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The Arup Journal

Contents

Selfridges, Birmingham

Ed Clark David Gilpin

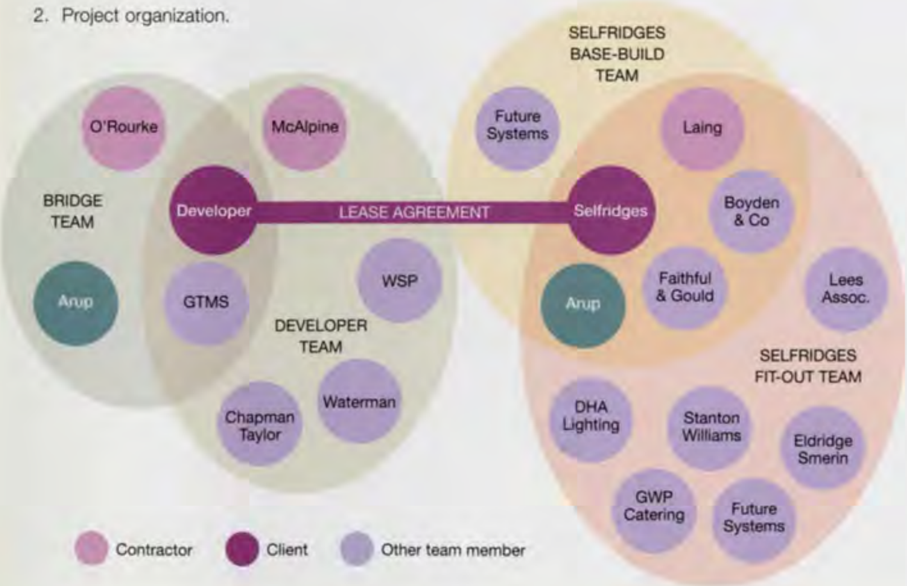
Introduction

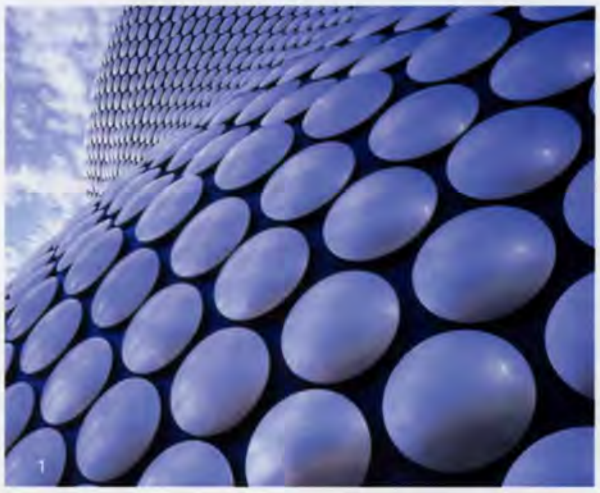
The Selfridges building in Birmingham, England, is the larger of two anchor stores in the newly-rebuilt Bullring shopping centre. Hitherto, the firm had been wholly associated with its famous flagship store in Oxford Street, London, and its decision to expand into new premises beyond the capital was highly significant. Having decided to open its first new-build store in the UK's second largest city, Selfridges made its acceptance of the building tenancy conditional on choosing its own architect to design the complete building, rather than provide only fit-out within a building shell designed by the Bullring architect, Benoy. Bullring's developer consortium, the Birmingham Alliance, accepted this condition and Future Systems, with Arup, was appointed in October 1999.

Future Systems' vision was a building form that would fit the contextually diverse site whilst embracing Selfridges' demand for an internally-focused, windowless box. The resulting unique façade gives scale, texture, and an accentuation of the building curvature (Fig 1). Arup provided full multidisciplinary engineering design: structure, services, façades, fire, communications, and acoustics, with specialist input from Arup Research + Development.

Selfridges' store programme remained inextricably linked with the four-year Bullring development programme, despite having an independent design team. This long timescale and the complex contractual arrangement led to the project being built in several phases. McAlpine, the Bullring main contractor, built the structural frame for the Birmingham Alliance, whilst Laing O'Rourke was appointed directly by Selfridges to construct the remainder of the store including the façade and fit-out – the latter broken down into off-retail and retail phases. The bridge link between Selfridges and the adjacent car park building was procured by the Birmingham Alliance under a third contract on a design-and-build basis. Arup's Selfridges team undertook the engineering design of all three contracts, despite the differing client and contract teams (Fig 2).

2. Project organization.



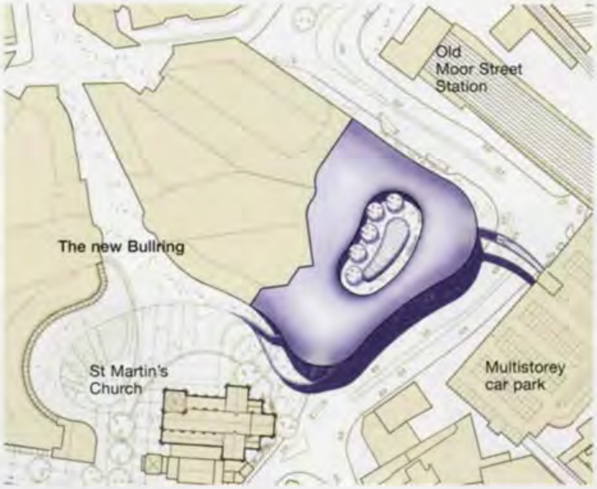


Inspired by a Paco Rabanne sequined dress, the Selfridges building glistens in the heart of Birmingham's Bullring.

This phasing had a major impact on the building design, with many decisions taken years in advance of the design and construction of the relevant packages. For example, the four designers for the retail fit-out (one for each floor) were only appointed after completion of the structural frame and tendering of the base-build services, and the bridge detailed design took place only after construction of the structural frame supporting it.

Combining this phasing with the high architectural aspirations, complex brief, and demanding budget, the project was destined to be an engineering and design management challenge from the outset.

The evolution of the resulting highly-integrated and holistic engineering solution under these circumstances added further complexity to the design challenge. However, the close-knit design team saw this as the only way to deliver the client's often-quoted aspiration for an iconic store, and achieved it by commitment and shared vision. The result was worth the effort, with the store opening to critical acclaim, on time and on budget, in September 2003.

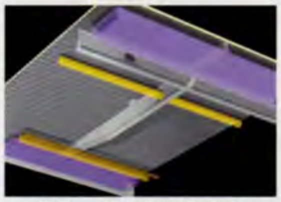


3. Location plan.

**Framing option 1:
Regular column grid
imposed on irregular plan.**

**Framing option 2:
Irregular column grid.**

4. Conceptual column grid options.



5. Co-ordination of services and structure: 3-D conceptualization.

6. Co-ordination of services and structure: the built reality.

Structural steel frame

The primary functions of the frame are to provide a support skeleton for the free-form building façade and to create large, column-free retail spaces of maximum height. To meet these goals, the design embraced CAD/CAM technology and mass customization to allow the irregular framework to be fabricated economically. It also achieves a high degree of integration with the services feeding the retail floors, to maximize floor-to-ceiling heights. Neither strategy was ground-breaking in isolation, but in combination they created a truly holistic solution, an economic synergy of architecture and building engineering that could not have been achieved more conventionally.

The starting point for the frame design was to derive a suitable column layout. Superimposing a standard cartesian column grid onto the irregular building plan seemed inappropriate and incompatible with the architectural layout, so a string of columns was located around the perimeter, approximately 12m apart, with a separate necklace around the two atria at the same spacing. A handful of extra columns was required to limit primary and secondary beam spans to 12m and 16m respectively - the maximum considered economically feasible. Again, these additional columns were individually and strategically placed to suit both the structural and architectural requirements (Fig 4).

The plan shape of the building changes from floor to floor to match the curvature of the envelope in section. This requires secondary beams to cantilever from the perimeter column line by different distances around the slab edge and at each level. At the 'waist' of the building the columns sit tight against the inside of the façade, whilst at the 'hips' and 'shoulders' the floor cantilevers to the façade by up to 4.5m, deemed to be the maximum practical limit and thus controlling the vertical curvature of the building. It was these relatively long spans and the lack of a regular grid that drove the design towards a steel solution.

A desire for maximum floor-to-ceiling heights in retail areas led to structure and services being integrated within the same 1.5m deep zone. This required a balance of practicality and flexibility, allowing the potential for future rearrangement and refitting of retail departments. The chosen strategy provides fixed routes for primary ductwork through standard notches at beam ends, with secondary ducts and pipework running through 650mm diameter holes in beam webs. These holes are not located specifically for the current services arrangement (indeed this arrangement was unknown until after the completion of the frame erection), rather they were designed to ensure that a reasonable level of variation in layout was possible. This standardization of notch and hole sizes/spacing simplified the fabrication requirements and allowed some repetition despite the many different beam lengths. The co-ordinated structure/services strategy also steered the structural design towards a deep but light beam solution with good stiffness characteristics and hence good dynamic performance. Asymmetric plate girders of a standard depth were chosen for most beam sections, working compositely with the 150mm deep concrete floor slab. Using plate girders allowed greater control over the distribution of material than having equivalent-depth rolled sections, resulting in much lighter beams and less fabrication waste (Figs 5, 6).

7. Atrium steelwork.

8. External view of completed frame.

It became clear during design that the secondary floor beams comprised over two-thirds of the total frame tonnage, and that small improvements in their design would yield significant overall weight and cost savings. The optimization/rationalization process was complicated by the many different beam lengths and support conditions, resulting in a vast matrix of different demands. The resulting designs and number of different beam types are a balance of performance and practicality (Figs 7, 8).

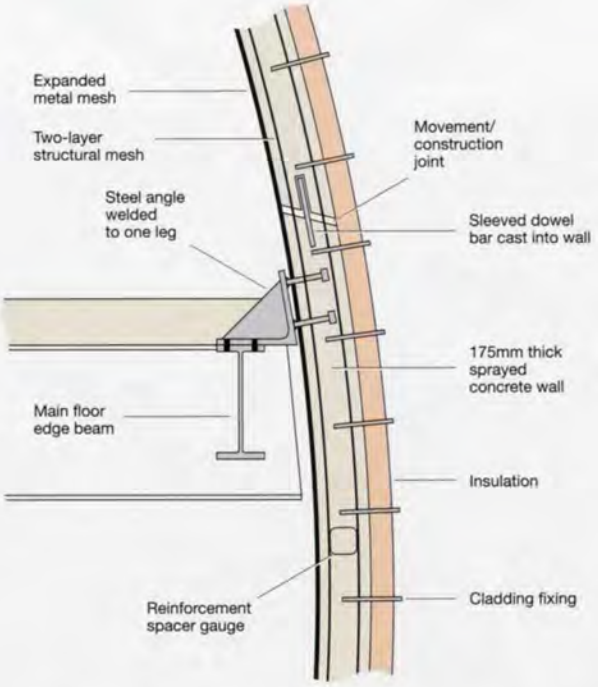
Structural façade substrate

The need to form the curved geometry of the façade without incurring high construction costs presented one of the most complex design challenges. The varying curvature and non-developable shape of the building precluded efficient modularization of structural components or formwork, which prompted the team to look at more homogeneous and unconventional methods of façade construction. Options such as steel mullions, precast concrete, ferrocement, and GRC were investigated, but eventually rejected in favour of sprayed concrete (Fig 9), which could be formed to the required geometry and sprayed to a thickness whereby it could hold its own shape and resist wind loads without the need for a supporting sub-frame.

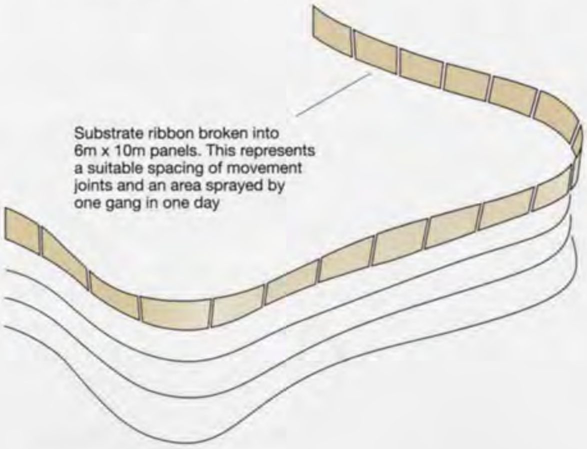
Expanded metal mesh was used as permanent formwork, bent on site to the required curvature and held in position by an adjustable scaffold system supported on the floor slabs within the building. Four layers of structural reinforcement were then fixed to the formwork, and concrete sprayed from the outside to a thickness of 175mm. The wet spray method was used for most of the substrate, covered by a final 30mm thick dry spray coat using a pre-bagged mix with smaller aggregate to allow a final trowelled finish suitable to receive the spray-applied waterproofing membrane.

The chosen structural system divides the surface of the façade into storey-height ribbons. This avoids the problems of supporting a 30m high concrete façade around the ground level window openings and off the edge of a retaining wall structure designed and constructed as part of the wider Bullring development relatively early in the Selfridges design process. This decision allowed each storey of façade to be hung from the floor structure above and only laterally restrained at the connection with the storey below. Thus the likely importance of buckling effects is reduced, and the loads from the façade can be associated with a particular supporting floor, simplifying the analysis of the combined structure (Figs 10, 11).

The façade structure was analyzed in GSA using a 2-D finite element model linked to the 1-D element floor plate models built previously to design the main frame. The results from these analyses were used to tune the thickness of the concrete skin to achieve a substrate of adequate strength and stiffness whilst minimizing the load to be carried by the supporting frame. Design of reinforcement requirements vertically and horizontally was carried out by post-processing analysis results using Arup's in-house software RC2D (Fig 12 overleaf).

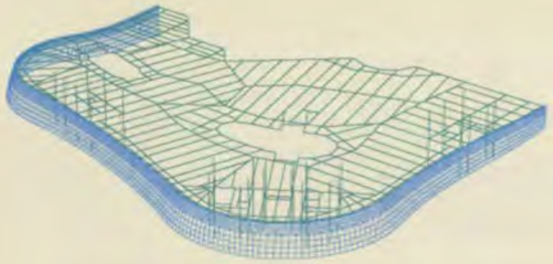


9. Indicative section through sprayed concrete wall, showing fixing detail.

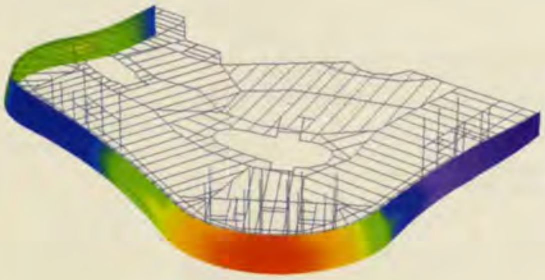


10. Façade substrate panelization.

11. Spraying the substrate on site.



a) Combined floor frame/façade model used to study the composite behaviour of the system.

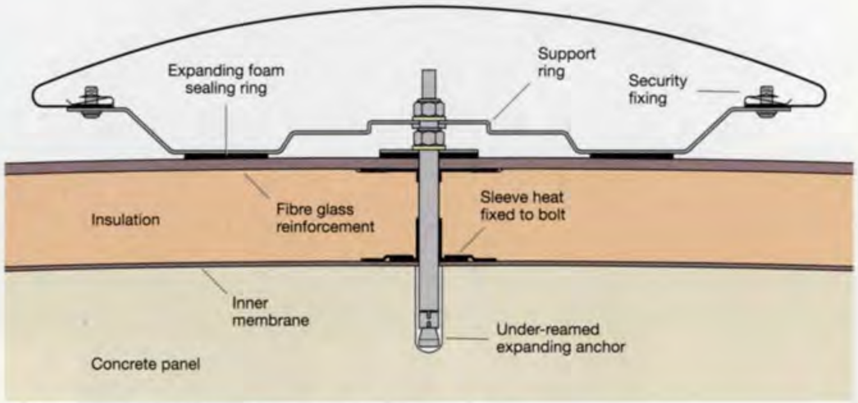


b) Façade displacements around a typical storey ribbon under full loading, showing the extent to which the façade evens out the localized deflections of the supporting steel frame.

c) Forces on the restraint detail at the bottom of a storey ribbon under vertical loading. Wind forces only predominate in a few areas.

12. GSA analysis of façade.

13. Glazing at terrace-level entrance.



14. Indicative detail of façade construction and fixing.

Façade cladding

The distinctive façade construction covered the sprayed concrete substrate with a liquid membrane vapour barrier, insulation, and an outer, spray-applied, coloured membrane on a glass reinforced render. Finally, the building was clad in 15 000 anodized aluminium discs, each of which went through stringent quality control (Fig 14). The final design of the cladding followed extensive research by the design team with cladding material suppliers. Apart from the technical challenges of cladding such an unusual building, cost control was a major driving factor. Amazingly, the final design is comparable on cost terms with the more traditional metal and glass façades on nearby Bullring buildings.

Point-fixed, laminated glazing with a ceramic frit and mirror-finished border is located around the base of the building and in small windows at high level. The glazing is set into polished stainless steel rainscreen cladding where the public have access to the façade (Fig 13).

In the centre of the building is a lightweight atrium roof. It was detail-designed by Haran Glass and is a suspension structure in which pretensioned rods support the point-fixed laminated glass. The weight of the glass is sufficient to counteract uplift loads, resulting in an extremely light structure.

Extensive structural and weathering tests were carried out on the various cladding systems. These included accelerated ageing of the blue finish, impact resistance of the glazing, and load-testing of the aluminium disks should they prove an irresistible challenge to climbers.

Rainwater from the curved roof and façade is collected by integrated, 'invisible' gutters at the façade 'shoulder' level, where it is brought into the building and connected into downpipes in the cores. Additional gutters are also provided around the windows at entrances and display windows.

Building services strategy

Apart from meeting the budget, three principles governed the design of the building services: comfortable internal conditions, flexibility to accommodate future churn, and energy efficiency.

Some 15% of the retail area fit-out will change each year to maintain the store at the cutting edge of fashion, and this churn will be continuous whilst the store is operational. In response to this, the design team developed a 'plug-and-play' system of retail services, with power, air-conditioning, data cabling, lighting control, and building management system (BMS) all available locally in retail areas without the need to access perimeter risers. Central controls are then reprogrammed as necessary.

At the concept stage, computer modelling of the daylight through the atrium rooflight enabled the angle and shape of the atrium to be developed to bring natural light deep into the store (Fig 15).

15. Atrium with the store in use.

Mechanical services

Retail is energy-intensive, with high lighting and design occupancy loads. However, occupancies vary considerably and are usually below design values. As occupancy also drives fresh air requirements, and the Birmingham Selfridges has few windows, the occupancy governs the building energy pattern. Systems were therefore developed that took advantage of the varying loads to provide calculated annual energy savings of over 40%, compared with the standard constant volume retail air system with fixed fresh air percentages and fixed speed chilled water system.

A variable air volume (VAV) system was selected instead of a constant volume system to give savings in fan energy at non-peak loads, and avoid chilled water on floor plates - this was a client request. Eight similar air-handling units on the roof provide air to VAV boxes using low-loss distribution ductwork. The VAV boxes serve swirl diffusers 4.5m above the floor, which were extensively laboratory tested during design to ensure good air distribution at 40% of peak volume. Local temperature sensors provide zone control of VAV boxes.

Full recirculation, with CO_2 sensors monitoring the return air to control fresh air against occupancy, reduces peak heating and cooling loads. Free cooling using 100% outside air is employed when the external temperatures make it more energy-efficient. Perimeter heating was separated from the VAV system to avoid the need for terminal reheat, and reduce cost and complexity.

The size and routing of primary ductwork was optimized with the structure as already described. The final routing of fit-out ductwork from VAV boxes was co-ordinated with the structural beams using as-built structural 3-D models from the steel fabricator transferred onto layout drawings, ensuring co-ordination and saving considerable time on site. Complex areas of services behind the curved skin were modelled in 3-D (Fig 16).

Off-retail areas are provided with minimum fresh air using dedicated air handling units, with local fan coils providing heating and cooling. The staff restaurant uses an all-air, constant volume system to provide comfort cooling and make-up air for kitchen extract. Kitchen extract fans are also provided to the cooking islands in the food hall and to restaurant kitchens.

The chilled water system uses a two-speed primary circuit that switches out half of the air-cooled chillers when not required, saving considerable pumping energy. Variable speed, two-port controlled secondary circuits further reduce pumping costs. Temperature rescheduling allows fan coils in back-of-house areas to use 11°/17°C water temperatures at night and in winter, significantly increasing the coefficient of performance. Separate, direct exchange cooling is provided to the main communications and security rooms.

Central boilers were removed as a cost saving early in the design. The low supply air temperatures and use of recirculation mean that electric heater batteries in the retail air-handling units are seldom used, providing significant cost savings over a central system.

16. 3-D modelling of services and structure.

Public health

Central hot water generation is not provided. In line with the 'plug-and-play' strategy, local storage heaters are sized and controlled to meet local needs and power can be metered for billing to concessions. The change between base-build predictions and confirmed fit-out catering requirements demonstrated the benefit of this approach.

Cold water and gas risers with capped connections to each floor are provided around the building to meet future fit-out catering demands.

Extensive gravity drainage connects the food hall and other areas to the sub-slab drainage system, co-ordinated early on with the Bullring team to avoid the need to use sumps.

Electrical systems

Power for the store comes from two independent HV rings serving the Bullring development. One serves two 1250kVA transformers that provide the non-essential loads, whilst the other, from a different sub-station in Birmingham, serves a 500kVA transformer that provides a standby supply for essential and life-safety systems, avoiding the need for a stand-by generator.

Panel boards with metering facilities serve 160A three-phase busbars and a modular wiring system at high level in the retail area. All general retail power is taken from tap-offs connected to the busbars, whilst 'landlord equipment' - VAV boxes and security equipment - uses the modular wiring system that can be served by the emergency supply. This simple system provides 'plug-and-play' power, as retail fit-out only needs access to the local busbar, not to the risers. Tap-offs can be metered for billing of concessions.

