint when open.*
- *Temperatures for spectators should be able to be raised or lowered by ±30°F (±17°C).*

Team structure

Four design teams were invited to take part in the competition, Arup being asked to join one based around the architectural practices of HKS Inc (Dallas), NBBJ Sports and Entertainment (Los Angeles), and Epstein Uhen Architects (Milwaukee). Mitsubishi Heavy Industries Ltd (MHI) provided input on roof mechanisms. This team was selected, and shortly afterwards a separate competition led to the selection of a construction management team of Huber Hunt & Nichols (Indianapolis), Clark Construction Co (Chicago), and Hunzinger Construction Co (Milwaukee) (HCH Joint Venture).

The stadium was built on a fast track, using multiple bid packages, with early piling, foundation, and steelwork packages. Bidding for piling opened at the end of 1996, with steel following in summer 1997.

1 top:
Interior of stadium with roof closed.

Design principles

Early in the competition, the team decided on a fan-shaped roof as the best response to the brief. This respected the natural geometry of a baseball field and offered the best opportunities for integration with field and bowl. With a span of around 600ft (183m), the roof dominates the design, and most of the key principles of moving, stacking, and structural span were sketched at this early stage. Several meetings were held with the client team, culminating in a detailed presentation with drawings, renderings, video, and a motorised scale model of the roof in operation.

The Bowl

The stadium seating bowl has about 11 000 tons of exposed steel framing, with concrete slab on metal deck floors and precast seating above. There are four levels of seating and concourses, the highest some 110 ft (33.5m) above the field, forming a splayed U-shape around the field along first base, home plate, and third base. The plan recalls traditional American ballparks in its irregular field geometry (each ballpark has its own quirks). The seating structure follows this so that plan geometry and setbacks vary at each level, necessitating many unique connection and cantilever steelwork designs. Movement joints divide the bowl into three segments; the wind loads in each are resisted by steel cross-bracing around the perimeter and integrated into the concourses. As in traditional ballparks, beam / column connections are typically bolted, with large exposed plates. The massive columns supporting the roof pivots behind home plate feature built-up box sections with exposed lattice bracing. To speed erection during the cold months, field bolting was preferred to welding.

For maximum seats with good sightlines, the depth of the cantilever seating supports had to be minimised, and so the design was driven by vibration criteria. The stadium is intended only for baseball, so data from Canadian codes and advice from Arup's Advanced Technology Group led to the design criterion that tip acceleration should not exceed 5%g for the first harmonic mode. A time history analysis was carried out for the 25ft (7.5m) steel seating cantilevers, using a 2-D SAP computer model of the entire seating support structure. Modification to the frame bracing improved vibration performance.

To function properly and control temperatures and airflow with the roof closed, the stadium has to be effectively an enclosed space under some conditions - but also act as an open stadium when the roof is open. The outer walls around the bowl have a continuous façade, but the outfield area below the roof track support beam is enclosed by curved, lightweight *Kalwall* panels some 100ft (30m) high. To open the outfield to the outdoors, these move aside on tracks, with horizontal trusses tying back to the support towers. The cantilever tower steelwork for the outfield area had to be designed for reactions from the roof, the weight of the track beam, wind on the outfield wall, and the horizontal trusses that carry all the scoreboards.

The lowest, service, level of the stadium is below grade at the exterior and open to the field on the interior. Poured-in-place concrete walls and columns with a concrete pan joist floor above were used, allowing concreting to start while the steel was being fabricated.

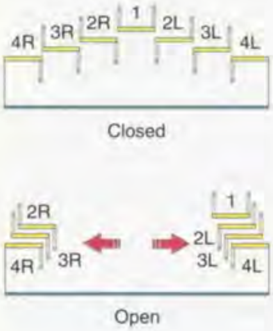
Foundations

The site has uncontrolled fill, organic silts, and granular soil overlying bedrock that slopes steeply from depths of about 15ft (4.5m) to 55ft (17m). The compressible nature of the clays meant that spread footings could not be used except for the lightest loads, and slabs on grade had to be carefully detailed to accommodate settlements. Cost evaluation of several alternatives led to two deep foundation systems being used for the column and retaining wall loads.

The outfield area has the deepest bedrock, so groups of 16in (0.4m) diameter driven steel *Monotube* pipe piles were used. The home plate area has 26in (0.66m) and 42in (1.1m) diameter drilled piers into the bedrock. Foundation design for the roof supports was a particular challenge, due to the large overturning loads on the slender outfield towers and the major horizontal roof loads on the pivot frame supports. The solution for the towers was a 7.5ft (2.4m) deep mat under each, supported by over 100 *Monotube* piles. In the event, the original pile capacities were not achieved and thus were increased in size during construction. In the home plate area, diagonal tie beams below grade distribute lateral loads between all the pile caps.

2.
Bowl framing.

3 below:
Cross-sections of the roof closed and open.



The roof

Geometry

At competition stage, the roof design included seven panels moving on concentric tracks at outfield and behind home plate, plus two fixed panels. During scheme design the number of moving segments was reduced and the home plate track replaced with fixed pivots, so that the final design has five moving segments and two fixed segments in a fan shape. Moving panel 1 is the highest, most central, panel and is aligned with the stadium centreline when the roof is closed. There are two mirrored versions of each of moving panel types 2 and 3. The moving panels rotate about pivots behind home plate, three opening east and two to the west. When open, the moving panels stack over the fixed ones.

Each moving panel has similar geometry: wedge-shaped on plan, with the surfaces curved to a maximum 30° slope. Segments towards the centre of the ballpark are progressively longer and higher so that they stack above each other when open, and give maximum clear height at centre field when closed.

Structural principles

One basic decision was whether to create roof elements that rely on outward thrust for support, like domes or arches, or to adopt structures needing only simple support, eg trusses or tied arches. The team went for the latter - simple support on the tied arch principle. By avoiding the need for large outward thrusts, the size of the support structures around the outfield and home plate could be controlled and the forces transferring through the mechanism minimised. Also, each segment was independent, and could thus be separately designed and constructed.

The main spanning elements needed sufficient overall structural depth to span across the field and seating, while also being able to stack neatly one above the other when open. The inner and outer sides of each panel are, therefore, different. The long edges of each segment are supported on arched trusses. On the sides of panels 2, 3, and 4 towards centre field, these arches are restrained by a tension tie below, comprising four 4in (100mm) diameter steel cables suspended from the arch truss. On the outer long side of panels 2 and 3, and on both sides of panel 1, the edge trusses are restrained by an upstand compression chord of 60in (1.52m) x 30in (0.76m) fabricated box sections. Together, the two primary trusses of each panel span about 600ft (183m) across the field and seating. Between the primary trusses, secondary trusses span to support purlins and cladding, their upper and lower surfaces cross-braced to form a stiff 'torsion box' to contribute to roof stability.

The upstand / downstand arrangement allows each panel to maintain truss depth and stack in the open position. Since much of the total load is the weight of the structure itself (around 12 000 tons), significant quantities of stronger grade 65 steel were used in addition to grade 50, to reduce the weight of material to be carried.

Loading

The primary applied loads on the roof are from wind and snow. Wind analyses by Rowan Williams Davies & Irwin, Inc (RWDI) at their laboratories in Guelph, Ontario, investigated the critical directions of flow, to derive maximum design pressures. They tested rigid and aero-elastic models of the complete roof, and determined loads derived for structural analysis, taking into account the dynamic modal characteristics of each panel.

The basic ground level snow load for Milwaukee is 35lb/ft^2 (170kg/m^2), though distributions determined by RWDI's flume testing and computer analysis predicted drifts up to 200lb/ft^2 (1000kg/m^2) locally at the steps between roof segments.

Structural analysis

The main elements of the roof were analysed using SAP90®, together with Arup's GSA software. Stress checks were made in accordance with the American Institute of Steel Construction Load resistance factor design code. Analysis models for each panel included all structural elements except the purlins. Roughly 100 basic load combinations were required for each panel, and further analyses also included frictional effects from the bearings and, notably, buckling analysis of the upstand chords, which are critical elements of the roof structure. These upstand chords are generally in compression, and restrained against buckling by a combination of their own stiffness and the bending resistance of the hangers that attach them to the torsionally stiff roof deck.

A calculation method was needed that could not only assess the strength of the compression chords themselves, taking into account the flexibility of the deck and the hangers, but also determine the restraint forces induced in the hangers and the deck. Also, a comprehensive assessment of buckling effects had to be combined with the results of all the primary loadcases to check the combined stress ratios in the individual members.

The analysis of the upstand elements was not adequately addressed in any structural design code, since it required overall consideration of the buckling behaviour of an entire roof panel structure. The team had to take into account the range of potential initial imperfections caused by tolerances and residual stresses that might affect performance. To build up understanding and confidence in the design, various analysis methods were applied, from simple assumptions for preliminary sizing to sophisticated methods for final analysis. The latter involved consideration of potential imperfections based on buckling mode shapes, applied in combination with normal loads, using a P-delta analysis. The basis of the method was demonstrated to be equivalent to code assumptions, and allowed Arup to extend the underlying principles to a far more complex case. This analysis gave great insight into the structural actions involved and reinforced confidence in the roof design.

Mechanical systems

The mechanism was designed and constructed by MHI. The pivots include spherical bearing elements, to receive both vertical and horizontal loads, while releasing rotations around all axes. The outfield mechanisms include an electrically powered bogie under each corner of each moving panel. A roller bearing was included to allow longitudinal expansions and contractions up to ±20in (500mm) for each panel. Each panel runs on its own load-bearing circular track. The tracks, however, are not concentric, since the pivots are offset from each other on plan. The mechanical system includes side-stabilising rails, end buffers, locking devices for the open and closed positions, and holding down restraints.

Roof support structures

At the pivot end, the panels are all supported on the steel pivot frame, spanning between two major columns. This frame is propped to resist wind loads from the roof, delivering forces to the bowl structure behind home plate.

At the outfield end the roof panels are supported on curved rails at high level on a concrete track beam 16ft (4.8m) deep, spanning some 150ft (45m) between steel-framed towers. Concrete was chosen due to the curved geometry, and to provide continuity across spans. Each rail has its own beam with the four beams tied together, with cross members, to work as one unit. The resulting open grillage structure minimises snow build-up around the rails and mechanisms.

Roof details

As the steel sections were being shipped from Asia, a bolted structure was required. Most of the connections use slip critical friction bolts, with cover plates to webs and flanges. Generic designs were developed, plus many special conditions to deal with the complex geometry.

The roof cladding includes a perforated acoustic deck, with insulation and waterproofing membrane on a board substrate.

Above the deck surface, a series of upstand steel guards stops snowslides, whilst the roof drainage flows to gutters occupying the full depth of the deck structure at the pivot and outfield ends of each roof panel. The gutters cascade from upper to lower panels, discharging into 20in (500mm) diameter down-pipes.

The roof panels have gaps for structural deflections and to allow for relative movements between them during opening and closing, caused by the offsets between pivots. These gaps are sealed by flexible overlapping flaps.

Arup was also consulting engineer for the Los Angeles Dodger Stadium and the Paul Brown Stadium for the Cincinnati Bengals.

Los Angeles Dodger Stadium

Jonathan Phillips

In early 1999 Arup was approached to provide building services (mechanical, electrical and plumbing engineering) for refurbishing the historic Dodger Stadium, built during the early '60s and a major landmark within both Los Angeles and American baseball. The project was very ambitious and involved:

- demolition of the club level and building new executive suites
- refurbishment of the stadium club
- breaking open the field line slab behind home plate, excavating and creating a new high end dug out club below grade
- extending the field line seating nearer to home plate and providing new line expansion seating
- a seismic upgrade to the home plate section of the stadium.

The project had to be carried out, start to finish, between the last game of the 1999 season and opening day of the 2000 season.

This provided some six months to do the work, with expenditure in the order of US$50M of construction cost.

The suites were to be something different and to move forward the standards of high end corporate entertainment. The dug out club had similar aspirations - but also the constraints of head room clearance beneath sloped precast seating above. NBBJ Sports and Entertainment provided their usual imaginative concepts to the project for both architecture and the interior design and produced a unique experience and level of quality.

Substantial survey work and a flexibility to adapt design concepts hand-in-hand with the contractors on site as real conditions became clear were an integral part of both the project and its success.

5.
One of the new executive suites.

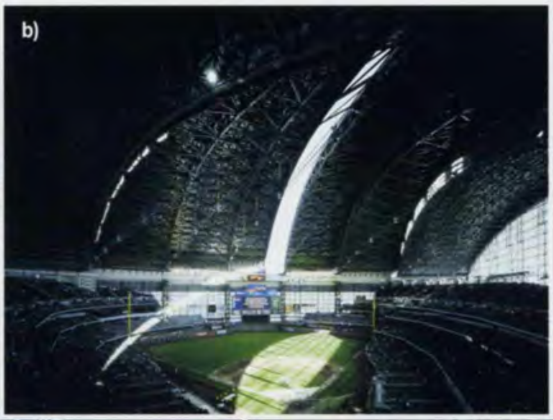
6.
Home plate at the Dodgers.

The project pace was punishing and almost every aspect was on the critical path. Huge credit goes to the project managers, the contractors, the client team and the Arup staff involved for staying the pace and seeing the job through to the end. Feedback on the finished stadium has been tremendous and Arup's involvement with the club and stadium continues to bring project work.

4 a) to e) below:
Opening the roof.

a)

b)

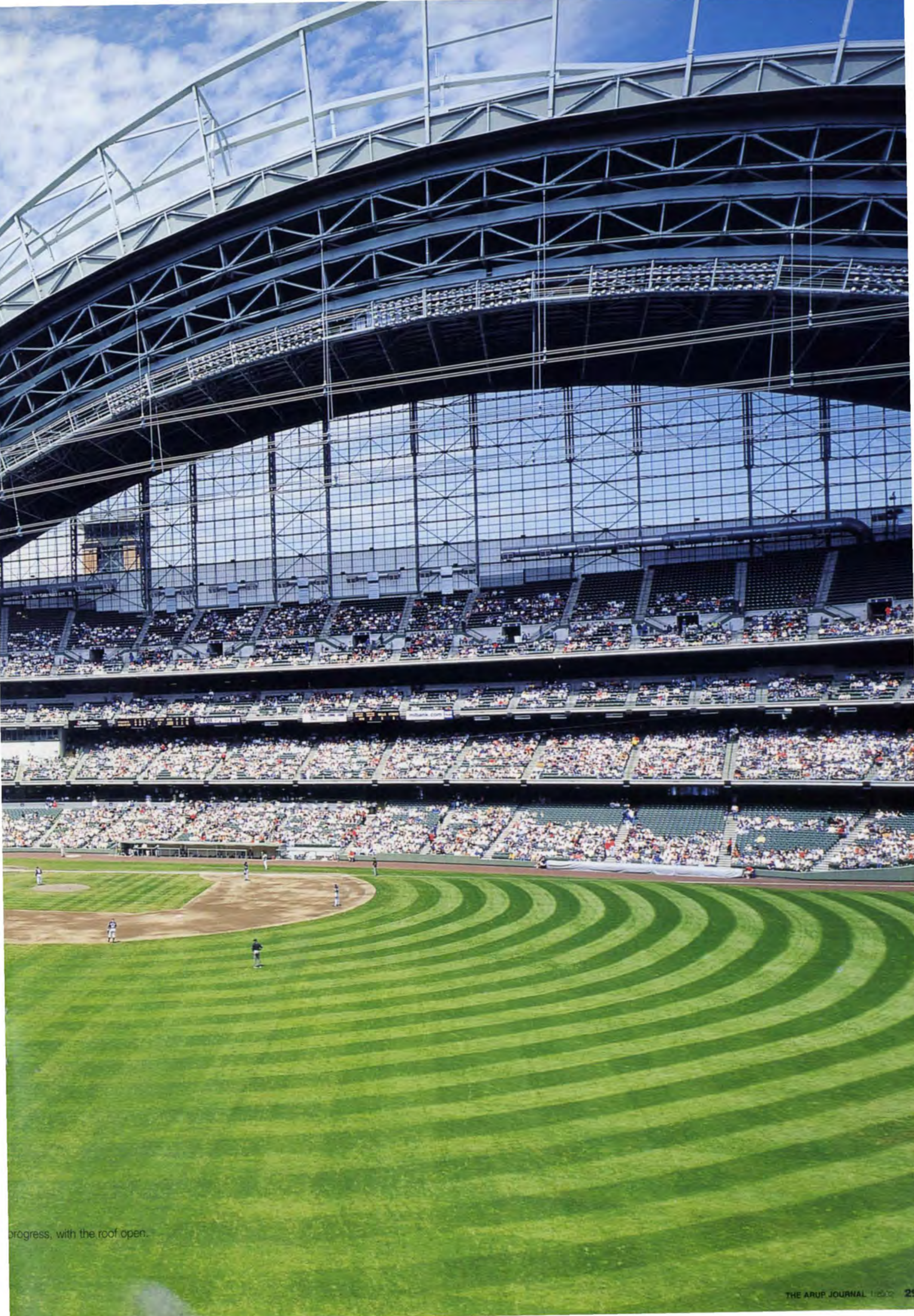


c)

d)

e)

7
Miller Park stadium: a game in



progress, with the roof open.

Crescent walls

On either side of the stadium, glazed crescent walls close the gap between the seating bowl beneath and the arching truss of panel 4 above. However, at 580ft (180m) long and up to 130ft (40m) high, these walls have to do more than just to support cladding.

The edge of panel 4 facing the field spans the full length of the stadium, but to reduce steel weight the other edge is propped by the vertical members of the crescent wall. Whilst carrying these vertical loads and the cladding's wind forces, the wall must also accommodate the geometrical shift from the regular radial setting out of the roof to the more irregular bowl columns beneath. Finally, it must allow panel 4 to move freely longitudinally by ±12in (300mm) as loading changes, ensuring that damaging movements are not transmitted to the wall's cladding. Everything had to be accomplished with an attractive structure fully visible from both inside and outside the stadium.

The crescent wall's truss columns, spaced at between 20 and 40 ft, are supported by the bowl's columns from beneath, and horizontally propped at their head by panel 4. Pairs of truss columns are cross-braced together to form stable towers, and all are linked horizontally by trusses that support the cladding. Towers can move independently in plane, so some cladding trusses have movement joints at their ends that are mirrored in the cladding.

Key members in the wall are the pairs of 'swingers', each up to 29.5ft (9m) long. Pinned at both ends, these carry vertical loads from the panel above to a bracket part way up the truss columns. The swingers can rock to and fro to accommodate the longitudinal expansion of the panel, isolating the truss columns and cladding from distortion.

Construction

Groundworks and bowl construction

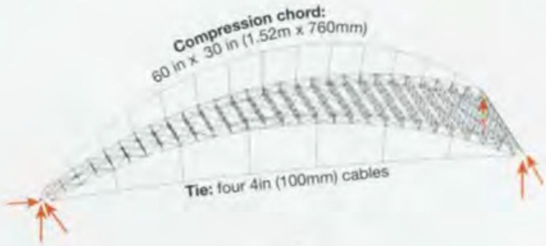
The site was previously a landfill and so, once the piles were in place and before concreting, a barrier was installed over the subsoil to prevent methane escaping. The steel in the bowl structure was fabricated and supplied by Havens Steel of Kansas City, and is remarkable in that it not only supports the stadium itself but also the roof above it, which is of almost equal weight. Columns, some over 300lbs/ft (450kgs/m) in weight, were erected first with floor beams bolted in place temporarily, aiding stability until the structure could be plumbed. Trusses for the club level cantilevers then arrived in segments and were welded complete in the field using a purpose-built jig. Cranes erected the finished trusses into place on the columns whereupon the floor decking was laid out ready for the slab pours. Mechanical services and architectural finishes promptly followed.

