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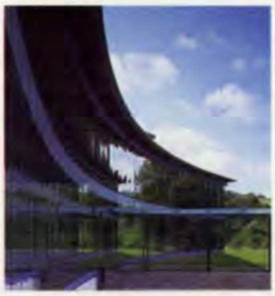
Front cover:
American Air Museum, Duxford (Photo: Peter Mackinven)
Back cover:
Museum of New Zealand Te Papa Tongarewa, Wellington
(Photo: Michael Hall)

The national treasures of New Zealand are now housed in this new building on a prime waterfront site in the nation's capital. Ove Arup & Partners' design responsibilities embraced both a wide range of structural applications - including all of the building steelwork, several internal and external bridges, structural support for the large areas of glazing, and the precast concrete cladding system - and the civil engineering design. The latter included dynamic consolidation and the requirements to accommodate the interface between a base isolated building designed to withstand the earthquake forces anticipated in this seismically unstable region.

The new permanent home for the Imperial War Museum's collection of American aircraft consists of a 90m span double-skin precast concrete shell, designed to accommodate the giant B52 bomber plus 20 other aircraft. Several of them, weighing up to 10 tonnes, are hung from the roof. The design team's concept aimed to combine visual calmness of form with effective passive environmental control and use of natural light, all within a very tight construction and maintenance budget.



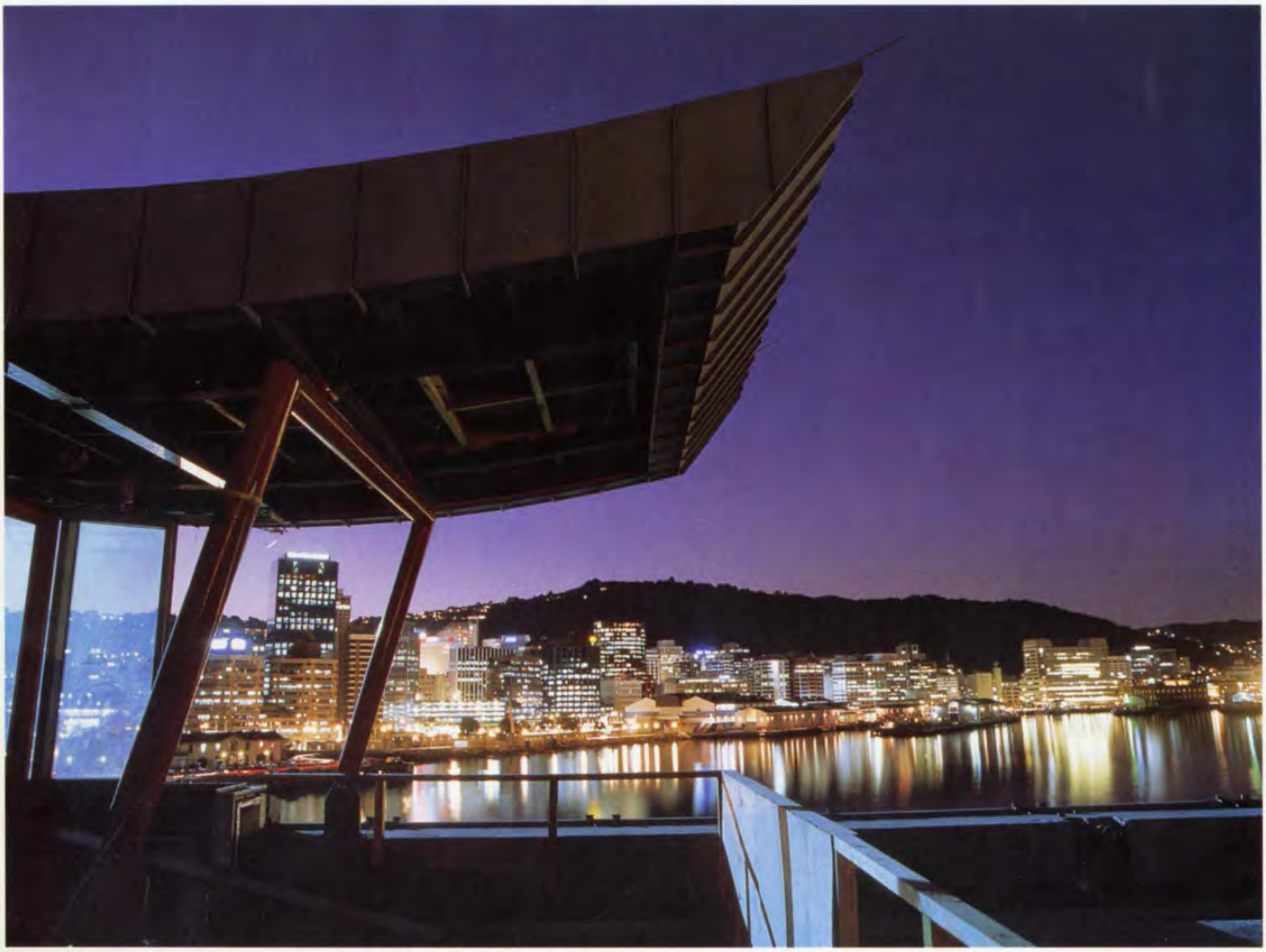
The client's brief was for a research & development headquarters and administrative centre separately accommodated within a single building. Arup Associates' two-storey design met these requirements in a curved plan shape that exploited the natural contours of the greenfield site.

The question is often asked 'What new materials are available to designers and constructors?' To develop a meaningful response, this article takes a fresh look at how materials used in construction may be categorised, and sometimes re-categorised, as their properties and capabilities become more thoroughly understood and in some cases developed and enhanced by materials scientists.

This article, based on a report by Arups for the UK Construction Industry Research & Information Association (CIRIA), describes the continuous process of predicting, monitoring, reviewing, and modifying geotechnical designs which has come to be known as the Observational Method. The OM is shown to have a number of advantages over the alternative method of a fully developed and predefined design, as demonstrated through several practical applications on Arup projects.

Museum of New Zealand Te Papa Tongarewa

Pippa Connolly



1. Wellington waterfront reflections viewed from the Marae in the new Museum.

2. Site location.

Introduction

New Zealand's National Museum and Art Gallery opened in 1936, and is the repository of the nation's treasures. However, because the original main building was reduced in size during its design phase it was always too small, which forced the unsatisfactory compromise of the collection being housed in several locations around the capital city, Wellington.

A series of consultations with groups throughout New Zealand led to the proposal to build on the Wellington waterfront the Museum of New Zealand Te Papa Tongarewa ('Te Papa') - the Maori part of the name loosely translates as 'treasure house' (Fig 2). In 1986 the Government approved the project in principle and directed the then Minister of Internal Affairs to continue consultations. The concept was given the go-ahead for planning purposes in April 1987.

Further approval for design and construction was granted in early 1990. In the same year an international two-stage competition was won by JASMAX Architects, supported by a team of consultants including Ove Arup & Partners in joint venture as structural, civil, and façade engineers with Holmes Consulting Group. In May 1992 the Government authorised construction.

A distinctive characteristic of New Zealand is the two mainstreams of cultural heritage: that of the Tangata Whenua (those who belong to the land by right of discovery) and the predominantly European Tangata Tiriti (those who belong to the land by right of the Waitangi Treaty). The Museum's fundamental concept is to integrate the essence of these two cultures, expressing their interaction, while at the same time revealing and retaining their diversity.

3.
Carvers at work in the Marae.

4.
350-seat auditorium: Ove Arup & Partners were responsible for structural design of the extensive timber acoustic panelling and raised/tiered seating.

A unique feature of this philosophy is the positioning of a Marae (Maori Meeting House) within the Museum (Fig 3). Traditionally Maraes are focal points for individual Maori tribes, but this new Marae is open to every tribe and culture, and all New Zealanders will be able to use it for their festivals and events.

The Museum's total floor space of more than 36 000m² accommodates - apart from the Marae and the permanent exhibition spaces - a children's learning centre, a touring exhibition gallery, a temporary exhibitions hall, purpose-designed storage facilities, visitor viewing rooms, visible collection storage areas, a library, a resource centre, a 350-seat auditorium (Fig 4), a 'theatrette' for 50 people, demonstration areas, classrooms, a restaurant and cafe, the Museum shop, workshops, and offices for Museum staff. Incorporated in the lowest level is a car park for 250 vehicles.

The final design is geometrically unusual with many sculptural forms linked to interpretation of the building incorporated in the structure (Fig 5). External landscaping enhances the spectacular site with an external exhibit area known as the Harbour Park (Fig 6). This aims to give visitors the chance to explore New Zealand's varied environment and experience at close hand a selection of its unique flora, fauna, and geology, an effect achieved by incorporating different areas of vegetation and rock displays, including a recreated limestone cave and simulated fossil dig.

5. Site plan

6.
The Harbour Park.

Project responsibilities

Arups was responsible for the structural design of all the steelwork - comprising mainly sculptural roofs, bridges, and glazing restraint - the civil design of all external works, and the design of the precast cladding system. The project involved staff from many Arup offices: façade expertise came from Sydney, as did much technical advice on specifications; Arup Research & Development in London provided further input, and Arup Fire gave advice after a fire during construction caused some damage. The Brisbane office provided peer review for civil works, while the Advanced Technology group in London peer reviewed the seismic design parameters for the structure and verified the base isolation system.

The site

The waterfront site for the new Museum is spectacular: surrounded by hills, it faces down the harbour towards the Rimutaka hills (Fig 7). It also has several features that significantly affected the building design. Located mainly on land reclaimed post-war, the Museum site could be susceptible to flooding, like all the Wellington waterfront. Of particular concern was the likelihood of seiching (the immediate wave in the harbour due to earthquakes on the nearby Wellington or West Wairarapa Faults), as well as tsunamis from more distant earthquakes. Wellington is one of the most highly seismic regions in New Zealand, and as well as everything else, wind gusts there have a legendary strength.

The brief

The extensive brief prepared by the Museum incorporated the specific performance requirements of a 150-year design life; in particular:

- the probability of less than 50% significant damage in 150 years, corresponding to a 250-year return period for seismic design
- a less than 7% probability of collapse in 150 years, corresponding to a 2000-year return period for seismic design.

Site preparation

Work began on the site in mid-1993. After demolition of some basic warehouse structures, a five-storey reinforced concrete hotel was moved off the site (Fig 8) and across the adjacent main road (Cable Street). With the hotel out of the way, the inherently unstable site was dynamically consolidated by dropping up to 30 tonne weights from a height of up to 30m at regular intervals (Fig 9). The process of consolidation lowered site levels by up to 1m, improving its capacity sufficiently to found the whole structure on pad footings. It also reduced the risk of liquefaction and potential for the site to slide on an existing marine interface layer.