17. The bookshop, showing services integrated with structure.

18. The impression of well-lit spaciousness pervades the store.

Whilst most retail power is required at high level, tills and shop-fit lighting require power at low level. Raised floors were originally included, but removed as a cost saving. Power to low level is provided by connecting a tap-off to the busbar in the ceiling of the floor below, and drilling through the slab.

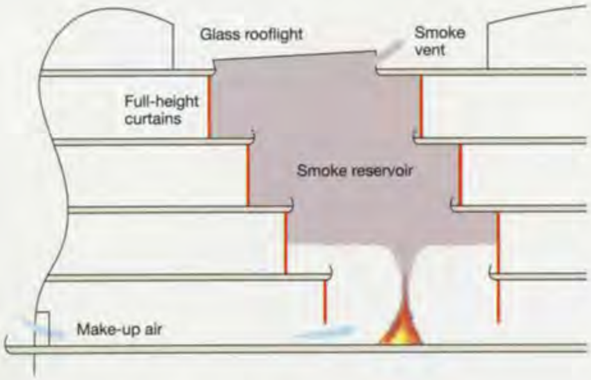
Much of the building power load is associated with lighting, and a modular lighting control system was an essential client requirement. A system of three basic levels of retail lighting was developed - security lighting, general/cleaning lighting, and display lighting which is only on when the store is trading. In addition, scenes can be set as required to cater for special functions and events. Back-of-house lighting is controlled independently. Modules on the floor plates control both the lighting at high level and the floor boxes that serve low-level display lighting.

There is no central battery or UPS system. Emergency lighting throughout the store is provided by local battery packs, whilst local UPS units supply back-up power to tills on retail floors and to the central communications room. This strategy maintains flexibility and reduces complexity and capital cost.

Security is an essential element; there are systems for access control, intruder alarm, merchandise protection and CCTV, interfaced with other systems as required. Article tag sensing is buried under all exits from the retail area, maintaining security without compromising the store's visual impact.

The 12 escalators in the curved atria add drama, and afford the main customer circulation routes around the store. Two double-sided customer lifts connect the retail floors to the bridge and street-level entrances. The three fire-fighting lifts were used to minimize space requirements and co-ordinate with the curved roof of the building; all the machinery is contained within the lift shaft, avoiding the need for additional machine space.

Two goods lifts provide separate goods-in and goods-out routes to all floors from the loading bay level via different cores. Space has been allowed for an additional goods-in lift and an additional passenger lift.



19. Smoke control strategy: atrium fire scenario.

Fire engineering

The two atria and the entrances into the rest of the Bullring shopping centre enhance the feeling of space and openness, and to enable this without compromising safety for staff and public in the event of fire, a holistic fire engineering approach was adopted. It has two innovative aspects. The base of the main atrium is used as retail space (currently the food hall) and the usual way to allow this to happen would be to have sprinklers controlling the size and spread of fire. Instead an alternative approach was taken, to have 'islands of combustible load'. The amount of combustible load within each 'island' is limited to control the size of fire, and the islands are separated from each other by sufficient distance to prevent spread. Smoke is extracted naturally via the atrium roof. This 'islands approach' required Selfridges to stick to quite strict guidelines when placing retail displays within the atrium base, but they were happy to accept this.

The second innovative aspect is that a mechanical smoke control system, using the air-conditioning extract ductwork, keeps the smoke layer above head height, maintaining a clear escape zone for occupants. This allowed for an increase in the allowable evacuation time from the building and hence a reduction in stair core sizes. To support the smoke control strategy, curved drop-down curtains around the two atria prevent smoke passing from one floor to another, or from escaping from the main atrium in the event of a fire there. The main atrium is canted and so the smoke curtains had to be carefully located (Fig 19).

Selfridges is independent from the rest of the Bullring in fire-protection terms, with side-operating fire shutters providing two-hour fire separation to the mall at each level. These close if a fire is detected within the store to prevent fire spread to other parts of the Bullring and to prevent people entering the store during an evacuation. On the other hand, if there is a fire elsewhere, Selfridges can continue trading.

The store has an L1 fire alarm system and a voice alarm/public address system to support the early detection of fire and early initiation of evacuation needed to support the extended evacuation time. The whole building operates as a single fire zone for evacuation purposes. The alarm system is interfaced with the Bullring so that information of fire status can be shared.

Sprinklers are distributed throughout the store except for the atria. The large atrium is treated as described above, whilst the small atrium base is considered a sterile zone with no combustible contents. Water storage and sprinkler pumps are provided centrally within the Bullring, optimizing space in the development.

A reduction in structural fire rating from 120 mins to 90 mins was allowed, based on the provision of sprinklers and the number of floors being less than would normally be expected within the height of the building, due to the large floor-to-floor heights.

None of the fire engineering approaches adopted would have been possible without the good relationship established with the supportive (and patient) local authority team.

Communications

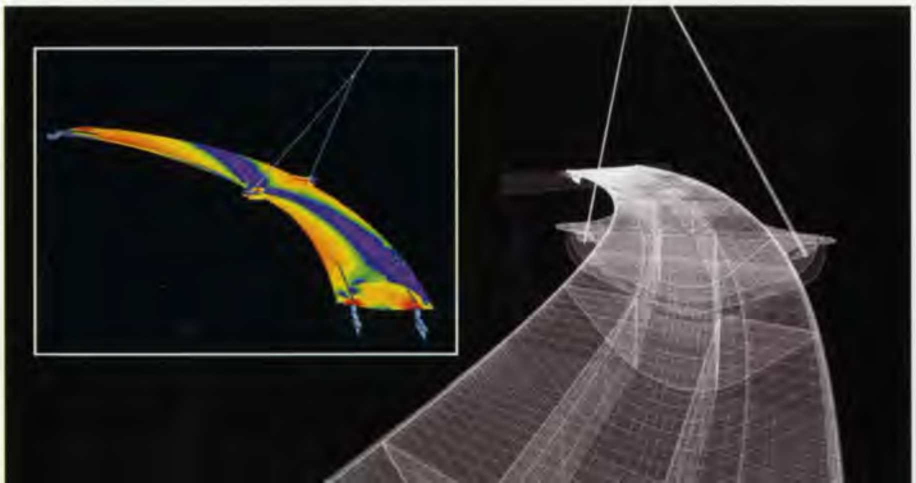
The communications strategy continues the 'plug-and-play' approach to retail servicing, whilst providing network resilience to the store's IT systems. From equipment rooms on all floors, cabling serves a grid of floor distribution points - groups of outlets mounted together to act as a local point for final connection to tills and other items. The structured cabling system also provides cabling for the BMS network on the retail floors, avoiding the need for parallel cabling infrastructure systems. It is believed to be the first time such a system has been used in a retail environment.

The bridge

The design of the 37m span footbridge linking to the Moor Street Car Park was driven by the architectural aspiration for an elegant form with a clear relationship to the Selfridges building. By using the structure as an exposed sculptural surface the design team could minimize the deck depth and avoid the need for additional cladding. The bridge is a steel box girder with internal stiffeners, curved both on plan and elevation, akin to an aeroplane wing. Further support is given by cable stays tied back to the Selfridges frame at roof level.

A 3-D model was produced in Rhino to demonstrate that the deck could be fabricated entirely from warped but developable steel plates and segments of bent tubes. This model was also used to produce developed cutting patterns for the warped surfaces and to extract all other fabrication information. The bridge was analyzed in GSA using a 2-D finite element model derived from the Rhino geometry, and detailed design carried out to *BS5400* by slight adaptation of clauses intended to justify conventional rectilinear box girder sections (Figs 20 & 21).

20. Rhino model and 21. (inset) GSA analysis of the bridge.



22. The completed Selfridges store and its link bridge in their Birmingham setting.

The bridge is covered by a polycarbonate canopy supported off a series of T-section steel arches at varying angles of inclination, supported in turn by the bridge deck and restrained laterally out of plane by connection to a continuous handrail. The cross-sections of these arch elements vary continuously, allowing the tops of the Ts to lie parallel to the freeform canopy surface whilst the stems remain in the inclined plane of each arch. For this reason the arches were also built up from plate with developed cutting patterns for the top plates generated from the Rhino 3-D model.

Conclusion

Selfridges Birmingham is a grand gesture of a building and a testament to the vision and courage of client and design team alike. Whilst no wholly new engineering technologies were developed, the innovation came from challenging convention in every area and wholeheartedly embracing multi-disciplinary working. Where standard solutions were appropriate they were used; where they were not, new solutions were found or transferred from other applications.

If this building has a hallmark, it is in the design team's approach of uncompromisingly pushing what can be done one step further. The result is a well-co-ordinated but flexible building, delivered on time and on budget. Selfridges has transformed the appearance of Birmingham's much-maligned centre, and now provides an experience that has redefined department store shopping. It will undoubtedly lead to other buildings 'borrowing' the techniques and solutions of which it is composed, and is fast becoming an icon for the city.

Awards

Concrete Society Outstanding Structure Award / Institution of Civil Engineers Regional Award / Royal Fine Art Commission & BSkyB Retail Innovation Award / Royal Institute of British Architects Regional Award / Structural Steel Design Award

Credits

Client: Selfridges & Co/Birmingham Alliance/O'Rourke Civil Engineering (bridge link) **Architect:** Future Systems **Retail fit-out architects:** Future Systems, Eldridge Smerin, Stanton Williams, Cibic/Lees Associates **Structural, building services, fire, façade, acoustics, and communications engineer:** Arup - Peter Bailey, Jacqueline Barnes, Simon Barden, Colman Billings, James Bishop, Anna Broomfield, Stuart Bull, Tony Campbell, Ed Clark, Ida Coppola, Emmanuelle Danisi, Jim Deegan, David Easter, Steve Evans, Suzanne Freed, David Gilpin, David Glover, Warrick Gorrie, Peter Hartigan, John Heath, Rachel Hughes, Paul Hyde, Roy James, Adam Jaworski, Bob Jones, Kieron Kettle, Ken Kilfedder, Brian Lake, Paul Malpas, Paul Marchant, David McAllister, Chad McArthur, Jon McCarthy, Simon Morley, Ed Newman-Sanders, Chris Peaston, Anthony Proctor, Oliver Riches, Ian Rogers, Adrian Savage, Andrew Sedgwick, Jim Smith, Edwin Stokes, Edward Tricklebank, Lee Van Achter, Paul Verdi, Terry Watson, Ian Wilson, Malcolm Wright, Roddy Wykes **Cost consultant:** Boyden & Co **Project manager & planning supervisor:** Atkins, Faithful & Gould **Contractors:** Sir Robert McAlpine (frame), Laing O'Rourke (façade & fit-out), O'Rourke Civil Engineering (bridge) **Lighting design (retail fit-out):** DHA **Catering consultant (retail fit-out):** Grantham Winch Partnership **Illustrations:** 1, 6-8, 11, 13, 15, 17-18, 22: ©Arup/Graham Gaunt; 2, 9-10, 14, 19: Nigel Whale; 3: ©Benoy: 4-5, 12, 16, 20-21: Arup

Combining 21st century design with local building techniques, this shingle-clad form is a striking addition to the mountain resort.

Chesa Futura, St Moritz

David Glover Jan-Peter Koppitz

Introduction

St Moritz is a small Swiss town, nestling 1800m high up in the Alps and surrounded by the natural beauty of the Engadine Valley. St Moritz is famed for its winter sports, and in the season the population of 5000 increases to over 50 000.

The Chesa Futura is a residential building, commissioned by a private client from architect Foster and Partners, working with Arup engineers. It fills a gap between other buildings on a hillside overlooking the lake in this densely built town, and its unique form and the fact that it is raised off the ground on eight steel piloti make it a striking addition to the urban context. Its creation combined state-of-the-art computer-aided design with traditional building techniques: a novel shape brought together with indigenous timber knowledge.

The team

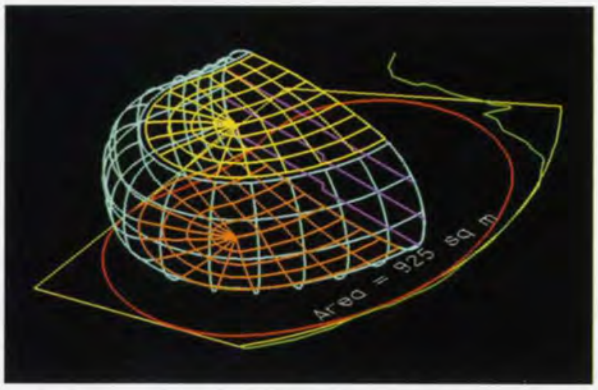
The international design team consisted of architects and engineers in both London and St Moritz from the outset of the project. Arup and Foster and Partners worked on the scheme design together in London, while the local consultants not only offered client and local contacts but also carried out tender and construction work. Holzbau Amann, the timber contractor based in Germany, joined after successfully bidding for the tender.

The geometry

The building's shape stems from the interaction of several factors, including the nature of the site, local planning regulations, and weather conditions. Increasing the width of the upper floors maximizes the net area and ensures that the building stays within its 15.5m height limit. The south side has an ample curvature with spacious balconies and large windows to allow sunlight in. The north side, by contrast, has a tight curvature and is dotted with small openings, as it faces north towards the weather-beaten mountainous side. These windows, which are chamfered, also follow local building traditions by maximizing light penetration through the smallest possible opening.

Raised buildings have an enduring tradition in Switzerland, by their form mostly avoiding the damaging moisture rising from ground that is snow-covered for many months of the year. Chesa Futura's raised superstructure ensures that views of the historic town centre from behind the building are maintained, whilst the balconies offer panoramas of the valley and lake over the existing buildings lower down the hill.

1. External view with one-year patina on shingles.



2. Parametric computer model: defining the setting-out surface.

The computer model

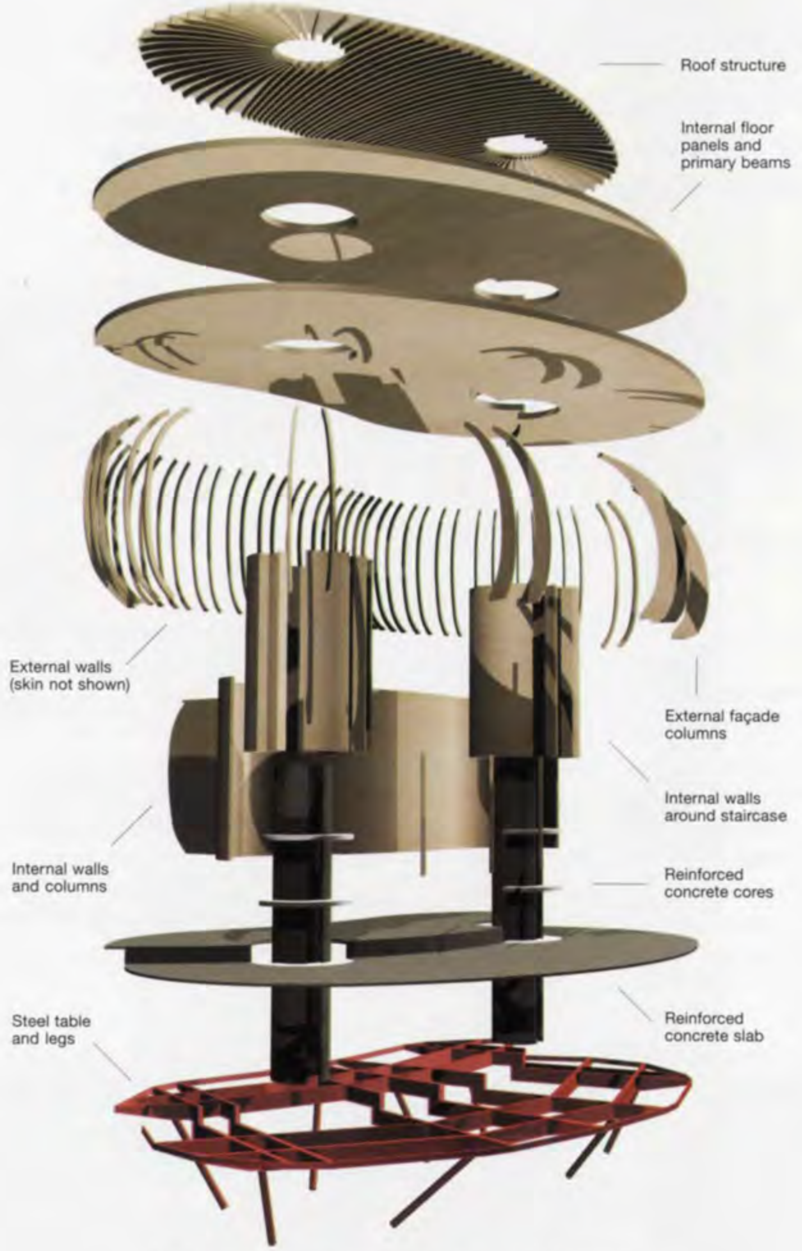
A parametric computer model was set up to define the building's geometry in plan and section and create a three-dimensional volume. This model enabled the members of the design team, whether they were in the UK, Switzerland or Germany, to integrate their work with a constant exchange of design ideas. The model's ability to regenerate its entire form by altering individual parameters allowed studies and variations to be carried through. A myriad of possible architectural variations could be easily explored, whilst still ensuring that the volume conformed to all planning regulations.

The model also allowed the design team to define exactly a setting-out surface for the entire building. From this master surface, grids were set up on which all windows, rib, and floor positions were defined, in turn allowing the individual elements to be defined for prefabrication. This information was exported and shared with the timber contractor. Via their software they firstly checked all data and then steered the five-axial CNC (computer numerical control) cutter for manufacturing. All element data and drawings were also produced from the original computer model.

The structure

The building has a simple and straightforward division of functions: the timber superstructure houses six residential apartments totaling 2500m^2, with parking space, storage, and plant accommodated in the large concrete basement. Structurally and functionally these main elements are connected via two circular concrete cores.

A highly efficient structure was needed that would not only be light in weight, to make the elevated superstructure viable, but also achieve the necessary double curvature. The natural choice of material was therefore timber, a sustainable local resource as well as a durable and thermally efficient building material. The timber superstructure was delivered to the site, which has limited access,



3. Exploded axonometric view of the structural elements.

4. Partly transparent view of the structural elements.

in the form of lightweight and manageable prefabricated panels. The resulting swift construction sequence ensured that the building could be erected entirely within the eight-month summer building season.

Its geometry makes the timber structure an extremely rigid shell, as well as being light in weight. Each panel was constructed from glulaminated elements, bent and cut to the exact curvature by the five-axial CNC cutter using the exported geometry from the parametric model. These elements were then set out in adjustable jigs and the doubly-curved plywood skins bonded to the inner and outer surface, forming single stressed skin panels to be joined together on site. The continuous inner and outer plywood stressed skin created a very strong and stable shell, with connecting ribs providing structural depth and room for insulation and services. An absolute tolerance of ±0.5mm was upheld throughout the manufacturing process, and ±20mm for the completed structure.

The entire remainder of the superstructure is also timber: prefabricated timber floor plates that offer integrated thermal and acoustic performance and act as diaphragms, timber sheer walls adding lateral stiffness and providing service routes, and a roof which for aesthetic reasons has only an outer stressed skin.

The building, apart from the copper on the roof, is clad entirely in larch shingles, cut from local trees hand-picked by the shingle-maker in the Engadine Valley. They were all felled at the same altitude during winter when the wood is dry, so that the timber will not shrink. Simply nailed to battens by hand, the shingles should last for at least 80 years, responding to the environment by changing colour.

Steel structural elements support the timber superstructure in its elevated position are steel: a grillage of orthogonal cross-beams supported by eight inclined steel columns or piloti. An edge beam runs around the perimeter and picks up the timber outer shell, which comes down on the cantilevering grillage and slab. The concrete slab offers composite action and also mass to help the dynamic performance of this light-weight timber superstructure.

At ground level two circular glass walls around a concrete core create the entrance to the building. These two cores provide stability and allow for vertical people flow. Each comprises an inner core housing the elevators and an outer core enclosing spiralling stairs and vertical services distribution to the apartments. The inner core is continuous from the bottom level basement to the roof, while the outer core is hung from a stiff top lid off the inner core. Additional lateral stability comes from the arrangement of the eight steel piloti.

The services strategy

High internal comfort expectations for the apartments and stringent Swiss standards required the services concept to be integrated with all other design factors from the start. Thanks to the building geometry, the large openings on the south side allow solar warmth into the building while the north front, studded with its small openings, protects the building. To minimize loads on the superstructure, all plant is accommodated in the basement. The vertical distribution flows up special tubes to the rear of the circular cores and also through shear walls, and at floor level the shear walls and a prefabricated flooring system allow under-floor heating and further horizontal distribution. A fully integrated house management system allows each individual apartment to be regulated to accommodate individual preferences, with remote access around the year. This allows for off-season control while the house is unoccupied and pre-season control to prepare for times of occupation.

Conclusion

Chesa Futura was commissioned from the design team in March 2000, and local planning permission granted in August the same year. Work began on site in April 2001, and although the local weather conditions allow only a short building period, topping out was achieved on time in November 2002. After intensive design and construction work on the building interior and the fit-out, Chesa Futura was completed and handed over to the client in February 2004.

The building has exceeded the client's expectations and received well-earned attention in the timber construction world. As can be expected for such a unique building, it has had mixed opinions from residents and local visitors. For those involved it was a rewarding experience to work on such a challenging project in a very diverse team.

5. View of the balcony and beyond, over the village.

Credits

Client: SISA Immobilien AG, St. Moritz **Architect:** Foster and Partners **Concept and scheme structural and MEP design:** Arup - David Glover, Simon Hancock, Jan-Peter Koppitz, Marc Lehmann, Tim Lucas, Andy Pye, Brian Streby **Tender and construction structural design:** Edy Toscano AG, St. Moritz **Tender and construction services design:** EN/ES/TE AG, **Zuerich** **Local architect:** Kuechel Architects, St. Moritz **Quantity surveyor:** Davis, Langdon & Everest **General contractor:** O Christoffel AG, St. Moritz **Timber contractor:** Holzbau Amann, Weilheim, DE **Shingle-maker:** Patrick Staeger, Untervaz **Illustrations:** 1, 2, 5: Foster and Partners; 3, 4: Arup

A 16th century palace becomes the new home for the work of Pablo Picasso, Málaga's first son.