Roof steel supply and fabrication

MHI was subcontractor for the roof steelwork - which was much travelled. The high strength Grade 65 and 50 material was forged at Trade Arbed Inc in Luxembourg, and then shipped to MHI's fabrication yards in Japan and China. Now with shop welds and bolt holes for field assembly, the steel then took another sea voyage to Los Angeles, from whence it finally came by lorry to Milwaukee. Offsite at local yards, the separate elements were assembled like a vast jigsaw puzzle into recognisable truss sections, and then trucked to the field for cranes to slot them together. These partial sections of roof, called blocks, weighed around 300 tons (275 tonnes) and measured about 150ft (45m) across.

Roof construction

Once assembled, the blocks were craned up to sit on the columns of the crescent wall and shoring towers. Then, with bolted splices between them and tie cables erected and tightened, one side of a panel could be free-spanned the full 600ft (180m). This done, the other side of the panel, containing the upstand, could be jacked up to fan out the hangers so as to fit in the overlong box chord.

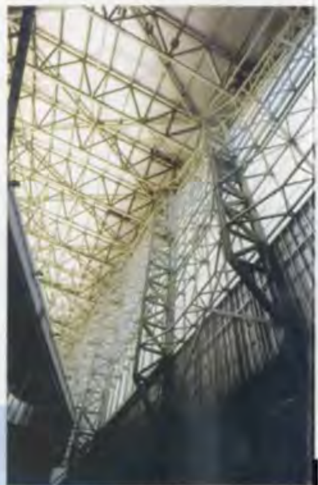


8.
Typical truss.

This over-length favourably redistributed forces within the truss. In the construction sequence developed by the contractor, the panel above used both the free-spanning panel below and the shoring tower and crescent wall structures for temporary support of its separate blocks until it too could be made to free-span. This complex load-sharing arrangement, or 'stacking', involved using large jacks on roller bearings smooth enough to be pushed with a finger, to accommodate the multi-directional differences in movement between the segments.

Crane collapse

On 14 July 1999, Lampson's 'Big Blue', the large crawler crane that was erecting the roof panels, collapsed in high winds while carry a large section of panel 4R. Three workers were killed, the building suffered $100M of damage and a year's delay, and the lives of all those involved with Miller Park and the community of Milwaukee were forever affected. In the months following, all parties worked together to fulfil the wishes of that community and rebuild the stadium. A Demag crane replaced the destroyed Lampson and completed the project without incident; when raised it was one of the tallest structures in Milwaukee - and it could move as well.



9.
Block assembly.

11 above:
Crescent wall.

10.
Block erection.

Paul Brown Stadium

Bruce Gibbons

The existing Cincinnati Riverfront stadium, built in the 1960s, was typical of its genre, being configured for both football and baseball. Nowadays demands for improved sightlines, and added revenue-generating streams for the teams such as luxury suites and club-seating, have led to their replacement with dedicated facilities to specific sports. The new Paul Brown Stadium for the Cincinnati Bengals opened in August 2000 to wide critical acclaim.

The contemporary design of this National Football League stadium breaks the mould of traditional designs by opening the seating bowl at the end-zones, a strategy which eliminates the undesirable corner seats and allows the city to interact with the action inside. The facility comprises luxury suites, club areas, concessions, team offices, and training facilities on eight levels.

The elegant swooping signature roof is a key feature of the building's design, providing intimacy within the bowl and focusing attention towards the field.

Arup was structural engineer for the project, which was built on a fast-track schedule requiring a close working relationship with the construction manager.

Awards

- Chicago Atheneum American Architecture Award 1999
- American Institute of Steel Construction, IDEAS, Innovative Design and Excellence in Architecture Using Structural Steel, Award 2000

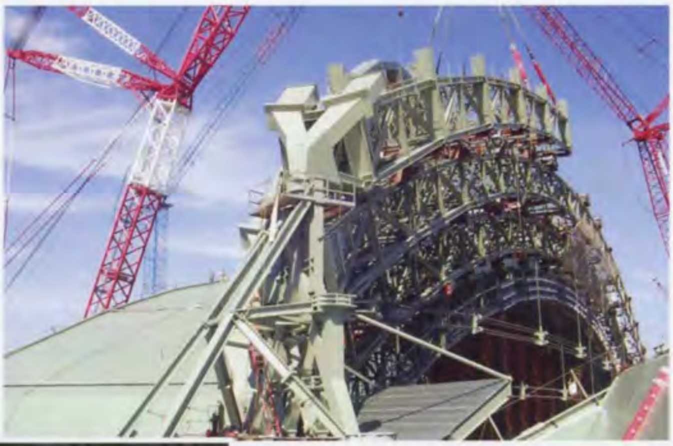
15. Main entrance.

Stadium facts & figures*

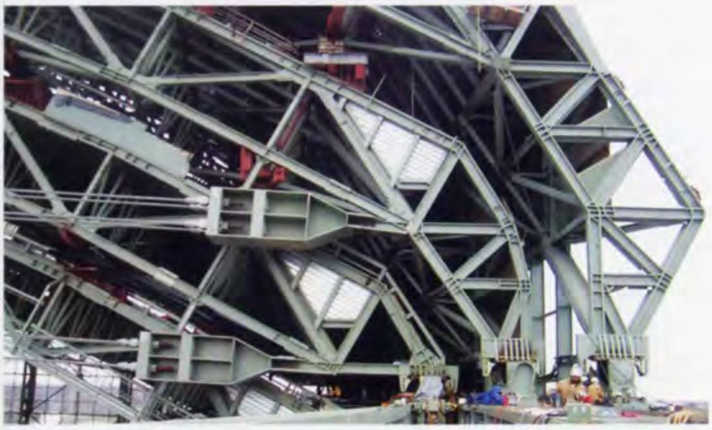
- home of the Cincinnati Bengals National Football League team
- 65 535 seats on three levels, including 7600 club seats and 114 private suites
- total enclosed area: 1 850 000ft^2 (172 000m^2)
- over 11 000 tons of steel reinforcing bars
- approximately 95 000yds^3 (72 500m^3) of concrete
- over 9100 tons of structural steel

www.bengals.com* (Official web site of the Cincinnati Bengals)

12. Pivot frame.



13. First movement of panel 1.



14. Track beam.

Electrical design

Power distribution

Power supplies have to be maintained with minimum disruption during games. After careful evaluation, cost benefit analysis, and co-ordination with the local power company, a dual-feed 26.4kV primary service from Wisconsin Electrical Power Company (WEP CO) was specified. This was based around an automatic change-over design to allow WEP CO to switch from one circuit to another in the event of failure.

Two separate circuits were brought to the stadium and terminated in 35kV rated switchgear, including a tie switch for switching over to either of the two circuits. Two WEP CO utility meters were housed in the switchgear, in a single-storey high voltage switch room near the central plant.

From this switchgear, two sets of high voltage cables in overhead conduit were installed in the service level through the utility corridors.

16 above:
The roof and outfield wall in open position.

17 right:
The roof and outfield wall in closed position.

Early on it was realised that soil conditions were unsuitable for any major conduits to be directly buried; also any conduit penetrations of the soil protective membrane had to be avoided. The architects helped co-ordinate a route for the conduits with other services, at high level within a dedicated zone to one side of the service corridor. Other services running here include the mechanical ductwork, fire sprinkler lines, plumbing pipes, beer supply pipes and cable trays for the various communication cables, sound and broadcasting cables. Vehicle clearance was also necessary here, and all the services required maintenance access as well as physical separation.

Predicted load requirements and the need for optimum voltage drop distribution required five electrical equipment rooms along the service level. For the all-important maintenance of power during games, a double-ended substation installation was selected. Each unit substation comprises a high voltage switch and fuse, a cast coil transformer, and low voltage circuit-breakers. A cross-tie circuit breaker is provided between substations, allowing load sharing should a transformer fail, and additional redundancy. The transformers have aluminum windings.

From the substation, power is distributed at 480V/277V, three-phase, four-wire. Vertical electrical aluminum busway risers at strategic locations supply upper electrical rooms, each housing electrical panel boards, distribution boards, and dry type transformers for 280Y/120V, three-phase, four-wire systems. To avoid problems from generated harmonics, K-13 rated transformers were used to service sensitive electronics equipment for the sound and broadcasting systems, press room, and office computers.

Motor control centres - circuit breakers and starters - at the mechanical rooms serve the HVAC equipment. For variable frequency drives, drive isolation transformers reduce harmonic distortion to the electrical system.

'The client's wish for a modern baseball park combining a state-of-the-art roof with a traditional architectural feel was successfully achieved.'

Emergency power

The multiple substations reduce the risk of complete power failure to a minimum. The general lighting and sports lighting is served from multiple sources to reduce the risk of complete darkness, but emergency power was required for fire pumps, emergency egress lighting, all essential broadcasting systems, smoke evacuation system, and elevators.

Two outdoor emergency generators serve the two halves of the stadium, operating at 480V/277V, three-phase, four-wire, with their own under-frame fuel tanks. Auto transfer switches and emergency switch boards are located in the electrical room. Emergency power is distributed via power distribution boards for critical equipment and lighting, with dry type transformers for the 208Y/120V system.

Each major broadcasting area has dedicated K-rated transformers and panel boards. Separate neutral wires for each branch circuit minimise overload on the neutral wires from harmonic effects. Touring company switches are provided for visiting TV companies as well as performers. Special raceway and designated routing was developed to avoid electrical noise interference to the broadcast and sound equipment from other electrical sources.

Lighting

Both the major lighting systems use metal halide lamps. The general stadium lighting is from overhead pendant fixtures, whilst the field sports lighting, illuminating the playing area, is mounted on the edge of an access and maintenance catwalk, together with dedicated lighting control panels. All the fixtures operate at 277V, one-phase, except those on the emergency circuits, which are 480V.

A DOS-based central processing unit, video monitor, and keyboard control the lighting, with communication for integration with the lighting controllers for the field and architectural lighting as well as the perimeter lighting. Emergency, security, and some non-public spaces are separate from the lighting control system. Local manual control overrides were also provided at each lighting panel in case of lighting control system failure.

Lightning protection

Single masts mounted at roof level form the lightning prevention system. Down conductors connect the masts to ground rods around the building perimeter.

Fire alarm system

This is an addressable system with microprocessor-based control panels. The main control panel, with a graphic display of the stadium, is in the fire control room, linked with remote transponder units strategically located throughout the stadium. Pull stations are at the emergency exits. Smoke detector coverage is to code requirements, including the atrium, smoke-free corridors, elevator lobbies, elevator shafts, mechanical and electrical rooms, and signal equipment rooms. There are detectors in the mechanical ductwork for smoke control and HVAC equipment shutdown. The fire alarm system has a fireman's microphone interlinked with the stadium public address system, which in the event of emergency is automatically overridden by fire alarm announcements and the fireman's microphone.

Mechanical / HVAC

Originally the seating bowl was to be air-conditioned and heated whenever the roof is closed. Due to the use of natural turf the roof is mostly open, and only closed at game time during inclement weather - originally defined as rain, snow (which can occur through May in Milwaukee), and excessive heat and humidity. This was reduced to rain and snow due to the cost of cooling plant necessary for the bowl (about 6500 tons / 6000 tonnes). Although space was left in the building and bowl systems for cooling to be added in future, heating was the dominant condition for sizing the air systems. A wind study analysed the summer airflow through the bowl with the roof closed for shade during play, and showed that the primary wind condition was towards the outfield wall. This was therefore made operable to allow this wind to penetrate the bowl.

Additionally, operable louvers above the terrace seating relieve the hot air rising from the occupants and seating deck. Air is thus induced across the fans giving good air movement, which can be supplemented by the heating system. Due to the roof stacking, most of the seating bowl is in shade and thus the concrete does not receive direct solar radiation - a significant advantage for not providing cooling.

The focus of the design was thus to heat the bowl and concourses by 30°F (17°C) above ambient. The strategy adopted was to introduce air via jet nozzles above each seating level to create an envelope of warm air, supplemented by jets at the highest level introducing more warm air into the downdraught from the roof, creating the dominant air movement in the space. The two airstreams mixing is enough to temper this cold air stream but not prevent its downward momentum. The airflow then rises due to the gains above the seating deck. Air is returned through the concourse and vomitories to the air handling units (AHUs). Displacement ventilation was considered, but abandoned early due to the primary function being heating - plus hygiene considerations (Coke, beer and peanuts is a potent mixture). The team spent much time with the client discussing operation of the roof and heating system. The original requirement was to close the roof and start the system assuming an instantaneous comfort condition. This had to be discussed, and an early closing implemented to allow time to overcome the cold built-up within the seating deck. This required a change in operation strategy so that the roof would be closed.

Five AHUs serve the lower field bowl (90 000ft^3 (2550m^3)/min total), four serve the club level bowl (20 000ft^3 (570m^3)/min each), and two the terrace level bowl (94 000ft^3 (2660m^3)/min each). Each unit contains indirect gas-fired heaters to give 70 000Mbh heating capacity for the bowl and concourses, as well as smoke control capability.

These systems utilise a minimum outside air quantity of 5ft^3 (0.14m^3)/min per person. The quantity of air equivalent to the ventilation requirements for the bowl is exhausted by the concession hoods or dissipated through the façades.

This system was checked and optimised by a computational fluid dynamics (CFD) study, allowing the final permeability of the exterior skin to be determined as well as verifying the total capacity of the systems. By offsetting permeability of

18.
Players warming up in the new stadium.

the fabric (final 5% open) against system size it was possible to work with the architect and contractor to significantly reduce the size of the mechanical system and save costs. The primary move was to detail a flap that closed the gap between each roof panel. The half-bowl CFD model required 420 000 cells. The external skin pressure coefficients were determined from the wind study. Both winter and summer conditions were studied, the latter showing enough air movement in most of the seating area for adequate comfort.

Besides the seating bowl there is an additional 300 000ft^2 (27 800m^2) of enclosed, fully conditioned space including offices, restaurants, locker rooms, and storage, all served by conventional air systems with distributed AHUs adjacent. These have a 1600 ton (1460 tonnes) central cooling plant and 33 000Mbh hot water heating plant which also gives frost protection to the turf via buried pipes. This system is only used before game time so the same boiler plant can be used without increasing overall capacity. Both systems contain 30% ethylene glycol to protect against freezing. The concourse food services have local split system heat pumps above each unit; a total of some 53 000ft^3 (1500m^3)/min of grease exhaust ascends to the roof.

Public reaction

The public has been overwhelmingly enthusiastic about the new stadium. At topping-out, they covered the final upstand segment with thousands of signatures, and months later hundreds of thousands of people turned up for open houses before the start of the season, jamming the freeways.

The pre-season games and the 6 April opener itself were spectacular events featuring tributes to everyone involved and the community itself, which hopes to finally shake its association with dated TV shows and the like. Indeed, the fact that the stadium has been built there at all is a testament to its spirit - apparent during the early games when thousands of seats stood empty as people wandered around the building in awe, jaws dropping at the first sight of the roof high above their heads like a man-made sky soaring into the distance. Most of them also waited after the end of the game to watch the roof move in a silent, smooth, 10-minute motion to the sounds of the opening of Strauss's *Also Sprach Zarathustra* from *2001: A Space Odyssey*, cheering as it did so. And, in a month when it has been known to snow, for once people complained of the stadium actually being too warm!

Conclusion

Dirt from the batter's mound in the original park was ceremonially placed in the new field, and the traditional tower where the mascot 'Bernie Brewer' slides down into a replica of home plate when a home run is scored has also moved into its new residence. At the opening game the first pitch was thrown by President George W Bush.

The Brewers certainly have a unique, state-of-the-art park - and an indication of its wider impact came in October 2001 when the magazine *Popular Science* gave the roof one of its 2001 'Best of What's New' awards in the 'General Technology' category.

Credits

Owner:
Southeast Wisconsin Professional Baseball Park District

Architects:
HKS Inc
NBBJ Sports and Entertainment
Epstein Uhen Architects

Construction manager:
HCH joint venture

Consulting engineer:
Arup Arif Bekiroglu, Jon Bell, Luis Bernal, Jacob Chan, John Chan, King-Le Chang, Chung-Chi Chu, Keith Chung, Tony Cocea, Chuan Do, John Gautrey, John Hewitt, Richard Hough, Swaminathan Krishnan, Samir Kulenovic, Morgan Lam, Gary Lau, Alan Locke, Surinder Mann, Hideki Nishizawa, Barry Ralphs, John T Roberts, Bruno Sum, Dan Ursea, Catherine Wells

Subconsultants:
FLAD Structural Engineers (structural)
PSJ Engineering, Inc (mechanical/plumbing/ fire protection)
Powertek Engineering, Inc. (electrical)

Roof steelwork and mechanism:
Mitsubishi Heavy Industries America

Bowl steelwork:
Havens Steel
HVAC
Advance Mechanical

Electrical:
Pieper

Illustrations:
1, 2, 4, 7, 15-18: Tim Griffith
3: Daniel Blackhall
5, 6: ©Milroy & McAleer
8: Sean McDermott
9-14: Surinder Mann

1.
The CGS floating in the dock preparatory to being towed out.

Malampaya: the first CGS built in Asia

David Collier

Background

The Malampaya Deep Water Gas to Power Project, a major development in the Philippines, presented an opportunity to demonstrate the benefits of a concrete gravity substructure (CGS) in South East Asia. The gas field is in 850m of water, to the north of Palawan Island. Arup Energy had been studying CGS applications in the region for 10 years, during which time the Wandoo CGS was successfully installed on the north west shelf of Australia in October 1996[1], but Malampaya offered the chance to prove a CGS could be delivered in a developing country.

The overall development concept was to process the gas offshore and export it dry to an onshore plant for final processing, whence it will be used as fuel to generate electricity from three combined cycle gas turbine power stations of 2700MW overall capacity. Associated with the gas was condensate, a light oil, which was present in sufficient quantity that it could not be carried in the gas stream. The condensate was therefore to be separated and stored offshore before being exported via shuttle tankers.

The original development scenario led to two main concepts:

- *a tension-leg platform installed at the deepwater offshore field location*
- *subsea facilities tied back to production facilities in shallower water, 30km from the field.*

The options for the support of the shallow water production facilities included a jack-up, a steel jacket, and a CGS.

Feasibility and bid

In 1996 Arup Energy was commissioned by Shell International Exploration & Production BV (SIEP) to confirm the technical feasibility, the cost, and the schedule for constructing a CGS in the Philippines.

The inauguration of the Malampaya Deep Water Gas to Power Project marked the birth of the Philippines' natural gas industry.

The study was in two phases. The technical feasibility was assessed using the Arup Energy CGS sizing expert system, modified to take account of the implications of significant earthquake loading. Local investigation then took place to obtain accurate information on the capability and cost of construction in the Philippines. Contractors were interviewed and suitable CGS construction locations identified.

The indications were that it was technically feasible to construct a dock and build a CGS in the Philippines, with the preferred execution strategy being to select a contractor who had established a joint venture arrangement with a local contractor. Two construction locations were identified, Subic Bay and Batangas Bay, both on the east side of the main island, Luzon. Subic Bay is three hours' drive north of Manila and Batangas Bay two hours' drive south.

Compared with other shallow water development options, the CGS offered the two significant advantages of integral oil storage and the potential for local construction. All the other solutions considered required a separate structure, such as a tanker, to provide the condensate storage capacity, and it was generally accepted that none of the steel solutions could be fabricated in the Philippines. Although there was a perceived political risk associated with building in the country, the technical and economic advantages of the CGS resulted in it becoming the base case development option. Arup Energy and one other designer were each awarded a Front End Engineering Design (FEED) study in early 1998.