Base isolation

The basic building structure is a five-storey reinforced concrete frame, with shear walls in one direction and frame action in the other; most of its beams and slabs are precast. The decision was made to base-isolate the whole building as this offered the best compromise between initial cost and optimum performance in the case of earthquakes. The principal advantages of seismic base isolation are:

- a significant reduction of seismic design forces
- much-reduced ductility demand in the structure
- a reduction in the anticipated level of structural and non-structural damage
- reduced floor accelerations, limiting potential damage to both the artifacts housed in the building and to its services
- reduced floor-to-floor drifts, which simplifies detailing of cladding, stairs, etc.

7.
Looking down the harbour from the touring exhibition gallery, during construction.

8.
Moving the Museum Hotel.

9.
Dynamic consolidation.

142 hysteretic damping base isolators, consisting of layers of steel plates and rubber with central cores of lead, were supplied to the site (Fig 10) and installed with simple bolt fixings to the pad foundations. They dampen horizontal seismic accelerations generated during an earthquake to such a extent that it was possible to detail the structure for a 1 in 2000-year earthquake without collapse. Inter-storey deflections are minimised, typically to 40mm for a 150-year design life. Movements at the level of the isolator are up to 500mm, requiring the detailing around the building perimeter to take into account movements of non-isolated adjacent structures so that there is only minor damage to either.

10.
Base isolator on pad footing with formwork being installed around it to cast the protruding bolts into the ground floor beams.

These bearings were not suitable for wall locations where high compression and tension forces occur, so here PTFE (*Teflon*) sliding bearings were used (Fig 11).

11.
Two sizes of sliding bearings, awaiting installation below walls.

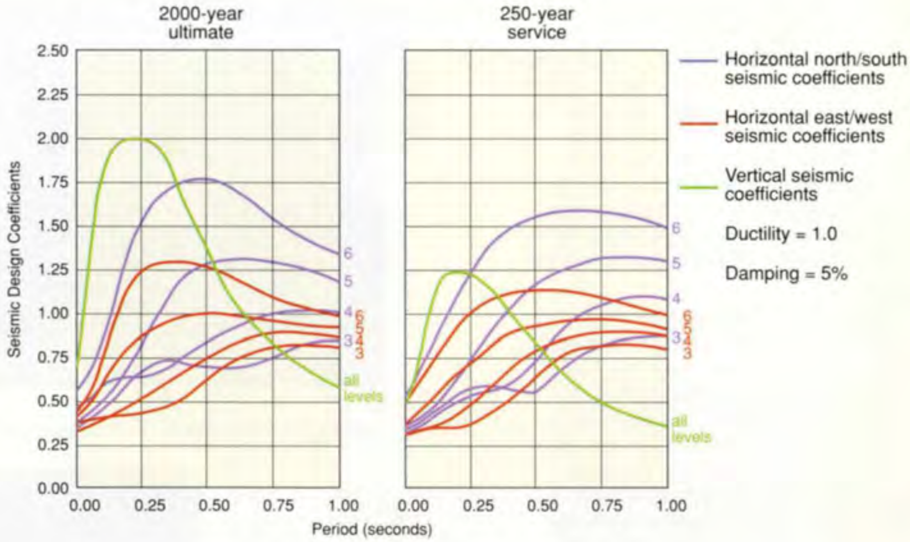
Site-specific earthquake acceleration time histories and response spectra were generated for each of the return periods, and appropriate damping was used to generate design spectra specific for the Museum. These spectra were then used as design criteria for every element of the structure (Fig 12).

Precast concrete cladding

As base isolation techniques protect the building from earthquake damage, so Wellington's extreme weather is kept at bay by the 15 000 unreinforced precast concrete cladding panels that cover the exterior. These are all 70mm thick and mostly 1.87m x 865mm, though on some the long dimension is extended to 1.95m. The panels form the outer layer of a double skin which operates as a pressure-equalised rain screen system. The uniform 15mm joints between panels are partially filled with a purpose-made gasket. Each panel is supported at its corners by stainless steel kerf brackets; these are bolted to stainless steel secondary brackets which in turn are supported off reinforced blockwork walls built around the building perimeter between the concrete frame. The face of the blockwork is coated with a waterproof membrane with a layer of insulation incorporated in the gap between the wall face and the rear of the panels. The total distance from the base blockwork wall to the panel face is 200mm (Fig 12).

13
Panel/wall connection detail.

12.
Coefficients for ultimate and serviceability design, depending on the calculated period of the structural element; coefficients vary depending on the element orientation as a result of the varying building stiffness in each direction. Vertical accelerations are unaffected by the base isolation system.



The blockwork walls are built off the perimeter floor beams at each level and are secured only at their heads by shear fixings which can slide horizontally. Gaps of 40mm to adjacent columns allow for inter-storey deflections under peak seismic loading; these joints incorporate flexible waterproof 'bandages' and fire-preventing material.

14a.
Blockwork jointing at the south end of the Wall. The black stripes are the flexible waterproofing installed across 40mm movement joints prior to application of waterproof membrane across whole Wall.

14b. (Below)
South end of the Wall fully clad in basalt precast cladding.

It was unavoidable that the precast cladding would span all the movement joints between the blockwork and the concrete frame (Figs 14a & b), and creating the building's complex geometry while catering for those movements presented one of the most challenging aspects of the design. The principle of the movement is that the cladding moves with the blockwork, not the concrete frame. To achieve this, across the movement joints the secondary brackets are replaced by stainless steel rolled hollow square sections. These are fixed to the blockwork, but have a sliding joint on the adjacent concrete (Fig 15).

15.
Bridging steel across seismic joint.

16. View of the Museum from the Harbour Park, with the 'wetlands' in the foreground and the orientation building, with associated Harbour Park bridge, to the right. The north end of the 'Wall' is to the right.

17.
East elevation showing dolomite cladding panels in varying forms. The sloping panels at the base of the building in the foreground are retaining walls, forming landscaping and a ceremonial approach to the Marae.

Wind loads (of up to 68m/s basic wind speed) governed the design of the panels themselves, while seismic loads governed the bracket and fixing design.

Development of the kerf bracket design led to a single bracket being used to support the adjacent corners of four panels. Each bracket takes the vertical load of the two panels above while simply restraining the two below against wind load. The turned down 'tang' of the lower support also acts as a flashing to direct water away from the cladding cavity.

The panels are made from a 25mm structural facing mix with 45mm of standard grey concrete backing mix; both mixes have a strength of 35MPa. The facing mix for each panel incorporates one of two types of aggregate, either a yellow dolomite or a dark grey basalt. Two types of finish are used, an exposed aggregate and a polished face.

The darker, grey, panels are used exclusively internally and externally. This is on 'the wall', the strong 100m element that leads right through the building, while the dolomite panels are used everywhere else, with the difference between polished and exposed finishes providing emphasis as necessary. Some panels are curved in order to define the geometry of the building (Fig 17).

Grade 316 stainless steel was used for all brackets and bolts to give optimum durability.

18. Orientation lobby from Harbour Park, showing curved precast panels.

Steel design

The steelwork design required close collaboration with JASMAX to establish a multitude of solutions for the differing locations. Much of the steelwork is exposed and forms a fundamental part of the architectural expression. Uses ranged from basic staircases to the five-storey high entrance glazing support and restraint system, other large openings in the orientation lobby (Fig 18), and a three-leaf, variably opening, ceremonial door, 8m wide and two storeys high.

The roof forms incorporate many curves and geometrically unusual shapes, all formed in a variety of structural steel (Figs 16, 17 & 20). The main exhibition spaces are column-free, spanned up to 27m by square hollow section trusses, all of which incorporate in their design hanging points for exhibition loads. The heaviest was judged to be a Tiger Moth aeroplane currently owned by the Museum, followed closely by the complete skeleton of a rare Pygmy Blue Whale.

Bridges form an integral part of the museum. Internally they criss-cross the multi-storey voids, a notably unusual one, the Ihonui bridge, curving across the wedge-shaped central space (Fig 19). Its support is taken substantially from four hangers fixed to the roof above, articulated with large pin joints. Differential movements at each end of the bridge are accommodated with sliding bearings. Bearings to allow for movements up to ±500mm were required for the Harbour Park bridge, which spans from the main building out to the orientation building in the Harbour Park. This is essentially a propped cantilever, painted yellow, mostly hung from the main structure (Fig 16). The requirement to cater for large movements results from the bridge connecting a base-isolated building and a traditionally-founded building.

Part of the visitor experience in the Harbour Park is the swing bridge, the brief having required a 'moving bridge' capable of being negotiated by wheelchairs. This bridge, which consists of a series of cables strung between abutments and carrying boards at their base, passes over a stream flowing into wetlands and the more adventurous visitors can certainly instigate a significant swinging motion (Fig 20).

Corrosion of external steelwork was investigated in depth with Arup Research & Development. The environment is very corrosive, being right on the waterfront with strong winds to carry moist, salt-laden air onto every element. All external connections are either fully welded or pinned, all pins being stainless steel (grade 316) as are the plates they connect. Where these plates connect to the structure the weld interface is painted to prevent corrosion.

19. Ihonui bridge.

Construction

Building the museum incorporated several techniques new to New Zealand. The first was the concept of construction management. All the work was let in construction packages, starting with the hotel move. The main structure and body of the building formed another, while all the services were let individually, with many other packages running alongside. Carson Project Management managed the individual contractors with assistance from a partnering agreement. As soon as each contractor was appointed, a partnering meeting was held with members of the construction and design teams and the client body, with the goal of producing a charter aimed at improving team relationships. The principal benefit of this approach was to put a mechanism in place where issues were aired as soon as they surfaced and solutions agreed early in the process, thus avoiding lengthy negotiations and adversarial stances.

All work was carried out under *ISO9000-9003* principles.

Conclusion

New Zealand's Prime Minister Jim Bolger has been involved in the whole process and laid the foundation stone in 1993. Construction started the same year, and Jim Bolger was on hand again in 1995 for the topping-out of the main structure. The Queen also visited the site in her trip to New Zealand in 1995. At the time of writing, the project was on schedule and budget for the opening in February 1998; exhibitions were being installed, with aspects of the structural design tested to their full extent. One window on level 4 had to be designed as fully openable to allow the ingress of a full-sized war canoe as one of the maori exhibits - which was successfully achieved in May 1997. The raised 33mm thick plywood floor covering the 10 000m^2 of exhibition space was designed to carry a forklift for exhibit installation. The flexibility provided for cabling routes and fixing of partitions and the like proved invaluable as exhibits have been installed.

The true drama of the building is only now taking shape as the exhibitions bring life to the diverse spaces. The whole project has been undertaken very much in the public eye, and it will be some time before the final verdict is reached as to its success.