The engineering design of the Museo Picasso, Málaga

Mark Chown José de la Peña Karsten Jurkait Tudor Salusbury

That Málaga on the Costa del Sol in southern Spain is Picasso's birthplace is perhaps most visibly reflected in the naming of many establishments there. The city has, however, long aspired to have a museum to celebrate its famous son, and in collaboration with the Picasso family and the regional government (the Junta de Andalucía) has assembled an important collection of the artist's work - paintings, drawings, sculptures, sketches, and ceramics. Some of these items have been on show in Madrid, while some were part of the Picasso family's private collection, but there has been a strong interest in bringing them all together under one roof.

2. The Mudejar tower of the Buenavista Palace.

❶ Palace
❷❸ Temporary exhibitions
❹ Offices and meeting rooms
❺ Theatre/auditorium
❻ Workshops
❼ Cafeteria and shop
❽ Library

1. The palace with adjacent properties for conversion.

The 16th century Palacio de los Condes de Buenavista in the historic centre of Málaga was identified as a possible site for this museum by the Junta de Andalucía, which decided to acquire the palace and some adjacent properties to convert into the new home of the Museo Picasso (Figs 1 & 3). The Palacio was built between 1516 and 1542 by Diego de Cazalla, and was declared a national monument in 1939. Characteristic of 16th century Andalucían architecture, it combines Renaissance and Mudejar elements, such as its emblematic tower (Fig 2). The building also features remarkable artesonados (artisan wood ceilings). Subsequently more adjacent properties were added to the complex, which finally comprises some 9000m^2, providing various permanent and temporary galleries and workshops to display and conserve these unique artworks. In addition there are viewing and support facilities (cafeteria, shop, library and offices), as well as a small theatre. The new museum complex has been designed by Richard Gluckman of Gluckman Mayner Architects New York, with Isabel Cámara and Rafael Martín Delgado of Cámara/Martín Delgado Arquitectos in Málaga. Arup has been involved in the project from its inception as structural, geotechnical, building services, natural lighting, and acoustic consultant.

Roman archeological remains are quite often found in excavations within the city centre; however, in 1998 significant Phoenician metallurgical objects from the second half of the seventh century BC were uncovered, as well as 11m of a well-preserved defensive wall, dating from the sixth century BC. These discoveries have changed historians' views of the Phoenician presence in Málaga at that time and the uncovered walls are now included in the public exhibition area (Fig 6).

Structure

The existing Palace structure consists of brick and stone load-bearing walls of different thicknesses supporting structural floor slabs made of steel beams backfilled with masonry waste. The foundations are generally continuous strip footings of brickwork masonry.

The adjacent properties were of varying historic importance and state of preservation, but due to their poor construction and condition, most were demolished in the refurbishment, leaving only some historic façades preserved.

Refurbishment of existing walls

Despite its age, the original palace wall construction was found to be in generally good condition, apart from some local deterioration of brickwork with subsequent loss of material, most probably due to thermal expansion and contraction.

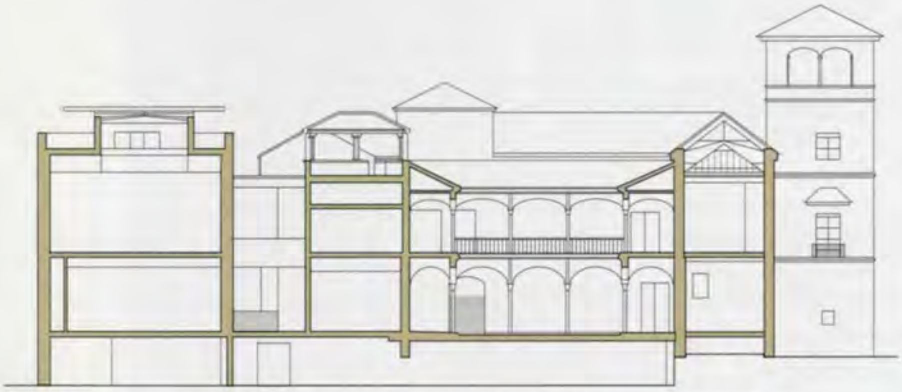
The new configuration of museum spaces made it necessary to underpin some existing walls with concrete block foundations under the existing substructure, or by placing an additional parallel wall to take the lateral loads from the surrounding earth as well as the vertical load of the existing wall (Fig 5).

Micropiling was used for the underpinning, not only because its machinery can operate in restricted spaces, but also because the method posed little or no risk of damage to the archaeological remains. In total, around 11 000m of 180mm diameter micropiles were installed to a depth of 25m.

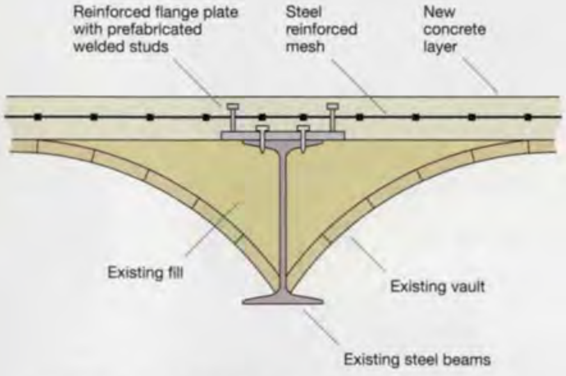
To incorporate the archaeological remains as an exhibition space within the basement, the existing palace walls here were partially removed to create open circulation areas, and a new steel transfer structure constructed in place of the walls to carry the upper levels of the palace.

6. Phoenician wall ruins on permanent exhibition in the basement.

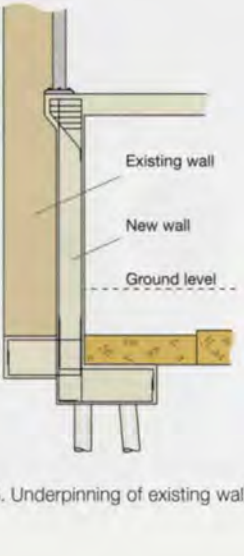
7. Wooden artesan ceiling hung from existing floor slab.



3. Cross-section through the palace (right) with its courtyard, and temporary galleries (left).



4. Reinforcement of existing floor slab.



5. Underpinning of existing walls.

Refurbishment of existing floor slabs

The Palace's floor slabs mostly comprised unidirectional beams of timber, metal or concrete, the low resistance and poor dynamic behaviour of which made them inadequate to take the loads required for the new museum.

Wherever possible they have been replaced, but in some areas of the Palace the slabs carried wooden artesan ceilings beneath (Fig 7). Given the artistic and historic importance of the latter, it was not therefore possible to replace all the existing slabs, so an ingenious system of steel reinforcement plates was used to strengthen the structure from the upper surface, leaving the wooden ceilings below unaffected. The upper compression flange of the beam was uncovered and the reinforcement plates inserted and connected by rivets or bolts, to avoid the risk of fire associated with welding (Fig 4). The structural slabs were thus made composite, combining the need for resistance and the good dynamic performance necessary for the new galleries.

Because the floor slabs supplied the loadbearing walls' structural integrity, they were replaced a section at a time, thereby maintaining the building's overall structural stability. Its seismic stability has also been improved by the refurbishment, as new concrete shear walls constructed around the new lifts have consolidated the existing loadbearing walls.

8. Temporary façade support.

Retaining existing façades

As noted already, some historical façades have been kept and refurbished from surrounding buildings incorporated into the museum complex. For these to be integrated into new structure, temporary auxiliary structures had to be built to stabilize the façades at each floor level (Fig 8). As well as maintaining stability, these also held the façades in tension to offset any lateral forces during construction.

New concrete walls were built inside the existing façades and, at each floor level, connected by stainless steel ties into existing holes in the façade where the old structure was previously supported. These new walls also help to absorb any existing misalignment of the façade.

New structures

The new structures were designed in concrete and steel for stability against seismic loads via shear walls, rigid cores, or cores and bracing structures.

Air-conditioning a 16th century palace

Any museum's building services must comply with one basic criterion: the conservation of the works of art, in terms of both internal environment and security. But here, the integration of modern technological systems into both the 16th century palace and the contemporary architectural design was another important factor for the design team to consider. Finding solutions to these sometimes contradictory demands was a considerable challenge.

The rooms within the Buenavista Palace characteristically have artisan timber ceilings, whitewashed walls, and windows opening into a typical Andalusian central patio. This original architectural character clearly had to be preserved, but the rooms also had to provide ideal conditions for the exceptional works of art to be exhibited inside them. The temperature and humidity conditions had to meet internationally accepted standards.

The thermal loads and inherent thermal inertia in the Palace's structure were studied using in-house Arup ET & A software and, based on the results, individual zones inside the palace were identified (Fig 9), each one to have its own independent air-conditioning system.

These studies indicated that the thermal inertia of the brick walls help considerably in reducing the impact of fluctuations in the exterior conditions, and that with a careful detailing of the windows to avoid excessive heat gains and solar irradiation (UV protection), the resulting thermal loads are dominated by the effects of lighting and people. This meant that air supply volumes could be minimized, thus reducing the impact of the system being installed within the existing palace structure.

For each zone small technical spaces were identified to accommodate climate control systems; these had to have reasonably good access for daily maintenance, and be connected both to the outside for fresh air intake and to the gallery itself, though not so close to the exhibition rooms that noise would penetrate.

Due to the limited space available inside the Palace, one system had to be located above an exhibition, and exhaustive measures were taken to guarantee the plantroom's vibration isolation and watertightness. All other plantrooms were designed with acoustically isolated structural slabs, and acoustic absorption on both the walls and ceilings to reduce noise ingress to the exhibition spaces. From the outset, careful integration of the services installations in the structure and function of the building was one of the main objectives of the design. Horizontal water distribution, for example, was installed in the basement to avoid any risk of leakage above galleries and moisture damage to artwork.

9. Air-conditioning zones in Areas 1, 2, and 3.

10. Ground floor temporary exhibition gallery.

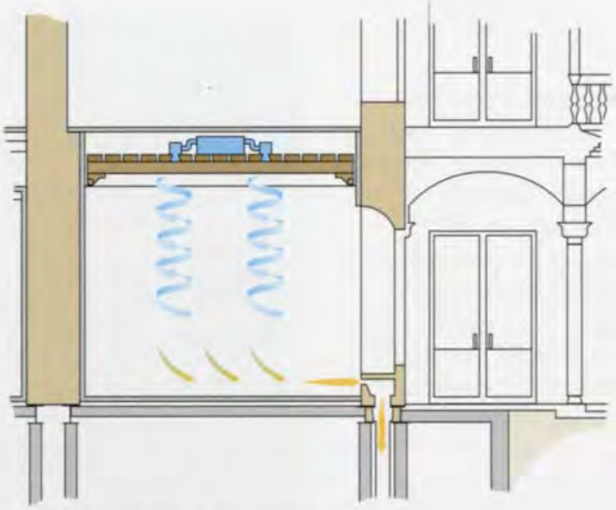
The central heating and cooling equipment is in area 6 above the administration offices. Three-cycle chillers with heat recovery were chosen to reduce space requirements and avoid the use of gas on the site. The roof design ensures high noise and vibration isolation, and air-borne noise emission to adjacent properties was studied and reduced to acceptable standards by low-noise units and acoustic panels.

The existing roof spaces above the galleries were examined in detail by the design team to identify possible routes for horizontal air distribution from the central units to the galleries, as well as for electrical, data and security cabling, Once again, this service distribution was designed to ensure minimal impact on the structure.

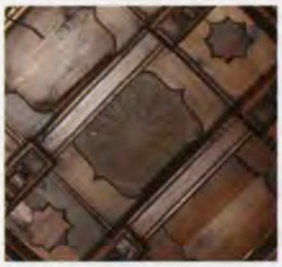
After studying their structural capacity and identifying appropriate areas, the vertical distribution was installed in recesses in the walls; this necessitated metal supports to strengthen the brick structure.

In the galleries, the original wooden panels of the false ceilings provided a particular challenge to integrating the air diffusion grilles (Fig 14). A high-level supply and low-level return system was chosen, thus achieving adequate air distribution and circulation whilst still minimizing the air supply volume (Fig 12). Rotational diffusers with perforated metal faceplates were selected as providing good air distribution and the ability to be integrated in the wooden panels without damaging them or their appearance (Fig 13).

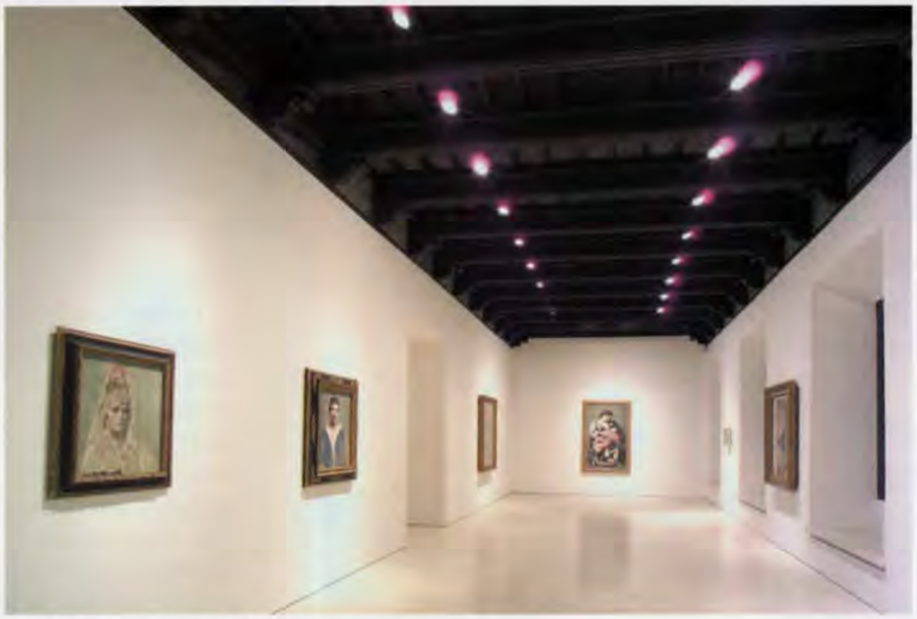
The return air path was designed into new false windowsills and the jambs of the doors between the galleries. In the latter case, plenums were designed with faceplates sculpted in marble, to blend in with the surrounding finishes.



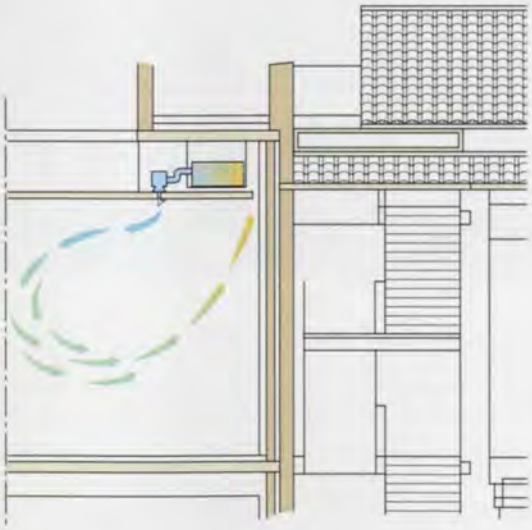
12. Air distribution in permanent gallery.



13. Ceiling panels with integrated air diffuser.



14. Permanent gallery in the Palace.



11. Air distribution in temporary exhibition gallery.

Galleries for temporary exhibitions

Some of the galleries have been designed to house changing exhibitions on loan from other collections (Fig10); rigorous ambient conditions for these spaces had to be met in order to comply with international loan agreements. As these galleries were to be located in new structures, a slightly different air-conditioning strategy could be employed.

As for the Palace galleries, all zones were thermally analyzed, and based on the results, each gallery was then allocated its own air-handling unit, ensuring close control of the ambient conditions. The adjacent, non-exhibition zones were comfort cooled to provide buffer zones between the exhibition gallery and outside. The air distribution ducts were integrated with the new structure to optimize the floor-to-ceiling height in the galleries. Supply and return were both integrated in the ceiling, the supply by linear diffusers combined with the lighting tracks, and the return through slots along the ceiling edges, all following clear sightlines as demanded by the architectural aesthetic (Fig 11).

Basement display

To create conditions to preserve the archaeological remains, the engineers worked with archaeologists and identified humidity as the main climatic criterion. Keeping the humidity constantly above 65% would avoid drying of the Phoenician walls, which had survived more than 2000 years in the moist ground. Since air-conditioning systems inherently dry air whether in heating or cooling mode, a special system with minimum outside air and CO_2 detection for air quality control was developed to provide a design with minimum 'mechanical interference'.

Art storage

A new store has been located in the basement to hold those works of art not on display. Working with art conservation specialists, the engineers designed special physical and technical measures to ensure the security of the stored art. Massive concrete walls help to control the environmental conditions inside the store, providing good insulation and auto-regulation of the temperature and humidity.

To determine what mechanical services would be needed, the extent of variations in ambient conditions were analyzed. These results helped in designing a system that supplies minimal outside air whilst circulating the air inside the store; any increase in relative humidity is controlled with a dehumidifier installed in parallel with the return air ductwork distribution.

15. First floor temporary exhibition gallery, showing large roof skylight.

16. The Palace courtyard with the roof of the temporary exhibition gallery beyond, showing louvres.

Natural lighting of temporary galleries

Considered and careful lighting design is crucial for the successful display of works of art. The visual environment for viewers and occupiers should avoid discomfort through rapid changes of brightness or glare, allowing smooth transitions between spaces of different character. Natural light can make a dramatic contribution to the quality of a space by providing a link with the external environment as well as affecting the architectural volume.

In the temporary exhibition galleries on the first floor of areas 2 and 3, the design includes large horizontal roof skylights for natural lighting (Fig 15). Clearly, exposing works of art to direct sunlight and glare has to be avoided as it is potentially damaging; in addition, glare is distracting for visitors. A key design criterion was therefore to avoid direct sunlight entering the spaces. There were two potential types of solution: exterior shading over the glazed skylight, and the use of a translucent glazing layer.

Another important factor in the lighting design strategy, apart from the general luminance levels, is uniformity of illumination. Uniformity, particularly on the walls, allows art works to be viewed under an even natural light distribution which can then be reinforced by artificial lighting. It is also important to keep the floor luminance in proportion to the wall luminance in order not to distract or create unwanted reflectance. Complete uniformity, however, is not desirable, as it prevents appreciation of shape and volume; normally a figure of 2.5:1 is adopted for the design of natural lighting systems. This level of uniformity can be achieved in toplit galleries by adding a ceiling layer to diffuse the natural light at ceiling level.

In terms of overall lighting levels the aim was to achieve 150-180lux on the walls; this translates to around 100-120lux natural lighting level on the walls under maximum exterior luminance levels. To reduce the approximate maximum external luminance of 100 000 lux and prevent direct sunlight entering, the possible options were clarified as:

- a 45°-angled shading device running east-west
- vertical egg-crate louvres
- translucent glazing.

Although the vertical egg-crate mesh louvre was the most efficient architecturally at preventing entry of direct sunlight, there was an architectural aesthetic preference for the 45° louvres and translucent glazing options (Fig 16). With 45° louvres some direct sunlight penetrates early in the morning and at late evening in summer. However, it was proposed to add translucent layers to control the sunlight and provide the option of various levels of natural light within the galleries.

Both daylight factor and clear skylight computer analyses were carried out to ascertain the natural lighting levels within the gallery spaces and to define and specify the light transmittance for each of the layers which make up the rooflight system.

The final design for the rooflight system consisted of the following main layers to control natural light (Figs 17 & 18):

1. external glazing with exterior sunshading device or translucent glazing
2. retractable blinds to control the level of light transmission into the gallery space
3. glazing to separate the gallery from the rooflight void space
4. diffusing ceiling layer.

Construction started on site in the area 2 and 3 structures in 2002. In July 2003 site measurements were taken inside the rooflights and galleries to make minor adjustments and define the roller blind materials to achieve the internal luminance levels required.

Conclusion

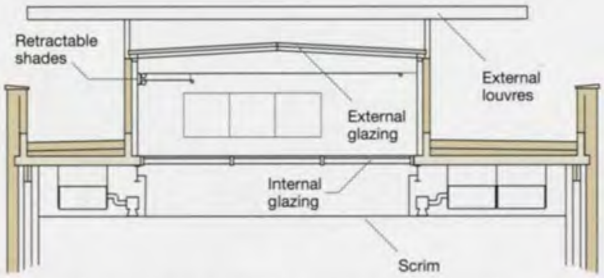
The museum (areas 1, 2, 3, and 6) opened to the public in October 2003 with permanent and temporary collections including more than 200 paintings, drawings, sculptures, ceramics, and graphic works illuminating the entire range of Picasso's long and prolific career. The ancillary areas 4, 5 7, and 8, including the theatre, opened in September 2004 (Fig 19).

The engineering of a museum must complement and enhance the experience for the visitors. This can only be achieved through close co-ordination and integration and many long hours discussing and reviewing different options until agreed optimum solutions are found. The design team would like to thank all the participants who helped to engineer the Museo Picasso which, it is hoped, now provides a memorable experience to all who visit it.

Credits

Client: Fundación Museo Picasso de Málaga **Project director:** Carmen Giménez **Architect:** Gluckman Mayner Architects / Cámara/Martín Delgado Arquitectos **Structural and M&E engineer:** Arup - Kenia Arrechea, Alfonso Bodelón, Javier Calderón, Salvador Castilla, Mark Chown, Javier Feu, Marta Figueruelo, Steve Fisher, Alejandro García, Luis Gay, Ernesto Glocer, Elias Gómez, Chema Jiménez, Karsten Jurkait, David Labrado, Florence Lam, Enrique Mellado, Jesús Moracho, Estrella Morato, José de la Peña, Nieves Pérez, Boguslaw Polot, Tim Robinson, Jacinto Ruiz, Tudor Salusbury, Jeffrey Sújar **Main contractor:** Ferrovial-Agroman SA **Co-ordination:** Sandra Akmansoy **Illustrations:** 1, 2, 6, 7, 10, 14-17, 19: Ferrovial-Agroman SA; 3-5, 9, 11, 12, 18: Esther García-Salamanca/Nigel Whale; 8, 13: Arup


17. Void above temporary exhibition gallery.



18. Natural lighting design for temporary exhibition gallery.


19. The complete museum, with Areas 6 and 7 in the foreground, temporary galleries centre right, and the Palace courtyard on the extreme right.