From the outset, the fundamental design aim was to develop the most economic and practical CGS design, consistent with the following objectives:

- *to maximise safety*
- *to optimise the overall field development cost, not just the substructure cost*
- *to minimise the structure required solely for transportation and installation*
- *to maximise the proportion of the enclosed volume used for oil storage*
- *to minimise environmental impact*

2.
Location plan.

- *to provide a flexible design and thereby minimise the impact of late revisions of the design brief*
- *to design a structure which would be simple and straightforward to build, with repetitive elements without excessive amounts of reinforcement and prestressing.*

Following the FEED study, the Malampaya CGS Alliance was assembled by Arup Energy to bid for delivery of the CGS. The team comprised Arup Energy plus John Holland, a leading Australian civil contractor, and Van Oord ACZ, an internationally known marine contractor. Arup Energy had originated the shallow water CGS design, and Arup had had a permanent office in the Philippines since 1990. John Holland had been operating in the Philippines for over 10 years and had good local knowledge and experience, whilst Van Oord ACZ was selected on the basis of their specialist skills in dredging, rock dumping and installation.

On 25 September 1998, following an international tender, the Malampaya CGS Alliance was awarded the contract to design, construct, and install the CGS. The only key date in the substructure contract was that it had to be fully installed on the seabed before 1 September 2000.

The fundamental design aims were economy and practicality.

Objectives

At the outset, the Alliance organised workshops to facilitate positive alliancing behaviour and build good personal relationships between the team members in the three companies. This proved very beneficial, as none of the parties had worked together before.

These workshops also included representatives from both the Alliance's client, HMI (a local subsidiary of Brown and Root) and its client, the field operator Shell Exploration Philippines (SPEX). It was recognised that, although HMI and SPEX were not Alliance members, their contribution was critical to the project's successful outcome. During the initial workshop, all parties committed themselves to achieving five key objectives:

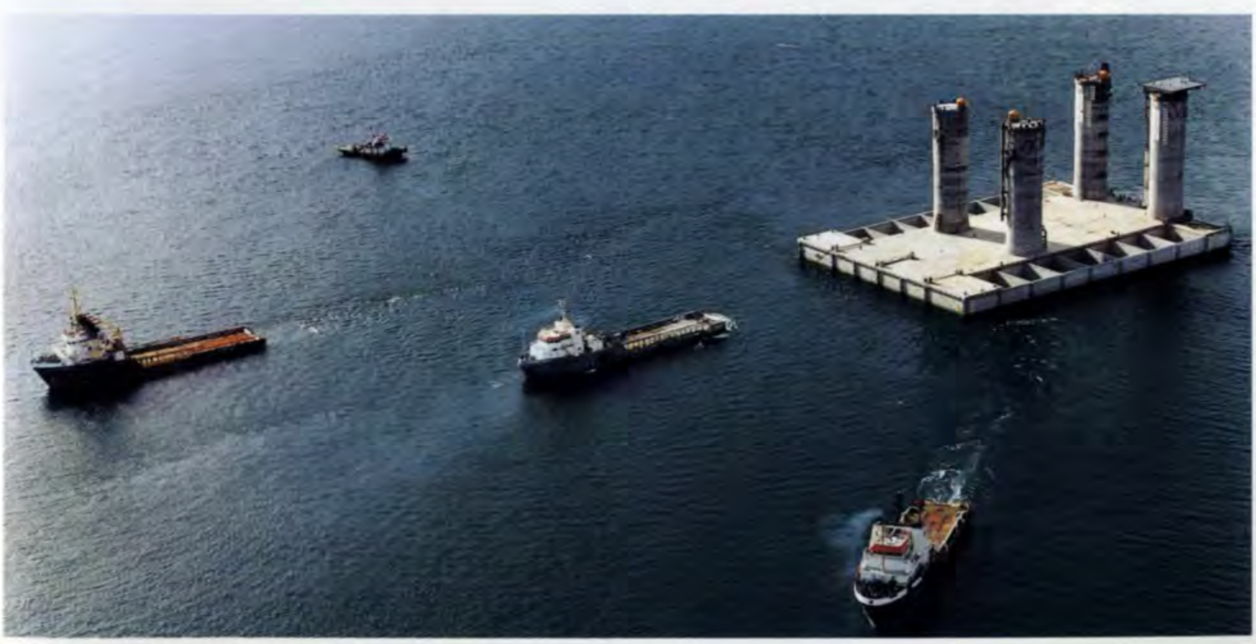
- *to build a CGS without injury or incident*
- *to minimise the project's environmental impact*
- *to meet all quality requirements*
- *to deliver the CGS for 1 September 2000*
- *to achieve the financial objectives of all parties.*

Individual team members of the Alliance developed and implemented strategies to meet this challenge. In addition, several stretched targets were identified to focus the team on identifying improvements in how the project could be executed to the benefit of all the Alliance personnel, the Alliance companies, the local community, and the client.

Site selection

In 1996, as part of the feasibility study, Arup Energy had identified Subic Bay, an ex-US naval base, as a good potential construction location. It has a natural deep-water harbour, reasonable road access, and plenty of local labour living just outside the former base. However, the local authority was very keen to offer SPEX a different location - an area of land on the other side of the Bay previously used by the US military as a firing range. It was found to be adequate in terms of area and access to deep water, but it had no road access. Nonetheless, its selection as the site was confirmed following a limited site investigation that showed that soil conditions were suitable, if not ideal, for building a dry dock.

In terms of project execution, the remoteness of the site was a challenge. All plant, materials, equipment and labour had to be imported by sea. Landing craft were a logical choice for supplying the site in the Philippines. However, it was considered undesirable to transport 1000 workers to and from site every day, so one of the first activities was to build a construction camp with site offices whilst the casting basin was being excavated.



3.
The CGS *en route* to the field 80km north west of Palawan Island.

Although the area had no road access, there was an adjacent fishing village. The relationship between the village and the project remained very good throughout construction - indeed, many villagers were employed on the site.

Once the area had been cleared and checked for unexploded ordnance, construction of the dry dock could commence. A slurry wall was installed in the sea bund to cut off the sea from the excavation. Deep wells were used to draw down the water table generally and rings of well points placed to dewater the soil locally. The soils mostly comprised silty marine deposits, which are very easily eroded by surface run-off and difficult to dewater fully. The latter fact was most important in demonstrating acceptable seismic performance of the bund separating the dock from the sea.

Design solutions

Outwardly the CGS appears similar to previous Arup designs. Many of the details Arup Energy had developed over the previous 12 years could be directly employed on the new project. The main functional requirements of the CGS were to store 385 000 barrels of stabilised condensate and to support a 16 500 tonne topsides, to be installed by the floatover technique, in 43m of water.

4. Utility shaft under construction, October 1999

The major departures from previous practice were that: the seabed at the proposed site was uneven and could not directly support the CGS without the introduction of a levelling layer; there was a significant level of seismic activity at both the construction site and the offshore location and the environmental conditions were the most severe yet encountered on a shallow water gravity platform.

At tender, the design solution consisted of a base caisson 112m long by 70m wide by 16m high, with four 11m diameter shafts located eccentrically on the base caisson to minimise mechanical outfitting. It had been based on a water displacement condensate storage system that permitted direct discharge of ballast water to the sea. Arup Energy had reservations about this system because, of the possible storage systems that could have been selected, it posed the greatest risk to the environment.

One shaft on the end supported four external risers - two infield flowlines bringing gas from subsea wells to the platform, one export gas pipeline to shore, and one condensate export line to a CALM buoy. It also housed the condensate storage equipment internally. The other end shaft contained 11 J-tubes through which passed umbilicals that controlled the subsea equipment in the field. The two shafts towards the centre of the substructure were under the safe end of the platform topsides and only supported utilities caissons.

Design of the concrete structure followed what have become tried-and-tested techniques. Once the installation sequence was confirmed, and the structure found to be stable in tow and installation, the detailing and verification of the concrete elements could be progressed.

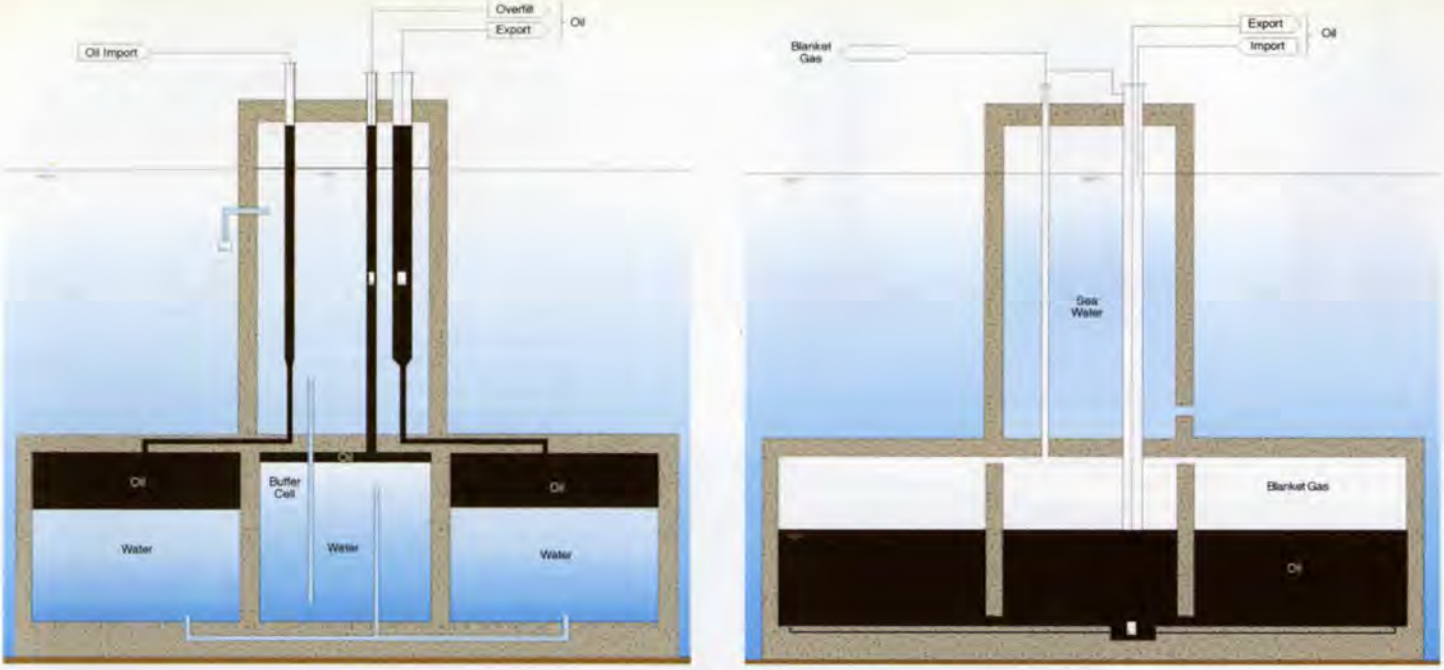
The key early design decision was how to overcome the unevenness of the seabed and resist the earthquake loading. One benefit of the alliance approach is that it enables discussion to be free-flowing, and the design and marine teams were able to identify the best answer unencumbered by company contractual considerations.

Several solutions were assessed, including placing a levelling layer on the seabed or gravel bed, or casting variously shaped downstand beams onto the underside of the base slab, or combinations of both approaches.

The aim was to limit the local contact force on the underside of the base and prevent overall bending of the caisson, and the final solution that appeared to satisfy most of the criteria was to install a series of equally spaced gravel humps on the seabed, to an out-of-level tolerance of ±100mm.

The benefit of humps to the design team was that their crush characteristics were tractable to analysis and variations in the heights of individual humps were statistically independent. The experience of the marine team in predicting the 'as-installed' shape of the humps was critical, as it was not possible to carry out any trials before base slab construction commenced.

5. The CGS in the casting basin, with slipforming of the base caisson in progress.



6.
(a) Above left: Open wet storage system.

(b) Above right: Dry storage system.

Levelling the seabed, however, was only half the solution. The humps also had to give good resistance against wave and seismic loading. It was successfully argued that the performance criteria for the ductility level earthquake (DLE) and strength level earthquake (SLE) should be horizontal movement limits for CGS sliding. To maximise the performance of the sliding interface between the CGS and the humps, a series of tests was undertaken to assess the best method of roughening the concrete. The chosen solution was to cast the base slab on a dimpled plastic sheet, which had the effect of increasing the interface friction angle by 3° compared to plain concrete.

One unusual feature was that although the site was in 43m of water, it was surrounded by much deeper water. This proved to be challenging for calculating the extreme wave loading on the CGS, as the deep water wave was likely to be near breaking as it passed over the caisson. After taking advice from external experts, additional non-linear surface forces, rarely encountered on CGS designs (Faltinsen, Newman, Vinje forces), were accommodated. These act over a depth of around 5m below the instantaneous water surface and increase overall wave loading by about 10%.

The innovative aspects of the Malampaya CGS design described above are presented in greater detail in reference[4].

As on Wandoo, a change to the performance criteria of the substructure was made after construction had commenced. This, once again, tested the flexibility of the dry-build CGS concept. By the end of February 1999 the first base slab reinforcement drawings, detailed by a team established in Subic Bay, had been issued to site.

Then the carefully planned production of site information was radically disrupted. In March 1999, due to concerns about the quality of ballast water discharged from the storage system, the Alliance was asked to quantify the impact of changing from the open system to a dry storage system where seawater is not used to displace condensate. The only constraint was that the original schedule had to be maintained.

Within three weeks a revised scheme was developed and costed, and measures to accelerate the programme to meet the original schedule identified. Within a very short time the decision to change the storage system was made, and the pressure was on the design team to re-do the analysis, design, and provide a new set of drawings.

Changing from a wet to a dry system had two major effects on the design. In a dry system, when the storage compartments are empty, there is a significant buoyancy effect, tending to lift the substructure off the seabed. This can only be overcome by adding more solid ballast to hold the substructure down. To accommodate this extra ballast, the open cells were increased in volume by 50% and the structure had to be strengthened to resist the extra weight. The second effect is the fact that the base caisson can experience the full external hydrostatic pressure under normal operation, which requires additional strengthening to the external caisson walls and slabs. The combination of these two effects resulted in the concrete volume increasing from 27 000m^3 to 34 000m^3 and the reinforcement weight from 7500 to 12 000 tonnes.

The interface with Brown & Root, the topsides designers, ran very smoothly, founded on mutual understanding of each other's requirements and the desire to find the best overall solution for the project. This was most evident in the approach taken to satisfying acceleration limits in the topsides, a contractual requirement placed on the CGS designer. Acceleration of the topsides under seismic events had to be limited to 0.4g for the SLE and 0.65 for the DLE respectively, and this was achieved by adopting an integrated approach.

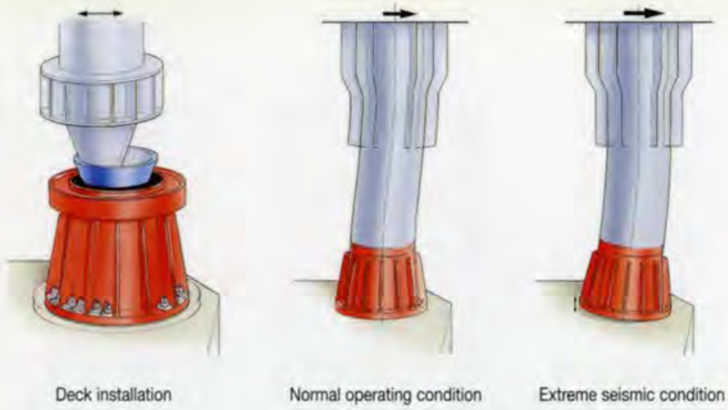
The two main structural models of the substructure and topside were connected and subjected to a non-linear time domain analysis to determine the earthquake response. It was found that accelerations in the topsides could be tuned by varying the stiffness of the connection between the topsides and CGS, the final solution consisting of a steel tubular connection with a flange supported by but not bolted to the top of the concrete shaft. Under extreme seismic events, the flange will tend to lift off one side, introducing flexibility into the connection. This effect was found to limit the acceleration in the topsides to an acceptable level.

Construction

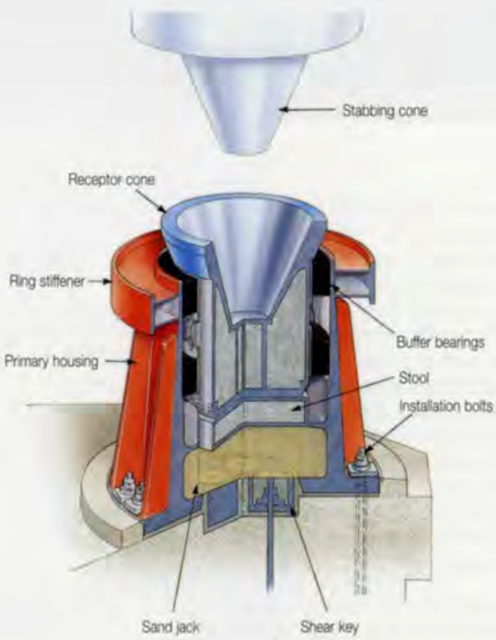
Within six weeks of the decision to change from wet to dry storage, reinforcement drawings were issued allowing concrete works to proceed. In the same period, the dry dock and sea bund were extended to accommodate the extra width of the base caisson. The first base slab pour was completed on 10 June 1999, some two months later than the original schedule.

Construction was by civil engineering techniques that have become conventional through their use on previous dry-built CGS projects. The slabs and caisson walls were split into eight sections for pouring, and the caisson walls and shafts slipformed. Construction was managed by foreign staff, with the labour and most of the supervision from the Philippines.

Malampaya, the third successful CGS designed by Arup Energy, won the International Projects section of the Concrete Institute of Australia's 2001 Awards.



7.
Deck connection behaviour.



8.
Topside connection detail.

Considerable attention was given to training the local staff to achieve requisite levels of quality and safety on site, and the result exceeded most people's expectations. The standard of steel fixing and the finished quality of the concrete was acknowledged to match if not exceed that produced on similar projects anywhere in the developed world. The level of safety was also exceptional, with only two lost time incidents being recorded. The first occurred near the beginning of the project. Subsequently, over 4M manhours were worked without further mishap. Productivity also was higher than expected, the local labour proving highly motivated and very capable.

Once the first concrete slab had been poured, the benefit of all the preplanning and training became evident. There was a continuous improvement in the speed in forming walls and shafts. In fact the final slip was completed at twice the rate of the initial slip. All the reinforcement, apart from the first pour, was detailed on-site to suit the agreed method of construction. By December 1999, the original schedule had been regained and the construction was running approximately one and a half months ahead of programme.

A modular approach, successfully introduced on Wandoo, was again used for the mechanical outfitting inside the shafts. This greatly benefited the construction schedule and productivity as it minimised the amount of work inside the shafts. A modular steel tower was developed for the utility shaft, which provided support for the oil storage pipework and routing for the controls and instrumentation caisson.

This was fabricated offsite in sections and outfitted horizontally at low level, before being lifted into the shaft and bolted together. Being self-supporting for vertical loading, it only required a small number of connections to the shaft wall. Overall, Malampaya is the fastest dry built CGS yet to have been constructed[5].

Marine operations

The concrete structure was complete by March 2000. Meanwhile, the marine operations were well under way. The fall pipe vessel 'Rocky Giant' was busily installing 361 humps to level the seabed - and their shape and size turned out exactly as predicted. However, positioning the fall pipe proved to be time-consuming. The main problem was that the global positioning system was not very stable, even though there was theoretically sufficient satellite coverage in the area.

Each hump was typically placed with more than one dump of rock, to ensure that its height was not overshot. Dumping rock on an existing hump was found to be relatively fast as the existing hump provided a visual reference. The overall accuracy of the hump placement was very good, with only a few outside the specified tolerance. The stiffness of each hump was determined from its 'as built' shape and height. This information was used to calculate the peak reactions to compare with the design forces. A small number of humps were modified using an airlift to ensure that their reaction satisfied design criteria.