Credits

Client:
Museum of New Zealand Te Papa Tongarewa Board

Architect:
JASMAX Architects

Exhibition consultants:
Ralph Appelbaum & Associates

Project manager:
Carson Group

Structural and civil engineers:
Holmes Arup Joint Venture

Ove Arup & Partners Mike Brading, Paul Callum, Pippa Connolly, Joanna Fenwick, Roger Lovell, Colin Roberts, Dan Ryan , Pete Tillson, Rob Walsham, Martin Wehner (structural)
Clive Humphries (civil)
John Perry (Arup Façade Engineering)
David Moorehead (Arup Research & Development)
Mike Willford (Advanced Technology)

Geotechnical engineers:
Tonkin and Taylor

Quantity surveyors:
Russell Drysdale and Thomas

Landscape architects:
Boffa Miskell Partners Ltd

Environmental wind consultants:
Works Consultancy

Building contractors:
Dynamic consolidation: Mainzeal
Base building: Fletcher Construction
External works: McKee Fehl
Base isolators: Skellerup Industries
Steelwork: Stevensons Joint Venture
Precast cladding panels: Precision Precasting

Illustrations:
1, 3: Norman Heke
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Te Papa Tongarewa)
2: Courtesy JASMAX Architects
4, 16, 19, 21: Michael Hall
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5, 12: Sean McDermott
6, 14b, 17, 18, 20: Rob Walsham
7, 10, 11, 14a: Pippa Connolly
8: Jan Nauta
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Te Papa Tongarewa)
9. Ove Arup & Partners
13, 15. Colin Roberts

20. Harbour Park 'swing bridge' springing from replica limestone cave.

21. Southern elevation from Cable Street. Uplift pressures of up to 7.5kpa were designed for on the cantilever roof..

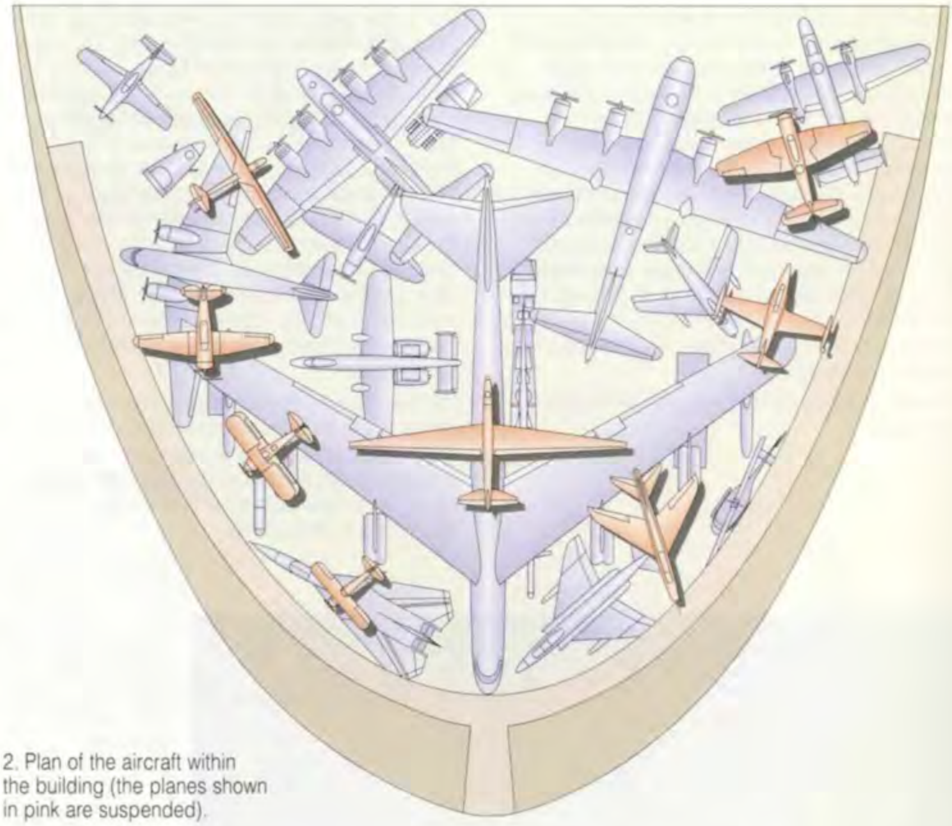
The American Air Museum, Duxford

David Andrews Gabriele Del Mese Kevin Franklin Chris Wise

Introduction

Duxford, about 8km south of Cambridge, England, has been a working airfield since 1918. Founded to train British pilots for the Great War, its association with American military aviation extends from 15 March that year when the 159 US Aero Squadron marched in from nearby Whittlesford railway station. They lived under canvas and built their own mess to cater for their different tastes in food and drink (coffee not tea). The historic listed hangars from that time survive to this day, except one which was blown up, on purpose, during the making of the Battle of Britain film. In the Second World War, Duxford was used by the USAAF 8th Air Force as a fighter base, active from 1943 to 1945. It was closed in 1961, but was taken over by the Imperial War Museum in 1972 to be opened to the public four years later as a Museum housing a fine collection of historic British and American aircraft. Some of these still grace the skies with the beauty of their lines and the roar of their engines, whilst many others have been lovingly restored and still more are undergoing countless hours of diligent restoration by Imperial War Museum staff and volunteers.

For many years the Museum's collection of American aircraft, the finest outside the USA, had languished in the open air, and an initiative was taken almost 12 years ago to launch a campaign to fund and build a new American Air Museum for the American planes - a project conceived in part as a tribute to the nearly 30 000 American airmen who lost their lives during the Second World War, flying from English airfields including Duxford. The centrepiece was to be the sinister B52 bomber, with its 61m wingspan and tail fin 16m high. The scheme that evolved with Norman Foster as architect, Ove Arup & Partners as structural, geotechnical, and acoustic engineers, and J Roger Preston as environmental engineers, was largely shaped by the need to house this giant, and the desire to hang many smaller planes from the roof. The suspended planes, weighing up to 10 tonnes, range from an F100 Supersabre to a U2 spy plane, from a PT13 Stearman to a TBM3 Avenger. The grounded planes in the exhibition include - apart from the 80 tonnes B52 Stratofortress - an F111, a B25, a B29, an F4, and a P47 Thunderbolt, amongst others. A 45 tonne section of the notorious Iraqi 'Supergun' is fortunately mounted on the floor.



2. Plan of the aircraft within the building (the planes shown in pink are suspended).

Funding

After the initial effort, the project had to be shelved due to recession and lack of sufficient funds, and detailed design only took off again early in 1995, thanks to fund-raising on both sides of the Atlantic. The film actors Charlton Heston and the late James Stewart led the campaign on the American side, and Field Marshall Lord Bramhall in Britain. 60 000 individual donations were made to the project, much of it from the USA. With great foresight, this money was mainly used to finance detailed design work so that the project was well placed to receive the first ever grant, of £6.5M, from the Heritage Lottery Fund. This was later supplemented by a further $1M from Saudi Arabia in gratitude to the US and British Forces for their efforts in the Gulf War.

The design

Key aims of the design were:

- low capital cost
- low cost in use
- ease of construction
- effective passive temperature control
- maximum use of controlled natural light
- effective condensation control.

Elegance and grace of form were prerequisites.

The structure of the building aligns completely with these aims, and is deliberately underplayed to give a very calm background against which to view the exhibits. In the end the design team chose the essentially simple form of a great shell partly buried in a raised landscape.

Early in the design process, the team compared steel and concrete roof solutions, showing that a concrete building could keep the temperature above the dew-point so that condensation did not occur, with a minimum of dehumidification plant. A detailed life cycle cost study showed the concrete solution, with its inherent low maintenance and minimal dehumidification, to be in overall terms the most cost-effective, even though the structure itself with its larger foundations was marginally more expensive.

The roof

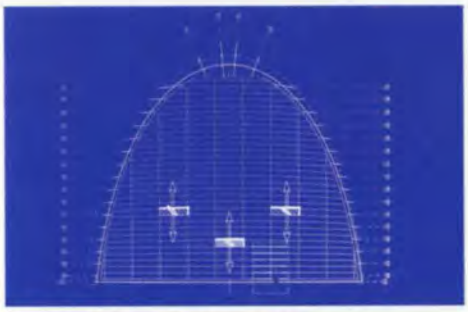
The roof spans up to 90m, and is made from two precast concrete shells only 100mm thick, spaced 900mm apart. At the front of the building the structure behaves mainly as an arch, and at the back, where it is very flat, as a beam. The membrane action of the shells allows load sharing in two directions, especially under the weight of the suspended aircraft. Forces from the concrete roof shells are collected into an in situ curved upper concrete ring beam, and then passed across a 'daylight slot' via 34 steel arms spaced at approximately every 4m to a lower in situ ring beam and finally to the abutments and foundations.

1. The 21 aircraft accommodated, starting with the B52 (far left).

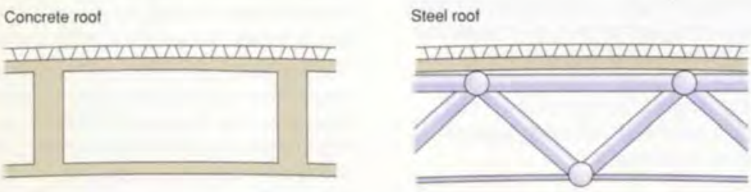
The project would be affordable if it were possible to create a very efficient structure that was simple to manufacture and build. Key to this was the choice of a rational construction geometry for the curved roof shell so that it could be made from high quality, factory-produced components. Under dead load, a funicular shape would give simple direct stresses in the shells, but manufacture in concrete of a doubly curved structure of constantly changing radius would mean that there would be nearly 1000 one-off components. In any case, the structure needs significant bending capacity to deal with the point loads from the suspended aircraft and other asymmetrical loads, and this means it needs depth.

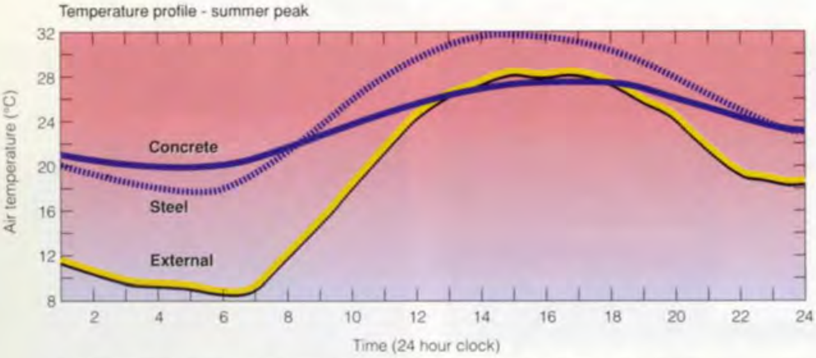
The geometry was solved by designing the roof out of components cut from a torus (doughnut), which is defined by only two constant radii. In this way the 924 precast panels of the roof could be made from only six sets of standard shell components. The 274 lower precast curved panels have an inverted T cross-section, and weigh about 12.5 tonnes each. 650 upper precast units stitched to the ribs of the lower T-shaped panels complete the whole roof, which weighs about 6000 tonnes and covers 6500m^2 of floor area. Each lower precast T unit is provided with two aircraft suspension points by means of cast-in steel sockets with a capacity of 13.5 tonnes in any direction. The sockets were neatly used during construction to clamp the shell units onto the temporary staging.