1.

The National Gallery of Victoria, Melbourne

Peter Bowtell

Introduction

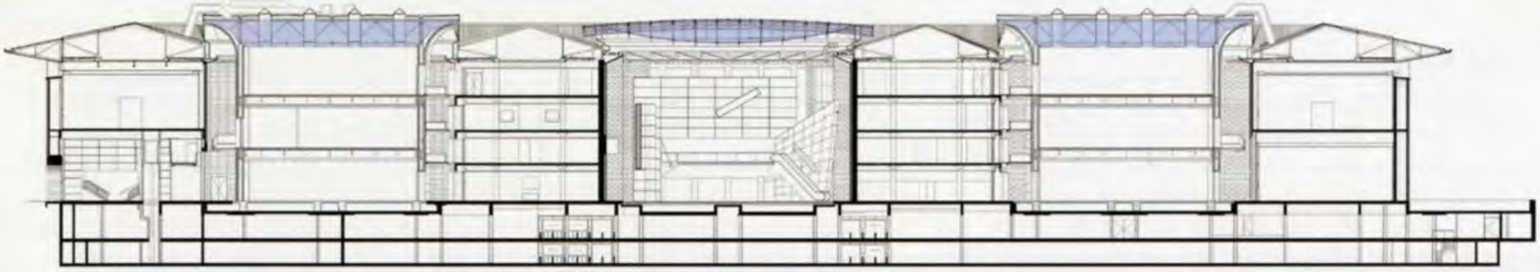
You don't have to be a Victorian to truly understand how important the National Gallery of Victoria (NGV) is to Melbourne, but it helps; such is the connection between this collection and its community.
From modest beginnings in 1861, the NGV now houses one of the most diverse and internationally significant art collections in the world.

> **'Good architecture can have a series of new lives'**
> Mario Bellini

How did this come to be? Underpinning the NGV collection is the Felton Bequest. In 1904, an eccentric Melbourne businessman named Alfred Felton died, having lived his life in a modest bedroom above a hotel in an inner-city seaside suburb. But his donation of the then massive sum of £400 000 enabled the NGV to purchase, over time, some 15 000 works by masters such as Van Gogh, Monet, Cézanne, Rembrandt, Turner, and Constable, together with one of the best collections of Australian art in the southern hemisphere.

Having established the collection, a permanent home was needed to display these treasures, which were hung for some years at Melbourne's Swanston Street library, museum and art gallery. In 1956 (the year that Melbourne hosted the Olympic Games), the Victorian Government of the day passed the National Art Gallery and Cultural Centre Act, and planning for the new NGV commenced. Roy Grounds (1905-1981), now recognized as one of Australia's leading Modernist architects, was commissioned to design the building. Thus began what was at times a controversial 10-year journey. It was to end in the delivery of what became the defining work of his career.

The NGV's new home in St Kilda Road, Melbourne, was first opened to the public in 1969, and the architect was knighted in the same year. Like a fortress, surrounded by defensive moat and high bluestone walls, the building focused inward on gallery spaces, surrounding and separated by three imposing courtyards. A Water Wall, flowing continuously from ceiling to pavement, dominated the large formal entry though a single masonry arch. More than anything else, it was this that captured the hearts and minds of Victorian children as they came to discover the wonders within for the first time.



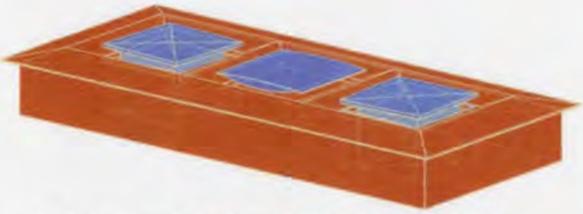
2. Longitudinal section showing, left to right, Coles Court, Federation Court, and Murdoch Court.

Re-visioning the Gallery

By the mid-1990s, the Gallery's collection had expanded to over 60 000 items, with hanging space at a premium. An international competition to redevelop it was held, and the Italian practice of Mario Bellini Associati, working with Arup in London, won the competition. Bellini, best known for his industrial design and work for Olivetti, was then appointed, in conjunction with local Australian architects Metier 3. While early plans considered substantial extensions to the existing NGV, a separate decision to also build a new gallery for Australian art at Federation Square meant that attention at the NGV turned to maximizing space for the international collection within Grounds' heroic complex.

Bellini came to the project with a European vision, determined to bring world-class gallery standards to the collection. At the same time, a fine balancing act was required between the heritage aspects of the building fabric to be preserved and meeting the need to increase and extend floor area. Bellini and Metier 3 turned to Arup to help redefine the standards to be delivered for the premier gallery spaces, and to propose ways to extend the building within the confines of the original design. Given the purity of the building's form and layout, the new floor and curatorial space had to be won mainly from within the existing envelope.

3. The dramatic entry to the new exhibition spaces, showing the steel ramps with glass floor, cantilevered from the side of the exhibition boxes.escalators and circulation spine.



4. 3-D modelling of the three new roofs over Coles Court, Federation Court, and Murdoch Court.

The primary aim was to increase exhibition space by 25%, providing greater access to Victoria's marvellous collection. At the same time it provided the opportunity to deliver new laboratories and technical facilities to enhance conservation and curatorial activities, and to upgrade other back-of-house facilities, as well as catering and retail provision.

Original design for internal environment

From the beginning, Arup worked closely with Bellini and Metier 3 to develop the concept and schematic design for all engineering aspects of the project, including temperature and humidity control, lighting and power, fire engineering, acoustics, and structure. With a considerable track record in conservation standards and innovative servicing solutions for galleries, Arup's building services team in London worked with Bellini to establish the principles for conditioning each of the proposed spaces. These were then passed on to a local consultant team to implement and deliver.

The key features of the conceptual designs were:

- construction of two major new gallery spaces within existing courtyards
- enclosure of the central courtyards and establishment of a clear circulation spine
- low-level floor ventilation systems for the new gallery spaces, to save energy and achieve good environmental quality
- environmental control standards for temperature, relative humidity, and air quality
- an integrated services distribution strategy working within existing spaces
- a performance-based approach to fire egress and fire protection.

Delivering the building

After the building concepts were successfully agreed in late 1997, attention focused on turning the vision into reality. A six-year journey to project completion in 2003, at a cost of A$160M, had begun. Arup's role, following the services design concept work already noted, concentrated on the full structural, civil and façade engineering of the redevelopment, carried out by Arup's Melbourne office. David Beauchamp (Beauchamp Hogg Spano), one of the original engineers on the building in 1969, worked with Arup's structural team to provide an insight into the original design, which at times was found to be both novel and inventive. For example the building, far from being a single structure, had been subdivided by expansion joints into over 30 separate segments, each independent of the others. The stability and integrity of each element had to be carefully considered each time a new intervention was considered.

Re-working the plan

In plan form the building is a simple rectangle, divided into three squares each with a central courtyard, known respectively as Coles Court, Federation Court, and Murdoch Court. In Bellini's revised treatment, these courtyard spaces have been utilized to redefine the visitor's experience of the Gallery. Having passed the Water Wall at the entrance, visitors arrive in the heart of the building in Federation Court, originally an open-air sculptural garden. From here a clear decision about what route to follow can be made: either to pass into the newly-created gallery spaces in Coles and Murdoch Courts, or to take the new escalators up into the upper level galleries, or to continue on, passing through the Great Hall, under the magnificent Leonard French ceiling, and out into the sculpture garden beyond.

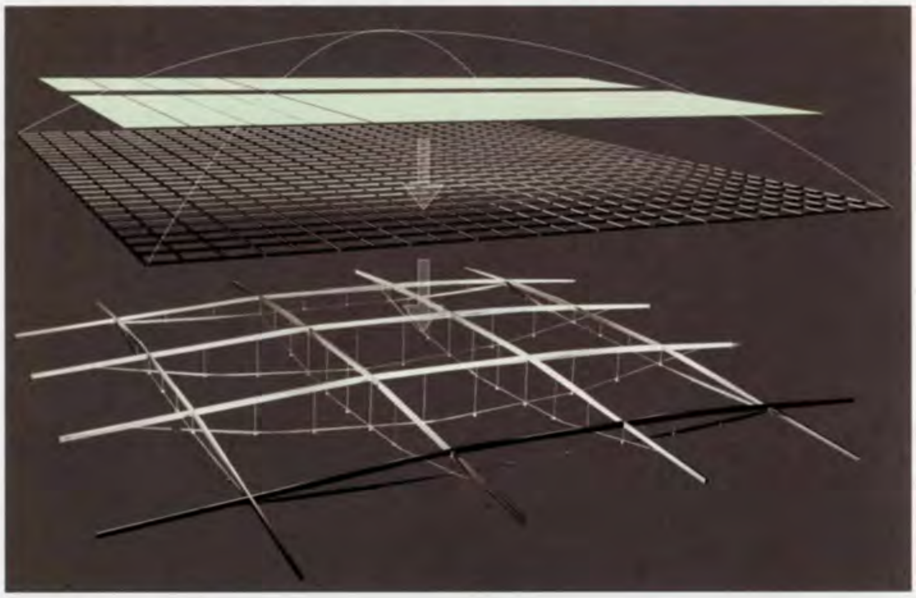
5. Detail of Federation Court roof 'spider' clamp.

Federation Court roof

Addressing what was regarded as one of the difficulties in the original design, the new plans focused on providing visitors with clear and unambiguous circulation within the Gallery. The cornerstone of this effort was to roof Federation Court, which thus becomes the clear starting point for all subsequent visitor exploration of the building, by whatever route. The new glass roof spans clear across the 28m square courtyard, supported by a filigree of four orthogonal cable trusses in each direction, barely visible from floor level. Based on the geometry of a sphere, each glazing bar lies on a great circle of over 3000m radius, keeping every element consistent in length and curvature.

The most substantial roof elements are the 150mm x 100mm rectangular hollow sections on each of the cable truss lines, but typically the dimensions of the other hollow sections reduce to 150mm x 50mm on each of the glass lines, the minimum width required for support. The self-weight of the glass is sufficient to resist uplift from wind loadings, keeping the structure simple and elegant in form.

6. Exploded image of the steel roof structure and glass over Federation Court. The white lines demonstrate how the entire roof structure is derived from a sphere.



7. Close-up of the completed roof.

8. Federation Court on the opening day of NGV International.

While the roof geometry created by the surface of the sphere dictated a warped surface for each rectangular piece of glass, the variation was kept to a minimum so that simple flat square glazing could be adopted. Careful detailing enabled these minor variations across each panel to be accommodated in glazing gaskets. External spider bracket clamps are located in the frame at each corner of every piece of glass, providing a mechanical fixing in addition to a structural silicone seal. This avoids holes within the glass, ensuring that water cannot enter the space below.

The result is a roof that is delightfully light and elegant, and at the same time extremely cost-effective.

Bistro slab and mezzanine

An entirely new entry lobby welcomes visitors. Existing lift slabs and escalators have been removed and replaced by a steel-framed mezzanine, clad in a shimmering stainless steel mesh. Limited to support on two grids of existing columns, the 16m square mezzanine connects to the concrete columns through steel collars and dowels, cantilevering forward by up to 10m to support new escalators and circulation spine. Arup's fire engineering strategy enabled the use of unprotected steel, permitting its clear expression as part of the architecture. On the upper levels, the steel floor framing doubles as mechanical distribution ductwork, avoiding the need for separate ducting within the space.

Coles and Murdoch Court Galleries

Flanking Federation Court are two new major exhibition spaces providing an extra 2500m^2 of gallery space over three levels. Inserted into the existing Coles and Murdoch Courts, they are shaped as two cubes with skewed-off axes.

By careful reanalysis of the existing structure, it proved possible to accept the addition of the extra floors on the existing piled foundations and columns, with only limited transfer structure needed to spread concentrated loads. The new boxes are steel-framed, with composite steel floors clear-spanning the 20m between walls. A cruciform of 900mm deep primary steel beams and 460mm deep secondary beams was adopted for the floor, to provide the best co-ordination with the low-level servicing strategy.

The floors are designed for uniform live loads of 5kPa and point loads of up to 2 tonnes. A fire engineering design approach, which considered the protection provided by plasterboard ceilings and walls, avoided the need for additional passive fire protection.

To provide taller galleries of 4.5m (5.3m on the upper floor), the new suspended floors sit halfway between the floor levels in the existing building. Access is via a steel ramp, cantilevered from the side of the exhibition boxes, with a floor comprising two layers of 19mm glass, laminated, with a sacrificial top sheet of 8mm fritted glass. The result is a dramatic entry to each space that also enables light to spill from the top skylight to the floor below. What could otherwise be a dark and gloomy space becomes a dramatic and vibrant transition between the new and old structures.

Slab strengthening

In several areas, existing openings in the floor slab had to be infilled. To minimize demolition, externally-mounted, epoxy-bonded steel plates, 100mm wide by 4mm thick at 400mm centres, were surface-fixed to the underside of the slab. This achieved the required ultimate slab strength.

Detailed study of the performance of this approach to strengthening enabled confidence to be developed in the design methodology and installation.

9. The 16m square mezzanine connects to the concrete columns through steel collars and dowels.

10. Completed European Gallery.

European Galleries, south end

The NGV wanted to tailor spaces to suit the items on display, and in the south wing the floor-to-ceiling height was doubled by removing both the existing floors at levels 1 and 3, together with two rows of columns previously passing through the floors. Commencing with the installation of new columns within the existing wall zones, new steel beams were introduced below the existing slabs and jacked to take over the load of the floor. Beams were arranged in pairs, each side of the columns, enabling the columns to be cut out and removed after preloading was completed. This design approach minimized the temporary works required for the demolition and at the same time maximized the amount of structure that could be recycled.

Internal environment of galleries

Arup's concept for the galleries' internal conditions took its cue from the firm's successful design for Tate Modern[1] in London. A low-level air supply solution was proposed, and acknowledged as energy-conscious and cost-effective. This entailed supplying air at 18-20°C, with a minimum of 4.5 air changes/hour for environmental stability. A full CFD analysis confirmed the system's performance and ability to maintain conditions within the onerous tolerance bands of relative humidities.

The servicing solutions as built reverted to an overhead supply in the existing galleries, but the displacement system was kept in the critical areas of Federation Court and the new courtyard gallery boxes. This gives the new spaces improved levels of environmental control and comfort, and significant energy benefits.

Mouse hole entry auditorium and theatrette

At the north end of the building, two new lecture theatres have been fitted neatly in the original galley wings. Deliberately stacked 'head-to-tail', they minimize space take and modifications to the existing fabric. Displacement ventilation from the floor plenum assists in minimizing the overall envelope for the spaces. Specially treated to give total acoustic separation from the rest of the NGV, the theatres have been engineered for full multimedia presentation and lecture facilities.

Water Wall

The Water Wall, a key feature of Grounds' original design, had always welcomed visitors at the St Kilda Road entrance, but in the refurbishment it has been moved forward. Previously located on grid, the new shear glass wall now sits closer to the main entrance, proud and free of the existing columns. Arup Façade Engineering worked with Bellini and Metier 3 to reinvent the system, now one smooth sheet of water over 11m high and 20m long. An innovative glass dam collects water at the head of the window, ensuring a uniform flow over the entire face. The result is more translucent, an uninterrupted curtain of water cascading from head to toe. To see it is to be drawn into its spell, and to resist touching the flow denies the inner child!

Conclusion

In realising the new National Gallery of Victoria - now NGV International - Melbourne has established a world-class home for its significant collection. In a sensitive refurbishment, this gallery has been touched by the hand of another European master, that of Mario Bellini. With skill and passion the spaces within this important 1960s edifice have been renewed and reinterpreted. For some, the 'blank canvas' is the ultimate creative confrontation, but to rework spaces within the physical constraints of what already exists can be equally challenging. The design team has endeavoured to ensure that the engineering systems and structures add clarity of form and elegance of detail to the new interventions within the NGV's spaces, contributing to what may be regarded as one of the best galleries in the world.

Web links

http://www.ngv.vic.gov.au/ngvinternational/
http://www.bellini.it/main/index.cgi
http://www.metier3.com.au/
http://www.majorprojects.vic.gov.au/

Credits

Client: National Gallery of Victoria **Project manager:** Major Projects Victoria **Architects:** Mario Bellini Associati in association with Metier 3 **Multidisciplinary engineer:** Arup - Peter Bowtell, Peter Duggan, Peter Haworth, Brendon McNiven, David Shrimpton, Barry Steinmeyer, Tim Thornton, Debbie West, Neill Woodger, Mohsen Zikri **Associate structural engineer:** Beauchamp Hogg Spano **M&E, fire, security and hydraulic engineer:** Lincolne Scott **Acoustic engineer:** Marshall Day **Builder:** Baulderstone Hornibrook **Illustrations:** 1, 3, 9,10: John Gollings; 2: Metier 3; 4-6: Julio Monterrosa; 7: Peter Bowtell; 8: Martin Saunders

Reference

(1) HIRST, J, *et al*. Tate Modern. *The Arup Journal*, *35*(1), pp3-11, 3/2000.

Salt Lake City Public Library

1. Patrons enjoy the Library's glass, ovoid-shaped atrium.

Daniel Bonardi David Richards

Introduction

On a typical afternoon at Salt Lake City's new Main Library, children circle for story time under a canopy of man-made clouds, scholars study in curved glass reading nooks overlooking Utah's Wasatch Mountains, whilst tourists ascend the inclining wall to the rooftop garden.

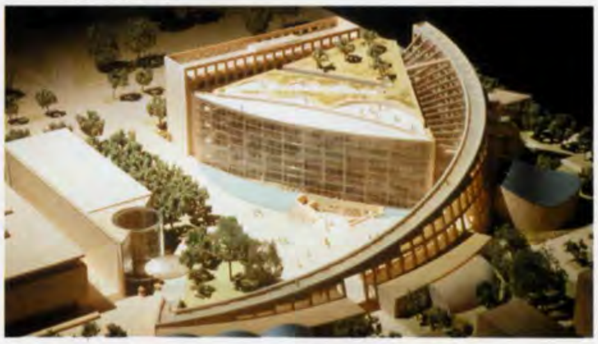
The Main Library opened in February 2003 and since then has enjoyed triple the number of visitors and double the circulation of the former library - remarkable statistics considering that Salt Lake City's library system was used at double the USA national average even before the new building. Many attribute the Main Library's success to the building itself.

The building is actually a series of structures born from a competition entry by Moshe Safdie Associates in Boston, VCBO Architects in Salt Lake City, and Arup in Boston and New York. The competition in 1999 challenged four prominent American architects paired with several Arup USA offices to design a response to an extremely thorough programme developed by Library Director Nancy Tessman and her cadre of committees and consultants.

In Safdie's winning design, a five-storey triangular building housing the stacks, a rectangular 'bar' building for administration, and a glass ovoid-shaped atrium, all flow into a public plaza. The plaza and its buildings are embraced by a crescent-shaped reading gallery with shops and cafés at ground level and a walkable roof that ascends to the triangular structure's rooftop garden. Atria occupy the spaces between the three buildings and bring the total floor area to 240 000ft^2 (22 300m^2).

> 'This building embodies the idea that a library is more than a repository of books and computers - it reflects and engages the imagination and aspiration.'
>
> Nancy Tessman, Library Director

2. The crescent gallery embraces the triangular and 'bar' buildings.



3. Visitors on the plaza can see the Wasatch Mountains through the crescent-shaped wall.

Structural design

Safdie's concept for the triangular building called for slender concrete columns in the stacks and an exposed architectural concrete ceiling with vaults in one direction. Engineers at Arup explored various structural systems in steel and concrete and concluded that anything but a cast-in-place system would impose changes on the vaulted ceiling envisioned by Safdie. The built design uses large reinforced concrete perimeter moment frames to provide stability. This enables interior columns to be relatively slender (24in (610mm) diameter) since they resist gravity loads only and allow the ceiling to vault in one direction only; the curvature of the concrete ceiling directs light even to the lowest bookstacks. Exposed concrete - both a structural solution and an architectural feature in the triangular building - is also used in the adjacent bar building. The design team maintained a high degree of co-ordination to refine dimensions and proportions in both structures.

The triangular building's southern façade meets with a clear glass ovoid atrium (dubbed the 'Lens') that rises five storeys and features a curving 240ft (73m) long glass wall. Reading spaces tucked into the triangular building's glass façade look across the Lens atrium to the plaza, the city, and the Wasatch Mountains beyond. Arup sought to maintain as much transparency as possible through the Lens wall, and the structural solution uses slender columns to support the roof and a system of vertical cable trusses to stiffen those columns to resist wind loads. Additional horizontal cables resist wind suction. As well as being economical and lightening the structure, the cables are an elegant feature of the glazing system.

'The great sloping wall that sweeps from the rooftop garden around the piazza like a spiral galaxy's arm has been the subject of speculation by every skateboarder in the city', wrote the *Salt Lake Tribune*. The 600ft (183m) long wall, that leans in as it curves like a circle in plan, became a subject for structural speculation as well. In order to stabilize this inclined building that reaches as high as six storeys, engineers needed to introduce significant bracing. Since traditional braces would have

4. Visitors ascend the crescent-shaped wall to a rooftop garden.

5. Varied geometries sit atop a two-level underground car park.

interfered with headroom clearance in the corridors, Arup designed the braces with a Y configuration. Again, a structural solution emerged as an architectural feature.

All this striking geometry sits atop a two-level underground car park that is best suited to a regular column pattern. The plaza level acts as a transition between the upper grid and the grid below with a minimum number of transfer beams.