By the end of April testing of the structure and the outfitting was complete. The dock was flooded on 16 May, and dredging the sea bund then commenced. The moment of truth for the weight control engineer occurred early in the morning of 28 May when his prediction of the final weight of the structure could be checked with the draft at float-up. The final weight was back-calculated to be within 250 tonnes (ie 0.3%) of the predicted weight - a testament both to the quality of the dimensional survey and the method of establishing concrete densities through correlation of the cube testing with coring of selected elements.

Time line

1996 → 2001

Feasibility study: June-July 1996

Front end engineering study: April-June 1998

Tender: July-August 1998

Contract award: 25 September 1998

Site clearance: November 1998 - January 1999

Casting basin construction: December 1998 - May 1999

Base slab construction: May 1999 - October 1999

Caisson wall construction: June 1999 - December 1999

Caisson roof construction: August 1999 - January 1999

Shaft construction: September 1999 - February 2000

Prestressing: December 1999 - March 2000

Mechanical fit-out: October 1999 - March 2000

Dock flooding: May 2000

Tow: May 2000

Installation: 1 June 2000

Topside Installation: 17 March 2001

Inauguration: 16 October 2001

9.

Installation

Float out from the dock took place in the early afternoon of 28 May 2000, using two harbour tugs and one main tow tug. Once outside the dry dock, the marine fleet was reconfigured and the tow to field commenced. It was uneventful. The weather was fine for the whole route, and the fleet arrived at the field early on the morning of 1 June.

Four tugs moored in star formation were used for installation, each moored to prelaid anchors to control the position of the CGS during the inclined installation. Ballasting commenced at 13.00 hrs, with the leading edge of the base slab touching down on the prepared bed five hours later. Thereafter the CGS was rotated to the horizontal position before touching down completely just after midnight. The crushed rock scour protection blanket was placed around the structure, followed by placing of iron ore in the open cells.

Installation of the deck was completed on 17 March 2001. It was transported on a specially modified barge which was moored to the shafts during the floatover operations. The total weight of the deck at mating was 11 500 tonnes.

Operation

On 16 October 2001, Her Excellency President Gloria Macapagal-Arroyo inaugurated the Malampaya Deep Water Gas to Power Project at the onshore gas plant inside the Shell Tabangao Refinery in Batangas City.

The inauguration, three and a half years after the Project's declaration of commerciality in May 1998, marked the birth of the Philippines' natural gas industry.

The success of the Malampaya CGS project in the Philippines has demonstrated that concrete gravity substructures can be constructed to internationally recognised levels of quality and safety in developing regions of the world.

The fact that the CGS was installed three months early, in spite of delays caused by the change from a wet to a dry storage system, can be attributed to the alliance method of working and the dedication and commitment of the team.

The CGS concept has once again shown itself to be economical, flexible, adaptable and, above all, robust.

References

(1) JACKSON, G. *and* CARE, R. Wandoo concrete gravity substructure. *The Arup Journal, 32*(4), pp18-25, 4/1997.

(2) COLLIER, D. Concrete achievements. *Offshore Engineer,* pp36, 39, April 2001.

(3) COTTRILL, A. Floatover puts Malampaya on final straight. *Offshore Engineer,* pp29-32, 35, April 2001.

(4) McNULTY, A, *et al.* New development in the design of concrete gravity substructures - the Malampaya CGS. Offshore Techology Conference (OTG) Paper no 14889. Houston, May 2002.

(5) CHUDACEK, J et al. Construction of offshore concrete structures in developing regions - the Malampaya concrete gravity substructure. OTG Paper no 14223. Houston, May 2002.

10.
The CGS during installation.

11.
The CGS fully submerged in position awaiting topsides.

12.
The topsides approaching the CGS for installation.

Credits

Client:
Shell Philippines Exploration BV

Alliance Partners:
John Holland Group
Van Oord ACZ

Arup Energy Keith Ali, Christian Allison, Jolyon Antill, Steve Armstrong, Arnel Bautista, Terry Bell, Juliet Bird, Danny Bonnett, Phil Bramhall, Craig Braynion, Ian Brooks, Chris Buck, Simon Cardwell, Bob Cather, David Clare, Justin Coe, David Collier, Clare Courtney, Xiaonian Duan, Nelson Eustaquio, Neil Evans, Matteo Farina, Ian Feltham, Rowel Galan, David Gration, Martin Greenacre, Andrew Grigsby, Hayley Gryc, Richard Henderson, Peter Hoad, Andrew Horton, Charlie Houston, Chris Humpheson, Kathy Hurley, Conrad Izatt, Robert Lea, Michael Locock, Steven Long, Zygi Lubkowski, Alan MacLeay, Sarah McKenna, Andrew McNulty, Rhonda Nicoll, Ian McRobbie, Henry Medina, Charles Milloy, Hector Montalbo, Chris Murgatroyd, Pierre-Yves Mutel, Rachel Nicholls, Ai-joon Ong, Chris Owen, Ed Palaganas, Navin Peiris, Bernie Pemberton, Kevin Power, Martin Preene, Richard Purdy, Rene Quiambao, John Redding, John Roberts, Rupert Rowland, Tony Ryan, John Salter, David Scarr, Richard Seago, Greg Smith, Rob Smith, Chris Stowe, Bruce Stowell, Allen Teh, Jomel Uy, Michael Willford, Matthew Wilson, Jason Yeomans, Peter Young

Specialist consultant:
Noble Denton Consultancy Services Ltd

Illustrations:
1, 3, 10-12: Stevenson Kinder & Scott
2: Martin Hall
4, 5: MCL Alliance
6: Arup Energy
7, 8: Fred English
9: Desmond Wyeth

The Braun headquarters, Kronberg, Germany

Brian Cody

Introduction

The principal ideas behind the environmental concepts for the new Braun HQ building in Kronberg, near Frankfurt, were developed by Arup together with the architects Schneider + Schumacher during the invited competition in 1996. This building represents a 'second generation' of the design philosophy of this particular team of architects and engineers, who worked closely together on a series of earlier projects. The building Schwedlerstrasse 6[1] in Frankfurt belongs to the first generation of this series, and the design principles established there were developed further, optimised, and combined with new approaches in this second generation. The team is currently working on a low energy office building in San Diego, California.

Competition

Design principles carried forward from the earlier Schwedlerstrasse project include exposed concrete slabs (thermal mass), displacement ventilation, raised floors, glass-enclosed space used as a thermal buffer, and thermal zoning. Due to the heavy traffic on the south west of the site, a double façade was provided here for sound insulation. A mixed mode ventilation concept was conceived, whereby the offices would be predominately naturally ventilated, the mechanical displacement ventilation system being used only in extreme weather. An unheated central atrium would act as a thermal buffer, in which trees, water features, and an air supply via an underground duct system improve the environmental conditions. For office planning, the client's brief called for a so-called 'combi-büro' concept with small cellular offices on the perimeter and a flexibly-used central 'combi-zone' inside. However, total flexibility, with the capacity to switch to traditional cellular offices with a central corridor or open plan, was also required. The external zone would have constant mechanical ventilation, and perimeter heating by trench heaters in the raised floor void.

Design development of environmental concepts

One characteristic of a double skin façade is that the outer surface appears smooth, though a semi-external shading system can still be provided.

To achieve this smooth appearance all round, it was decided early in the project to extend the double façade to all sides of the building. The resulting improvement in the façade's thermal performance then allowed the question to be posed as to whether the offices could be heated and cooled by a heated or chilled ceiling surface alone. This would allow the mechanical ventilation system in the external zone and the trench heaters to be eliminated, resulting in a large reduction in the building services' costs.

Using the ceiling as a heating surface is feasible, as long as the temperature difference between the surface of the ceiling and the room is no larger than about 5°K. It is also important that the temperature difference between the room and the internal surface of the façade does not lead to cold draughts, the design external temperature in Frankfurt being -12°C. Both conditions were met by the proposed façade design. The specific heat capacity of water is roughly four times greater than that of air, so the same energy content can be transported by much smaller systems. The decision to cool the building using chilled ceilings instead of the original air system enabled a significant reduction in space requirements for plantrooms and shafts. The resulting design comprised small bore plastic tubing embedded in a plaster layer on the underside of the concrete slabs, connected to pipework running in the void of the floor above. Access panels for the valves are in special elements cast into the slabs, which also contain the lights, sprinkler heads, and smoke detectors.

1 top:
The finished building at dusk.

'The client is very happy with the building's performance, and occupants have found that the thermal environment is very pleasant...'

Early in the project Arup carried out feasibility studies on the viability of these façade and HVAC services concepts, looking at the following aspects:

- thermal performance in winter
- thermal performance in summer
- acoustic performance
- condensation risk
- control stategies (ventilation, solar shading)
- effect on the heating load of the building
- effect on the cooling load of the building.

Two alternatives were compared - a single-glazed external skin plus a double-glazed internal skin; and a double-glazed external skin plus a single-glazed internal skin.

The former was chosen, mostly because of better acoustic performance and the lower internal surface temperature of the façade in summer.

The proposed HVAC system was also examined and compared with the conventional air-conditioning system preferred at first by the client, in particular the US parent company, Gillette. Extensive computer simulation showed that the proposed concept could deliver comfortable conditions in both warm and cold weather. The lower surface temperature of the ceiling slab in summer and the higher temperature in winter enables a higher air temperature in the room in summer and a lower air temperature in winter, leading to energy savings. Since the external offices are naturally ventilated, the cooling capacity of the system is compromised when external conditions are warm and humid, as the flow temperature of the chilled water has to be adjusted upwards to avoid condensation on the ceiling surface. The studies showed, however, that the desired internal conditions are not attained due to the above during only 50 hours per year (less than 3% of the working year).

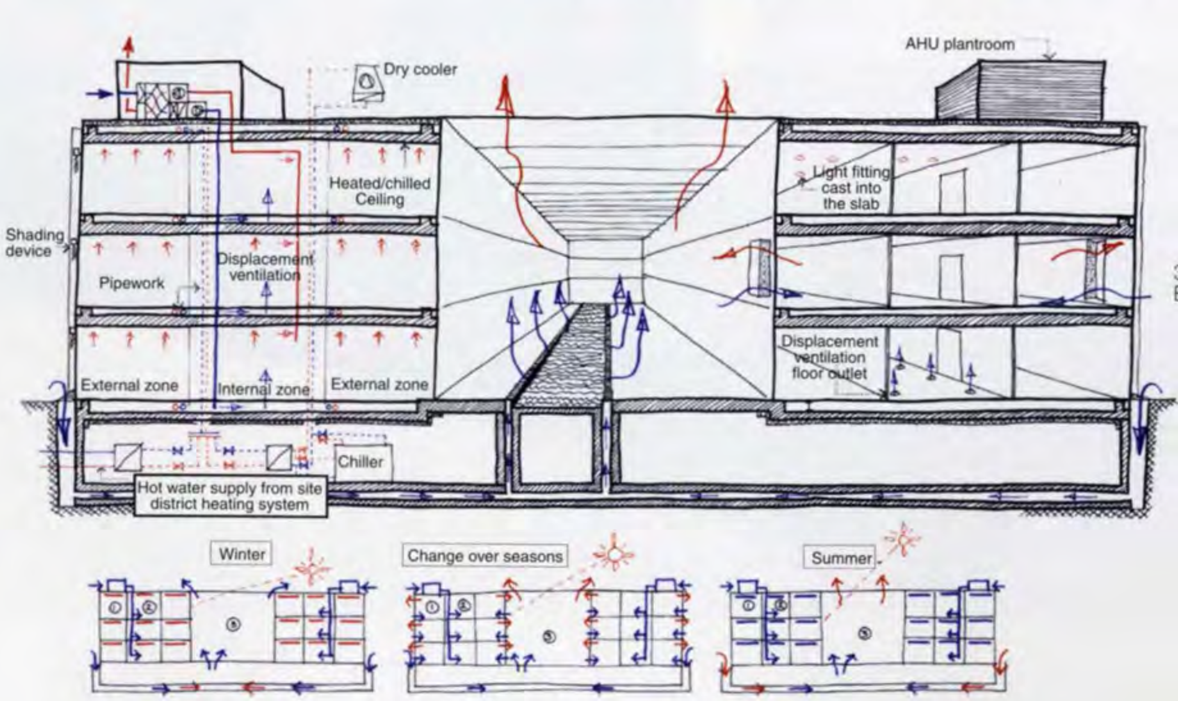
The capital costs of the proposed system, about 300DM/m^2 (€150/m^2), were significantly lower than the cost of conventional air-conditioning. The estimated reduction in running costs was calculated as DM40 000 pa (€20 000 pa). As one complete system - the conventional perimeter heating - could be dispensed with, the financial viability of the double façade concept is greatly improved compared to other built projects of this type to date. On the basis of these studies the client was convinced to go ahead with the proposed concept. The aim was a completely transparent glass-faced building, which by virtue of the proposed ceiling system would have an internal climate approaching that of traditional heavyweight construction and with no visible HVAC services in the rooms.

Façade design

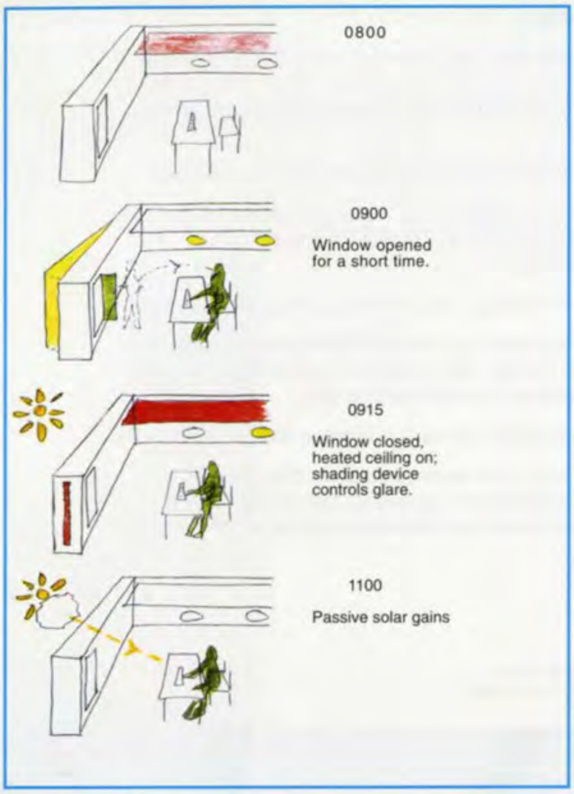
On the external faces the double-skinned façade is achieved by adding a second glass skin; on the atrium side the atrium roof provides the second skin. The following advantages result:

- improvement of sound insulation against external noise
- heating from the ceiling, which reduces capital costs as the ceiling system is provided for cooling in the summer anyway
- reduction in running costs; heating, cooling, ventilation
- night-time ventilation in summer flushing the building and cooling the rooms, with protection against break-ins and adverse weather from the second skin
- more comfortable internal conditions in the perimeter zone
- installation of a semi-external solar shading device (external façade appearance is smooth; solar shading device is protected from the wind and bad weather).

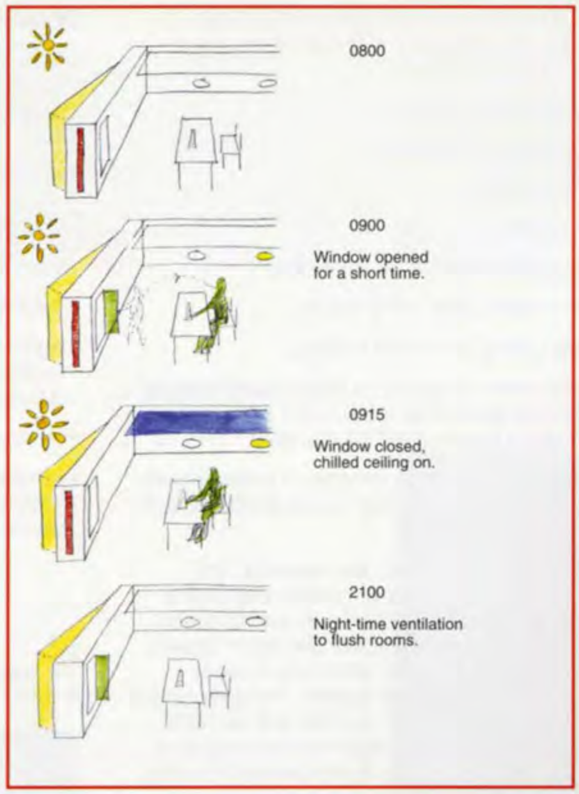
2.
The façade, the atrium, and the PTFE roof (open).



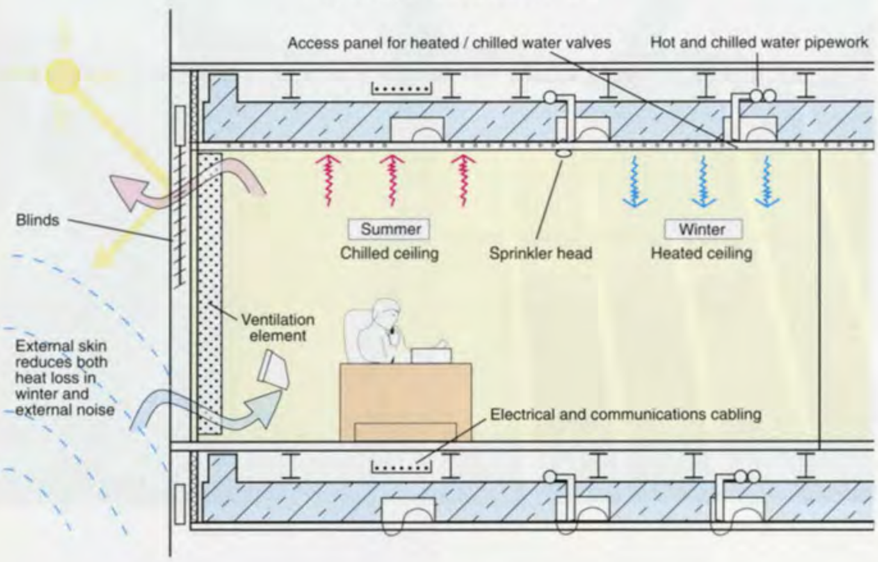
3.
Environmental concept.



4.
Winter day environmental control.



5.
Summer day environmental control.



The internal skin of the double façade is double glazing while the external skin is single glazing. Blinds in the cavity provide shading; they are controlled centrally by the building management system but can be adjusted via an override switch by individual users. To prevent condensation on the glass surfaces, there are openings in the external skin. The façade grid is 1.45m; each segment has an openable window in the external skin and a 200mm wide opaque insulated openable ventilation element in the internal skin.

6.
Section showing HVAC concept.

7:
Atrium roof in the open position.

8.
Typical office space, before occupation.

10:
Typical cellular office.

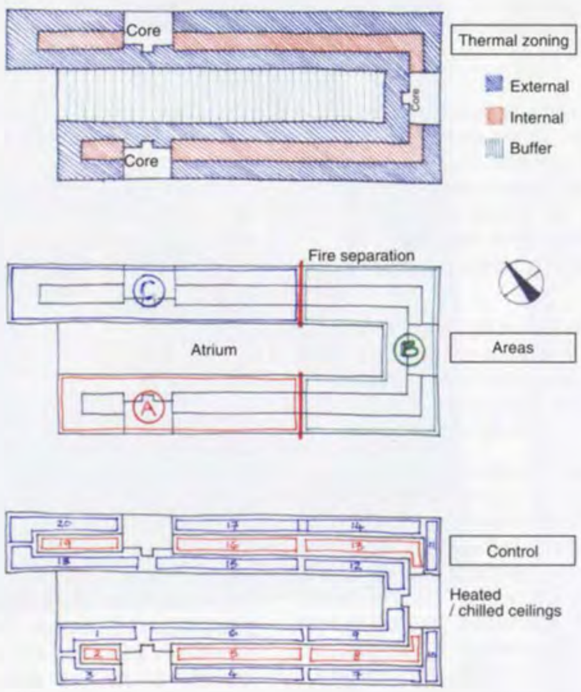
The remainder of the internal skin is transparent glazing and can only be opened for cleaning. The façade cavity has horizontal breaks at each floor level and vertical separation at each gridline. The U-value is approximately $1W/m^{2\circ}K$: in warm weather, under certain external conditions, the outside windows are automatically opened to remove the excess heat. In cold weather the outside windows remain closed unless an inside window is opened; then the associated external window opens automatically to ensure fresh air supply to the room concerned. After a preset time of about five minutes, the external window closes again automatically to reduce unnecessary heat loss. The external windows are automatically closed in the event of wind or rain. The façade facing the atrium consists of neutrally coloured solar control glazing with an internal shading device.