4. Definition of the torus geometry to accommodate the B52 plane: major radius 277m, minor radius 63m.

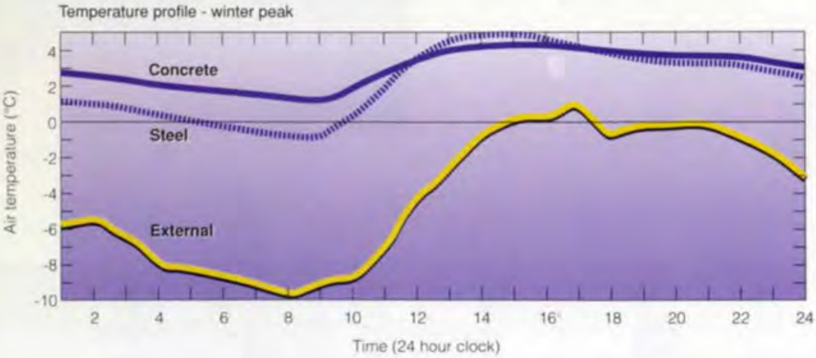


5. Precast concrete roof modules.





3 (Above and below). Roof study: concrete and steel as climate modifiers.



6. Shell roof detail showing lower T precast units, upper precast roof units.

7. Lower precast units showing cast-in reinforcement for the in situ connections.

Soil/structure interaction

The roof discharges its thrusts through the abutments onto spread foundations constructed against chalk. Horizontal thrusts are of the order of 100 tonnes/m, with a vertical load of 40 tonnes/m. Close to the surface, the chalk is weathered to Grade 1 to 2, but reaches a competent Grade 4 within 2m-5m. Chalk fractures into blocks which makes prediction of its properties complex and rather empirical. While there are considerable data on its vertical stiffness and creep performance, data for chalk's horizontal stiffness do not exist and so had to be derived from first principles.

Given the sensitivity of shell structures to movements of their supports, this was the subject of much debate during the structural analysis. Eventually, a series of parametric analyses were carried out using the Arup non-linear program FABLON. The softness of the chalk was varied well above and below expected values so that the sensitivity of the roof to movements of its foundations could be properly explored. Extremes of construction tolerances, concrete shrinkage, and temperature effects were built into the same parametric study to build up an overall picture of the roof behaviour.

The chalk strata themselves were analysed to ensure an adequate margin of safety against slip-circle failure.

8. Load path from roof to foundations showing possible slip-circle failure.

9. Corner junction of four lower precast units prior to concreting.

10. Pouring in situ stitches to roof lower precast units.

11 (below). Erecting and placing upper precast units.

The glazed wall

At the front of the building the arched opening is closed by a glazed wall some 90m across and 18m high. The glazing support structure is a series of twin vertical steel plate mullions 25mm thick and 40mm apart, spaced at 3m centres. It is stabilised out-of-plane by the roof, but is otherwise self-supporting, using single-glazed 19mm sheets of glass, the largest of which are 3m wide by 5.5m high. (The thickness of the glass is beneficial in limiting the transfer of solar radiation.) As the height of the opening varies, the twin mullions are simply plasma-cut from 25mm steel plate to match the bending moment diagram. The taller mullions are deeper, the shorter ones shallower, but all are within a family of curved profiles.To prevent buckling of the compression zone, the plates are clamped together in pairs by studs. To ensure overall stability of the façade in its own plane, the double plate mullions are linked into vierendeel frames, each with two mullions and one set of transoms. Between the vierendeel sets the transoms are loose-fit to provide erection tolerance.

The glass façade was assembled in situ once all the aircraft had been placed inside the building or suspended from the roof structure, and eventually erected by rotating the assembled pairs of mullions around their pinned feet into their vertical position. The whole system can be lowered to the ground in the same manner to allow major changes in the aircraft exhibition. This is planned to happen every 10 years or so.

Analysis

The structure was analysed in 3D also using FABLON, which catered for the p-delta effects of foundation movement and shell deflection together with a study of the effect of setting-out construction irregularities. A comparison of linear and non-linear analyses of the roof showed that the behaviour of the shells was only mildly non-linear. The non-linear model was also used to explore the buckling behaviour of the roof, showing that it has a factor of safety against buckling failure in excess of 6.

The circular geometry given by the torus departs from the ideal funicular shape that would maximise arch action. This, and the fact that the roof must accommodate suspended loads, means that the structure has to resist significant bending stresses as well as membrane ones. Boundary conditions for the model (and in details of the real building) were carefully selected, with thermal and shrinkage strains controlled as follows:

- The front of the roof is fully restrained.
- The steel arms are given flexibility on plan.
- The back of the roof is supported vertically but is free to move laterally on sliding bearings.
- The curvature of the roof allows out-of-plane movement.

The assembled loadcases, around 17 in all, included allowances for wind, snow, temperature changes, creep, shrinkage, and patch loading of the suspended aircraft. Post-processing of the analysis output was spreadsheet-based, ideal for manipulating large quantities of numbers - a result of the 'one loadcase at a time' side of non-linear work. A 'worst credible' scenario was also considered with reduced load factors, drastically reduced foundation stiffness values, and the worst structural setting-out imaginable, up to 100mm out of position.

Structural engineering often involves thousands of man-hours distilling a complex idea into something that appears very simple. Lengthy and sophisticated analysis of the Duxford roof eventually proved that the shells could be reinforced extremely simply, with typically two layers of 8mm bars at 150mm centres in two directions. Areas of reinforcement were generated in this manner and attributed to zones of the roof surface to build up a map of required reinforcement so simple that it could be contained on one sheet of A4 paper.

The predicted deflections of the front arch were about 50mm upon depropping, doubling in the long term. The measured deflection upon depropping was also about 50mm. Long-term movement monitoring, including foundation movement, is ongoing summer and winter until 2000.

12. Aerial view of the nearly completed shell. Formwork for the in situ canopy in the foreground, June 1996.

14. Laboratory tension tests on 100mm roof panels.

13 A to L. General construction sequence:

A. 2 February 1996.

B. 7 February 1996.

C. 20 February 1996

D. 26 February 1996.

15.
The shell at the topping out ceremony, July 1996. The perimeter light slot is visible, starting from the front foundations and increasing in width as it moves to the rear of the shell.

16. Positioning a section of the Iraqi super-gun, weighing 45 tonnes, September 1996.

17.
The completed shell roof prior to de-propping, June 1996.

18.
Suspending the first aircraft, the U2 spy plane, weighing 5.9 tonnes, September 1996.

E. 27 March 1996.

F. 2 April 1996.

G. 8 May 1996.

H. 5 June 1996. *Sequence continues:* ▶

Environmental/structural interaction

Humidity

The nature and material of the building were in part determined by the need to provide a carefully controlled humidity regime with minimum active control. This is because, although planes do not mind extremes of heat or cold, they are sensitive to condensation, which attacks their frames from the inside. The Museum is divided into two distinct areas: a large display area for the aircraft, where temperature control is unnecessary, and humidity is at 50% RH maximum, and a small exhibition space for displays and artefacts. For the latter area the environmental conditions are temperatures of 22°C±2°C in summer and 17°C±2° in winter, while humidity is 55% RH. Conditions in both spaces are maintained 24 hours/day.

Temperature

The thermal mass of the concrete shell, together with the partly buried form, is sufficient to buffer extremes of heat and cold, effectively averaging out day and night time temperatures. In the exhibition space, conditions are maintained by a close control air-conditioning system with electric heating coils, a direct expansion (DX) cooling coil and a steam humidifier. Toilets are tempered in winter with electric convectors. Cooling for the exhibition space is achieved by a DX coil connected to an air-cooled condensing unit with integral compressor.

Light

Lighting is critical in achieving the desired viewing conditions. The great glass wall faces south east, flooding the adjacent part of the interior with natural light, but the deeper parts of the plan would be dark unless daylight was artificially introduced into them. After analysing schemes with strips of rooflights, individual rooflights, and indirect bouncing of light, the team chose to introduce a glazed slot around the perimeter. Daylight pouring through the slot meets a sloping reflective wall which bounces it back to gently light the great curve of the roof.

This is supplemented by 2000W floodlights - 46 in all - for winter evenings.

Construction

Work began in earnest in October 1995, just before the onset of winter. As chalk excavation was involved, the project was fortunate during the foundation works to have very little rain, but it was affected by severe cold. Frost blankets and heating were used to protect the concrete during curing. Some five months on, the structure of heavily reinforced abutments emerged from the ground, allowing placement of the first steel arms that support the roof at the rear of the building. The precast units were then craned into position on temporary falsework. Some 800 tonnes of steel falsework was used to limit roof deformation during construction, and the entire roof was kept propped until all precast units were placed, so that no transfer of loads to the foundations took place until the whole structure was assembled and ready to work as predicted. On a good day the contractors erected either eight lower precast units or 40 upper units. Depropping began at the end of June 1996 and took about a week to complete. Jacks were unwound in steps of 5mm progressively across the whole structure, with 20 passes needed across each of the 600 or so jacks.

The internal works, including casting the ground-bearing slabs and the elevated ramps, proceeded after the falsework was removed, and the structure was essentially complete by September 1996. Installing the aircraft, erecting the glass wall, and completing internal finishes and exhibits continued until the official opening. This took place on 1 August 1997 when Her Majesty Queen Elizabeth II met the project team and, in a rather moving ceremony, was watched by some 4000 American Air Force veterans.

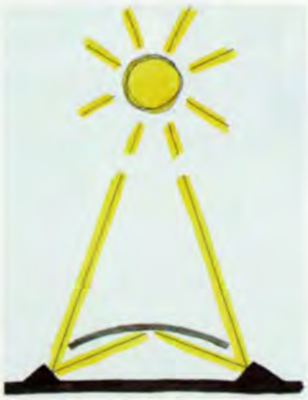
Cost

The total cost of the project was about £11M. Of this, construction totalled approximately £8.4M, while the cost of all the concrete work was tendered at £4.5M. The glass wall cost £1.1M.