Because Salt Lake City is in an active seismic zone, Arup specialists in Los Angeles performed a seismic analysis of the design - a challenging plan for a high-risk seismic zone with essentially three buildings separated by little but glass. A non-linear pushover analysis was able to ensure a safe design with lower seismic loads than a traditional analysis would have required.

Mechanical design

The engineers' earliest concepts for the library included an underfloor air system. 'Our top priority was flexibility', stated Library Director Tessman. Taking the environmental strategy one step into the future, air in the plenum is cooled adiabatically by misting the air with cool water. Salt Lake City's climate is well suited to this concept - being very dry the air has great capacity to absorb the misted water. Once it has been cooled, the air is ducted to a low-pressure floor plenum and enters the room through round diffusers in the floor. Within the room, the cool air is drawn to heat loads where it gently rises due to buoyancy. This is believed to be one of the first times in the USA that an underfloor air system has been combined with adiabatic cooling. The low-maintenance, low-energy cooling system pairs with the thermal mass of the exposed concrete structures to deliver a simple, straightforward, and inexpensive design.

Safdie created the five-storey Lens to focus on Salt Lake City's view of the Wasatch Mountains to the southwest. In doing so he subjected this completely glazed structure to the greatest sun exposure, so Arup put the atrium to work as a chimney. As the sun heats air within the glass-enclosed space, the heat rises and escapes through openings at the roof. Solar gain is expelled before it enters the rest of the library - a particularly important approach needed to match the cooling capacity of the underfloor air system.

6. The sun-drenched Urban Room features shops and a café.

7. Above the Children's Library a fabric shade shields the sun in warm weather and deflects cold downdraughts in cold weather.

8. The plaza amphitheatre seating forms a city gathering place.

By placing the Children's Library at the base of the Lens, the architects created a magical space that is flooded with sunshine. If the sun's heat becomes too intense, the Children's Librarian can shield the space with 'cloud cover' by pressing a button to roll out a fabric shade designed by the architects and Arup. In winter the shade is used to deflect the cold downdraught from the glazed façade.

The void between the triangular building and the crescent wall is an atrium known as the Urban Room. The Library's website describes it as 'a space for all seasons, generously endowed with daylight and open to magnificent views'. The Urban Room is comfort-cooled by free spill air from the triangular stack building. In winter the occupied zone is warmed by a radiant heated floor.

The roof garden, atop the triangular building and accessed by the inclining walkable wall, is another feature of the Library's environmental strategy. The garden helps reduce rainwater run-off and, with its heavy mass, minimizes the building's impact on the so-called 'heat island effect' - the dome of warm air that gathers over an urban area due to structural and pavement heat fluxes. This heavy roof helps by absorbing and storing the sun's heat rather than immediately adding it to the Salt Lake environment.

9. The Library is essentially three buildings; from left to right here are the sloping crescent-shaped gallery, triangular stack building and rectangular administrative building.

Fire engineering

Since the Library is remarkably open, fire engineering decisions needed to be made early in the design process. A key feature of the building is that the central triangular stack building does not contain any escape stairs and is surrounded by atria on each side. All egress routes from this part of the building are therefore via open bridges that span the atria and lead the occupants to conventional protected escape stairs.

10. Smoke extract strategies for the atria saved costs significantly.

To demonstrate that the means of escape would be adequate for the building, a performance-based approach to the fire safety strategy was adopted. An equivalency approach, using code compliance to gain approval, would have required most of the floor plates to be closed and glazed, reducing the openness of the building.

Arup Fire built a dynamic evacuation model of it to determine likely evacuation times. Smoke control systems were then analyzed and designed, based on defined fire loads and the specific building geometry, to ensure that occupants would be able to evacuate in tenable conditions. For the stack building, smoke extract was provided by the introduction of exhaust slots at the edge of each floor plate to extract smoke before it could spill into the atrium. To address the scenario of fire occurring at the base of an atrium, smoke extract was also provided at the top of each atrium, although the slot extract system greatly reduced the size of these systems as it prevented smoke spilling from the stack building into the main atrium. This scenario would generate far higher volumes of smoke than the atrium base scenario, due to the geometry of the wide spill plume.

Another example of the performance-based approach involved Arup's study of fire scenarios involving the exposed steel Y-braces used in the inclining 600ft (183m) long structure. The team calculated the likely fire that these elements could be exposed to, and assessed the resulting thermal performance of the structural elements. These analyses showed that the location of the elements relative to the likely fire meant that the degree of fire resistance inherent in the steel elements was sufficient to maintain their integrity in a fire, without the need for additional fire-resistant coatings.

These analyses were presented to Salt Lake City Building Department and Fire Department by formal presentations using graphics and explanatory material, and they were discussed in detail. The performance-based fire strategy was accepted, with clear benefits for the design and cost efficiency of the building.

Electrical design

The Main Library serves as a focal point for the community and a central data point for Salt Lake City's branch libraries. To ensure a reliable power source, Arup provided two primary 7.2kV feeds into a double-ended switchgear arrangement from the local utility company. In addition to the two services, the library can also rely on an emergency generator in the central plant room.

The Library's configuration, with its three independent structures linked by a series of bridges and a common roof, coupled with the architect's desire to not have services crossing between the structures, led to the electrical power distribution design. Each building has its own normal and emergency power supplies with common coupling in the basement of the triangular building.

Secondary power distribution to the buildings is provided via a series of 480V risers in each building. Transformers on each floor transform the voltage to 120V for the receptacle circuits. All other power supplies are at the higher 480/277V, reducing the need for large secondary lower voltage power feeds.

The lighting designer selected primarily high output T5 fluorescent indirect light fixtures for the open stack areas. These, combined with the architectural vaulted ceilings, give a very diffuse lighting distribution within the Library. A central control system, interfaced through a PC, manages a series of interconnected relay panels to provide a flexible, centralized, energy-efficient lighting control scheme.

Flexibility is ensured by raised floors in the triangular stack building and the bar building. Power and data outlets can be, and are regularly, moved with ease. As well as aiding library staff, the raised floor and flexible outlet arrangement have greatly enhanced the public's experience; there are public power and data outlets throughout the library - and not only in study carrels but also nestled on the floor beside armchairs.

Communications and audiovisual systems

Public power and data outlets are just one feature of the library's approach to technology. In the project's earliest days, designers from the Arup technology group joined a round table of industry experts for a workshop in Salt Lake City. Library experts, vendors, university specialists, and designers were asked to propose technology that would expand the library patrons' horizons.

Based on the client's requirements and the guidelines set by the workshop, Arup designed an extensive infrastructure to support not only Day One but also future wired and wireless technologies. Building upon this infrastructure, the library has implemented a wireless local area network (LAN) for patron use.

In addition to designing the technology infrastructure, Arup consulted during the Request for Proposal process and helped the library select a vendor for a high-end LAN/WAN for the Main Library and its branches.

A favourite technological feature is the library's self-checkout system where patrons may borrow books without staff assistance. A radio frequency identification (RFID) scanner can read RFID chips in a pile of as many as 10 books. This RFID system interfaces with library security.

Since Arup was also responsible for designing the library's audiovisual systems, IT and audiovisual share a common cabling system and backbone, and consequently benefit from economies of scale. Audiovisual features include a multi-use auditorium equipped with multimedia presentation capabilities for video, slide, and computer display, as well as cameras for recording and long-distance learning. A divisible multipurpose room includes sound reinforcement, projection capabilities and tie lines from the auditorium for overflow. Two computer rooms, intended for staff and public training, are equipped with video projection / computer display capabilities. Another staff training room features video conferencing and a SMART Board™ that brings interactive computer functions to a projection surface. The Library's boardroom has rear projection video / computer display and audio and video conferencing. In addition, Arup designed a building-wide satellite TV distribution system with drops in multiple locations.

Credits

Owner: City of Salt Lake Library System **Design architect:** Moshe Safdie and Associates Inc **Architect of Record:** VCBO Architecture **SMEP, fire, communications, audiovisual, acoustics, security engineers:** Arup - Julian Astbury, Peter Berry, Daniel Bonardi, Roberto Calalang, Caroline Fitzgerald, Anthony Goulding, David Jones, Al Palumbo, Andy Passingham, Nicos Peonides, David Richards, Jose Rivera, Ron Ronacker, Jeff Tubbs, Neill Woodger, Atila Zekioglu **Associate structural engineers:** Reaveley Engineers & Associates **Associate electrical, communications and security engineers:** BNA Consulting Engineers **Associate mechanical engineers:** Colvin Engineering Associates **Associate audiovisual and acoustics engineers:** Spectrum Acoustical Engineers **Lighting consultant:** LAM Partners **Landscape consultant:** Civitas Inc. **Project manager:** Construction Control Corporation **General contractor:** Big-D Construction **Illustrations:** 1, 3, 6, 8, 9: Timothy Hursley; 2: Peter Vanderwarker; 4, 7: David Richards; 5: Moshe Safdie and Associates Inc; 10: Arup/Nigel Whale; 11: Dan Bonardi

Awards

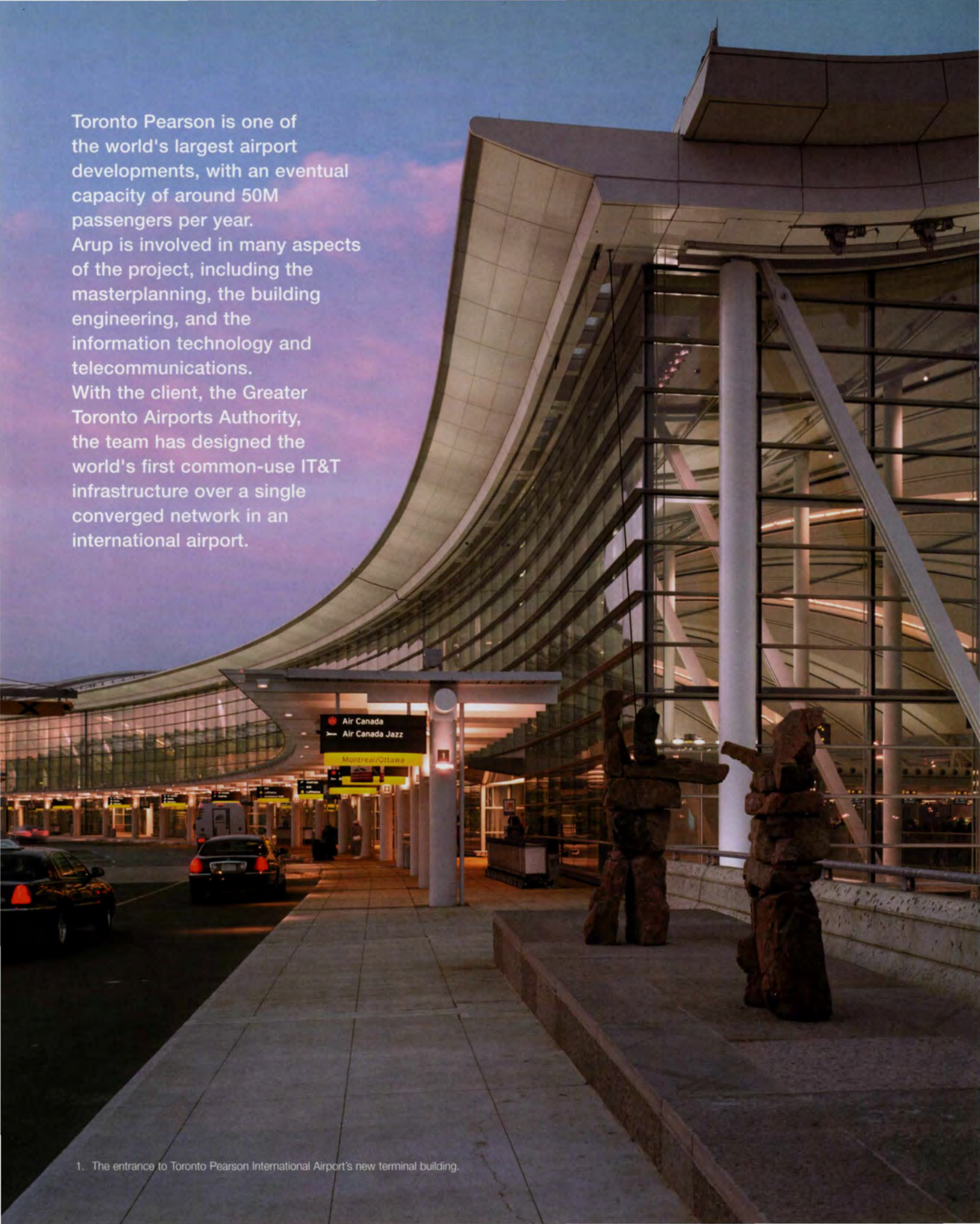
- 2003 PCI Design Awards: Best Public/Institutional Building
- American Institute of Architects Honor Award for Outstanding Architecture 2004

Conclusion

In 1998, the voters of Salt Lake City passed a bond for design and construction of a new downtown library to house more than 500 000 books. What the voters received was a home for their books and a new living room for their community. In an age of home Internet connections, all-pervasive television use, and declining urban communities, Salt Lake City's $65M Main Library ($50M for the library and $15M for the underground car park) is so popular that its crossroads have become the busiest intersection in the City.

11. Travelling within the Library is a pleasure.

Toronto Pearson is one of the world's largest airport developments, with an eventual capacity of around 50M passengers per year. Arup is involved in many aspects of the project, including the masterplanning, the building engineering, and the information technology and telecommunications. With the client, the Greater Toronto Airports Authority, the team has designed the world's first common-use IT&T infrastructure over a single converged network in an international airport.



1. The entrance to Toronto Pearson International Airport's new terminal building.

Toronto Pearson International Airport

Planning growth and change

Andrew McAlpine

History

When the airport planner NAPA (now ArupNAPA) began work on a new terminal masterplan for Toronto's Lester B Pearson International Airport in 1995, it encountered a facility that bore the marks of over 35 years' continuous but often short-term adaptation to rapid change and growth. In the late 1950s, when the first terminal at Pearson was conceived, the era of accessible air travel was in its infancy. The daring and inventive design by John B. Parkin Associates - a predecessor firm to NAPA – comprised a circular terminal wrapped around a parking structure and approached by a tunnel below the apron. Opened in 1964, it was planned as one of four similar terminals, but was the first and last to be completed. Only three years later the first Boeing 747 came into service and this new scale of aircraft, much larger passenger loads, new technologies, stiffer security requirements, and continuing rapid growth in air travel, made Terminal 1 increasingly obsolete.

In anticipation of a new airport to serve Toronto, Terminal 2 was completed in 1973 as a linear, bare-bones, temporary building for eventual conversion to cargo operations, but instead was expanded and upgraded in several phases to become Air Canada's primary hub when the new airport dream died in the face of public opposition. Terminal 3 arrived in 1991 as one of the first privately financed, built, and operated airport terminals in the world. With its crescent form and two piers and one satellite, it represented a third planning concept at Pearson.

This history, with its equally piecemeal cargo and support area development and complex road system, yielded an uncohesive and inefficient airport seriously at odds with long-term growth. When a contract also to privatize Terminals 1 and 2 was cancelled following a change in government in 1993, a new Canadian policy of not-for-profit airport authorities was introduced, finally paving the way for a cohesive long-term development strategy.

Early planning strategy

As the Greater Toronto Airport Authority (GTAA) was being created, ArupNAPA was selected to develop a new terminal masterplan, working initially for the Federal Government. Planning inside the old constraints, with a strong desire to preserve as much of the existing infrastructure as possible, good long-term solutions were hard to come by. Then in the fall of 1995, industry veteran Louis Turpen arrived from a similar position at San Francisco Airport to run the GTAA. Turpen brought a clear vision and the skill and determination to see that vision through. He saw the need to sweep much of the past away, and thus ArupNAPA's task was set: develop a 'blue sky' concept for a single integrated terminal facility, on a scale that could ultimately accommodate 50M passengers annually, matching the capacity of what would eventually be a six-runway airfield. The team was not initially to concern itself with cost or implementation.

Planning at this early stage focused on finding a footprint that would optimize the perimeter available for gating aircraft, provide an adequate terminal depth, and accommodate the road system, curbs, and parking - all in a balanced relationship. By stepping back to view the site as more of a 'green field', and by ignoring the constraints that had hampered previous plans, a simple, clear concept emerged very quickly. A crescent terminal form wrapped around a tightly planned groundside, with multiple piers extending to the airside, was proposed and quickly accepted. The idea was simple, but moving it forward to create a firm plan that could be implemented became the challenge that occupied the ArupNAPA team over the following months and years. The result of their work was the masterplan for the Can$3.5bn terminal development project (TDP) and a significant contribution to the Can$4.4bn total airport development plan (ADP).

Underpinning every airport plan is much numerical analysis, that translates high-level air transport demand forecasts into specific requirements for aircraft gates, passenger processing facilities, curb lengths, and parking spaces over time. Critical to most of this analysis are planning day schedules, which represent close to peak day levels of flight activity that the airport is forecast to experience for specific planning horizons. ArupNAPA prepared numerous versions of these, and the initial planning relied heavily on this analysis to begin translating the initial concept into a concrete master plan. Physical planning progressed on several fronts. Conceptual building plans and sections and gate layouts were developed, access roads were planned, costs were estimated and, most critically, an operational and construction phasing plan was developed.

The phasing approach

In principle, the phasing approach adopted appeared superficially easy. The new terminal building 'processor' could be constructed behind the existing terminals on the non-secure groundside, and the piers would be added singly as existing cargo and terminal facilities were sequentially replaced and demolished to make way. But imposing a green field concept on the heart of an operational airport was, and remains, the single greatest challenge for the planning team. Roads, utilities, terminals, and operational airside areas have had to be sequentially transformed even as the airport remains operational, grows, and changes. ArupNAPA to date has developed close to 100 iterations of the phasing plan.

Several elements were critical to the phasing, including continued operation of Terminal 1 through the beginning of construction. With its access road running through the heart of the processor construction site, there was a strong initial impetus to close and demolish Terminal 1 early on. Although numerous options for its temporary replacement were considered, ArupNAPA eventually determined that the access road could be accommodated within the construction zone by linking the third below-apron level curb of the new terminal to the existing tunnel access to Terminal 1, a strategy that saved many millions of dollars and at least two years in time. In the next step, existing cargo and support areas between Terminals 1 and 3 were replaced with new facilities in the 'infield' zone between the runways. When the old facilities were demolished, the first pier could be constructed. This first phase of construction was successfully and uneventfully opened in April 2004.

Terminal 3 became an essential component in the airport's capacity. Early in GTAA's life, it was purchased from its private operators, and this enabled planning and implementation in a far more integrated fashion. ArupNAPA prepared a masterplan for expanding and developing Terminal 3 to provide additional gates, processing capacity, and much more flexibility. But these changes would not be sufficient to provide necessary capacity for critical periods in the overall phasing plan, and plans were therefore developed for an 11-gate infield terminal, essentially a passenger holding area connected to all of the terminals by buses. Although the concept was initially accepted with some reluctance, the operation of this facility has gone very smoothly and the additional flexibility and capacity it has provided are essential to the masterplan's implementation. It is currently handling Star Alliance international operations, with passengers being bused to and from the new terminal.

The need to accommodate three sectors is a unique and complicating characteristic of terminals at Canada's major cities. In addition to domestic and international traffic, they support pre-cleared 'transborder' traffic to the USA market. Both Canadian and USA immigration and customs facilities need to be accommodated, and a much more complex system of segregating passenger flows within the terminal is required. This potentially inhibits flexibility, but an approach was developed that should enhance long-term flexibility of the terminal. The initial concept proposed that, by about 2010, there will be three primary piers, each supporting a single sector. Under challenge from Air Canada, who wanted to see improved connectivity between sectors to support its hub operations, the plan was adapted to weave transborder gates between piers supporting domestic and international traffic. This yielded numerous gates that could be flexibly allocated between sectors both hourly and over longer periods of time. This significantly reduced overall demand for gates as

1995 site plan

At the commencement of the project three terminals are in place, a cargo and support facilities complex (Area 4), and a tangle of access roads and utilities. Numerous pinch points on the airside limit aircraft gating and movement.

Stage 1A

In 1998 there is the ground breaking for the five-level processor, the most complex portion of the project, with the longest lead time. It is built to the groundside of the three existing terminals, allowing them to continue operations largely unchanged. A road tunnel links under the construction site to the circular Terminal 1. On the groundside an elaborate phasing of a new road system and site utilities infrastructure is undertaken (not shown). Construction of the eight-level parking structure also commences, as does work to replace support facilities elsewhere, enabling the next phase of construction to proceed. A new 11-gate holdroom terminal served by buses is also constructed in the infield between the runways, and a new tunnel linking the terminals to the infield is built below the runway and taxiways. Numerous design and construction contracts need to be fully co-ordinated.

Midway through this stage, Air Canada absorbs Canadian Airlines, necessitating a shuffling of airlines and operations between terminals to partially consolidate the much bigger airline.

Stage 1B

Cargo and other support facilities are demolished to make way for Piers D and E. Terminal 3 is expanded by adding gates to Pier C. Terminal 2 is largely unchanged. Available gates on Terminal 1 are reduced to allow construction of Pier E. Extensive portions of new apron are constructed. Work also commences on a new airport people-mover (APM) to link the new terminal to Terminal 3 and support areas and remote parking to the north.

Stage 2A

At the end of Stage 1 in April 2004, the new terminal (now Terminal 1) becomes partially operational with access to gates on Pier D and half the gates on Pier E. Air Canada's domestic traffic is moved from Terminal 2 and international traffic is moved from the Terminal 1, with gates being used at the infield holdroom terminal. The transition goes without a hitch. Work begins immediately to dismantle the old Terminal 1, and demolish a small portion of Terminal 2, all to make way for the construction of Pier F and apron areas between Piers E and F.