Thermal zoning

The building is divided into five thermal zones:

- *External zone:*
  up to 4.25m from the façade,
  natural ventilation,
  heated / chilled ceiling,
  room temperature in winter = 20°C,
  maximum room temperature in summer = c28°C.
- *Internal zone:*
  further than 4.25m from the façade,
  displacement ventilation,
  heated/ chilled ceiling,
  room temperature in winter = 22°C,
  maximum room temperature in summer = c26°C.
- *Cores:*
  staircases, toilets.
- *Atrium:*
  unheated buffer zone.
- *Basement:*
  parking, computer rooms, plantrooms.

In line with the client's wish for a high degree of flexibility, cellular office layouts with a central corridor, open plan, or so-called 'combi' layouts are possible. The building services design caters for this.



9.
Building zoning.

Offices

The external zone is heated and cooled via the ceiling system and naturally ventilated by windows, which in extreme weather are opened for short periods to give the required outside air quantity. In the change-over seasons, natural ventilation is used to achieve the desired internal conditions. On summer nights, users can leave the windows open to flush the building and cool the exposed thermal mass in the rooms, while the outer skin provides protection against break-ins and adverse weather. The heated / chilled ceilings consist, as designed, of microbore plastic tubing attached beneath the concrete slabs and covered with 20mm of plaster. The main flow and return pipework is in the floor void of the floor above.

11.
The central artium, showing the air supply grilles from the underground ducts beside the water feature.

Elements are cast into the concrete slabs to accommodate the light fittings, sprinkler heads, smoke detectors, and the access panels to the isolating valves for the heated / chilled ceiling. A two-pipe change-over system with a dead band control zone between heating and cooling is provided. Within the dead band the building does not need to be mechanically heated or cooled; free cooling can be provided by window ventilation.

Conventional individual room temperature control is not provided, due to the high thermal inertia of the system and the prohibitive costs of individual control in each possible room, given the high degree of flexibility required from the client. 20 zones are provided on each floor level.

Individual control for each zone is achieved by the use of two port control valves; occupants operate the windows and shading to achieve the desired internal conditions. The internal zone is provided with a mechanical displacement ventilation system (two air changes per hour) via floor outlets. Extract grilles over the doors to the central core area collect the return air at high level. Motor-controlled dampers in each zone allow users to dis-enable the ventilation if necessary, but variable speed fans operating in conjunction with pressure sensors in the ductwork systems ensure that turning off the supply to some areas does not lead to undesired effects elsewhere. A heated / chilled ceiling is also provided in the internal zone.

Atrium

The atrium is an unheated buffer zone incorporating a water feature and a tree to improve the microclimate. Its roof is a transparent openable membrane construction (PTFE air cushions) with a U-value of approximately 2W/m²°K. The atrium is heated by passive solar gains and heat gains from the adjoining office areas, and is naturally ventilated by air drawn in through shafts next to the external faces of the building and tempered via its passage through underground ducts before entering the atrium through grilles beside the water feature. In the winter, used air escapes through ventilation openings on the sides of the roof, which can be closed when it is very cold outside.

The offices facing the atrium receive fresh air from it via operable windows, whilst in summer the whole roof can be opened up to allow warm air to escape. The make-up air is pre-cooled via the underground ducts, which are laid with a fall to sump pump units, so that condensation is drained away. CO_2 and temperature levels in the atrium are used to control the ventilation openings in the roof.

Energy supply

The building is connected to the local district heating system supplied by a boiler house on the site. Chilled water is supplied by a central water cooled chiller in the basement, whilst dry coolers are on the roof. The building's electrical supply is from the site's existing 20kV ring main. The step down transformer is in the basement.

Electrical and public health services

Electricity circulates via distribution boards in the core areas of each floor. The horizontal distribution is in the raised floor void. In the office areas floor outlets are provided with electrical and IT-sockets. Basic lighting in the offices is from downlights integrated into special elements cast into the concrete slabs, which also contain the sprinkler heads, smoke detectors, and access panels to the heating/ cooling valves. Daylight control of the office lighting is provided. Rainwater is used to flush toilets and irrigate the green areas.

Conclusion

The building has been in operation since January 2000 and the client is very happy with its performance. Summer and winter temperatures were within the predicted levels and many occupants have remarked that the subjective thermal environment is very pleasant, probably attributable to the radiation from the ceiling.

The same team of architects and engineers is now working on a low energy office building in San Diego, California...

Reference

(1) CODY, B, LEWIS, D, *and* VAN AERSCHOT, C. Schwedlerstrasse, Frankfurt am Main, Germany. *The Arup Journal, 31*(2), pp14-16, 2/1996.

Credits:

Client:
Braun AG

Architect:
Schneider + Schumacher Architekten

Building services engineers:
Arup GmbH
Brian Cody, Marcus Ebeling, Susanne Flis, Karl Pudwitz

Structural engineer:
Bollinger + Grohmann

Landscape architect:
Ulla Schuch

General contractor:
Hochtief

Illustrations:
1, 2, 7: ©Arup/Jorg Hempel
3-6, 9: Brian Cody/Daniel Blackhall
8, 10, 11: Brian Cody

Values and Change: benefit or problem?

Duncan Michael

This article is based on Sir Duncan Michael's Gold Medal Address 2001 to the Institution of Structural Engineers, given on 20 June 2001.

Introduction

We see our society as changing fast. We are often surprised when we realise that what we know is no longer how things actually are, and we realise that we had not even anticipated the changes. The traffic arrangements in our streets are a good example. Go away for a month and when you return there will be new priorities of movement, often seemingly capricious changes.

Whilst the claims are often exaggerated, currently change seems exceptionally rapid, especially in major external ways like global warming. And human society has always been changing, for internal and external reasons. Some things matter a lot to us and we do not want to change them. Values are an example. They can change, but mostly we want to sustain them or at least to change them very slowly and with great care. Big changes and Values interact. Changes cast light on Values and test them. Paradox, conflict, and priorities emerge. So how can we take benefit from the destabilisations of the interactions?

So far as Arup is concerned, Ove gave his name to the firm, he gave his ownership into trust for the benefit of the people of the firm, and he gave his Values to the firm: a powerful triple package. At 75, in the 'Key Speech', he spelled out the Values, our Aims, that remain today the basis of Arup's being. There are only three, all simple: excellence in all we do, prosperity, and fairness and integrity in our relationships. They are about the classic trilogy of work, money, and people.

In Arup we need to sustain our three Values (and test them occasionally). And the need also to change continually makes a perpetual tension. Some fear change as a risk for their sacred Values, whilst others see the celebration of the Values as an excuse for the comfortable to bumble on without the bother of Change. Fortunately so far, the Values have continued, still strong and little changed, whilst considerable changes have been made. It is this interaction between Values and Change that I will try to explore a little more.

Yins and yangs

Humans create many pairings akin to the 'Values versus Change' example. We find the pairing model attractive for some reason, and we can wage battle for ever on the interface inside each pairing, neither side able to win, neither side needing to lose. In the East, indeed, all this pairing has a developed philosophical culture in yin and yang.

'Imagine my amazement to see Shahyad Ariamehr still glittering and beguiling at Tehran Airport. To my delight it has been adopted as the people's Azadi monument.'

In Arup one great issue is defined as 'product or process'. Some passionately declare that effort on process is from second-raters to compensate themselves with power in place of praise and prizes, and that all the best people should concentrate on our product. The design of our bridges is more important than the design of our timesheets. It gets personalised into a two-type personality structure, the 'yogis' and the 'commissars', and our debate has been running longer than the 50 years of Agatha Christie's *The Mousetrap*.

In plain words it is about 'what you do' and 'how you do it' - two clearly separate concepts and not competing alternatives.

1. Shahyad Ariamehr, Tehran (photo: Henk Snoek).

Nonetheless it is amazing how difficult it is for educated, trained, and successful people to separate 'how' from 'what'. Engineers are especially susceptible to dropping into the 'how' box when they ought to be, and think they are, considering 'what'. Maybe it is as well that successful engineers have this tendency. Our cars, planes, trains, dishwashers, and computers would be a lot more dangerous if 'how' was not such a compulsive focus for engineers. The price that society pays for this high reliability (and it is very high - think of the outrage when something goes wrong) is that the holistic skills of engineers atrophy.

The 'what/how' difference translates, though imprecisely, over to 'quality versus quantity'. There is a strong British belief that quantity and quality are alternatives, but they are much more usefully seen as two axes of a graph. I am deeply aware that the quality of Arup's work is hugely enabled by our size, our quantity. It lets us aspire, it lets us replay when we get a wobble, it gives us access to optimum people in a remarkably fine-tuned way, and it moves the cash cliff edge over a bit.

The military see the coexistence of their pair clearly: strategy and tactics. When the fundamental issue you are dealing with is your own life or death, you have to be clear-minded! I just wish that management people would leave such high words in peace and stop corrupting them into meaningless slippery words. I think of the annexation of 'strategy', as an adjective to put in front of any title, like parsley with fish. And of 'executive', which only means 'action' but which has come to mean nothing.

Revolutions

Social revolutions are events of dramatic change, of heroes and history books and films. Britain emphasises its continuity, its heritage, and its lack of revolution, so that one does not go around expecting to see symptoms and symbols of revolution like Oliver Cromwell's remains embalmed.

Visiting Beijing and Moscow, I thought to go and see how their political and social revolutions of 1949 and 1917 had translated on the ground. We see these particular two revolutions as cataclysmic events, and I felt sure that the urban changes would be obvious. I was curious to see if, for example, buildings symbolic of their *anciens régimes* would be displayed with contempt as remnants of rejected pasts, unless they had been quite destroyed to erase those shameful pasts. Imagine my sense of anticlimax when I found in Beijing that the Imperial Palace, the Summer Palace, and the Temple of Heavenly Peace are all reverently cared for and now shared with the people; that central government departments are still housed nearby; and that the best residential and now diplomatic quarters have hardly moved. The Kremlin continues as the very heart of Russia, and St Petersburg is being lovingly preserved as best they can.

The national and cultural Values in these great countries have not changed at all. Indeed the styles of government have hardly changed either, with the land basically in the same political pieces as always and the centres obsessed with their huge task of holding the nation together. Paris is the same and its Revolution was even greater, given the state of human development at the time. Change, however great and drastic, has scarcely changed their national Values at all - just new management, one could say. My interest arose from the Arup dilemma of being in love with our Values but feeling the need to change a lot and fast. The Beijing and Moscow experiences gave me the confidence that any reasonable changes in Arup would not be at the cost of our Values.

I experienced this differentiation also very personally and directly in Tehran. Around 1970 I engineered and mathematised a big beautiful monument for the then Shah of Persia, built at Tehran Airport, made of thick chunks of crystalline white marble and shimmering tiles. It was called Shahyad Ariamehr (Fig 1). Come the Islamic Revolution in 1978 and I assumed that the monument would be destroyed in the eradication of the hated Pahlavi regime. Imagine my amazement every time I see it glittering and beguiling in a Sunday supplement. It has been adopted as the people's Azadi monument, to my delight.

'My query is whether change is a benefit or a problem for us. The fashionable word is 'challenge': a cunningly empty term....an evasive concept.'

The Housing Corporation

I do some work for The Housing Corporation, sitting on its Board plus some committees and going out and about for it in the North of England. The Housing Corporation is 35 years old and owned by government. Its business is to look after the investment of money for social housing and to regulate how it is run in England, typically through housing associations and housing co-operatives for those who need such help: the poor, the infirm, the old, the harassed. What was a voluntary movement has become an essential part of the nation's make-up. At present, government wants us to take under our wing much of the council housing that can be detached from local authorities, about 1M homes. This will put in our care about 2M homes, assets of about £80bn, and debts of about half that. It may be surprising that in affluent England there is and will be so much need. Our aim is a decent home for everyone, and our task for the short term, say 25 years, is to work at it. The long-term solution is of course to have less poverty, illness, and distress: that is to remove the problem, as an engineer would do, rather than to solve it, however well you do the detail. For that we have to call up the whole picture and in particular raise expectations and aspirations.

A device like The Housing Corporation does not have the cultural luxuries of 5000 years of nationhood like China, or even 55 years of philosophy like Arup. But it knows it has to change, often to follow events but also sometimes to lead them. Much of its culture is expressed in its processes, not surprising in a state-owned company with such a huge business and so many customers. For me it is a test case of my belief that you can retain the bits you want to retain and dump or change the rest simultaneously, and get away with it. I am helping as well as watching, though that may spoil the quality of my science.

Through The Housing Corporation, 20 000 new homes a year are built in England: more than any private housebuilder. Being 'almost government', we try to be excellent followers of the 1998 *Rethinking construction*[1] initiative. Its emphasis on processes, measurables, jargon, incrementism, and reporting makes it a comfortable theme to incorporate in Housing Corporation guide packs. But construction is a field where, however much you process, the heart has a part as well as the head. The UK's new Strategic Forum for Construction, also to be chaired by Sir John Egan, has a remit which reads as if it is still blind to the humane, the creative, and the optimistic part of our needs. The built environment is too close to each of us for it ever to be wholly reduced to a processed, packaged part of life. This is not a plea for incompetence or cowboy builders; it is for a whole and complete picture.

Public service

There is a presumption that less state activity - be it collecting taxes or providing services - is good: 'Less is better', unless of course you want something for you or yours like a new heart or a good teacher or a fair trial or a train to destination of choice, when any lack becomes a moral outrage.

Market forces are brilliant and Adam Smith did us all a great service by describing them 225 years ago in *The Wealth of Nations*. But they are limited and to see them as a law of nature and thus universal in their application is a dangerous error - like being a flat earther, except that flat earth is a safe error. There are hundreds of services which the individual / commercial / private world does /will / can not deliver, and we have invented public service, local or central, to fill the gaps. Towns did not aspire to own a gasworks or a waterworks or tramcars; the citizens just wanted safe gas, clean water and reliable transport. And it remains so today.

Transport, energy, and water cannot be delivered well enough by free markets; there are social, environmental, and health needs also. The sanction of a fully free market, like the weak going bust, is suspended: a water company closing down is unacceptable. Many services are as a practical issue best supplied by a monopoly.

Many gas producers can indeed pump gas into the network, but one pipe in one road is still the best answer. In Britain we have landed on the formula of very private sector suppliers + very fierce regulators, in acknowledgement of the public interest, but the private supplier / public regulator arrangement is only a next step. We have still to invent the optimum arrangement.

Economists also have a lot of thinking still to do.

When outcomes do not fit economic theories, the refuge of 'in the long term' provides the chance to hang on to the theory. Maybe we do seek gratification too instantly, but it is the expectation that should be damped, not the application of the theory that should get postponed. 'Imperfect markets' to me form a wonderful insight to the economist's mind. If results do not fit free market theory, then the market, not the theory, is said to be imperfect. Try that in engineering: Imperfect loadings, imperfect soil, imperfect gravity.

We would do better if we were much more rigorous in language. 'Third Way' words are fashionable. My query is whether Change is a benefit or a problem for us. The fashionable word is 'challenge', a cunningly empty term and not the neutral word that we really seek but an evasive concept. We get by through this oiling of our language, but we do not progress.

Social rules

The findings of scientists and the creations of engineers offer us all opportunities in huge richness - ideas, things, and services that we had not even dared to imagine - in fields that include all the electronic tools like phones, computers, televisions, all the GM foods, the pharmaceuticals, the bio applications, and a plethora of innovations in more established areas. The social rules for using these new goods are not prepared in anticipation and this worries us - as a failure of politics or religion or economics or law. It seems to me, however, that this is not so. The social thinking can only follow the new creations; no-one can establish the new mores even at the scientific findings stage. The number and variety of potential outcomes is so great, sometimes infinitely great, that it is impossible to anticipate in a usefully focused way. It is not that we have lost proper respect; we just have to let consequences clarify a bit before we rule on dos and don'ts. I realise that by then some dreadful result may have emerged and that we may not be able to reverse it, to put some genie back in its flask. But that issue is at least equally valid for some of the things we already do with the general support of society and the law. Irreversibility is not a question attached uniquely to the brand-new. Nuclear power has been around for nearly half a century.

Neither are we at all clear on what we mean by 'equality'. We have a presumption to support the concepts around equality. In the USA equality was built into the fabric of the Constitution from the start: 'All men are born equal'. Oddly, however passionate on equality you might be, the concept that all men are born equal scarcely stands up to the facts of life. Equality *per se* is a neutral description, an empty shell, a bit of mathematics, and an exceptional state. What matters is equality of *something*. Is it to be equality of opportunity, or of resource put in, or of outcome? They are all radically different from each other and it is not possible to have them all together. Diversity is a bigger idea - 'inequality', if you like. But again we will have to declare diversity of *what*, if we are to use it. Equality, uniformity, unity, diversity; we have a long way to go to sort out what we want.

Sustainability

'Sustainability' is a talismanic word. Write 'sustainable' over the design of the most gross out-of-town development and planning permission is yours. Say 'sustainable' and get re-elected. Let us look at what it is that we want to sustain.

In the 1960s our worriers thought that we would soon run out of resources - oil, gas, metals, food, even water somehow. It was more problem than solution; it was characterised by protest, by emotion, and I call it the 'Greens' phase. As people heard all that noise and thought about it, a more considered attitude emerged, with the banner of 'Environment'. It was still 'end of the world is nigh', but you could define it, teach it, pass examinations in it, even be a consultant and make a living at it. We are now in the third phase, with 'sustainable' as its marker, owned by the decision-makers and a basic for business.

'Sustainable' can be seen as, and often is, deeply selfish. It is about how much of the status quo we can retain for a very long time. It leads logically to the elevation of 'heritage' as a superior call and of 'new' as a matter of suspicion and even reluctance. Change gets a downgrade in 'sustainable'. It is not 'how much can we change?' but 'how little need we change to sustain our lifestyle?' This begs a lot of questions. Are we really at some optimum that should be sustained as our top priority? Who are 'we'? One can see that the richest 2% of the world's 6bn people have a big interest in being 'we'. And it is 'we' who control the media, write the books, set the educational syllabi, define success and its rewards. So not every human wants to run with our idea of 'sustainable'. Some prefer Change and taking their chance, like we all did until recently. I have not even touched on all the other life on earth, which so often we try to sustain only because it is part of our happiness package.

Further, Change is what has characterised the surface of Planet Earth and the life on it for millions of years. Only 10 000 years ago, only 200 grandfathers back, we were all in a fierce Ice Age. The sea round Scotland was 20-30m higher than it is today, despite so much of the sea being out of the sea and sitting on top of the land as ice. The block of rocks which is the UK is still rebalancing in a (to us) slow wave, in a tilt so that Scotland is going out and England is coming in. That experience has given us the lovely microclimates and ecologies of the raised beaches.

Essentially, Values and Change are still too confused in the 'sustainable agenda'.

Education

Academia has two roles, as the carer of our accumulated knowledge and the restless disturbing force that seeks better knowledge. Our education industry could play the key role in sharpening up the quality of thinking in the UK. Education for the majority up to the age of 21 is a great social aim, a good use of resources by a rich country, and civilising for our children. However, the methodologies for that are different from what works for a 5% population intake, since the cultural, wealth, intelligence, and aspirational characteristics are different, one should assume. Rabbiting on about 'dumbing down' is diversionary noise. Adapting the same old teaching methods is self-evidently sub-optimal. The productivity of academic personnel has to grow at the same 3% pa every year forever, as the general populace raises its output, just to hold steady in the national context. To enhance the personal reward, one has to become more useful even faster than the nation's average rate.