22. South-east side: inclined columns supporting the lower in situ edge beam at abutment level.

23. South-east side: shell supported by variable length steel arms through the lighting slot.

19. Pathway of natural light through perimeter lighting slot.



20. Front glass wall: detail of head sliding support.

21. Front glass wall: detail of foot fixed pin.

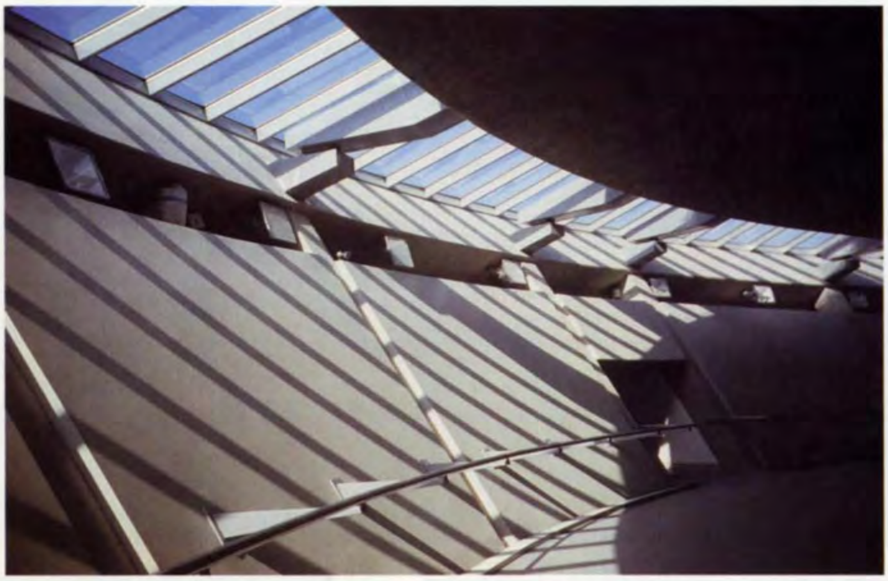
General construction sequence *continued*:

I. 12 June 1996.

J. 25 July 1996

K. 6 November 1996.

L. 11 March 1997.



24. Rear shell area supported by steel sliding steel arms through the glazed lighting slot, March 1997.

Credits

Client:
The Imperial War Museum, Duxford

Architect:
Foster and Partners

Structural, geotechnical, and acoustic engineers:
Ove Arup and Partners Steve Abernethy, David Andrews, Mike Banfi, Derek Bedden, Paul Cross, Gabriele Del Mese, Kevin Franklin, Richard Hough, Maggie Ricketts, Faith Wainwright, Sean Walsh, Chris Wise, Ray Young (structure)
Mike Francescon, Andrew Lord, Nick O'Riordan (geotechnics)
Iain Clarke (acoustics)

Services engineers:
Roger Preston and Partners

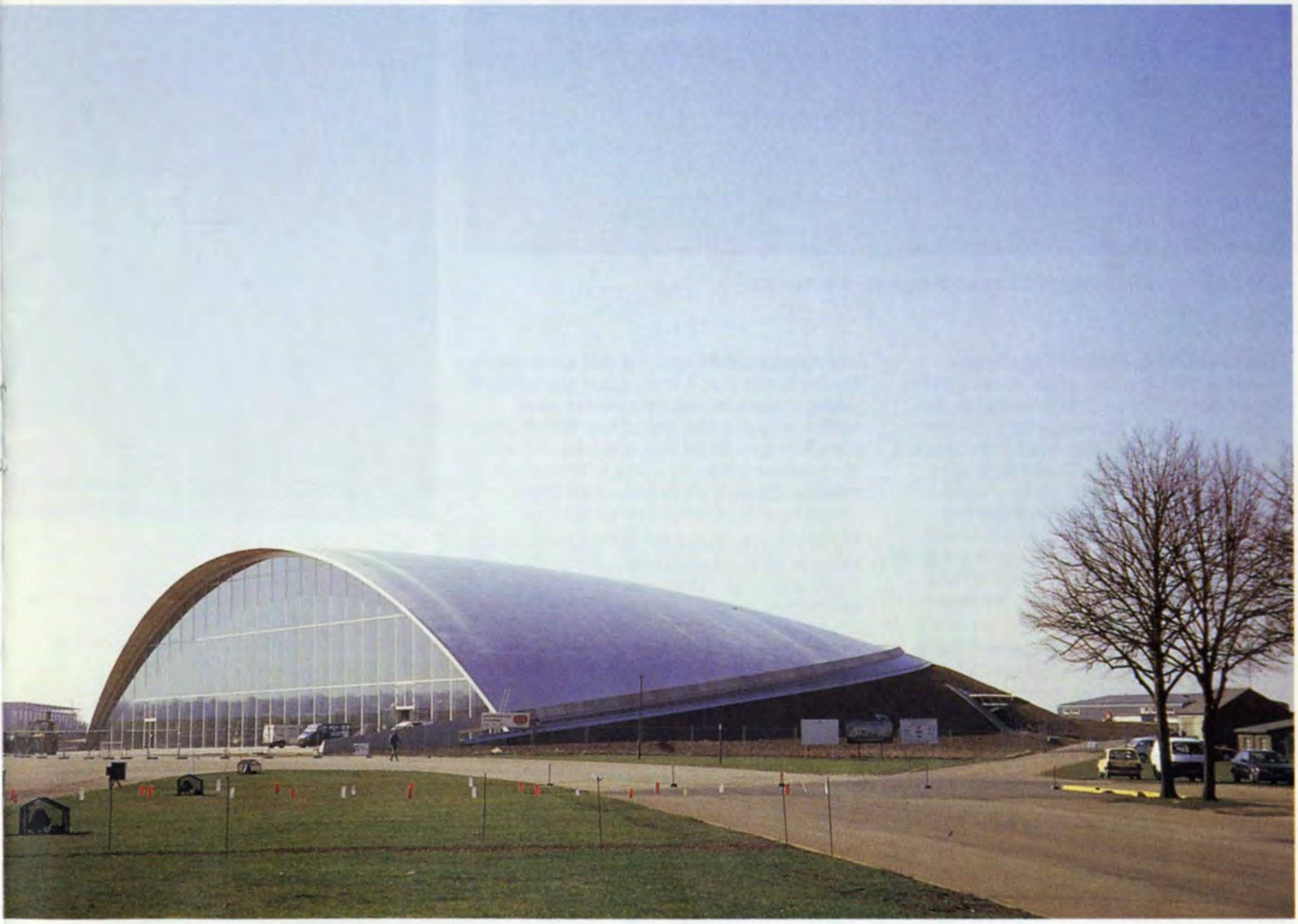
Quantity surveyor:
Davis Langdon and Everest

Safety aspects:
Hanna, Reed Associates

Main contractor:
John Sisk

Principal sub-contractors:
Concrete: O'Rourke
Precast roof: Malling Precast
Steel arms: Lindhurst Engineering
Glazing: Focchi
Roof membrane: Sarnafil
Aircraft hanging: Vanguard

Illustrations:
1-3, 8, 19: Martin Hall
4, 5: Ove Arup & Partners
6, 12, 17: Peter Mackinven
7, 9-11, 13A-L, 16, 18, 20, 22-24: David Andrews
14, 21: Gabriele del Mese
15: Roger Ridsdill Smith



Control Techniques' R&D HQ, Newtown, Powys

1. The east elevation, showing the circular dining pavilion to the north.

Arup Associates was originally appointed in November 1991 to design a new research and development facility for Control Techniques plc, adjacent to St Giles Technology Park, Newtown, Powys, where they had their existing headquarters and other functional units. Control Techniques manufacture variable speed drives for electric meters and were expanding their successful business. The new R&D headquarters building was part of this expansion, encouraged and grant-supported by the Development Board of Rural Wales who were also supporting a new factory, separately procured, and built first.

Control Techniques' primary requirement was to focus all the R&D and administrative functions in one place. They were to be under one roof but separately accommodated to give the R&D area the appropriate level of security. The building was to reflect the high tech nature of the company business, and Arup Associates' response to this brief took the form of a two-storey building, 18m deep, and curved on plan with an inner radius of 100m.

The site is a 1.2ha plot within a 2.8ha pasture, and the building's curve is centred on a natural landscape feature known locally as the Gro Tump. Because of this slope, the building is cut into existing ground to the west and rises above ground level on its east side. A landscape of grassed bank varying in size surrounds the perimeter up to window cill level on the ground floor, 650mm above office floor level. To the east, where the line of the site flood flow comes very close to the gable, a retaining wall holds the fill below the building, preventing encroachment into the flood area.

The overall layout is divided by the two-storey main entrance, which penetrates the building's full depth. On the ground floor, to the east, are the stairs, offices, meeting rooms, and lavatories. To the west is the R&D department itself, plus an exhibition space which can be viewed from the hall and accessed by visitors. Inside the R&D area is a machine test space, enclosed by blockwork walls to reduce noise. A bridge at first floor level links the R&D area to the offices, etc, on the east side, where the staircase provides direct access to the outside for fire escape.

A goods delivery and despatch area is located at the north-west corner of the building with a paved roadway for service vehicles alongside, whilst a separate pavilion building with glazed walls and an external terrace houses the 48-seat restaurant and kitchen. Like the main building, it is raised above the site flood level with a grassed, landscaped bank rising to window cill level around the perimeter, and is linked to the main entrance hall by an open-sided, glass-roofed corridor.

Most of the main building is air-conditioned, providing comfort cooling, heating, and mechanical extraction. Most of the plant is at the west end on two floors within the external envelope, except for the chillers, which are external. Natural ventilation has been used for the entrance area, the restaurant/dining pavilion, and the machine test area.

Detail design started in July 1993 and was completed in January 1994. Construction commenced in September 1994 and was finished for client occupation in February 1996.

Dick Lee Declan O'Carroll

2. South elevation of the main building. The main plant and service entrance is situated to the west.

4 (above). A fixed blade sunscreen is positioned along the southern glazed perimeter elevation, effectively reducing solar gain.

3 (below). The main entrance is central on the south elevation composition, signalled by a projecting glazed canopy.

5 (below). The office environment. The north-facing clerestory windows and transparent perimeter envelope provide good levels of natural daylight and fine views across the surrounding countryside.

Credits

Client:
Development Board for Rural Wales
Occupier:
Control Techniques plc
Designers:
Arup Associates Dick Lee (project co-ordinator)
David Thomas, Alastair Gourlay, David Laing, Declan O'Carroll (architects)
Peter Skead, Hanif Humayun (structural engineers)
Alan Ross (mechanical engineer)
David Hymas (electrical engineer)
Geoff Stevens, Nick Taylor (quantity surveyors)
Main contractor:
Norwest Holst
Photographs:
Andrew Putler

New materials for construction

Simon Cardwell   Bob Cather   Steven Groák

Materials are ever-present in our activities: without them, we would have nothing to construct with. For many, though, they are means to ends, not subjects worthy of study in their own right. We tend be over-familiar with them and have little of the detailed understanding needed to address the concepts underlying existing and emergent materials. 'What new materials are available for designers and constructors?' is a temptingly simple question asked by engineer, architect or client, but it may not bring the straightforward response expected.

As with many simple questions, the response starts with 'Well, it depends...': It depends upon the experience and perspective of questioner and respondent, upon the industrial background to the question, upon the history of materials use, and upon economic development within the country concerned.

The response developed here to the question is set essentially against the backdrop of an industrialised 'developed' economy. It shows a perspective of 'new' materials based upon the developing understanding of the science of materials. This has evolved over the past 30 years or so, for several reasons.

Prominent among them are the increased interest in how the chemistry and microstructure of materials governs their service performance; and how this understanding has been hugely underpinned by the development of sophisticated examination technologies. To some extent this has been possible for metallic materials for many decades, but their extension into non-metallics has been a major benefit. 30 years ago, scanning electron micro-scopes were barely invented; today they are common-place - at least in research and commercial laboratories.

To embark upon the question of what the new materials are, some simplifying assumptions can be made and then by following an argument, a wider perspective is seen to develop.