- ▨ Existing building
- ⬚ Demolished building
- 🟧 Building construction
- 🟨 Apron/taxiway construction
- ▨ New building (non operational)
- 🟪 New building (operational)
- — Domestic
- — Transborder
- — International

1995 site plan

Stage 1A

Stage 1B

Stage 2A

Stage 2B

By late in 2004, sufficient apron will be completed between Piers E and F to activate additional gates on new Terminal 1, including three large B747 gates to serve prime European routes. A further portion of Terminal 2 can now be demolished as these new gates become available. Work continues on Pier F with additional apron constructed in the summer seasons.

Stage 2 complete

At the end of Stage 2, Pier F will come on stream, with the new 'hammerhead' becoming the permanent home for Star Alliance and other international services. In addition, gates on both sides of the new pier will be occupied by transborder (US-bound) operations. Transborder regional jet and turboprop operations remain consolidated at the east side of the terminal area served from holdrooms accessed by buses from Terminal 1. The APM will also be operational, with the possibility of a new heavy rail link to downtown Toronto also in place.

This represents a potential pause point in development and options for the timing and scope of future stages are under review.

Stage 3

When demand warrants, Terminal 2 will be demolished, including its parking structure and access roads. Pier G will be constructed, likely as a multi-sector facility, geared to handle overflow from Terminal 3, which is expected to reach capacity between 2005 and 2010.

Stage 4

Again, as demand warrants Pier H will be constructed, likely in the 2012-2018 timeframe. This portion of the terminal will need to handle multiple sectors, and will ultimately provide a home for transborder regional jet and turboprop operations, allowing demolition of the remote holdrooms on the east apron. The processor will require expansion, primarily to accommodate additional Canadian and US inspection facilities. At this point, the new terminal will provide over 400 000m^2 of space, with an expected annual capacity of 30-35M passengers. With Terminal 3 fully utilized, the combined anual capacity would be in the realm of 50M passengers.

Beyond Stage 4

It is theoretically possible to extend the new terminal to the west to sequentially replace Terminal 3. This would only make sense if the runway capacity, through technological and procedural improvements, could provide capacity in excess of the current estimate of 50M passengers annually. More likely, and already in planning stage, is the new airport at Pickering, gradually providing the additional capacity needed to relieve demand at Toronto Pearson.

Stage 2B

Stage 3

Stage 4

Stage 4 complete

2. Phasing: 1995-2018.

well as providing a high level of robustness to shifting rates of growth between sectors.

ArupNAPA's role has been varied and extensive over the nine years leading to the opening of the first phase of the new terminal earlier this year. In addition to conceiving the plan and developing the implementation strategy, the team has contributed on a range of related issues. It assisted the GTAA with the selection process that eventually led the appointment of the architectural team composed of SOM, Adamson Associates and Moshe Safdie, with Arup as engineer, and worked closely with that team to evolve the plan. ArupNAPA also contributed as 'honest broker' to negotiations between the GTAA and Air Canada, who initially opposed the project.

Airports are never completed; rather they are continually being adjusted to new and unpredicted realities. Thus flexibility is at a premium. To date, the plan for developing Toronto Pearson has demonstrated the value of that flexibility, while providing a continuous stream of work for ArupNAPA. When Air Canada absorbed Canadian Airlines in 2000, ArupNAPA revaluated the plan, even as construction was under way, helping the GTAA formulate a strategy of terminal alterations and airline relocations to allow the now much larger airline to consolidate operations. ArupNAPA has regularly revaluated and adjusted the plan in the face of the many changes in demand and the airline industry in the wake of 9/11, the SARS virus outbreak, and Air Canada's financial difficulties. Changes to airline fleets, with a new emphasis on regional jets and the advent of the giant A380 Airbus which begins commercial flights in 2006, have placed more demands on the airport. In Canada as elsewhere, there has been a rise in low-cost carriers, who have shifted market share and placed a new emphasis on efficiency. ArupNAPA is now reviewing the timing of construction of the third major pier and the demolition of Terminal 2, to match current forecasts and financial constraints.

As the future of Toronto Pearson seems assured, thoughts have again turned to planning a second airport to serve the city. Working with the GTAA to create a plan to develop land at Pickering, east of Toronto, ArupNAPA helped lead a study to assess the financial feasibility of the project. More recently, the team prepared a comprehensive assessment of the general aviation markets and airports serving Toronto and considered the potential to develop this new airport initially as a GA facility. The team is currently working with the GTAA and other consultants to develop a long-term land use plan for the site. While one airport project becomes a reality a new one is born.

Information technology

Tara Durnin Al Lyons

Introduction

Many airports are expanded with the same goals as Toronto Pearson - to support growing air travel needs and to promote economic growth locally - but few with comparable foresight. With the appointment of Louis Turpen as leader of the GTAA, and ArupNAPA's commission to prepare the masterplan, a truly pioneering airport project took flight. To design the terminal complex, the GTAA selected Airport Architects Canada, a consortium of SOM, Adamson Associates, and Moshe Safdie & Associates, with Arup providing integrated engineering services through the project's design development. Arup's role soon grew to include information technology and telecommunications (IT&T) consulting and engineering, as well as building and systems commissioning management.

The plan has five major parts: a new terminal, gate expansion, infield cargo development, airside development, and new and upgraded utilities and airport support facilities. The 4.5Mft^2 (390 000m^2) terminal 'T1-New' is the centrepiece, with an eventual capacity of 50M passengers pa and planned ultimately to replace all three existing terminals. Construction stage 1 was completed in April 2004, with the curving terminal building and two (ultimately five) pier buildings radiating out into the airfield. Inside this 'central processor' are four main levels: arrivals, departures, an interstitial level connecting to the garage and people mover, and the ground level. The piers are concourses lined with gate holdrooms and retail space.

An IT&T revolution

From aviation's early days, airlines carried out basic passenger processing, with airports as operational landlords providing the building and services. Typically, airlines used their own systems and cabling in their own spaces in airports, causing much duplication and high operational costs. While airports deployed common-use terminal equipment (CUTE) and multi-user system equipment (MUSE) in the 1980s and 1990s, these systems were and are based on interfacing with legacy airline systems, and did not capitalize on all the efficiencies of sharing systems.

3. Ticketing machines adjacent to check-in desks.

Glossary

AOCC	Airport Operations Command Center
ATIMS	airport traffic information management system
BHS	baggage handling system
BMS	building management system
CAN	campus area network
CCTV	closed-circuit television
CUPPS	common-use passenger processing systems
CUSS	common-use self-serve
CUTE	common-use terminal equipment
DPT	dynamic packet transfer
FIDS	flight information display system
HVTMS	horizontal vertical transportation management system
IPT	internet protocol telephony
IT&T	information technology and telecommunications
LCD	liquid crystal displays
MPLS	multi-protocol label switching
MUSE	multi-user system equipment
PDA	personal digital assistant
PMCS	power management control system
RPR	resilient packet ring
RSMS	ramp services management system
VPN	virtual private networking
WLAN	wireless local area network
XML	extensible mark-up language

There is now an operational shift, with airports providing more than just basic building services and MUSE or CUTE. A full menu of shared/common-use systems and services is now possible. However, while sharing systems and technologies can reduce costs and improve performance, it requires that airports assert more control over their facilities, resulting in more efficient operations. By sharing systems at the check-in desks and gates, multiple airlines can share the same spaces, resulting in cost savings as well as maximizing airport capacity.

The enabler for this operational shift has been the emergence of IP (internet protocol) as the *de facto* transmission protocol. This in turn enabled convergence of voice and data systems, moving from analogue to digital. Maturing technology has opened up a new IT business model, not only for airports but many other sectors.

Implementation at Toronto Pearson

Toronto Airport is the first example of its successful deployment. Under Turpen's leadership, the GTAA became a service provider, not a landlord; the airport is a common-use facility with space shared among carriers and tenants, and resources like gates, check-in desks, baggage belts, and cabling infrastructure provided by the GTAA for a usage fee.

As the T1-New design commenced in 1997, the GTAA had yet to establish a powerful IT&T organization. Arup's scope expanded to include developing a basis of design for the IT&T systems and infrastructure. The natural extension of the common-use/service provider arrangement was for comprehensive voice, video, and data communications services over one converged network to be offered to airlines and tenants. Recent improvements in high-speed equipment made a shared network and systems technically feasible and financially realistic. But it had never been done before.

Turpen needed an extraordinary leader for this enterprise and found one in James Burke, who had over 20 years' experience in privatizing and managing IT&T services, infrastructure, and systems for the British Airports Authority. Burke and Arup saw that the GTAA, to achieve a common-use arrangement, had to own, control, and manage all the IT&T infrastructure and systems. To do so, the GTAA had to develop and implement a multi-service network, the first of its kind. The benefits would be enormous. It would:

- give significant return on investment and value, through increased revenue generation and vast reductions in operating and administration costs
- reduce the total cost of ownership due to lower capital and operating costs
- give availability, reliability, and capacity of a wide menu of IT&T services to airport constituents
- facilitate the integration of applications, and put in place the interfaces between diverse systems
- increase productivity and efficiency
- add flexibility in relocating and retrofitting airline and tenant spaces
- reduce space, infrastructure and energy needs due to sharing of IT&T spaces and systems
- increase the marketability and attraction of Toronto Pearson due to GTAA's ability to offer all airport constituents a comprehensive range of IT&T services quickly and cost-effectively.

Convinced of its benefits, the GTAA and Arup set out to show the airlines the advantages of this revolutionary approach. Though initially opposed, they were persuaded when it became clear that the common-use proposal would both increase an airline's resilience and lower installation and ownership costs. With falling revenues and rising costs, this solution would enable the airlines to better focus on core business. The GTAA and Arup worked with each of the airport's major constituents to gain acceptance and consensus on how to move forward with the ground-breaking plan.

IT&T systems procurement strategy

The goal was to maintain control and deploy the most current proven technologies possible. The challenge on long-term construction projects is to ensure these operate on opening day and that systems are designed to evolve with technology. During the earliest days on Toronto Pearson, Arup prepared a schedule, based on lead times, complexity, and interdependencies, that identified the 'last responsible moment' to finalize design, procure, test, and commission each IT&T system. The GTAA and Arup categorized the systems as:

(1) those closely integrated with the architecture/construction of T1-New

These, including the IT&T infrastructure (rooms, cable routes, and risers) and building technology systems, were procured via the construction process.

*(2) those closely integrated with existing airport IT&T systems and operation*s

These were procured by the GTAA and include the airport traffic information management system (ATIMS), campus area network (CAN) and CUPPS.

(3) those closely integrated with both (1) and (2)

These include the FIDS (flight information display system) and security system.

To maximize control over what was delivered and to control costs, the FIDS procurement was split into software, hardware, and installation. As software was the longest lead item, it was purchased first via a contract with the GTAA. At the last responsible moment the GTAA procured the hardware. Reductions in LCD costs (~25% annually during 2001 and 2002) enabled procurement of these instead of plasma screens, as LCDs offer a lifespan of 10+ years compared with around three years for plasma screens. Installation was assigned to the construction team.

4. Automated airport directory information.

All this enabled the GTAA to stay in control of system selection, implementation, testing, commissioning, acceptance, and turnover. Additionally, it avoided contractor mark-ups on systems and equipment where they add little or no value.

IT&T services delivery

Near the end of 2002, the GTAA asked Arup to help build an organization to ensure the best possible support to the growing demand for IT&T services at Toronto Pearson. Toronto's dominant telecommunications company was offering a non-integrated approach to the GTAA, handling public access, data services, data support, voice services, voice support, carrier services, and business services through different divisions. However, seeking a better fit for the airport's visionary new arrangement, the GTAA and Arup solicited proposals from local and global telecommunications service providers. The scope of the organization envisioned by the GTAA and Arup included assuming responsibility for:

- technical design for new applications and services supported by the CAN, including compliance with regulatory requirements, testing and validation of new services and applications, development and execution of carrier access agreements, and spearheading network and infrastructure growth planning

Systems design

5.Flight departure screens.

Infrastructure

During planning and design, all concerned grew more familiar with the advantages of shared common-use systems, including the fact that combining dedicated security and tenant technology rooms/closets with GTAA IT&T spaces would much reduce space and infrastructure requirements as well as operating and energy costs. The GTAA and Arup developed procedures and protocols for sharing, agreed by all major parties.

Campus area network (CAN)

By offering the finest possible services, the GTAA could entice the parties to agree to common use, and to outsource both telecommunications carrier services and internal IT&T services to the GTAA. But to achieve this the GTAA had to implement a secure, flexible, and scalable carrier-class network. As the advantages of common use became widely appreciated, these services were requested across the airport, and Arup's original assignment to design the new terminal's network was expanded to include the three existing terminals, cargo facilities, and office buildings. Arup assisted the GTAA in soliciting proposals for the CAN and with the rigorous evaluation process that followed.

The team chose a Cisco-based carrier-class network utilizing dense wave division multiplexing technology at its core. The system features MPLS, VPN, and DPT/RPR technologies for maximum scalability and reliability. Toronto Pearson's CAN interconnects and provides high bandwidth to all facilities, with greater availability than the systems typically used to support the communications requirements of security, airlines, and other mission-critical users.

Telephone system/services

Shared telephone services are critical to the success of common-use facilities. Since these don't permit individual dedicated systems, any airline can use any check-in desk and gate. Also there are no telephone usage charges for calls between common-use facilities (check-in desks, gates, etc) and dedicated airline facilities (back offices, lounges, etc) subscribing to the common-use services.

Based on a detailed return on investment study by Arup and the GTAA, the team selected and designed an integrated voice system that includes traditional telephony services via a shared Nortel switch and IPT services via Cisco call manager. IPT allows data, voice, and video to be transmitted over a single network infrastructure. By transporting voice as high-priority data on high-speed networks, IPT delivers new capabilities and significant cost savings over traditional telephone technology. The study recommended that initially IPT would only be rolled out to the airport/terminal operations' common-use areas - check-in desks, gates, boarding bridges, security areas, courtesy phone kiosks, and GTAA back office – and these were duly equipped by the GTAA with IP handsets.

Since IPT locations are virtual, its applications and management systems can be anywhere on the CAN, the resources immediately available to all users. Major reductions in operating costs are realized since physical moves, additions, and changes are much less needed. IPT was thus deployed primarily because of the cost savings in the backbone and horizontal cabling at little additional cost to the data network. However, the team also recognized that IPT would enable further productivity-enhancing services.

Toronto Pearson is the world's first airport to integrate IPT with common-use passenger processing system and has already achieved operational efficiencies associated with the niche airport IPT applications that Arup, Cisco, SITA (the supplier of the CUPPS system), and the GTAA devised. These include gate/check-in desk single sign-on, air traffic control, enhanced IP contact centre, emergency responder, flight mapping, courtesy phones, kiosk integration, wireless IPT, restricted area pass look-up, and airport security enhancements.

Common-use passenger processing system (CUPPS)

CUTE and CUSS (common-use self-serve) kiosk platforms offer airlines and airports the opportunity to reduce checking in cost and time, and improving passengers' experience. CUTE has been evolving since the mid-'80s into complex systems where airlines share equipment at check-in desks and gates to mutually access departure control and back-office operations. The more recently introduced self-serve kiosks operate on browser technology requiring no user training. These new CUSS standards are encouraging airlines to adopt browser-based departure control systems instead of deploying separate common-use terminal emulation and common-use kiosk systems.

An integrated CUPPS did not exist at the time of bidding, but the GTAA and Arup determined that it would be in the GTAA's best interests, and the airlines serving the airport, if one was implemented, comprising browser-based check-in desk and gate counter equipment and common-use check-in kiosks. The advantages include:

- simplified training of airline staff and better passenger support, since the kiosks operate similar to the check-in desk and gate counter equipment
- simplified service, maintenance, and stocking of spare parts, since all the systems are similar
- elimination of the need for separate communications links to airline and other systems for CUTE and common-use kiosks: CUPPS uses a single platform to support all passenger processing needs
- approximately 30% reduction in initial and running costs.

Security

Airport security can benefit significantly from the common-use concept. Since the system runs over the CAN it is supported by a redundant/resilient infrastructure. When advances such as facial recognition software are introduced, images can be transmitted airport-wide via the CAN and wirelessly to security personnel via wireless-enabled PDAs, enabling security breaches to be addressed without forcing the terminal to shut down operations.

In designing the system, the GTAA and Arup developed protocols and procedures acceptable to all for sharing one CCTV set-up. The system monitors and controls doors along the primary security line, and monitors access to security-sensitive areas.

Arup designed the system and evaluated and selected the technical solution, whilst a Toronto security firm co-ordinated design with the architect and door hardware consultant, and took responsibility for much of the construction administration. The system incorporates interfaced and integrated subsystems including the world's largest IP-based CCTV system (capable of viewing 1500+ cameras supported by high-resolution digital video recorders), and campus-wide access control/alarm monitoring and intercom systems that automatically call up cameras upon alarm.

The team determined that the most effective way to secure baggage penetrations would be to interface the baggage handling system (BHS) with the security system:

- Access control cards log users into the security system and start and stop the BHS.
- The BHS transmits all abnormal conditions (ie door held or forced open, belt stopped) at BHS penetrations in the primary security line to the security system. CCTV automatically records activity at the penetration(s) and displays it at security consoles in the AOCC.

Wireless systems

The GTAA wanted airport-wide wireless coverage. While many vendors offer to install systems 'free' and even share revenues, in fact they are only interested in installing where usage (and revenues) will be highest, rather than to provide high-quality coverage throughout. To ensure 100% coverage for private mobile phones, cellular radio, and WLAN, the GTAA and Arup agreed that the former must own and control all the infrastructure needed to support a distributed antenna system, a common-use private mobile trunked radio system, and a common-use WLAN.

Airport IT systems

The core of the airport IT systems - critical in optimizing the efficiency of common-use facilities - is the ATIMS. Its functions include collection and database storage of airport operations information, and interfacing with:

- airline departure control systems and Nav Canada (the private, non-share capital corporation that owns and operates Canada's civil air navigation service) to maintain and update flight schedules and actual departure and arrival times
- resource allocation tools (for gates, check-in desks, baggage belts, buses, etc) to optimize assignment of limited airport resources
- the flight information display system to update flight schedules, and change airline logos and other information displayed at check-in desks and gates
- the BMS (building management system) to automatically adjust the occupied/unoccupied status of mechanical and electrical systems
- security systems.

Building technology systems

The BMS is the heart of the building technology systems and the focal point for all their interfaces. It monitors and controls environmental conditions terminal-wide and the mechanical and electrical systems that maintain these conditions. It interfaces with:

- the ATIMS, to update the occupied/unoccupied schedule in response to the airport's dynamic needs (ie flight delays)
- the lighting management system to turn lights on and off based on occupied/unoccupied schedule
- the fire alarm system for smoke control and to provide secondary alarm alerts at BMS operator consoles
- the ramp services management system, to monitor utility usage (preconditioned air, fixed ground power, potable water, etc) and announce alarm conditions
- the power management control system to monitor all the airport switchgear status.
- the horizontal vertical transportation management system to monitor and control all elevators, escalators, and moving walkways
- the remainder of the airport-wide BMS and central utility plant monitoring and control system to support airport-wide monitoring and control.

Toronto Pearson's ATIMS automatically updates air-conditioning and lighting needs throughout T1-New. Systems on the same network interoperate and raise the level of efficiency significantly.

- marketing, sales, and customer/user support to provide a single source for all IT&T services and products. Duties include packaging existing and developing new services, preparing marketing and sales materials, compiling consolidated invoices for IT&T services, managing accounts receivable, and development and maintenance of key performance indicators to proactively measure/monitor the levels of service from all involved with delivering IT&T services and products. Tickets are issued to manage moves, additions and changes, and to remedy any troubles reported by customers/users or the Network Operations Center.
- developing and managing the Network Operations Center to proactively monitor voice, data, and CCTV communications, assure that desired quality of service and service level agreements are achieved, and provide field engineers and technicians for repairs and implementation of moves, additions, and changes
- infrastructure and common cabling system management to assure that facilities are available to satisfy all requirements. An asset and cable management system was implemented to maintain an inventory of cable plant and IT&T equipment.

Local exchange carriers, systems integrators and other service providers submitted proposals. After exhaustive review and analysis, the GTAA and Arup selected a consortium of several providers.

Realizing the vision: construction and commissioning

During 2002 Arup stepped in to aid the GTAA in the daunting task of co-ordinating and managing the interfaces between the building technology systems (BMS/fire alarm, BMS/lighting control, BMS/RSMS, etc) and between building technology and airport technology (ATIMS/BMS, ATIMS/BHS, etc). Arup worked with the GTAA to develop the 'book of interfaces' to facilitate co-ordination and vendor sign-off of:

- interface control documents and shop drawings
- preproduction (bench) and field testing procedures and protocols
- schedules for pre-production and field tests
- systems and interface commissioning.

The book of interfaces - an archive of all of the above documents and database/spreadsheets with hot links to facilitate locating information - was posted on the GTAA's extranet site to enable all involved parties to readily access current data.

The project team and the GTAA recognized the book of interfaces' value, and decided to apply a similar level of discipline to manage the testing, commissioning, and turnover of all building systems in T1-New. Again, Arup's role was expanded to include managing the commissioning of all these. The tools Arup had developed for the International Arrivals Terminal at JFK International Airport, New York, were enhanced as required for Toronto Pearson's much larger and more sophisticated terminal. These include:

- consolidated event matrices describing the knock-on effects of each action
- testing and acceptance forms and tracking tools
- integration testing and acceptance procedures
- commissioning reporting
- progress tracking tools
- fire alarm system event matrix.

As the project team and GTAA grew familiar with Arup's commissioning tools and reports, they also became indispensable for confirming handover schedules and identifying areas where overtime and shift work were required to achieve schedule.

Change management

Due to the size and sophistication of Toronto Pearson's building and airport technology systems, and T1-New itself, new and existing systems needed to be interfaced and turned over to the GTAA in stages. Arup was asked to review GTAA and contractor change management policies and procedures to recommend new approaches designed to mitigate the possibility of unanticipated impacts between new and existing systems.

6. Check-in desks.

Arup expanded the policies and procedures used by the GTAA's IT&T Department as a foundation for the new airport-wide change management policies and procedures; an approach that assured all parties are advised of and have an opportunity to review proposed changes before implementation.