Lest you doubt the potential of the poor to succeed, think of JK Galbraith's puzzle in *The Nature of Mass Poverty*[2]. How is it that immigrants from very poor countries do so well economically in their new country and then their children educationally do well, whilst their brothers and sisters remain in such abject poverty at home? Galbraith is a privileged Canadian from Scotland who became USA ambassador in Delhi, and even at 90+ is still thinking about it all. His conclusion is that people are the same, rich and poor; it is opportunity and stimulus that change.

Susan Greenfield's Maitland Lecture[3] offers support to Galbraith's insight, with her description of about a third of our brain cell connections existing at birth and the rest of the joining up in our brains happening throughout our lives to capture our experiences. This is the 'nature or nurture' choice closed out. It is nice to imagine the race going on in our brains. Can we join up cells and get that extra power into play faster than our brain cells die off?

I help at half a dozen universities and it perpetually surprises me that senior education, where I fondly imagine radical thought to be always on the boil, is so conservative, so internalised, so taken with its own processes, so content that inter-faculty collaboration is so difficult. Is being at the top in education so comfortable, so satisfactory, so end of career-ful, that arrival is sufficient in itself? I do feel strongly on this, because my expectations are so high. My views of professional institutions are similar, but I am not so upset as I expect less from them; they are set up in their charters to be responsible for the established world. I would like them to be a great force for change but I do not have such high expectation as I have for academic institutions.

Mathematics

It does seem that, for us humans, two is quite a big number. *The universal history of numbers* by Georges Ifrah is a big book, but an easy read, even in its English translation[4]. There remain, and in multiple jeopardy, tribes of Stone Age culture people in South America and on some Australian islands. Professor Ifrah says that their counting systems are all similar and go along as '1', '2', '1 and 2', '2 and 2' for 1, 2, 3, 4, and they then flip to a qualitative number like 'many', 'flock', 'herd', 'shoal', 'team', 'group'. So they need only two number words, plus a plus word. On reflection, it is a brilliant kit of numbers. If you have one cow or two cows there is a difference. After four cows you have gone beyond the need to count; or one husband, four husbands, many husbands; or one enemy, two enemies: After four it hardly matters.

Indeed in my own life a counting system of '1, 2, 3, 4, and many' deals with just about all my mental needs. After that a machine gets superior and it is the machine that needs the skill to manipulate, not me. But note that the '1, 2, repeat' system is not the binary system. Binary is the '0, 1, repeat' system. I know, we know, how important the zero cipher, '0', is in our numerical systems. You could almost say essential except that zero took a long time coming. One can see that '0' was not a useful concept in the Stone Age. To have zero cows or zero wives might put you in the same mathematical textbook as the guy with one or two of each but in real life you were in a different framework. Zero was a useless concept and so lacked a symbol, maybe even lacked a word. To have zero of something is a pretty refined concept.

'All the lovely software we have written and continue to write to put on our super-reliable cheap computers has liberated the engineer from his mathematics harness.'

The Romans got through 1000 years of magnificent and civilised empire without a zero. How with their clumsy numbers they did all their calculations for aligning a road and for bridge and arena building, with such a brilliant match of delivery from intention, is quite wonderful They knew how to be decimal - none of your Northern thirds and eighths and 12ths. But they did not take the very small step of having only 10 symbols and achieving infinity with no further effort. It seems it was in India, with all the subtleties of its culture and religion, that zero or dot arose. It reached Arabia 1500 years ago and first appears in West European texts around 1000 AD. There were doctrinal objections as well as practical objections to its arrival. And as for negative numbers and imaginary numbers, well these are stories for another day.

2.
Indian numerals as inscribed on masonry around 400AD: The first known use of the 'zero' symbol.

I say all this because we are in a period of Change and there are forces of anti-Change, even positively anti. Some believe, for example, that the A-level is a Gold Standard (not that anyone uses the Gold Standard any more), whilst others are just a little bit apprehensive to be moving into new situations from the old and comfortable. One such change is how engineers will be using mathematics.

Most engineers of my period will have studied a lot of mathematics, almost certainly beyond their comfort zone. It was not to give them education, as French or history does that equally; it was to equip them for handling engineering designs, fabrications, testing, and for some research. A lot of it was about numerical techniques like relaxation, moment distribution, or statistical analysis. Whether or not they ever used much of the mathematics in their actual work is not important here. What is important is that mathematics got bedded in as the foundation and therefore the entry / no entry portal to engineering careers.

Today engineering uses more mathematics than ever, but the explicit use of mathematics, hands-on manipulated by individual engineers, is less than it has been for the last 50, maybe 100 years. All the lovely software that we have written and continue to write to put on our super-reliable cheap computers has liberated the engineer from his mathematics harness. He does not yet know that and his educators are in no hurry to tell him.

My proposition is that we now accord to mathematics a place which for engineers is too powerful and which controls our actions to the overall disbenefit of engineering and the economy. Our engineering as a whole would be better if the overwhelming influence of mathematics was reduced.

I see evidence for my proposition in lots of situations and I am monitoring situations that may offer light on whether I am right yet or whether I have to wait a little. I want to develop qualitative or soft mathematics as respectable for engineers. My wife was describing a dish, an expensive dish, to me when I was thinking about this issue and I asked her which dish, the plate or the bowl. That helped me to see plate, dish, bowl, vase as a

mathematical series. We each know when to use each of these words, quite distinctly. They are a useful classification. But they are quite unsusceptible to quantitative mathematics, what I will unkindly call managerial mathematics.

Think not of the 10% of the populace who are even possible candidates to become engineers today. Think instead of the 90% whom we exclude from ever considering becoming engineers for their lack of formal mathematics in their teens, and think of the creativity and the diversity that we are denying to engineering, the sterility that we are continuing. How many engineering heroes - Brunel, Stephenson, Telford - did A-level maths?

Young researchers

The Institution of Structural Engineers brings together many of the UK's young researchers in civil engineering each year and they hold a fair. They do presentations, put up poster reports, and criticise each other. I went along this year and was uplifted by the quality of the people - a global collection - and by their work. It is a self-assured opportunity of recruitment, better than a quality-assured one any day, and I could not resist following up later with a couple of the researchers.

It is the sort of event that justifies an institution, a situation where the institution's constants - its neutrality and lack of private agenda - allow the competitors to find each other. It all led me to give some thought to what distinguishes research, design, and science from each other. Some will say that scratching at these differences is divisive and of no priority, that what matters is to stick together on life's survival issues. I half agree, but my variation is that robust unity comes from appreciation of the diversities that are combining. Unity is impossible where there are suppression and denial.

In research you are revalidating some item of human knowledge, or if you are lucky you are finding some new item or even re-finding it. With the domination of new knowledge garnered by the scientific approach, one tends to correlate all good research with natural science. But this is a distortion. Scholars obsessed with reaching the meanings in Pharaonic artefacts or piecing up fragmented old texts are doing research of the highest quality as well as of the highest interest, though they are not natural scientists.

There are in my view some absolutes in research: Integrity is one such. Research calls for a tense mix of creativity and destructivity. You have to have the strength and the clarity in yourself to spot the misfit in the existing truth. You are searching for the result that will not lie down. In engineering, the culture is of needing an answer and needing it soon. But research is still research. What I call 'confirmatory research' - exploring by test and by study whether a preferred outcome is valid - needs to be conducted with special rigour, to balance the very human wish to get the sought result, to assemble the evidence that supports the answer. Research is not cousin to the legal world.

One can compare design with research. And, yes, you can use research as part of the process of designing. And, yes, you will use design as part of the process of researching. To me, research is the search for new understanding, whilst design is the creation of a description of something that has a purpose but does not exist. Then in design you can choose which information to acknowledge or not; you can choose how rigorous you will be once you have chosen your design; and you can choose how widely you will bother to search in the first place. There is no one correct or unique design - unlike in most examination questions - though there are wrong designs, ones that do not work. But all designs can be improved. In design you can use science or mathematics or reason as much or as little as you choose. You can copy, you can hallucinate, you can and do limit the output by time and/or cost, you can call on music, drama, history - in fact anything you wish - or not - and it is still design. Some of the best design is eclectic as well as obsessional. A design is judged on its result and not on its methodology; here it differs totally from research, which can have negative results and still be top quality.

Let us also look at science, engineering, and technology. Our UK governments, the present, the last and the next, all place great store in SET. Despite being mostly Oxford lawyers and Scottish economists, the present UK government believes that the country's development has to be technically based, and not so much the big hardware as the clever, the small, and often the imaginary. So you get to IT, pharmaceuticals, biotechnology, and software very quickly. But not only do the country's bosses lack any feeling for technical things, we the engineers lack a good conceptual language for them to hook onto. We have a wonderful language of hardware from hoggin to grommets to widgets - but see what the silver tongues have done to widgets: It is now a put-down word. We, the engineers, are likely to be asked quite soon to subsume into 'science'. Our reward will be a good share of all the governmental munificence that scientists have and do succeed in collecting. But the idea is wrong and I do not yet know my tactics to save us - the government and the country and all of us - from this conceptual error.

Conclusion

You may think: what is in a word anyway? My plea is that words and images are the finest tools that we have for doing things together. Words have to be of the highest quality in the information that they carry. One's words also of course carry one's culture and Values. The information in a word is also a changing situation, as usages develop (degenerate, we oldies claim). English is a particularly informal and dynamic language. So my paradigm of definite, stable meanings in our words is itself sustainable only if I admit Change as well as Values into its elements.

Our choice is not between Values and Change. We must have both, lots of Values and lots of Change. We have to be able to think about both Values and Change fluently. That means having very efficient language. The problem is then simply which Values to choose to hold and which things to choose for Change. In a single model Values is very slow change and Change is fast change and then you can see a middle group available of gentle change. However, I do not like 'middle': 'middle' becomes 'muddle' too easily and lets the easy riders and charlatans have a better chance than they deserve.

We stand facing a brilliant future full of opportunity to do great things, or at least the young do. The limiting constraint will be ourselves, especially our ability to work together for a common good, based on integrity, respect, and courage. It is not so difficult. It is well within our grasp.

3.
Arup's design for a new pedestrian bridge across the Thames at Battersea maintains the aspiration to technical and aesthetic excellence, serving in this instance the planned changed usage of the former Battersea Power Station. (Image: Trevor Loveland)

'Experience has given me confidence that any reasonable changes in Arup would not be at the cost of our Values.'

References

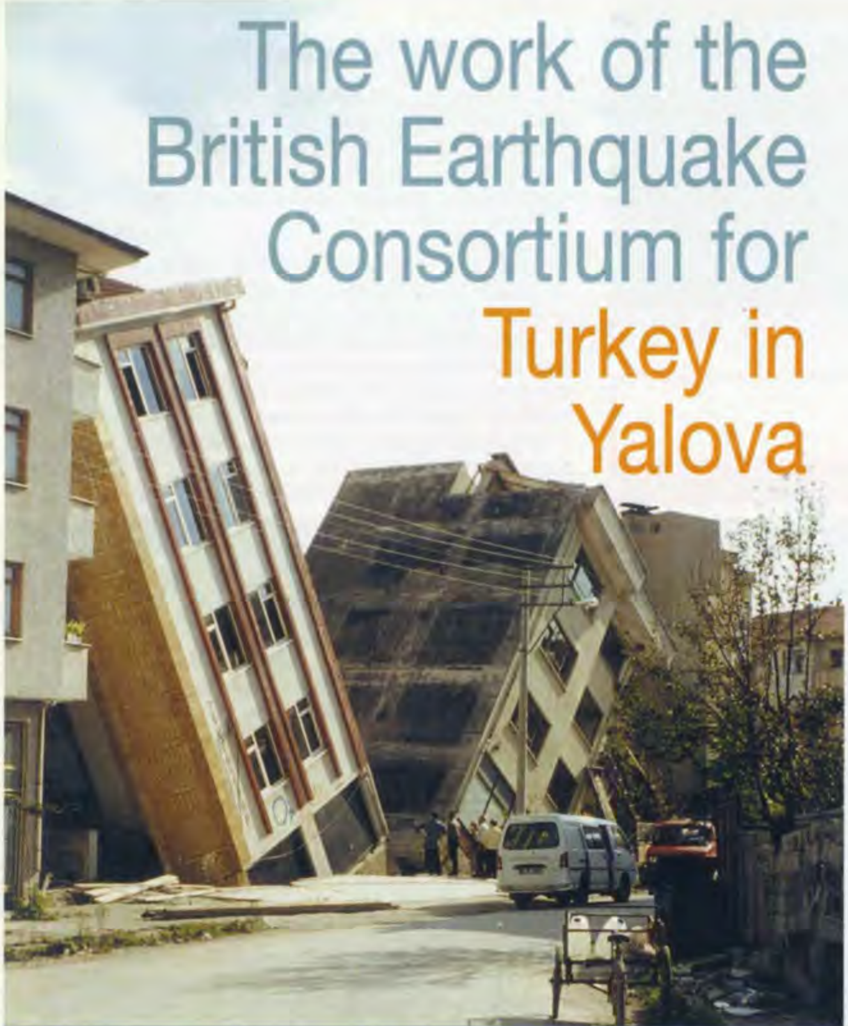
(1) DEPARTMENT OF THE ENVIRONMENT, TRANSPORT AND THE REGIONS. CONSTRUCTION TASK FORCE. EGAN, J, *Chairman*. Rethinking construction. DETR, 1998.

(2) GALBRAITH, JK. The nature of mass poverty. Penguin, 1993.

(3) GREENFIELD, Prof S. The brain of the structural engineer: myth or reality? The Institution of Structural Engineers' Maitland Lecture, October 2000.

(4) IFRAH, G. L'histoire universelle des chiffres. Editions Robert Laffont, 1994. [Trans as 'The universal history of numbers', by Prof Daniel Bellos, The Harvill Press, 1998]

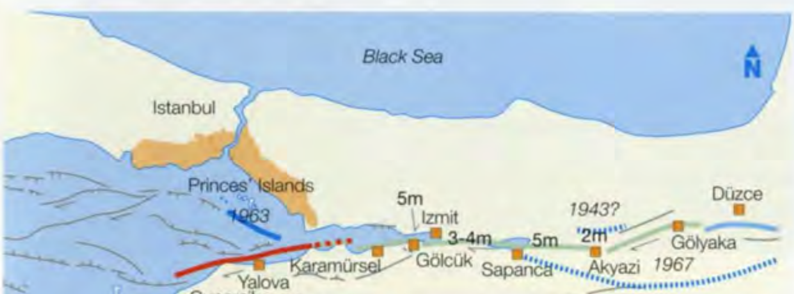
The work of the British Earthquake Consortium for Turkey in Yalova



Tim Chapman | Koray Etöz | Matthew Free | Andrew Lord | Mike Osborne

Introduction

At 03.02 on 17 August 1999, a large area around Izmit in Turkey (Fig 1) was hit by a devastating 7.4Mw magnitude earthquake, resulting in the deaths of more than 16 000 people with 44 000 injured. At least 80 000 buildings were destroyed - factories, offices and homes (Fig 2). The UK Minister of State for Construction, Nick Raynsford, visited Turkey the following month and, alongside help from other governments, immediately offered British assistance to help rebuild devastated areas.



1\.
Location of Yalova, showing recent and postulated fault ruptures. Dates are year in which fault segment ruptured.

2 top:
Typical damage.

The British Earthquake Consortium for Turkey (BECT) was one result, formed from six major British construction companies with significant interests in Turkey - Balfour Beatty, Bovis Lend-Lease, Laing, Thames Water, Hyder Consulting, and Arup. Funding came from the individual companies and the British government Department of the Environment, Transport and the Regions (DETR). The aims were simple: to provide improved planning procedures to choose areas less vulnerable to earthquakes for new building; to ensure that new buildings were designed to resist earthquakes; and to identify projects that could revitalise the area. The most depressing lesson learnt from the earthquake was that most of those killed would have survived if their buildings had incorporated standard features already required in the Turkish structural design codes to ensure life safety in earthquakes.

After discussions between the British and Turkish governments, the Province of Yalova, on the southern shore of the Sea of Marmara facing Istanbul, was selected as being most likely to benefit from BECT's help. Although it had suffered greatly with 2505 deaths and 6000 injured, comparatively little international assistance had been directed towards it because it wasn't industrial. Yalova is a small city of about 100 000 in winter and up to 400 000 in summer. The overall population of the province is thought to range from some 200 000 in winter to more than 1.1M in summer when the earthquake struck.

On 10 February 2000 the two governments signed the protocol establishing BECT, and five days later the first study group arrived for a fact-finding mission to Yalova and to visit the relevant Ministries in Ankara. BECT's initiative had four strands:

- to understand the geomorphological and seismic risks in potential development areas so that reconstruction could occur safely
- to produce a development framework which would lead to a reconstruction implementation plan, identifying projects to revitalise the area and provide opportunities for homeless and other displaced people
- to propose a plan to rehabilitate utilities, particularly water supply and wastewater treatment that had been badly damaged in the earthquake; later, treatment of solid waste was also identified as a priority
- to devise funding mechanisms so that priority projects identified in the studies could proceed without direct government subvention.

Leadership of the strands was allocated according to the six companies' perceived strengths. Balfour Beatty provided overall project direction, Arup led the ground engineering, Hyder dealt with planning, Thames Water looked after utilities, and Balfour Beatty supplied expertise in funding. Bovis supported Hyder's planning team and Laing supported Thames Water on utilities.

Nature of damage

The Turkish seismic code had long recognised the potential for major earthquakes in this locality, but many structures - generally 3-6 storey residential buildings - were inadequately designed to resist seismic loading. They were usually poorly detailed reinforced concrete frame structures with masonry infill panels, often with open ground floors, and badly built. They rarely had adequate foundations and in addition were sited on geologically recent soils such as soft clay, loose sand, or poorly compacted fill. Many of the damaged properties were relatively modern, built as part of the rapid development of the area over the last 20 years. All these factors contributed to the high level of destruction.

Maps, photos, and satellite images

A major problem with hazard mapping in developing countries is lack of reliable maps; for security reasons maps and aerial photographs are difficult to obtain in Turkey. Some 1:25 000 maps from 1974 gave useful coverage but didn't show the most recent occupation and development. Aerial photos of the affected areas taken by the Turkish air force immediately after the disaster had been promised to the study team, but declassifying them took longer than expected and it wasn't clear if they would be available in time. The study needed current images of the area for geohazard mapping and for assessing the extent of development, so a decision was taken to buy satellite imagery.

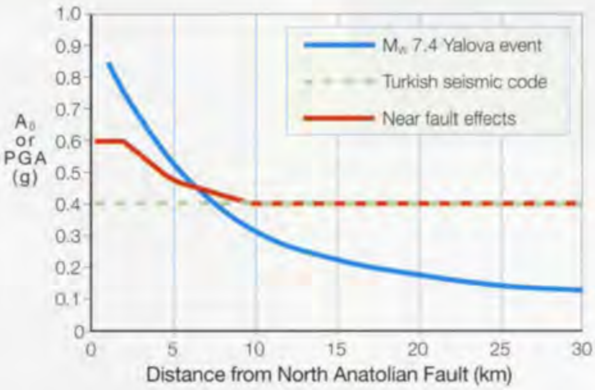
3.
(left and right)
IKONOS examples.

Table 1

Earthquake probabilities for faults in the Marmara Sea region

Fault	*Probability of fault rupture (%)*			*Maximum magnitude (MW)*
	30 year	10 year	1 year	
Yalova Fault	33±21	14±11	1.7±1.7	7.4
Princes' Island Fault	35±15	16±9	2.1±1.6	7.2
Central Marmara Fault	13±9	5±5	0.6±0.7	7.2
Combined	62±15	32±12	4.4±2.4	7.8

4.
Comparison of acceleration with distance from Yalova segment of NAF for the Turkish code and the postulated magnitude 7.4MW event.