One way of categorising a 'new' material is to define it as one with which we are ***unfamiliar.***

Unfamiliar Materials

- Composites
- Adhesive joining
- Titanium
- Super alloys
- Parafil ropes
- Honeycomb

It may be new in the sense of being totally new, but is more likely to be new to construction applications; it may have seen service elsewhere, in aerospace or defence systems, for example. 'Unfamiliar', therefore, implies insufficient real experience, so that engineers are not sure or confident in using these materials in building applications.

1. Glassfibre reinforced epoxy pipe.

2. The upper guys on Torre de Collserola, Barcelona, are of non-conductive aramid, invisible to radio signals.

Where they have been employed in other industries, something can be learnt, but the needs or methods of adoption may be different and thereby limit transfer. Some of the more obvious differences in other industries are:

- the ability to repeat production on a large scale, to use prototyping and component testing
- more developed concepts of, and shorter periods for, design life
- the ability of, or expectations for, inspection and maintenance in service.

To bring unfamiliar materials into wider use in building applications, confidence in their potential performance needs to be developed. How will the material or product behave and then fail, as at some point - before Armageddon - it must? When will failure occur and is this acceptable, given the desired design life and maintenance?

In some instances materials that are familiar will be asked to do unfamiliar things. We have become well used to sealants acting as weather seals - to exclude water and air - but when asked to be an adhesive, to hold components into the building, a range of new performance requirements is imposed.

Some construction applications can, because of their cost structure or lack of existing design solutions, have a stronger need for new materials and can more readily drive the adoption of them. A clear example is in the offshore and petrochemical industries, where the potential advantages of advanced composites for lightweight components and enhanced chemical resistance in pipes and safety and maintenance structures are becoming well established (Fig 1).

Elsewhere, the adoption of composites is at present perhaps more of a solution seeking a problem - can we really justify advanced composite footbridges, or are they an exercise in learning to better see what might be possible? Other advanced composite or new fibre materials have moved some way towards use, eg parallel filament ropes have for reasons of light weight or radio transparency been used to stabilise mast structures (Fig 2).

They are at present a small but interest-ing sector. These and other composites may become widespread or they may not: It is too early to predict.

In any assessment of new or unfamiliar materials there is clear benefit in understanding the underlying science of behaviour and performance, to predict what behaviour we might encounter from the new material in its new applications. In some physical sciences there may be the temptation from time to time to assume that all basic knowledge is known and it simply has to be applied. In materials science, however, we are still at the stage of basic understanding opening up before us.

A framework for understanding the structure and behaviour exists but is still developing in detail.

The approach and benefits of understanding unfamiliar materials are also valuable when applied to materials we believe we know well and treat as commonplace - the ***familiar***.

Familiar Materials

- Timber
- Stone
- Glass
- Concrete
- Ferrous alloys
- Aluminium
- Brickwork

The better understanding that can be developed of these familiar materials can be used in two broad ways. In conventional applications we might be able to improve the efficiency of use or to achieve the same efficiency at lower cost - initial or whole life - or with lesser environmental impact. The same knowledge base can also help Arups and its clients to achieve better solutions or to solve problems in new ways by extending materials performance beyond that which was previously thought possible. Examining the microstructure of timber before, during, and after extremes of loading can permit a more pronounced move for timber design from an essentially craft basis to one of more fundamental engineering design more common, perhaps, in steel (Figs 3-5).

We can progress similarly - but not as readily - for cement and concretes with craft-based boats to the bigger, engineered boats we call concrete gravity platforms, and beyond (Fig 6).

How far can engineers move with this developing knowledge? Building structures have already progressed from the more common 40MPa and 50MPa concrete structures to the 100MPa plus now being used in Hong Kong (Fig 7) and considered elsewhere. To some extent the anchor to this progression is the need to develop confident design rules for the material, its interaction with other materials, and the site practice to ensure the promise is fulfilled in our structures. For the concrete material alone, we can already make - albeit in

3. Microphotograph of epoxy-Khaya glueline.

4.
Traditional timber-frame boat-building.

5.
MS3 wind turbine generator with timber blades.

7. 100MPa high strength concrete structure at Taikoo Shing City Plaza, Hong Kong.

6. Ravenspurn concrete gravity oil platform.

8. Macro defect-free cement (MDF) spring; such a structure, a few centimetres long, is only achievable due to MDF's high tensile and compressive strength.

small quantities - components with strengths, both tensile and compressive, of 200MPa (Fig 8). The research fraternity are already working on 400MPa concrete and are wondering how to get to 600MPa! Be warned, these new concretes are not yet at the local ready-mix plant. In fact they are sufficiently different from the more familiar structural grey hard stuff that it will be necessary to think quite differently about the applications best suited to their particular properties. These applications may not be as primary structures at all. Some already in place are for abrasion-resistant, powder-handling machine parts, press moulds for steel sheet pressing, high strength washers, loudspeaker enclosures, and lightweight bullet-proof vests. Lateral thinking and cross-fertilisation of ideas and experience, applications and technologies can produce surprising results. Some of the high strength concrete products described here, evolved from research into cold-forming plastics materials following the 1970s oil price increases. These newer applications will tend to move our familiar material away from its more normal experience, and we will find that these demands will create an unfamiliar material about which we must predict and learn.

If we can visualise this way of looking at 'unfamiliar' and 'familiar' materials, and use our new materials science understanding to benefit, what of the materials we no longer use - the overly familiar discarded or ***contemptible*** materials?

'Contemptible Materials'

Thatch

Mud walls

Lime mortars

Cast iron

Waste products

Ice

By applying our understanding, can we relearn or re-use 'contemptible' materials?

Enquiries about thatched roofs, and on the engineering properties of ice, have both featured in Arups' materials advisory role. The potential benefits of lime mortars rather than the now more common Portland cement-based materials are being remembered. We have not yet perhaps applied our new science to these lime materials yet but the scope is there.

During the Industrial Revolution, (grey) cast iron was at the forefront of materials technology and firmly in the realms of the 'familiar'.

However, despite the great advances the material offered architecture and structural engineering, it was still inherently brittle and weak in tension. These constraints, in conjunction with the development and widespread availability of steel, led to the decline in cast iron use. As a result, today grey cast iron is considered by many as 'contemptible'.

As we have tried to illustrate, the understanding of materials, like most things, is dynamic. Progress in basic understanding is inevitable, and this is reflected in the application of the material. Grey cast iron may be regarded as 'contemptible' but by changing the distribution of the carbon, inherent in cast iron, from flake to spheroidal, spheroidal graphite (SG) cast iron is formed.

This change in microstructure results in a similar generic material, but with fundamentally different properties. The resulting improvements in tensile strength and ductility have given rise to exciting new opportunities, as in the

'Contemptible' materials continues ▶

9. SG cast iron glazing brackets at Western Morning News.

glazing brackets at the new Western Morning News HQ in Plymouth[1] (Fig 9), or more diversely (and somewhat ironically) as shock absorbers for nuclear waste containers.

Now, far from being discarded ('contemptible'), cast iron (SG) has become more familiar. The developments in casting technology and the adoption of a wider range of cast materials have resulted from new skills in:

- fracture mechanics
- computer modelling of casting processes and the effects on the cast product
- improved quality control of materials, and
- improved foundry practice.

The application of casting, particularly in ferrous materials, can give advantages in ease of fabrication, commercial viability, and in the visual quality of the construction. Other notable examples have included the nodes at Lee House on London Wall in the City[2] and the roof of the Ponds Forge swimming pool in Sheffield[3], as well as the Western Morning News façade.

As we may now consider iron and steel castings as familiar, the trend could be continued to other materials at present - as far as building applications are concerned - relatively unfamiliar. Again, recent projects have adopted castings of gunmetal and aluminium bronze.

Encouraged by the use of less common materials in castings, the possibilities of many other metallic materials can be seen where perhaps lack of familiarity with them in construction had previously limited designers' aspirations. Many metals, familiar in everyday practice in other industries, may offer advantages to construction. From aerospace, aluminium alloys are already being used in various forms: sheets and extrusions. Now titanium is also crossing the industry boundary - being widely used for metal roofing panels in Japan. Additionally, advances in manufacturing processes are also crossing industry sectors - super plastic forming (originally developed for aerospace applications) has been used for the manufacture of cladding panels. Similarly, highly corrosion-resistant alloys from the offshore market are beginning to find uses in construction applications.

Further ahead are metallic materials with a 'smart' capability, for example fire-resisting steels which change their microstructure on heating to compensate for the normal loss in strength in steels.

Smart materials are a subject in their own right and a separate study by Tony Sheehan of Arup R&D[4-6] is monitoring and reviewing the possible applications.

Continuing our theme we can see these materials in our current knowledge as ***unknown***; unknown not because we know nothing of their chemistry or microstructure, but because their characteristics and behaviour in any industrial application, construction or not, are still relatively unknown.

The possibilities are enormous - but what? And where? They encompass a wide range of materials and definitions. They can:

- detect and/or respond to their environment
- undergo controllable phase change, with consequent change of shape or property
- behave as selective membranes
- demonstrate self-healing and other biomimetic properties.

Unknown Materials

- Smart materials:
  - *- detecting / responsive*
  - *- fire-resisting steels*
  - *- controllable phase change*
  - *- shape-memory alloys*
  - *- biomimetic (eg self-healing)*

Other unknown materials have been discovered but we have less knowledge of their structures and properties and are as yet uncertain how to use them. New carbon-based materials not of the established allotropes, diamond or graphite, have been identified, the better known being 'buckyballs' (buckminsterfullerenes) and, more recently, 'nanotubes' - hollow tube microstructures with a diameter of the order of a few nm[7].

These materials appear to have incredibly high stiffness, and it is suggested that the normal chemical and physical behaviour of other materials is radically changed when placed within the tubes.

Beyond the unknown materials are the ***unknowable*** - unknowable in the sense that with our available technologies, analysing and understanding their composition and microstructure is difficult or impossible.

In this class of materials are many of the natural and organic systems. The processes in living organisms that make them function and adapt to their environment are intriguing and perhaps hold many new models for engineers to follow.

There is a challenge to develop the means of understanding these materials and systems, and the question of 'what are the new materials?' might then be taken to a new plane.