To facilitate processing, communication, and archiving of change requests, a new change management website was posted on the GTAA extranet. It was well received by the GTAA and has been expanded to support management of both technology and non-technology changes, including work schedule changes to confirm compliance with union agreements and HR policies.

Awards

In recognition of the advanced IT&T model at Toronto, the airport has had two awards. The first, received before opening, was from the Air Travel Transportation Information Systems Organization as runner-up 'Best User of Information Technology Systems in an Airport'.

The second award, made after completion, recognized the impact the innovative IT&T solutions have had on the airport operations. Arup was noted as a key player in the design and the success. The award, an Iroquois sculpture, was sponsored by SITA.

As well as the airport awards, the CIO, Jim Burke, was named 'CIO of the Year'. His philosophy that 'common use is common sense' is, like a lot of other common-sense approaches, now proving revolutionary.

7. The vaulted steel roof soars over the Departures Hall.

Structural engineering highlights

Mike King

Introduction

A key aspiration of the design team for T1-New was to create an iconic building - a dramatic gateway to North America, Canada, and the city of Toronto. To achieve this, Arup engineers worked in close collaboration with the architects to develop structural systems that would be elegant, functional, and cost-effective through their structural efficiency - an important factor in a building that in its completed first stage already incorporates 32 000 tonnes of structural steel. To this end, several systems were developed according to the functionality, architecture, and required spans for each of the three main areas of the terminal - the central processor, the piers, and the 'hammerheads'.

Central processor roof

The most visible aspect of T1-New's structure is the vast central processor building, with its vaulted steel roof soaring 217ft (66m) column-free over the Departures Hall. A primary architectural requirement of the roof was to keep the structural depth to a minimum in order to maximize the amount of natural light entering the Departures Hall through skylights, as the GTAA and designers had desired from the project's earliest days. One of the architects, Moshe Safdie, explained the motivation: 'Toronto is cold and dingy all winter; you want light. So the theme there was light working with structure.'

To achieve this, a steel arch structural system was developed, comprising 43 two-hinged arches spanning between pin supports. The arches are fabricated steel I-section girders of constant 4.6ft (1.4m) depth throughout the span, oriented radially so that their spacing varies from approximately 26.2ft (8m) to 36ft (11m). The ceiling is recessed at every fourth arch to fully expose the structure to view and to allow the formation of radial skylights. Elsewhere, only the arch bottom flanges are exposed. All arches bear on 8in (200mm) diameter

8. Central processor building with Piers D and E mostly completed.

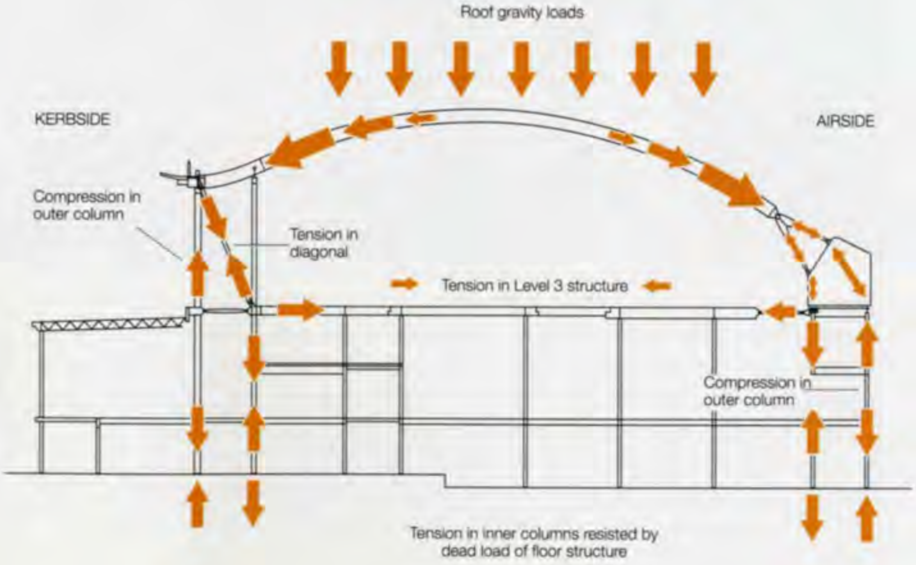
Grade 350 steel pins sleeved in graphite bushes to allow some rotation of the connections under load. The outward thrusts generated by the arches are transferred to the Level 3 structure, thus forming a closed loop of forces within the building (Fig 9). This not only avoids the need for intrusive ties across the roof space, but also means that no significant lateral thrusts are exerted on the foundations from gravity loads on the arches.

At the southern end of the span the arch thrusts are transmitted to the concrete buttresses through elegant, architecturally expressed steel wishbone-shaped assemblies. These are splayed relative to the arches, and also form part of the roof's lateral stability system. The individual components of the wishbone assemblies are bespoke fabricated I-section elements, fabricated from plates of varying depth.

At the north end of the arches the horizontal thrusts need to transfer down to the Level 3 floor structure, 42.6ft (13m) below. This is achieved through the use of twin 2.3ft (700mm) diameter, concrete-filled steel columns linked by a diagonal tension member fabricated from three parallel plates linked internally by a steel web. The inner columns support the vertical loads from each arch as well as vertical reactions due to the curvature change from a pure arch to an upward-sweeping curve towards the northern perimeter. The outer columns act as compression struts in conjunction with the diagonal ties so as to transfer the arch thrusts to the Level 3 structure. The radial primary floor beams have had their steel areas increased above that required to carry floor loads in order to complete the force loop back to the concrete buttresses at the southern end of the roof.

Construction programme constraints dictated that work on site begin before all the necessary building functional requirements could be determined and implemented for the floor structure design. As a result, it was decided to first design and construct the high arched roof with its supporting columns and caisson foundations, followed by the floor structure. This top-down approach was significantly complicated by the fact that the arch roof system required the Level 3 floor structure below to resists the outward thrusts generated by the arch action.

To overcome this, one central interior bay of columns and caisson foundations was also designed and issued for construction, so that one line of these interior columns could extend up to roof level, supporting the arches temporarily until the floor steel could be designed and installed under a follow-on contract.



9. Structural behaviour of the high roof.

Building superstructure

Below roof level, the building's superstructure consists of reinforced concrete floor slabs on metal deck, supported by structural steel beams, girders, and columns. At the lower levels of the central processor, columns are located on a maximum 32.8ft x 39.4ft (10m x 12m) grid, and consist primarily of 1.5ft (450mm) deep welded I-sections. Half these columns terminate at the first suspended slab level so as to minimize the number of columns passing up through the greeters hall and the baggage claim hall. This results in a 65.6ft x 39.4ft (20m x 12m) column spacing to support the Departures Hall at the uppermost level (Level 3).

As already noted, at the south end of the arch roof structure, concrete buttresses oriented radially transfer the arch thrusts down to the Level 3 floor system. These also provide lateral stability for the high roof area of the central processor building. Due to the asymmetry at building expansion joints, the buttresses are also subjected to out-of-plane loads from the wishbone frames. Although the buttress walls are solid above Level 3, large openings were required below to permit circulation of the baggage handling, mechanical, and electrical systems. As a result the buttress structures below Level 3 are a series of concrete moment frames.

Due to the top-down construction method, the buttresses had to be constructed around structural steel frames erected to initially support the arched roof. As a result the main reinforcing bars of the concrete columns, beams, and walls had to be detailed to avoid the existing structural steel beams, columns, braces, and connections. Additional concrete reinforcement was provided between the main bars for crack control and confinement purposes; and grout tubes were placed to permit subsequent grouting at locations of potential voids. Where interference between the concrete reinforcement and structural steel could not be avoided, holes were designed through the existing structural steel members to permit passage of the reinforcing bars, or alternatively the reinforcing bars were welded directly to the structural steel.

Lateral stability of all the central processor superstructure, including the roof, is provided radially and circumferentially by two different means. Circumferentially, architecturally expressed steel tubular diagonals brace the northern (or landside) perimeter. There is also steel bracing between the concrete shear walls at the southern (or airside) edge of the building, but it is concealed behind the internal dry-lined walls. Radially, all lateral stability is provided by the concrete shear walls/moment frames as outlined above.

10. Domestic pier.

Mechanical systems

Raymond Quinn

Distribution strategies

Several features of the ArupNAPA masterplan, and the architectural response to it, emerged as drivers for the mechanical systems' distribution strategy:

- The masterplanning (see pp30-33) showed a building that needed to be expandable in defined stages over perhaps 15-20 years, depending on traffic demands.
- The temporary highway through what would be the lowest level had to be kept open to traffic until after Stage 1 became operational.
- The sheer size of the building suggested that multiple service centres would be needed to limit mains sizes and run-lengths, and to meet the floor-to-floor height limits set by roadways and aircraft loading bridges.
- The architecture features a series of double-height spaces sliced into the building, giving a flood of daylight from skylights to the lower levels and providing physical security barriers. Services routes across these were either non-existent or very limited.
- Large, open-plan spaces such as the ticketing hall, baggage claim hall, gate lounges, greeters hall, etc, suggested that few, concentrated services risers locations be used.

These factors led to a strategy of 'regionalization': as far as possible, the team located services for a particular building 'region' within that region, minimizing the need to cross the Staging lines, the highway, the double-height spaces, and the structural expansion joints. Thus, a main hydronics room is located in each region of the central processor to serve it and associated piers. Air-handling equipment (AHU) rooms are located throughout the building's regions, including the central processor, nodes, piers and hammerheads at Levels S, 1, and roof.

For the central processor, the architects' vision of a large, open ticketing hall with an arched roof required AHUs to be located lower in the building, and it was only at the lowest level, S, that the necessary height of 24.6ft (7.5m) to accommodate the equipment for this enormous building could be created. The main hydronics rooms are also at this level.

Recognizing that airports suffer from poor outside air quality - polluted with jet exhaust - the team embraced the problem of getting outside air from roof level down to the Level S equipment. The total quantity was estimated to be 2.6Mft^3/min (1200m^3/sec): clearly a massive intervention would be needed.

At one of the first design team meetings, airshafts from roof level to Level S were sketched on the plans at the locations where each of the piers joins the central processor, almost forming gateways to the piers. The locations for the outside air intake and exhaust shafts, eventually eight in total, each 269ft^2 (25m^2), prompted what came to be called the 'five metre bar', a 16ft (5m) wide band of service space that ultimately included mechanical shafts, electrical closets, comms closets, bathrooms, stairs and elevators, baggage transfers, etc. The air shafts connect to horizontal air tunnels and corridors which in turn join with the systems in the Level S air-handling rooms. A second 'five metre bar' provides similar vertical services routes up to the ticketing hall for the landside of the central processor.

Vertical distribution routes and shafts in other areas of the building generally connect directly to mechanical rooms to minimize large-scale horizontal distribution.

Hydronic systems

Medium-temperature hot water (MTHW) and chilled water (CHW) are generated in the remote central utility plant and, with domestic/fire water, distribute along the landside of the central processor. Utility tunnels connect from these mains into the building's three central hydronics rooms, each of which contains MTHW tertiary pumps, hot water heat exchangers to create low-temperature hot water (LTHW) for distribution throughout the building, LTHW building pumps, heat transfer systems creating glycol/water heating fluid, CHW tertiary pumps, domestic water pumps, fire pumps, and independent chilled water system equipment, used to provide back-up for the mission-critical communications rooms.

The LTHW pumps and the tertiary CHW pumps are each split into two groups, one serving the central processor and one the nodes and piers. This was done to keep equipment sizes manageable, to provide some resilience in the service, and to capture energy savings by not imposing larger system pressure drops on all the water pumped.

Chilled water is available all year. However, the AHUs are provided with economizers and so, at least on good air quality days, the use of winter chilled water is limited to loads such as communications closets, elevator machine rooms, retail area fan coils, etc.

The main fire service originates at the fire pumps in the central hydronics room. From here, a private fire main distributes externally around the terminal building. Zone connections are made to zone control valve rooms, one room per zone for ease of access and maintenance.

Heating systems

A combination of the air systems and hydronic perimeter equipment heats the building. In areas with taller glazing the latter is integrated within the curtain wall at multiple levels to manage the potential downdraft problems. To deal with the typical terminal building problem of infiltration, all entrance vestibules are heated, air curtains are used at freight and baggage roadway openings, and hydronic heating is provided at baggage belt openings into the building.

Each main air-handling room contains a packaged heat transfer unit to generate low temperature water/glycol heating fluid. This is distributed to local AHU preheat coils and other nearby heating elements which may be likely to freeze, eg at baggage belt openings (Toronto's winter design temperature is 4°F/-20°C). Gas-fired, low-intensity radiant heating is provided in the baggage-handling areas.

Air-conditioning systems

In this complex building of almost 4.5Mft^2 (390 000m^2), many different types of air-handling systems and air distribution methods are used. Factors such as capital and operating cost, available distribution routes and efficiency of air supply methods influenced system choice:

- Ticketing hall: an all-air semi-stratified system with supply via ducts with long throw nozzles mounted on top of the ticketing desk canopies; return is from high level and the roof includes heat relief fans at the high points
- Gate lounges: overhead variable air volume (VAV) systems arranged to take maximum advantage of diversity in gate usage and between different sides of the piers
- Greeter hall and hammerhead gate lounges: a semi-stratified system with free-standing supply air towers and high level return
- Double-height baggage claim hall: overhead VAV systems with high throw diffusers
- Office areas: overhead VAV systems with central humidification (atmospheric pressure steam generated using the MTHW) included for the increased comfort of the permanent staff
- Concourses/circulation areas: overhead VAV systems
- Baggage handling areas: as the airport uses a diesel tug fleet, all interior baggage roadways are fully ventilated; supply air is provided by the building air-conditioning exhaust air systems and other dedicated make-up air units. Higher and low level extracts are provided
- Retail areas: a combination of minimum outside air plus fan coils and all-air systems with kitchen exhaust systems located on the roof.

11. Schematic arrangement of primary equipment rooms and risers.

Electrical design

Steve Walker

Strategy

The GTAA regarded reliability of power as critical, which made it a central factor in the design of the building's electrical systems. As a result, the team provided multiple levels of redundancy and contingency:

- Four independent 27.7kV grid feeders from Mississauga Hydro, the regional power utility company, service T1-New, each capable of supporting the entire building's electrical load (in excess of 20MVA).
- Transformer substations are configured so that should one transformer fail, another with fan cooling can support the connected load.
- Four diesel generators are distributed and provide sufficient power to run mandatory life-safety systems together with those considered essential for the airport's continued operation (including a percentage of lighting, ventilation systems, jetways, and some baggage handling system capability). The generator switchgear and controls allow a 'closed transition' transfer so that they can be tested fully against the building load without interrupting services.
- Uninterrupted power supply (UPS) systems were provided for the main communications rooms giving a limited period of autonomous battery operation and provide a last line of defence for systems critical to the airport. The UPS system was designed to continue to operate even after a single UPS unit failure. Over and above this, the communications equipment installed by airline tenants typically included local UPS units for critical equipment.

High voltage power systems

The high voltage systems are operated by Mississauga Hydro as part of the airport-wide system. Control and monitoring of this large, complex, and geographically extensive system are managed through a SCADA (supervisory control and data acquisition system). The high voltage cables are routed through the building at basement level and arranged so that a fire at any one point cannot affect more than a loop branch.

Low power distribution

The main low voltage (600V, three-phase) switchboards are located near to corresponding transformer substations at strategic locations throughout the building. Discrete feeders are provided to the larger equipment loads such as AHUs, baggage handling system control panels, 400Hz aircraft power units, aircraft pre-conditioned air units, and jetways.

A power management and control system supervises the transformers, generators, main switchboard circuit-breakers and power metering. In turn, the BMS monitors this system, allowing the status of the main power systems to be monitored remotely from the terminal building.

Electrical rooms containing power distribution equipment for lighting, 110V transformers for receptacle power, mechanical equipment, tenant concessions, and the many IT systems are located throughout the building and wherever possible are organized vertically. In the central processor they are designed into the 'five metre bar' and busbar risers are used to distribute power vertically.

A lighting management system (LMS) controls lighting throughout the building and features some 500 different lighting control zones. Along with time programmes and 'daylight harvesting' functions, the LMS interfaces with the flight schedule system, allowing lighting to be controlled intelligently to suit aircraft arrivals and departures.

Fire alarm and detection systems

Automatic fire detection alarm is provided in all building areas. Peer-to-peer system architecture was chosen for its intrinsic resilience and fault tolerance, the large physical extent of the building, and to facilitate the staged construction.

Voice evacuation functionality and paging are provided by a single system, and in some large spaces phase arrays speakers were used to achieve high speech intelligibility. In common with other airport systems these systems are monitored in a central facility in the airport.

12. 'Pavement cafes' enhance the travellers' experience.

13. Side elevation of the new terminal revealing the building section.

Making the system work

David Powell

The challenge

Toronto Pearson is the largest and most complex project currently under construction in Canada, and the magnitude and sophistication of the systems and interfaces needed to efficiently operate this state-of the-art terminal required a structured approach to the testing, commissioning, acceptance, and turnover (TCAT) of systems on scale not previously experienced by the trade contractors and construction manager.

The strategy

During Stage 1 the GTAA asked Arup to develop a plan and tools to manage the TCAT process for all systems and interfaces between them. To identify the best and most appropriate practices, Arup performed a gap analysis of what the trade contractors and construction manager were currently doing to identify opportunities for improving the processes. This showed that they did not appreciate the scale of what needed to be accomplished, nor the critical nature of a co-ordinated integrated systems TCAT process.

GTAA requested that Arup fill the gaps by:

(1) preparing and maintaining an extranet-based book of interfaces, which was used to archive and share information about each system and interface including:

- risk reporting on timely delivery of each system and interface
- schedule for implementation and TCAT of each system and interface
- contract specifications for systems and interfaces
- shop drawings for each system, including control documents detailing how each interface would be implemented and tested
- testing plans and acceptance criteria
- test results.

(2) helping the construction manager incorporate the TCAT process into the construction schedule by:

- identifying all systems dependencies to ensure that they are reflected in the schedule
- reviewing construction sequencing and making necessary adjustments to ensure TCAT requirements are reflected.

(3) developing detailed commissioning plans and acceptance criteria for each system and each interface between systems; this:

- identified conflicts between the plans of each trade contractor and the overall construction schedule, and facilitated resolution
- provided metrics to measure the progress of each trade contractor throughout TCAT
- communicated most effectively the GTAA expectations and contractual requirements to trade contractors and construction manager
- enabled the creation of tools to monitor and automatically report on progress.

(4) managing and co-ordinating the TCAT of each system and the entire building; by leading this effort for all systems, Arup could:

- identify and document the progress of each trade contractor on each system and system interface – showing who was and who was not ahead of schedule, so that resources and attention could be properly focused
- enforce a uniform quality process to assure that all required criteria were achieved and documented
- confirm that all systems would be operational on airport opening day
- ensure that GTAA staff were properly trained and familiar with systems prior to opening day
- ensure that all contractual requirements of all trade contractors were fulfilled.

Results

Arup leveraged team members with a broad range of experience in the design, commissioning, and operation of IT&T, instrumentation and controls, and building systems to develop a comprehensive approach to defining, managing and reporting on the TCAT process. Several groundbreaking tools were developed, enabling those responsible for delivering each system to independently upload progress data. This permitted accurate, comprehensive progress reporting on each of the thousands of activities necessary to complete TCAT, thus allowing Arup to forecast the effort and time required to complete each system.

Arup facilitated sessions with the design team, trade contractors, construction manager, and constituents from the GTAA to familiarize them with the TCAT process and ensure that all had a clear understanding of what was being delivered. Making sure that all parties had a common understanding of the process and were ready for turnover of interoperable systems ensured that opening day would be seamless.

The GTAA is so pleased with the successful completion of all of the systems and interfaces required for the efficient operation of Stage 1 of T1-New that it has engaged Arup to continue managing and enhancing the TCAT process for Stage 2. As Stage 2 is an addition to an operational terminal and all the systems in Stage 2 will interface with those in Stage 1, Arup is working with the GTAA to extend the discipline of the TCAT process to ensure that any changes to operational systems (Stage 1) are communicated to the construction team and vice versa.

14. 'Information tower'.

Credits

Owner: Greater Toronto Airports Authority; **Architects:** Skidmore Owings & Merrill, Adamson Associates, Moshe Safdie & Associates in joint venture as Airport Architects Canada; **Masterplanner, and SMEP and communications engineers:** Arup - Alex Acero, Scott Anderson, Leo Argiris, Gareth Ashley, Yuri Baklanov, Ignacio Barandarian, Alban Bassuet, Richard Batty, Graham Bolton, Ed Brabenec, Eric Bury, Trevor Carnahoff, Christina Carydis, Danny Chan, Colin Chow, Kevin Conway, Emmanuelle Danisi, Steven Davison, Alex de Barros, Tara Durnin, John Elissa, Paul Entwistle, Alexander Epshteyn, Pablo Fernandez, Dieter Feurich, Tania Flavia, Gregory Giammalvo, Ken Goldup, Anthony Goulding, Tom Grimard, Greg Hodkinson, Dennis Hromin, Peter Ibragimov, David Jones, Michael Keane, Mike King, Igor Kitagorsky, Amy Koerbel, Jayant Kumar, Iraklis Lampropoulos, Martin Landry, Janice Lee, Sam Lee, George Long, Jun Luo, Al Lyons, Martin Manning, Peter Manson-Smith, Geoff Marchant, Andrew McAlpine, Brian McMaster, Nitin Melwani, Angie Mende, Jason Millar, John Miller, Etret Mohammad, Andrew Morrison, Erin Morrow, Edward Murphy, Marta Nam, Ralph Orr, Jim Peacock, Nicos Peonides, Chai-Teck Phua, Ricardo Pitella, David Powell, David Pritchard, Raymond Quinn, Joel Ramos, Rene Rieder Jr, Philip Robilotto, Ron Ronacher Jr, Manan Shah, Anatoliy Shleyger, Peng Si, Michael Skura, Gerald Solis, Vojin Stefanovic, William Stevenson, Harold Strub, Kitty Tang, Chris Taylor, Adam Trojanowski, Margarita Vanguelova, Nellie Varvak, Isabel Vasconcelos, Steve Walker, Gina Wall, Regine Weston, Heidi Witteman, David Wong, Neil Woodger; **Civil engineer (landside and airside infrastructure):** Hatch Mott Macdonald Inc; **Associate structural engineer:** Yolles Partnership; **Associate mechanical engineers:** TMP Consulting Engineers, Inc, and Smith and Andersen Consulting Engineering; **Associate electrical engineers:** Mulvey + Banani International Inc; **Illustrations:** 1, 3-10, 12-14: ©Arup/GTAA; 2, 11: Arup/Nigel Whale

1. Free-flowing traffic on the new M6 Toll motorway in the UK Midlands.

M6 Toll

Traffic congestion is a daily fact of life; a hindrance to all of us. The UK's M6 motorway has been one of the country's busiest and most notorious routes. Ideally, a free-flowing alternative was needed – but how and when could this be achieved, and who had the expertise to deliver it?