Resolution has improved over the last five years and with the launch in September 1999 of the Ikonos 2 satellite with a resolution of 0.82m, a new tool was available[1]. Arup became the first UK company to order Ikonos imagery with its request for an image of 650km^2, containing 4.7GB of data across five spectral ranges. This allowed different types of terrain to be differentiated, and land scarred by the earthquake and by landslipping clearly identified. Unfortunately the satellite's stereo capability was not available at the time of the study, so when the air photos became available towards the end of the study period, they still provided useful additional data.

Design for hazards

A novel feature of BECT was that it involved ground specialists and town planners working together to choose locations with least risk for new development. Previously, the particular hazards relating to unstable ground and earthquakes were poorly understood but nonetheless influential in siting replacement buildings. Two principal hazards preoccupied local planners: design against earthquake risk, and how to avoid areas prone to landsliding, as the earthquake had triggered literally thousands of landslides across the province. However, the two hazards had very different consequences. It is thought that no deaths were attributable to landsliding; virtually all were due to building failures - a sad indictment on local building practices. An aim of the study was to provide a rational basis for ranking different areas according to the severity of the hazards faced. These are discussed in the following sections.

Geology

The most recent geological maps published by the General Directorate of Mineral Research and Exploration (MTA) in 1999 were obtained in digital format, and used as a base to develop a geology map for the study area and a series of geo-hazard maps in a Geographical Information System (GIS) framework. The maps were augmented with the most recent geological mapping of the Quaternary alluvial deposits after the August 1999 earthquake.

The geological boundaries and materials present in the study area had to be confirmed, so two experienced engineering geologists and an engineering seismologist from Arup made a two-week field reconnaissance in April 2000. This confirmed the accuracy of MTA's geological maps; geological materials were examined to confirm their engineering properties. The frequency of different types of landslide across the study area was also investigated using aerial photography interpretation, satellite imagery interpretation, and field reconnaissance, so that strategies for stabilisation could be developed.

Fig 3 shows typical Ikonos images: earthquake-induced landslides on the hilltops above Yalova and a chemical facility on the coast. Using these data, digital maps of the various geo-hazards could be developed.

Ground shaking

The study of earthquake hazards was based on a detailed review of the Turkish seismic code and available literature on the tectonics and seismology of the Sea of Marmara region, where the earthquakes are associated with the North Anatolian Fault (NAF) Zone. Most researchers agree that movement on the NAF Zone can be characterised by periodic earthquake sequences migrating along its length, and that each sequence allows the entire NAF Zone to slip. Each earthquake represents slip along an individual fault segment within the NAF Zone.

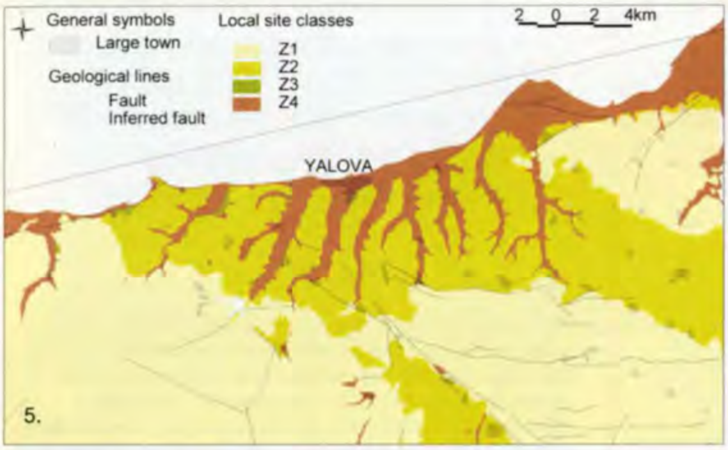
Assessing the tectonic stresses in the Marmara Sea region using the 'earthquake interaction' concept indicates that the August 1999 earthquake increased stresses at the eastern and western ends of the Izmit Fault segment of the NAF. Recent seismological studies have hypothesised that this mechanism triggered the later event of November 1999 centred around Düzce at the eastern end of the Izmit Fault, while clusters of aftershocks at its western end near Yalova, Çinarcik, and south of Princes' Islands in the Sea of Marmara were interpreted to indicate an increase in stress in these areas. This assessment estimated the probability of an earthquake on three of the major fault segments that could significantly affect Yalova Province: the Yalova Fault, the Princes' Islands Fault, and the Central Marmara Fault (Table 1). All would be much closer to Yalova than the August 1999 event, and so could affect it much more severely.

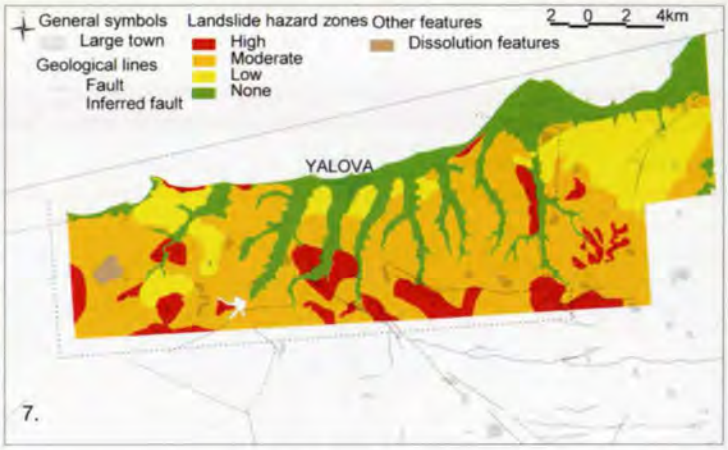
As part of this study, ground shaking due to a 7.4MW earthquake on the Yalova Fault segment of the NAF Zone was assessed. The peak ground acceleration (PGA) is compared in Fig 4 with the Effective Ground Acceleration Coefficient (A0 = 0.4g for Yalova) given in the Turkish seismic code. The value of bedrock PGA is shown in Fig 4 to be significantly greater than the currently specified A0 value within about 10km of the Yalova Fault segment, so the seismic design forces for 1-3 storey structures may be increased by the amount indicated in Fig 4. It was estimated that the seismic design forces for taller, longer period structures could exceed the current specification for a distance up to c15km from the Yalova segment of the NAF Zone.

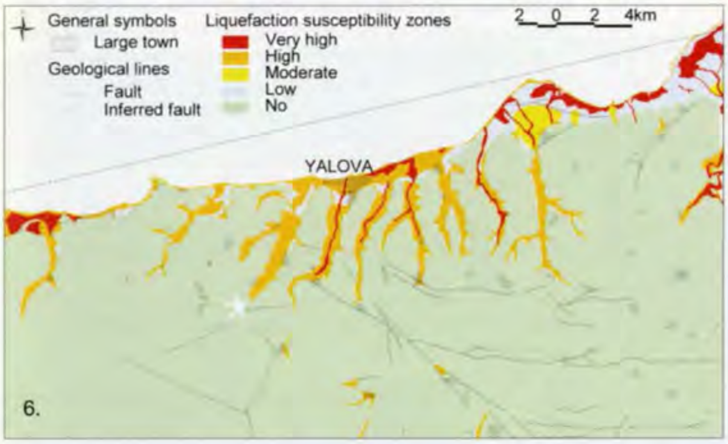
These conclusions are only indicative and could be influenced by various factors including soil type and depth (characterised as the local 'site class'), spatial variability in ground motion, and onset of liquefaction. These effects would need to be addressed when defining the seismic design forces for a specific project.

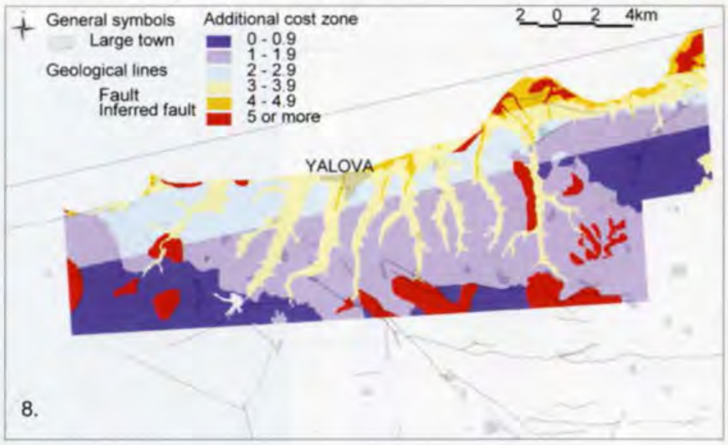
Local site class map

The geological review of the area classified the geological units into local site classes (Z1, Z2, Z3 and Z4) as shown in Fig 5. All the softer superficial deposits, which can increase the effect of earthquake ground shaking, were considered to be either Z3 or Z4, whilst the stiffer soils and rocks were considered to be Z2 or Z1. This information summarises the ground conditions in Yalova Province in terms of the parameters required to determine design seismic loads in accordance with the Turkish seismic code.









5 top left:
Local site class map.

6 above left:
Liquefaction susceptibility map.

7 top right:
Landslide hazard map.

8 above right.
Additional cost summary map.

Liquefaction

Liquefaction is the loss of strength in loose saturated granular deposits as a result of pore pressure increased during cyclic loading. The consequences were seen throughout the earthquake-affected region with many buildings suffering bearing capacity failures. The classification of geological units for liquefaction susceptibility was carried out using standard geological criteria that led to the liquefaction susceptibility map (Fig 6). This subdivided the area into six zones: very high, high, moderate, low, very low and none. The highest risk was in the softer superficial deposits - beach, coastal, delta, levee and flood plain - whilst the lowest risk was in older and denser gravels and the stiffer soils and rocks inland.

Landslide

New landslides and evidence of earlier slope instability were identified in the field, on aerial photographs, and on the Ikonos satellite images, and then classified and plotted onto overlays to the topographical maps at 1:25 000 scale. From these analyses, the landslide hazard map (Fig 7) was produced, based on a combination of the following criteria:

- presence or absence of landslide features, old or recent
- type of slope failure, shallow or deep-seated
- density of distribution of landslides
- geological formation
- general slope angle.

This map was zoned according to four hazard classes: nil, low, moderate, and high. It does not address lateral spreading, which is a liquefaction phenomenon. The Quaternary marine and alluvial deposits are flat, apart from low steps or banks at the edge of terraces, hence no slope instability was observed. The low hazard landslide zone is designated wherever none or only isolated shallow landslides have been identified. The moderate zone has only shallow landslide features widely dispersed on moderate-to-steep slopes of all rock formations. The high hazard zones have deep-seated rotational and/or a high frequency of shallow landslides on moderate to steep slopes of the inland mountain range. It also includes steep coastal locations subject to wave erosion and moderate-to-steep slopes of the Kiliç formation (a stiff overconsolidated clay) where there are fossil rotational landslide forms resulting from past river and coastal erosion when sea levels were higher.

Risk mapping

When considering the location and design of new structures, these three maps can be used to gain understanding of the severity of each hazard in an area and to design measures to reduce vulnerability and mitigate risk. However, due to their nature, they are intended for general zoning and not for site-specific design. Whilst it is important to consider each hazard individually for each site or project, it is much more useful for development planning to consider them in combination and to assess the overall risk. On this project, this requirement was essential to allow the planning team to identify areas where new development could take place. To assist this, an additional costs map (Fig 8) for 3-6 storey structures was produced.

Using design response spectra, the vulnerabilities of structures built to the Turkish seismic code of 1-2, 3-6, and 6+ storeys were assessed. The risk of damage to these different height structures from a major earthquake affecting the Yalova Province was presented as a risk matrix of additional costs for both foundations and superstructure above a reference level (see Table 2 overleaf). This uses a scale of 'increase in costs', where the reference level is for a site on flat ground underlain by hard soil or rock and the structure designed and built in accordance with the Turkish seismic code:

0 = reference level 1 = low 2 = moderate

3 = high 4 = very high 5 = extremely high.

Level 5 was applied to hazards considered unacceptable and thus to be avoided, such as deep landslides or the zone within 20m of an active fault. Cost increases are based on the need for increased design, site investigation, construction, and construction control, and are only intended to be indicative. The additional costs for foundations and superstructure were combined, assuming that the foundation and any substructure costs (including site investigation) was approximately 25% of the total design and construction costs.

Table 2

Risk matrix for increase in foundation (F) and superstructure (S) costs

Hazard	*Hazard level*	*1- 2 storey*		*3- 6 storey*		*6+ storey*	
		F	S	F	S	F	S
Ground motion – local site class	Z1	0	0	0	0	0	0
	Z2	0	0	1	1	1	1
	Z3	1	0	2	1	3	2
	Z4	2	0	3	1	4	2
Liquefaction	Normal	0	0	0	0	0	0
	Low	1	1	1	1	1	1
	Moderate	2	1	2	1	2	1
	High	3	1	3	1	3	1
	Very High	4	1	4	1	4	1
Landslide	None	0	0	0	0	0	0
	Low	1	0	1	0	1	0
	Moderate	2	0	2	0	2	0
	High (shallow)	3	0	3	0	3	0
	High (deep and shallow)	5	1	5	1	5	1
Proximity to fault	<0.02km	5	5	5	5	5	5
	<2km	1	1	1	2	1	2
	<5km	0	0	0	1	0	1
	<10km	0	0	0	0	0	0

As well as the hazards detailed in Table 2, other specific hazardous facilities such as a dam and several chemical-processing facilities need to be taken into consideration in development planning. A more detailed account of the risk assessment process will be published[2].

Table 3

Proposed projects and participants

Project	*Lead*	*Partners*
Solid waste management system	Arup	Balfour Beatty
Freshwater supply system	Thames Water	Balfour Beatty, Hyder
Wastewater collection treatment	Thames Water	Balfour Beatty, Hyder
Regional hospital	Laing	Balfour Beatty, Arup
University	Bovis Lend Lease	Balfour Beatty, Arup
Tourism project	Hyder	
Yalova province masterplan	Hyder	

'The most valuable and lasting benefit will be if local planners can ensure that when the next earthquake hits, people in new dwellings escape unharmed.'

The future

The inter-governmental agreement required BECT to produce a Reconstruction Implementation Plan to guide the Turkish authorities and potential investors in an orderly and phased approach to reconstruction. The consortium produced a developed framework and a shortlist of projects, and identified some of these to be advanced by BECT members. The final report[3] was submitted on programme on 16 August 2000, and officially presented to the Turkish Minister for Public Works and Settlement, Mr Koray Aydin, by Nick Raynsford on a return visit to Turkey. Seven TV crews covered the presentation, transmitted live on CNN Turk. BECT proposed seven projects as priorities with the various Turkish authorities (Table 3) and these were confirmed in an inter-governmental Memorandum of Understanding, signed on 9 September 2000.

Yalova's main commercial activity was tourism, as it has beaches and is only one hour by ferry from Istanbul. Before the earthquake, its popularity had started to wane and after the enormous loss of life many questioned whether they could continue to live in Yalova. Each project is therefore intended to fulfil particular development objectives, to revitalise Yalova city and province, and encourage people to stay. The first three aim to rehabilitate the damaged infrastructure to levels meeting EU standards, the next two provide a more diverse economy, and the last two respond to particular needs of local planners.

The geohazard zoning of the project is an excellent example of Arup's strengths in multi-office working, efficiently harnessing worldwide resources. The project was led from London office, its skills embracing geotechnics, seismicity, geomorphology, image manipulation and interpretation, with very important contributions from Istanbul (civil engineers), Leeds (geological and solid waste), Hong Kong (seismic and geographical information systems), and Sydney (geographical information systems).

Unfortunately, the Turkish economy faltered in late February 2001 and since then little real progress has been made on any of the projects because of the poor investment climate. It is hoped that they will restart when the Turkish economy recovers. Arup's input, however, was always intended to be broader than specific projects. Many valuable contacts were made in both governments and in partner companies, demonstrating what could be achieved in identifying hazards in a form readily usable by planners in a high-risk area. The most valuable and lasting benefit will be if local planners can ensure that when the next earthquake hits, people in new dwellings escape unharmed.

References

(1) 'Private eyes in the sky', *The Economist*, 4 May 2000.

(2) LUBKOWSKI ZA, CHAPMAN, TJP, and FREE, M. Identification of geo-hazards for the rehabilitation plan of Yalova Turkey. 12th European Conference on Earthquake Engineering, paper reference 618. [To be published in 2002]

Credits

BECT partners:
Arup Hamdi Ataoglu, Anthony Bowden, Paul Chan, Tim Chapman, Koray Etöz, Matthew Free, John Henry, Jim Johnson, Rachel King, Andrew Lord, Zygmunt Lubkowski, Jason Manning, Alain Marcetteau, Turlogh O'Brien, Mike Osborne, Jack Pappin, Alf Perry, Emily So, Louise Wright

Balfour Beatty

Bovis Lend-Lease

Laing

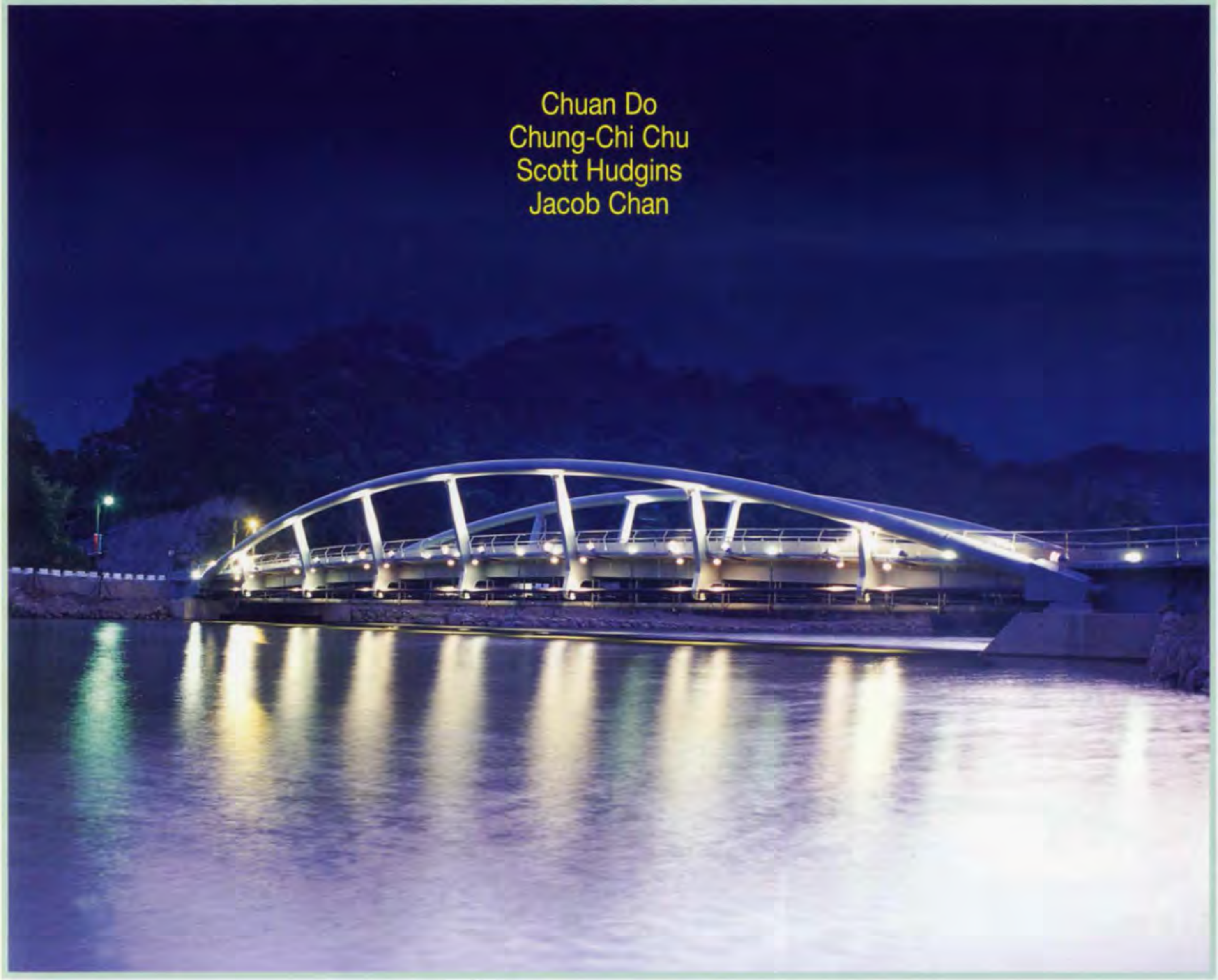
Thames Water

Hyder Consulting

Illustrations:
1, 5-8: Arup
2, 4: Sean McDermott
3: © Space Imaging LLC

Lotus Pond Bridge, Taipei, Taiwan

Chuan Do
Chung-Chi Chu
Scott Hudgins
Jacob Chan



1 above:
Lotus Pond Bridge complete.