Unknowable Materials
eg not detectable/analysable with current techniques

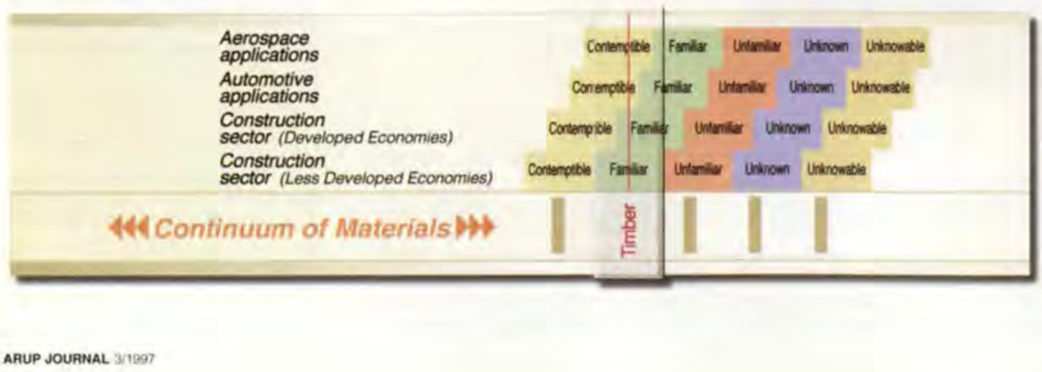
- Discoveries in sub-molecular structures
- Biotechnical
- Living organisms
- Symbiotic associated with human behaviours

The perspective of the new, familiar, unfamiliar, etc, explored here is - as was said at the beginning - dependent on the position and experience of questioner and responder. We can see materials in a continuum of categories, able to move from location to location in that continuum as knowledge and understanding of them changes. Viewed from other industries, the same materials would quite probably reside in different windows, their experience and use of them possibly being quite different (Fig 10).

Materials scientists in essentially construction-oriented activities have three broad tasks:

- to maintain and extend their fundamental understanding of the materials they find familiar
- to maintain a wider vision and understanding of the materials visible through the other 'windows', so as to maximise their flexibility to achieve desired and optimum design solutions
- to scan constantly the potential of materials, from the contemptible to the unknowable, to exploit their significant transitions across that spectrum.

10. Continuum of categories of materials.



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The Observational Method in ground engineering

Che-Ming Tse   Duncan Nicholson

Introduction

From civil engineering's infancy, visual checks have been made on uncertainties in the ground and on structural performance.

In the late 1940s an integrated process for predicting, monitoring, reviewing, and modifying designs evolved with the development of modern soil mechanics theories by Karl Terzaghi and Ralph B Peck.

They stated: 'Design on the basis of the most unfavourable assumptions is inevitably uneconomical but no other procedure provides the designer in advance of construction with the assurance that the soil-supported structure will not develop unanticipated defects. However, if the project permits modifications of the design during construction, important savings can be made by designing on the basis of the most probable rather than the most unfavourable possibilities. The gaps in the available information are filled by observations during construction, and the design is modified in accordance with the findings.'[1]

In his 1969 Rankine Lecture[2] Peck referred to this process as the 'Observational Method' (OM), and since then aspects of it have been used informally on UK civil engineering projects. Only recently, however, has interest revived in the method per se - partly due to concern for more economical use of resources and also because tighter health and safety regulations require project participants to assess risk. The OM has formidable potential: to provide benchmarking data; to improve value/economy; to increase safety; to reduce design uncertainties; to strengthen links between designers and constructors; to clarify construction control/management; and to motivate the project team.

In September 1995 the Construction Industry Research & Information Association asked Arup Geotechnics, in collaboration with Balfour Beatty Civil Engineering Ltd, to investigate these potential advantages. The *Funders Report CP/49* [3] for this has been completed and is now available to all CIRIA members. It highlighted the conservatism of some geotechnical design parameters and also developed a robust procedure for implementing the OM, compatible with current design codes and Health and Safety Regulations. This article describes some recent developments in the OM and examples of its application by Arup Geotechnics.

The traditional predefined design method and the OM

Peck's definition of the OM embodies the following eight 'ingredients':

- Explore sufficiently to establish at least the general nature, pattern and properties of the deposits - but not necessarily in detail.
- Assess the most probable conditions and most unfavourable conceivable deviations from these conditions; in this assessment geology often plays a major role.
- Establish the design, based on a working hypothesis of behaviour anticipated under the most probable conditions.
- Select the quantities to be observed as construction proceeds, and calculate their anticipated values on the basis of the working hypothesis.
- Calculate values of the same quantities under the most unfavourable conditions compatible with the available data on the subsurface conditions.
- Select in advance a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.
- Measure quantities to be observed and evaluate actual conditions
- Modify design to suit actual condtions.

Traditionally a single robust and possibly over-conservative design is fully developed before site work starts on a particular phase. Instrumentation monitoring is sometimes used but passively, to confirm that design predictions are not exceeded. There is no primary intention to vary the design during construction. The CIRIA report referred to this as the 'predefined design method'.

The OM, on the other hand, requires designers to consider the range of foreseeable conditions. Designs are developed for this range and construction modification strategies planned before work starts on any particular element of work. Planning is important to ensure that modifications can be implemented sufficiently quickly to avoid the development of failure conditions. Monitoring is essential and is used actively to provide data for the review stage. Here, the monitoring results are compared with predicted trigger criteria and planned modifications if appropriate or emergency plans if required can be introduced.

If there is little uncertainty about the ground, there will be no need to follow the OM, as there is no pro-active monitoring and planned modification. But if there is great uncertainty, the predefined design method could lead to a possibly unsafe or maybe unnecessarily expensive solution. The OM can take account of the monitoring results and provide a safer and more economic solution, if appropriate, on certain types of projects.

Recent developments in using the OM

After Peck's 1969 Rankine Lecture, the OM gained world-wide recognition and was used in a wide range of ground engineering operations. However, it has not been referred to in British design codes, although the final draft of *Eurocode 7*[4] recognises it as a design method and states the requirements for using it. Similar requirements have been adopted in the Hong Kong 'Guide to retaining wall design'[5]. One objective of the CIRIA Report is to clarify OM concepts and to provide a clear framework. For the first time, it was officially defined, as follows: 'The Observational Method in ground engineering is a continuous, managed, integrated, process of design, construction control, monitoring and review which enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising safety.'

The OM can be adopted from the outset or later if benefits are identified. However, it should not be used where there is insufficient time to implement fully and safely complete the planned modification or emergency plans.

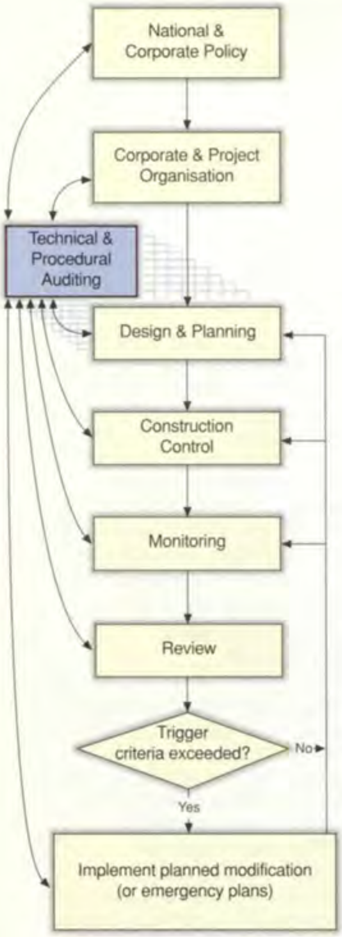
Technical considerations

The process of implementation (Fig 1 overleaf) emphasises national and corporate policies, eg health and safety regulations, quality assurance, conditions of contract, and design codes. Good corporate and project team organisations are also essential.

Design and planning are concerned with data gathering, design, data interpretation, risk assessment, and the allocation of resources to achieve objectives and decide priorities. Design cases should cover all the likely scenarios, and design modifications planned so that they can be introduced in time to stop safety reducing unacceptably. The construction control plan, monitoring plan, and monitoring specifications should be developed which set out agreed procedures and frequency for monitoring instrumentation and reporting results. Instrumentation records and construction progress information should be reviewed by competent people. The planned modifications will be implemented if the trigger criteria have been exceeded.

Table 1: Comparison of the predefined design method and the OM

The predefined design method	*The OM*
Normally one set of soil parameters: eg moderately conservative or characteristic values (EC7) – but may do parametric study.	The range of foreseeable soil parameters are considered: eg most probable and most unfavourable.
One design and one set of predictions based on limited construction method considerations.	Two or more design and construction methods are sufficiently developed to include predictions for trigger criteria.
A construction method option may be outlined sufficiently for the design to be progressed. This is subsequently developed by the contractor in his method statement.	A flexible construction method statement is developed which can incorporate design changes and modification strategies: often developed jointly by the contractor and the designer.
Monitoring limited to checking that predictions are not exceeded.	Comprehensive and robust monitoring, regularly reviewed, as the basis for management and design decisions.
Predictions unlikely to be exceeded. Therefore, construction programme not constrained by monitoring results. If predictions are exceeded then unforeseen conditions have developed and the work may need to stop whilst problem is resolved.	The design, construction method and construction programme may be changed depending on the review of monitoring results.
	Management of construction, monitoring, interpretation and modification plan or emergency plan implementation are required.
	The monitoring system must be sensitive enough to allow early discovery of a rapidly deteriorating condition. The modification plan must be rapidly implemented to ensure that the limiting trigger criteria are not exceeded.
Emergency plans are needed to control failure.	Emergency plans must be introduced in accordance with the Construction (Health, Safety and Welfare) Regulations 1996. This can be achieved as an extension of the OM trigger criteria beyond the serviceability limit state to ensure that failure does not cause injuries.
The OM may be initiated at this stage in its 'best way out' format.	It may be that the 'best way out' OM can be introduced to overcome unforeseen ground conditions.



1. Implementing the OM.

All control systems - including the OM - tend to become slack over time, so it should be audited at a frequency agreed by all parties in the project to provide independent assessment of the validity and reliability of all the components of the OM shown in Fig 1.

Management considerations

There is more interaction between designers and constructors on OM projects than on predefined design projects, and this needs management and co-ordination. Management considerations can be broadly divided into the categories of culture, strategy, competence, and systems (Fig 2). The commitment of the members of the project team and their willingness to 'own' and solve problems are of critical importance.

Arup projects

Arup Geotechnics has a long history of applying the OM to major projects. Three examples are given below.

Minster Court, London

At Minster Court (Fig 3), a 0.8m thick diaphragm wall formed a 9m deep basement. About 5m from one side of it are the LUL District and Circle Line tunnels (Fig 4). The basement was constructed using a 'semi top-down' construction technique, ie the sides of the basement wall were excavated top-down while the centre of the basement was excavated bottom-up. An earth berm was left to support the retaining wall, but concern was raised about possible movements on the side of the basement near the tunnels.

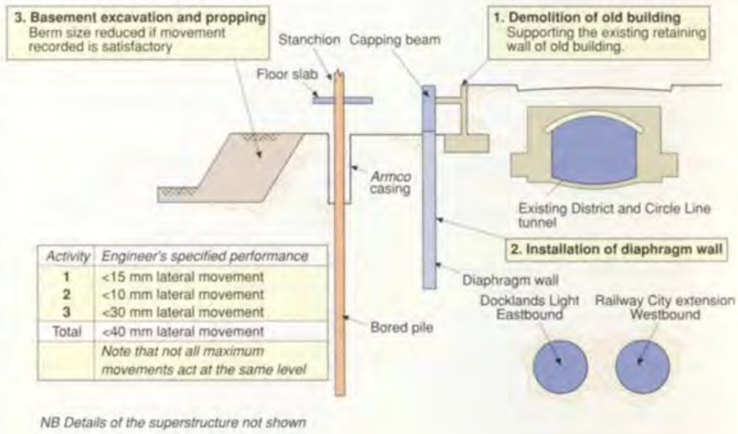
The construction movements included those from demolition of existing buildings, diaphragm wall installation, and berm excavation[6], and the following procedures were adopted in implementing the OM:

- The allowable movements of the adjacent tunnels were agreed between the owner of Minster Court and LUL.
- The behaviour of the diaphragm wall was analysed using the FREW program. In conjunction with case history data for similar construction methods and ground conditions, the allowable movement in each activity was defined. These, based on the 'moderately conservative' assumptions, were:
  1. Demolition.
  2. Installation of diaphragm wall.
  3. Berm excavation.
- Two berm sizes were designed:
  1. A small berm for the moderately conservative condition with a 4m wide top, 12m wide base, 5.2m high and a slope angle of 35°.
  2. A large berm for the most unfavourable condition with a 8m wide top, 12m wide base, 3m high and a slope angle of 40°.
- The ground movements were measured at an agreed frequency by surveying, inclinometers and extensometers. In-tunnel surveys were made and deformations of the tunnels measured by tape extensometer. The movements of the tunnel walls were measured by surveying.
- Construction of the basement proceeded with the excavation to the 'large berm' initially. The cumulative movement at end of this stage was about 10mm - significantly less than the specified criteria, giving the contractor confidence to trim the berm progressively to the 'small berm'.
- The contingency plan was to backfill the berm to its original size in case of large movements.

The measured wall movement at the end of the excavation of the 'small berm' was about 13mm and the contingency measure was not required.

3. Minster Court excavation.

4. Minster Court construction sequence.

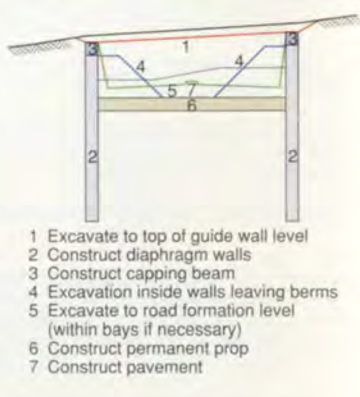


A4/A46 Batheaston/Swainswick Bypass, Bath

About 800m of this road was constructed within a diaphragm wall retained cutting; Arups assisted the contractor, Amey Construction, in designing temporary works.

As part of the permanent works 'predefined' design, the engineer proposed a construction sequence with props placed between pairs of facing diaphragm wall panels, followed by excavation to the formation level of the road. The temporary prop layout was to be designed by the contractor. The implication of this was that heavy steel sections would be required to prop between the diaphragm wall panel, resulting in restricted working space and a complicated construction sequence. After consulting Arup Geotechnics, the contractor proposed a simpler and more economical alternative construction sequence (Fig 5) using the OM. The temporary props in the engineer's original design were replaced with a controlled excavation sequence utilising earth berms (Fig 6).

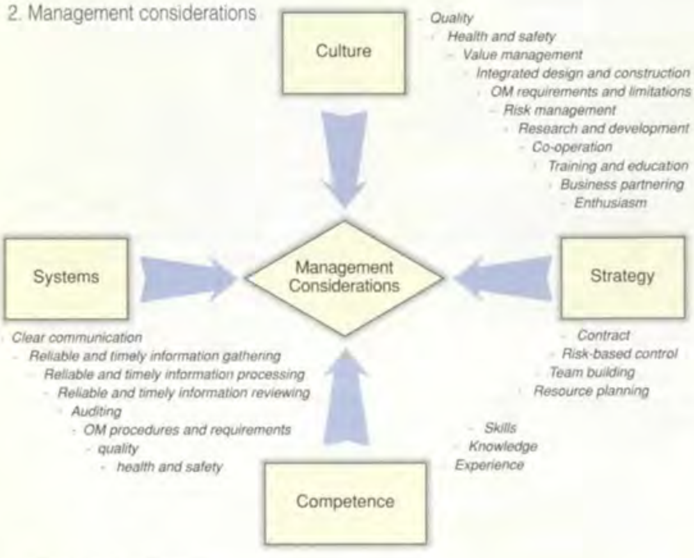
A construction control cycle was set up (Fig 8). Berm size and sequence of berm excavation were assessed during the temporary works design, and trigger criteria were defined. The wall deflection and the excavation sequence were monitored against the trigger criteria during excavation.



5. Alternative construction sequence.

6. Earth berm excavation at Batheaston/ Swainswick Bypass.

2. Management considerations



7.
The Castle Mall site.

Castle Mall, Norwich

The 11ha Castle Mall development in the centre of Norwich (Fig 7) comprises a two-storey shopping centre with a basement up to 18m deep, alongside a five-storey underground car park. The general stratigraphy across the site prior to construction was made ground up to 10m thick overlying Norwich Crag up to 10m thick and Upper Chalk, in which holes (solution features) were present. Pad footings founded in the Upper Chalk were adopted, with ground treatment of solution features.

Selecting the foundation type took into account:

- *Uncertainties in ground conditions*

The solution features were not located until close excavation, and there was only limited data on their nature, size and frequency.

- *Uncertainties in ground treatment results*
- *Cost-effectiveness*

The aim was to maximise benefit from good founding strata for spread foundations.

- *Programme time constraints*

Foundation construction had to start immediately on completion of excavation.

If a solution feature was encountered, three methods of treatment were envisaged:

- probing and grouting (bulkfilling or compaction grouting)
- excavating to backfill with concrete
- increasing the original size of the foundation.

Depending on size and location of the features identified, a case range of five likely design scenarios was developed:

Case 1: Solution features up to 4m across clear of foundations, or up to 3m across at a contiguous piled wall, would be probed to locate their extent below ground and bulkfilled with a cement/ pfa grout from 1.5m above slab formation level to fill any voids.

Case 2: Features up to 2m across below a proposed foundation would be probed and bulkfilled with grout as with Case 1, with the pad foundation possibly being increased in size.

Case 3: For medium-sized solution features, the feature would be probed and bulkfill grouted. A large mass concrete slab would then be constructed to spread the footing load on to good chalk around the feature.

Case 4: 2m-4m features beneath foundations would be probed and compaction grouted with a reduced bearing pressure allowed on the compacted feature. The effective footing size would be increased to allow for reduced bearing pressure by constructing a mass concrete slab below the footing.

Case 5: >3m features at the perimeter bored pile retaining wall would be compaction-grouted from a higher level. This required a minimum overburden for treatment at any one level and depth of excavation near the retaining wall was limited.

The foundation design on site was modified within the general design scenarios envisaged. To implement the different cases, contractual arrangements were organised to give high flexibility for programme and occupation of site areas. Grout pressures and volumes were particularly carefully monitored for compaction grouting, a relatively untried technique in the UK, and standard penetration tests (SPT) and plate load tests were made on treated solution features. Treatment techniques could then be modified as work proceeded.

Incorporating the OM into other Arup services

For many civil engineering projects, the ground is a major source of uncertainty because of variable geology, and difficulty in selecting design parameter values or in modelling the problem realistically. The above case histories show that, where there are large uncertainties, the OM can manage effectively the risks associated with them. Like value management, the OM is primarily intended to eliminate unnecessary or avoidable cost, while meeting other project objectives such as time and safety. It may also be used by other disciplines like maritime and environmental engineering where similar uncertainties exist.

The recent CIRIA developments in the OM have incorporated some Arup skill areas such as risk management and safety management.

Also, the OM has much in common with the Latham[8] principles of innovation, working together and partnering which are often at the core of Arups' design approach. The OM will thus enable Arups to offer clients cost-effective designs in the future where there are significant ground engineering uncertainties, for example:

- Tender stage - partnering with other Arup services like civil engineering, bridges, building, environmental, etc, to offer competitive tender designs. The same service can be offered externally, ie partnering with contractors and share savings.
- Post-tender stage - as an independent value engineering reviewer.
- Construction stage - as a best way out when unpredictable site problems develop.

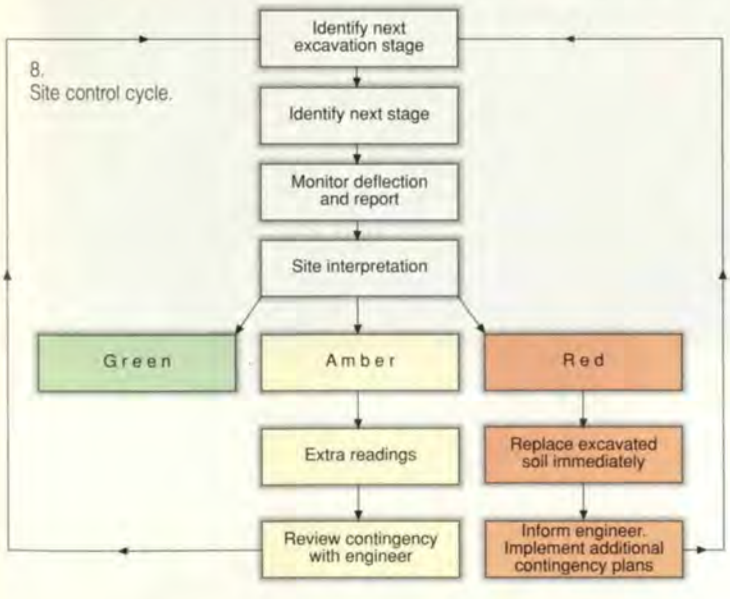
The design was carried out using two sets of soil design conditions - 'most probable' to calculate an 'amber trigger' and 'most unfavourable' as a 'red trigger'.

The construction programme was based on 'most probable' conditions in keeping with Peck's approach.

If movements exceeded the amber trigger, the following procedure would be carried out:

1. Increase the frequency of monitoring readings.
2. Review data, decide on further actions, and implement the following contin gency measures where necessary:
   - excavate within bays
   - counterfort drainage behind the wall
   - use ground anchors
   - excavate retained soil to reduce active earth pressure.

The application of the OM in the A4/A46 was successful. Using this alternative construction sequence, substantial savings were made in the temporary works.



8.
Site control cycle.

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Credits

CIRIA Project

Client:
Construction Industry Research and Information Association

Research contractor:
Ove Arup & Partners Duncan Nicholson, Che-Ming Tse
Balfour Beatty Civil Engineering Ltd

Minster Court

Client:
Prudential Portfolio Managers Ltd

Foundations sub-contractor:
Stent Soletanche Joint Venture

Consulting engineer:
Ove Arup & Partners

A4/A46 Bypass

Client:
Highways Agency

Consulting engineer:
Sir Alexander Gibb and Partners

Contractor:
Amey Construction Ltd

Temporary works designer:
Ove Arup & Partners

Castle Mall

Client:
Friends Provident and Estates and General

Consulting engineer:
Ove Arup and Partners

Grouting sub-contractor:
Keller Colcrete Ltd

Illustrations:
1, 2, 4, 5, 8: Jon Shillibeer/Sean McDermott
3, 7: Peter Mackinven
6: Amey Construction Ltd

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