Introduction

The Koos Real Estate Development Group in Taiwan has developed a beautiful, convenient, secure, multi-functional, and centrally located gated community called Lotus Pond, about 10km north east of downtown Taipei. Built on a hillside, the community looks over the mountain-ringed Lake King-Lung, one of the three largest lakes around Taipei.

The new Lotus Pond Bridge spans the lake. It fulfils a major transportation role between nearby communities and Taipei, as well as enabling many lakeside activities. In this serene habitat for bird-watching and fishing, the bridge had to be aesthetically appropriate (Fig 1).

Design brief

The design, construction, and maintenance of bridges in Taiwan are normally public works, with local government responsible for schedule, budget, construction, and maintenance.

An existing bridge - in effect a temporary earth berm - was the original entrance to the new community, but the Koos Group itself decided to contribute a bridge specially designed for the community. This bridge forms the new gateway to the community, with two traffic lanes and pedestrian walkways, and is already an iconic structure in the locality. After completion, the government took over maintenance of the bridge.

Arup was awarded the project because the client believed that the firm could provide a bridge unique in concept and form, given its track record of innovative and interesting structures in the Taipei area. Design began in June 1999, and construction was completed in September 2000. As no architect was involved, Arup was responsible for all aspects of the bridge's design. Because the bridge was planned as a symbolic gateway to the community, the design had to be sensitive to the site's natural beauty, and the challenge for Arup was to achieve harmony between technological and aesthetic considerations.

An arched structure offered an appropriate elegance, and the inherent aesthetics of double arches led to the development of the structural system. In defining the arches' vertical curvature, consideration was given both to maximising structural performance and to code requirements for vehicle speed limits and sightlines. The water level of the lake during the rainy season, the elevation of the connecting roadway at both sides, and its profile in the surroundings, were all important factors affecting the bridge's geometry.

'Arup backed up its proven track record by providing a bridge distinctive in concept, structure and form.'

Structural system

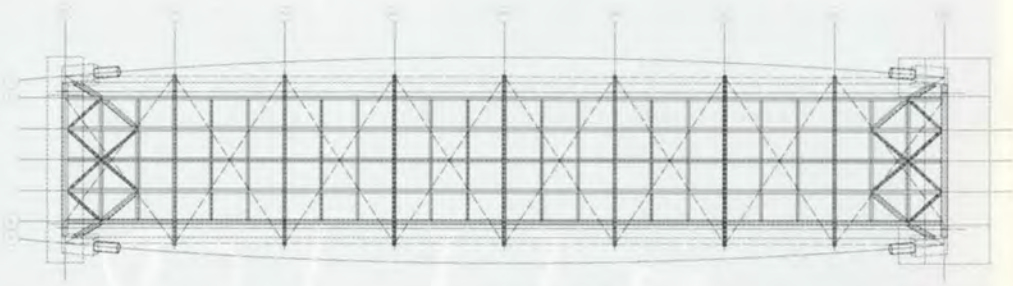
The gravity load-carrying system of Lotus Pond Bridge comprises two longitudinal inclined vertical tied arches, spanning 223ft (68m) between the concrete pier foundations on both sides of the lake. Each tied arch consists of one 31.5in (800mm) diameter steel tube and two prestressed cables. Seven H-shaped frames (Fig 2), in built-up steel box sections, are hung and supported by the tied arches every 28ft (8.5m) on centre.

The 6in (150mm) thick reinforced concrete slab on top of a 2in (50mm) deep metal deck acts as a composite diaphragm, supported by wide flange steel beams spanning between the seven steel H-frames. The two tied arches are carried on four bearings atop pier foundations at each side of bridge (Fig 2).

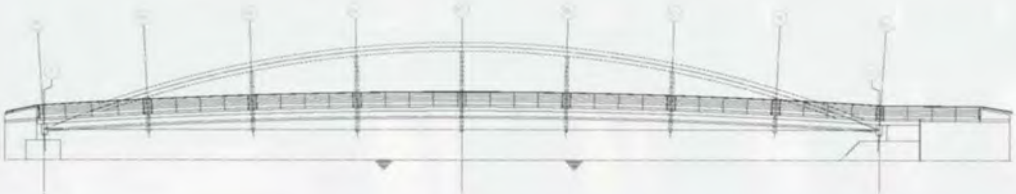
For seismic load resistance, forces from the mass of the bridge deck are transferred through the deck, acting as a rigid diaphragm, directly to the foundations.

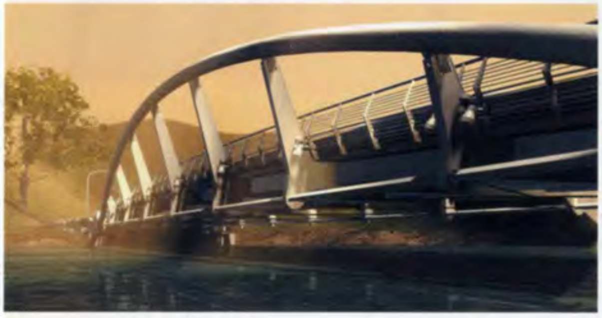
Seismic forces from the self-weight of the steel arches are transferred by the arches themselves longitudinally and by the seven H-frames and the bridge deck transversely. Diagonal braces under the deck are provided at both ends of the bridge to tie the arches with a slab diaphragm.

To maximise scenic views, in-plane bracing of the arches is eliminated and each arch inclines outwards. The H-frames restrain the arches from out-of-plane buckling, transferring the restraining forces to the concrete deck and to the tie rod bracing below. Wide steel flange beams span between the H-frames, rigidly connected as part of the slab diaphragm, which provided lateral continuity and stability during construction for the erection of the arches and during cable prestressing. The composite action of the bridge deck provides additional lateral stability for the self-weight of the structure and the live loads of automobile and pedestrian traffic.



2 right:
Framing system plan
and below: elevation.

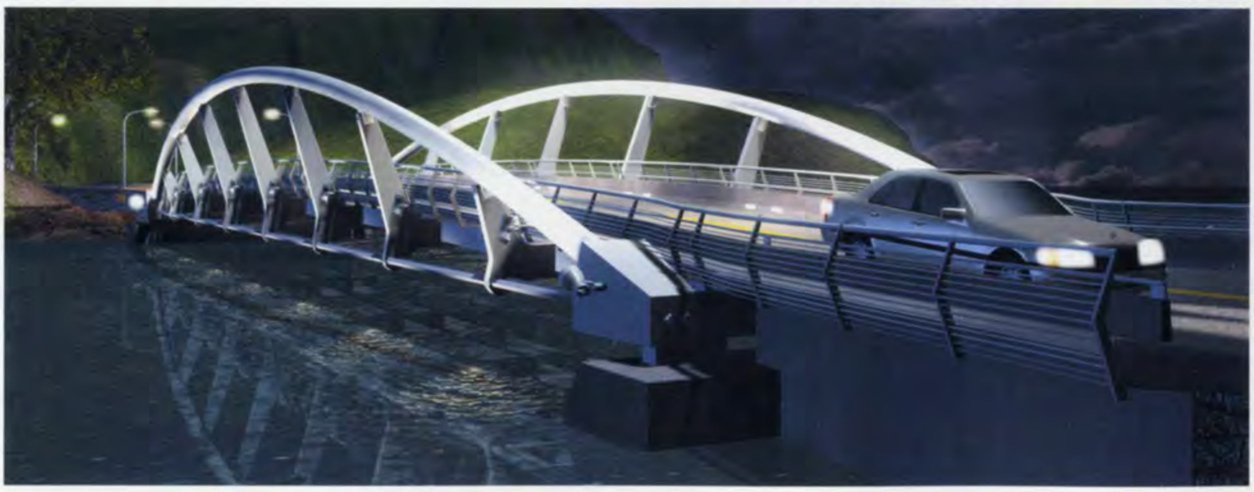




3a

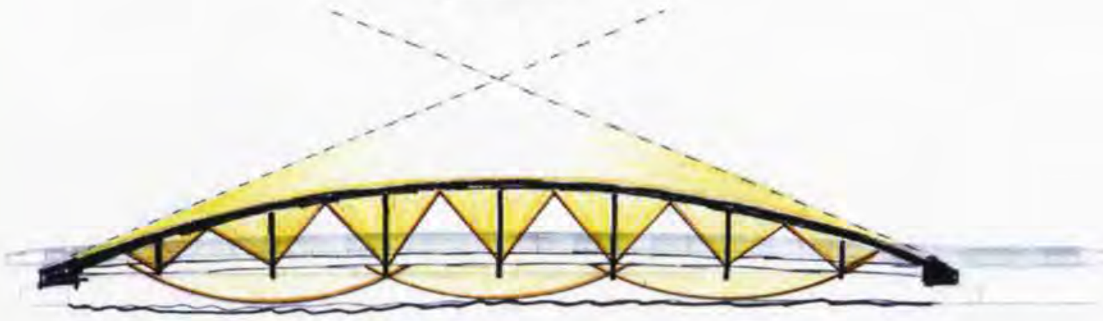
3b

3a to 3c:
Frames from the 3D visualisation.



3c

4.
Lighting concept.



The cables were prestressed after completion of the steel deck but before the concrete was poured. The prestressing action causes the arches and the deck to 'bow up', which in turn counteracts deflections and reduces the bending effects of the arch when additional vertical loads are introduced into the system. To avoid 'losing' the prestress force into the concrete deck slab, the cables were prestressed prior to casting the slab. As a result, the prestressing operation worked against the axial stiffness of the deck beam to pull the ends of the arches in. Two cables per arch were used to minimise the effects of cable replacement and maintenance in the future. Because the design life of the structure is much longer than the working life of the cables, the design allows for the structure to carry the dead load and a nominal construction live load with one cable removed. The bridge is also designed for a life safety load case, whereby the whole structure will not be irrevocably damaged if just one component fails.

At the four bearing points, bracing is provided in the plane of the deck as well as vertically between the pairs of points at each end by a transverse beam. The framing system provides the required degree of redundancy for transfer of the arch reaction to the foundations. The bridge is supported at the four bearing locations with different types of sliding devices, to allow movement in each direction. At both ends of the bridge, cast-in-place concrete pier foundations penetrate through the bedrock at different elevations.

Design analysis

The structural analysis of the bridge reflects the construction process by which it was built. Two different analysis programs were used. The construction stage loading, due to the self-weight of the steel members and prestressing force, was analysed by a three-dimensional non-linear analysis and design program. This same program was also used for the final stage loading, which includes the dead weight of the concrete slab and the live loads due to automotive and pedestrian traffic. GSA, Arup's own comprehensive general structural analysis program, was then used to analyse the stresses due to the buckling effects of the arch. A spreadsheet was created to combine the stresses in the members from the two analyses; this included three stages of loading: construction stage, the final stage loading, and the buckling effects.

3-D visualisation

Adding to the exceptional nature of the project was the use of 3-D computer-generated models to provide a continuous flow of data and images for design and analysis. The design team not only used computer-aided design to the full, but also had the knowledge necessary to share the data generated between applications to extract maximum value from the man-hours spent enhancing and streamlining the design process (Fig 3).

During the initial concept phase, the Arup team developed images from 3-D visualisation that brought client buy-in almost immediately, and through careful planning of the digital model, provision was made early on by the team for easy transfer to other applications. For the scheme design, the concept model was exported to the 3-D non-linear structural analysis program from AutoCAD for structural analysis, and also to 3DStudio Max 3.1 for visualisation. What would seem like divergent paths - structural analysis and visualisation - were instead linked in the design development through a physical model generated by rapid prototyping.

The final phase of the project was a virtual polishing of the digital model, adding detail to the landscape and the surroundings. At this point, the surrounding area was created, and cameras were animated in a fly-through that showcased the bridge in vivid volumetric lighting. This animation was recorded to videotape, as well as rendered out as a series of still frames.

Lighting design

The lighting was designed with three essential aims:

- to reinforce the image during darkness to create a focal point for the traffic, as the bridge is the gateway to the community
- to focus primarily on the bridge and avoid casting an unnecessary spill of light to the surroundings
- to enhance the bridge's lightweight appearance and illuminate the lake below.

Of the three sets of lighting fixtures, the first comprises compact fluorescent lighting flush-mounted along both sides of the sidewalk to assist both cars and pedestrians in crossing the bridge. The second set consists of two metal halide fixtures mounted along the bottom of the bridge canopy pointing upwards. These have warm beams, highlighting the individual columns. The final set are metal halide lights pointing along the lake to create a floating effect for the bridge. Metal halide lamps were selected to give a striking colour appearance for the steel members (Figs 1 & 4).

Conclusion

The Lotus Pond Bridge shows how integrating planning, design, innovation, and 3-D imaging can realise an aesthetically pleasing, structurally sound project, achieving and exceeding all the client's expectations in a very tight schedule. This relatively small-scale structure showcased not only the exciting fields of rapid prototyping and visualising, but also the tight integration and efficient design possible when working in 3-D from the outset. The client used the bridge visualisation as a showpiece in their marketing materials for the community that it leads to. Indeed, this bridge has already become a landmark in the area due both to the sleek design and the powerful marketing imagery.

'The Lotus Pond Bridge exceeded all the client's expectations in its sleek design and in its completion to a very tight schedule.'

Credits

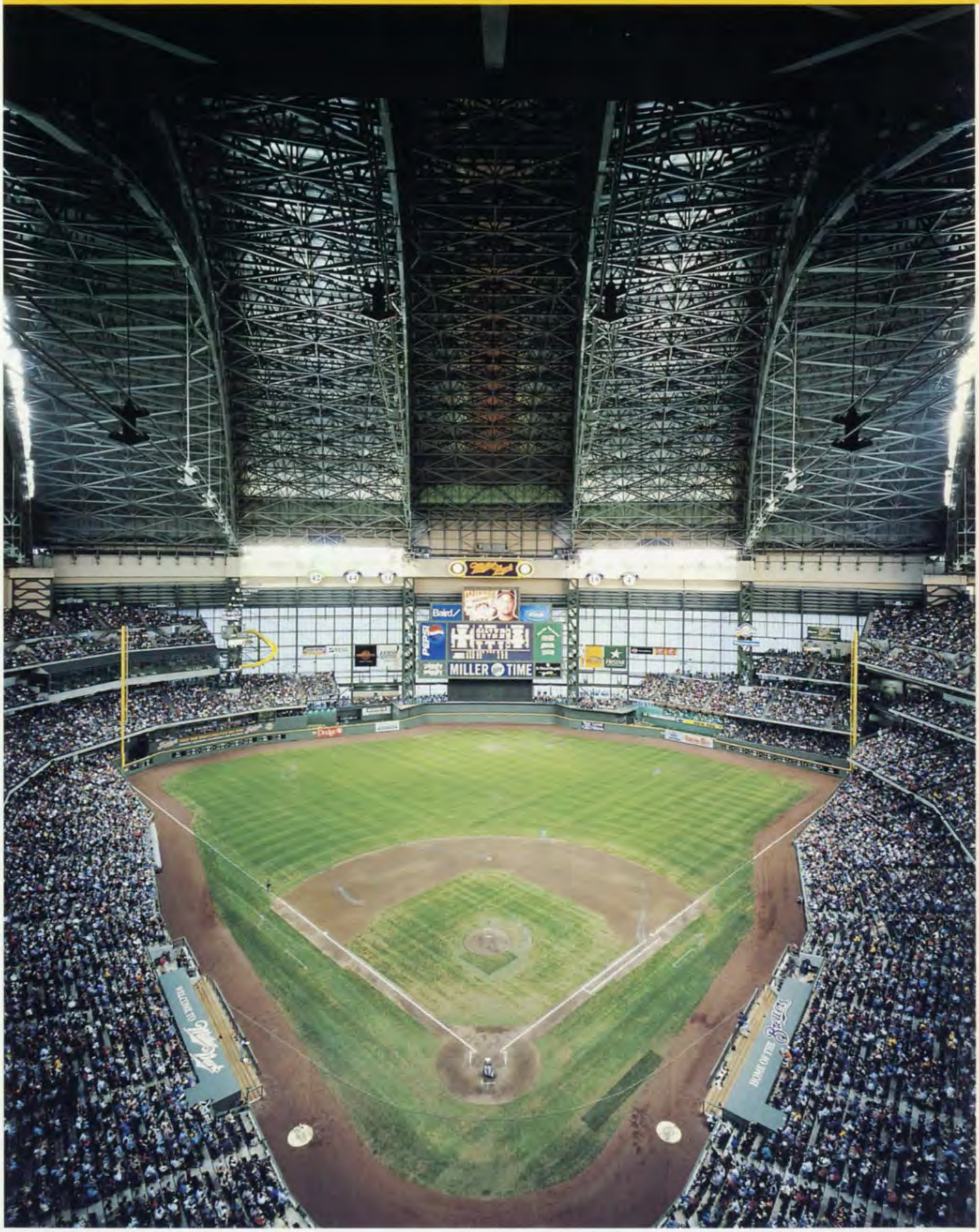
Owner:
Koos Real Estate Development Group

Designer:
Arup Anders Carlson, Jacob Chan, King-Le Chang, Waylon Cheung, Chung-Chi Chu, Keith Chung, Kurt Clandening, Chuan Do, John Eddy, Li-Tsung Huang, Scott Hudgins, Steve Kite, Mark Roche, John T Roberts

General contractor:
Continental Engineering Corporation

Local engineer:
JWLI, Jen-Wei Li

Illustrations:
1: © Koos Real Estate Development Group
2-4: Arup



Printed in England by Reedprint Limited, Windsor, Berkshire

THE ARUP JOURNAL

TO SUBSCRIBERS AND OTHER RECIPIENTS

Please note that two issues of *The Arup Journal* were published in 2001:

1/2001
Transportation for the Sydney Olympics
Manchester Aquatics Centre
Osaka International Convention Centre
Osaka Maritime Museum
Melbourne Museum
Watling House, City of London
Schwimmsporthalle, Berlin

2/2001
Jubilee Campus, University of Nottingham
The Irizar Coach
Dandaro Retirement Village, Harare
Munich Airport Centre Forum Roof
CargoLifter hangar, Brand, Germany
International Tennis Centre, Olympic Park, Sydney
Ibhayi Brewery, Port Elizabeth, South Africa
European datacentres for IX Europe
Corporation Street footbridge, Manchester
IT for the new Bank of China Headquarters, Beijing

ARUP

Arup, 13 Fitzroy Street, London W1T 4BQ, UK
Tel: +44 (0)20 7636 1531 Fax: +44 (0)20 7580 3924
e-mail: corporate@arup.com
Editorial:
Tel: +44 (0) 20 7755 3828; Fax: +44 (0) 20 7755 3716
e-mail: david-j.brown@arup.com
www.arup.com