History

Mark Praciak

The origins of the M6 Toll motorway date back to the early 1980s, when the UK Government identified a need for a scheme to relieve the heavily-congested M6 through the West Midlands conurbation. From its opening in 1972, traffic on the M6 increased significantly, and by 1980, peak flows of 130 000 vehicles a day - almost twice its design capacity - made it one of the most heavily-used motorways in Europe. Early suggestions to widen it were quickly dismissed as unrealistic, and after public consultation, the decision was taken to build a new motorway north-east of Birmingham.

Consultations on several route options for what is now officially the M6 Toll road (working title: Birmingham Northern Relief Road or BNRR) culminated in a preferred route announcement by the Secretary of State for Transport in March 1986, followed two years later by a public inquiry.

In May 1989, before the inquiry outcome was announced, the Government decided that, in line with its new policy objectives, the BNRR was to be procured at no cost to the public purse, and introduced a private sector competition to design, build, finance, and operate the new route. Following prequalification, three groups were invited to tender for the 50-year concession and one of them, Midland Expressway Ltd (MEL) - combining Trafalgar House and its Italian joint venture partner Iritecna - commissioned Arup to prepare a tender design for its bid submission. In August 1991, the Secretary of State for Transport announced that MEL's submission based on Arup's scheme proposals had won the competition, and in February 1992 the concession agreement was signed.

Arup was subsequently appointed as MEL's lead designer to develop the scheme in greater detail and take it through the UK's demanding statutory procedures, to obtain authorization for the road's construction and the associated land acquisition. During this time, Arup led and co-ordinated a group of around 10 specialist subconsultants in a major public consultation exercise and in preparing a comprehensive environmental assessment; this resulted in adjustments to the tender design and led to the confirmation of a modified preferred route.

2. The 44km route.

In conjunction with the Highways Agency, Arup undertook to prepare statutory order plans and schedules on MEL's behalf, and draft orders were published in June 1993. A public inquiry into the scheme began a year later, and throughout its 15 months, Arup provided technical support to MEL at the inquiry, and expert witnesses for the engineering evidence and much of the environmental evidence. The inquiry's length and complexity meant that the Inspector took over 18 months to report his findings, and the Secretary of State's decision letter, confirming that the scheme as proposed by MEL was to go ahead, was not issued until July 1997.

A legal challenge to the BNRR, launched in 1998 by an objectors' action group, was dismissed by the High Court but delayed the scheme's implementation for a further year. By 1999, Trafalgar House's stake in MEL had been acquired first by Kvaerner Construction and subsequently by Macquarie Bank. Negotiations with Kvaerner to build the road proved unsuccessful and MEL decided to invite tenders, asking Arup to assist in preparing contract documentation.

A tender competition for the detailed design and construction of the BNRR was issued in April 2000.

The financial stake in this major project – the first of its kind in the UK - has been great. MEL's investment to date is approximately £900M.

The tender process

Tony Marshall

Arup, together with Atkins, played a key role in developing the winning tender with a joint venture of Carillion, Alfred McAlpine, Balfour Beatty, and AMEC (CAMBBA). With only a 14-week tender period, running from April to August 2000, and working on a project valued at close to £500M, CAMBBA required a clear tender strategy and rapid deployment of an experienced team. The strategy (Fig 3) was based on three principles:

- Price the existing scheme as a baseline.
- Run a parallel challenge/value engineering process to identify variations.
- Develop the CAMBBA price using additions/omissions on the baseline.

By applying and following this strategy, the team could concentrate effort on aspects that appeared to give maximum scope for cost reduction. Work associated with lower cost elements could therefore be limited to risk/opportunity analysis and no design.

Workstream 1: 'Blue sky' value engineering

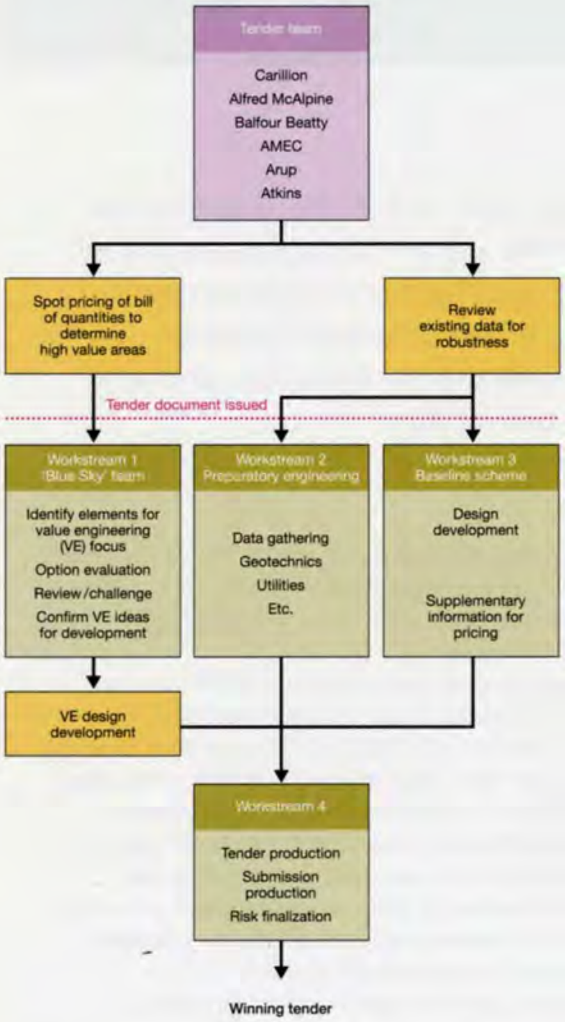
This was an intense four weeks of design review, brainstorming, and discipline-based value engineering workshops, involving people with significant experience on the project and new team members who had no previous history with it.

Workstream 2: Preparatory engineering

The purpose of this was to gather additional pricing data, in particular related to geotechnics and utilities. Again, this activity was carried out by an integrated team including contractor and designer staff.

Workstream 3: Baseline scheme

Here, an independent team within the Arup office carried out further work to support the pricing of the baseline scheme. Again, it focused on areas identified by the design and contract team, following an initial review of the tender documents.



3. Tender period, 14 weeks April – August 2000: the four workstreams associated with delivery of the winning tender.

Workstream 4: Tender and submission production

The teams from Workstreams 1-3 came together for the second half of the tender period to deliver the agreed tender scheme pricing and submission documents. Throughout this phase, design and construction team staff contributed to the development of project risk and opportunity registers.

Design and construction

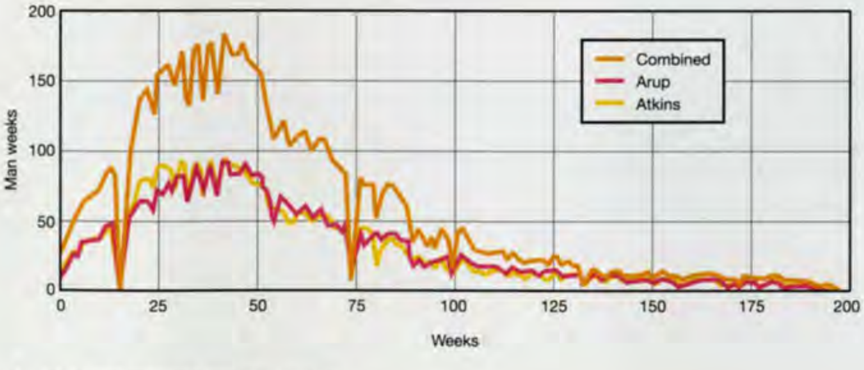
Barrie Ellis

Directly following award of the design-and-build contract, CAMBBA appointed Arup and Atkins, under a time-based design services agreement, to carry out the detailed design of the entire project, with the exception of the toll collection system and its hardware. The commission also included a site-based team of around 30 people providing design support to the contractor during construction, and inspection of the works to ensure compliance with the design. A Joint Venture Agreement between Arup and Atkins (AAJV) aimed to share the work equally and, generally speaking, this was achieved (Fig 4).

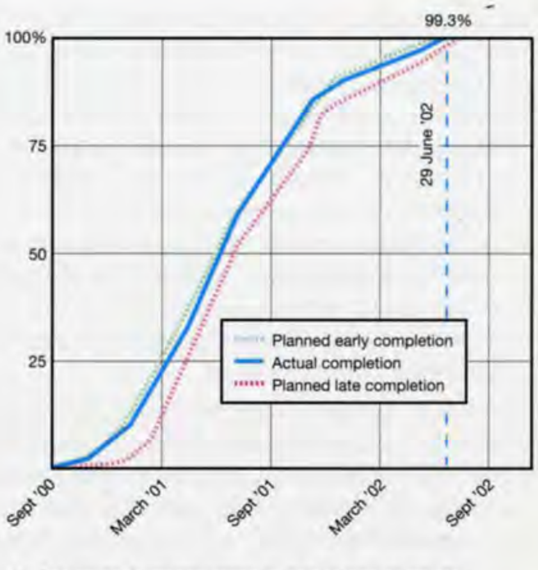
As the project was funded from the private sector, the terms of the design-and-build contract were particularly demanding with regard to opening the road on schedule, to start to generate toll revenues to deal with the considerable loan servicing charges involved. In addition to the challenging overall completion target of 173 weeks, several interim milestones were set, attracting bonuses if they were bettered and penalties if they were missed – the penalty for failing to achieve overall completion being approximately £170 000 per day. Needless to say, with such potentially large sums of money involved, the pressures on achieving the design and construction programmes were intense.

The design agreement called for a fully resourced P3 (Primavera Project Planner) programme, which was developed in conjunction with the contractor's own P3 construction model and linked to it across approximately 400 interfaces. To manage the risks of delay, activity durations were limited to a maximum of four weeks so that any slippages quickly became apparent and remedial measures could quickly be taken. Although the four weeks' limit led to a large model with upwards of 6000 activities, it allowed design production to be closely managed to the extent that it generally achieved early completion targets (Fig 5). The early design completions contributed to the motorway opening two months ahead of schedule.

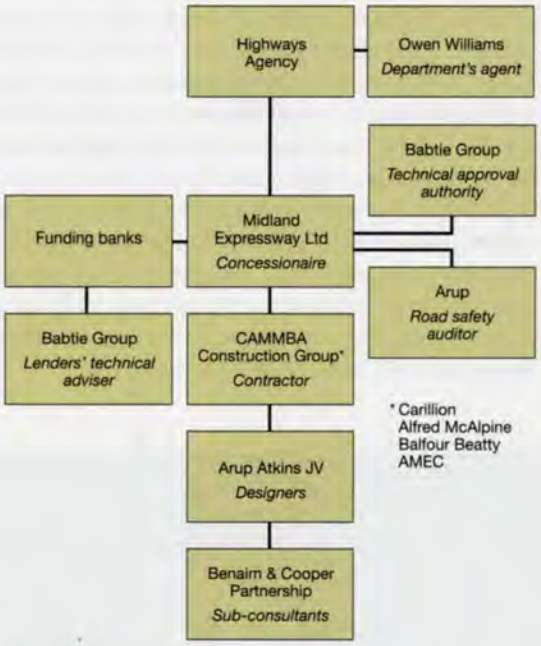
The difference between early and late completion was relatively short, ie activities generally had only small amounts of leeway (Fig 5). This allowed little flexibility in the production schedule and, more often than not, any change in the construction schedule engendered a corresponding change in the design programme.



4. AAJV joint resource input histogram.



5. Design performance monitor: percentage complete.



6. Project organization.

As well as the principal project participants (Fig 6), many other organizations were involved, including national and local agencies and authorities, utility companies, landowners, and a range of other interested parties. In addition, CAMBBA had upwards of 500 subcontractors, suppliers, consultants and advisors, each influencing the design to different degrees.

The resourcing peaks early in the project of approximately 190 man weeks per week (Fig 4) translated to a total AAJV team size of some 300 members, though some, particularly amongst the support disciplines, only spent part of their time on the project. The backbone of the organization was four highway design teams, each handling a section of the motorway corresponding to the sectional division used by the contractor for construction. Atkins designed the two northern sections in their offices in Birmingham and Epsom, while Arup designed the two southern sections, working from its Midlands Campus office at Solihull. The four sections are respectively:

- 5.9km from the northernmost point (where M6 Toll connects with M6 Junction 11a) to M6 Toll Junction T7 at Bridgetown (Atkins)
- 11.9km from Bridgetown, Junction T7, to Shenstone, Junction T5 (Atkins)
- 15.3km from Shenstone, Junction T5, to M42 Junction 9 at Cudworth (Arup)
- 10.4km from M42 Junction 9 to the road's southernmost point, where it links with the M6 Junction 4 (Arup).

Discipline co-ordinators (eg highways, drainage, geotechnics, structures, environment, building engineering, etc) operated project-wide across the four teams, ensuring uniformity in both technical and presentation standards and, in most instances, providing design services in their particular disciplines. Although the whole AAJV team came from the two firms, there was total integration and corporate boundaries never presented a problem.

For the first three months, as the project began to mobilize and the job planning started, the design team was based in Arup's Coventry Office. Thereafter, as numbers increased, production moved back to home offices. In all, 10 Arup offices were involved, including Melbourne, Brisbane and Perth, with a similar number in Atkins. Having the team spread across so many different offices presented major challenges in design co-ordination and the huge exchanges of data needed to deal with it. Likewise, there were equally large data exchanges with the contractor and the design review organizations. It was crucially important for each office and organization always to use the latest revision of the design and, of course, to maintain programme. These major challenges were largely solved by Arup's Integration software, which provided a website repository where all project data could be stored and accessed at any time by any project participant. As the project came to completion, the Integration site became the design archive, still open to anyone with the access permissions to use it.

7. Typical concrete underbridge, with new planting in the foreground.

There are more than 180 structures on the M6 Toll project, including 68 new and modified bridges, 66 gantries and various culverts, retaining walls, and toll plaza structures.

Structures

John Salter

The extremely tight construction programme called for the first 19 steel overbridges and six concrete underbridges to be fully designed and issued for construction within the first eight months of the programme. The design objective was to provide aesthetically pleasing, open structures that were simple to build and replicate, thus achieving significant resource savings from development of the tender design. The aim was to ensure that the structures would be constructed without impacting on other activities.

The overbridges therefore followed the following build principles:

- twin main beam, two-span steel composite (or ladder beam) decks
- open-bank seat supports above artificially-strengthened sideslopes in reinforced earth
- common elements such as piers and return wingwalls standardized
- skew taken out at the deck ends to simplify fabrication and connection detailing.

Widening of existing structures

The structures programme also involved modifying some existing bridges, and during widening of the M42 to accommodate the new toll route, five existing underbridges were extended by approximately 30m. Existing structures required a full structural assessment in addition to the new design, and so needed considerably more resource effort than brand-new bridges. Key to design was the ability to ensure consistency and compatibility between the old and new.

The existing bridge elements and their extensions had to comply fully with current design standards. The team took the opportunity to value-engineer the structure extensions to significantly reduce costs. A reduction in total length of piling of 70% (eliminating 10km of 600mm diameter continuous flight auger piles) was achieved.

8. Simple, consistent design and construction: typical ladder beam deck and reinforced earth end-supports for two-span overbridges.

9. Value-engineered structural solutions: extending underbridges for the widening of the M42.

Highways

Doug Balmer

Generally, the route follows existing major road corridors, thus minimizing the effects on the wider landscape, and with alignments carefully developed to optimize the cut-and-fill requirements. Whilst much of the route was in cutting or on shallow embankments, the creation of mounds and false cuttings helped blend the road into the countryside. During the detailed design, the alignments were optimized further to win more locally occurring aggregates, which were used in the pavement and concrete structures.

The junction layouts at each end of the scheme were complicated by the concession agreement which made the M6 Toll the 'through route', so that traffic wishing to continue along the M6 had to exit the M6 Toll to rejoin the M6. This requirement both complicated the junction layouts and influenced the performance of the interchanges.

At the southern end, a major interchange between the M6 Toll, the M42, and the M6 extends over approximately 8km. This complex section was heavily constrained by existing motorway links, local roads, and structures that had to be retained, as well as rivers and railways, and the proximity of residential properties.

To alleviate these constraints, the preferred design included a combination of parallel construction, asymmetrical widening, and symmetrical widening. The alignments were designed to reuse as much of the existing pavement as possible, whilst minimizing overlay thicknesses and not imposing unacceptable additional loading to the existing structures.

The route and interchanges were modelled using the leading-edge design program InRoads, and this 3-D model was then issued to the contractor to input directly into his setting-out equipment. The highways design team benefited from the models in use by the Channel Tunnel Rail Link team and also worked with the software house Bentley, suppliers of the programs used, where the process was developed further to simplify project team workflow.

A process was formalized, including the creation of a 3-D model of the road and then the export of this package to a GENIO format. The contractor imported the GENIO file into his setting-out software - Trimble or NRG - to either set out works or control earthmoving/pavement plant.

Technology played a significant part in conceptualizing how the M6 Toll would evolve. However, the paramount design consideration was that the alignment had to be carefully engineered to minimize environmental impact and maximize the use of materials from the site.

10. M42/M6 Toll junction, where the total width increases to 12 lanes.

Environment

Peter Braithwaite

Many measures were taken to mitigate the effects of the route on the local environment. Ecologists, a landscape architect, and environmental scientists were all involved at each stage of the scheme.

From the outset of construction, ecologists managed the clearance of site vegetation and helped in relocating significant flora and fauna. About 2ha of wet heathland was translocated to a carefully prepared receptor site - a double-lined lagoon, 1.5m deep, and backfilled with carefully stratified selected materials. This created a soil profile to match the donor site. Specially designed machinery was introduced to allow giant 2.4m x 1.2m x 0.3m turves to be lifted and laid, accessing the site on temporary floating sleeper roads. Ancient hedges were also moved to new sites near the motorway. The translocation has been successful enough to make it extremely difficult for anyone but an expert to tell that the vegetation has been disturbed.

Approximately 1ha of dry heathland was created through a combination of techniques, including prior harvesting of seed from a Site of Special Scientific Interest (SSSI) through which the motorway was being constructed. Heather turves and peaty topsoil were also recycled separately from this SSSI and respread on the motorway verge prior to seeding with the harvested seed. Elsewhere, heather brash harvested during management operations from a nearby country park was used to create new heathland on screening bunds.

11. New tree planting on the motorway verge near Weeford Park toll plaza.

12. Translocated ancient hedge.

A wide variety of wild fauna living on or frequenting the site, including white-clawed crayfish, newts, water voles, badgers, otters, bats, and Fallow and Muntjac deer, was relocated or otherwise protected as part of the works. Most of the roadway is fenced against various combinations of badger, otter, deer, and newts, and over 60 mammal passes and ledges have been provided in addition to road and pedestrian crossings, enabling animals to cross the motorway safely. Four otter holts, two badger setts, and hundreds of bat boxes were provided, along with numerous log piles for animal habitats.

It was imperative to maintain the rural landscape and feel of the region through which the route passed, and major shrubbery planting took place on and off the line of the motorway to help conceal and blend the scheme within the surrounding landscape. Approximately 1M trees and shrubs were planted over two winters during the course of the works. Almost 130 offsite plots were planted through agreement with landowners. In addition, ornamental planting around toll plazas includes herbaceous flower and ground cover beds in an effort to introduce human scale and create a more convivial workplace environment for the toll station workers.

Careful attention to the environment also enabled further aquatic habitats to be created as part of the drainage network.

Drainage

Graham Martin

Ecological and retained ponds

As a separate entity to the drainage system, 20 ponds were created. This was primarily for ecological purposes though the largest is intended to be used as a commercial fishing lake. They have common features to increase ecological value; translocated and imported aquatic plants were used and several of these ponds were perched and required lining. In addition, 11 existing ponds were retained and modified to maintain ecological and amenity value.

Streams and rivers

Watercourses totalling 9.5km were diverted, incorporating meanders, riffle weirs, fluctuating bank gradient, depth and width, sandbanks, aquatic planting. A wide variety of erosion control methods were built in, including gabions, riprap, geotextiles, coir rolls, live woven willow, and translocated rushes, in addition to in situ concrete.

At the motorway drainage outfalls, a total of 28 balancing ponds were built to limit or attenuate the discharge to adjacent watercourses. Each pond combines with an oil inceptor to provide pollution control.

Two-thirds of the ponds include further ecological mitigation features such as islands, static water areas separated from the main part of the pond, reed beds, and marginal/marsh planting shelves at various levels relative to normal water level, gravel beaches, and hibernacula (part-buried riprap hibernation areas). Where necessary, drainage channels were lined to protect aquifers.

Upstream of the ponds, the M6 Toll drainage combines kerbs, gullies and hollow kerbs; combined surface water and groundwater drains (filter drains); the longitudinal drainage channel (in the central reserve); and ditches.

The drainage is a gravity system, except for the outfall from the Shenstone cutting, west of Tamworth and south of Lichfield. Here, as it passes under the Sutton Coldfield to Lichfield railway, the M6 Toll is forced into a low point below the level of the nearest watercourse, Crane Brook, 500m south, and thus requires a pumped outfall. The gravity network outfalls into a wet well comprising a 12m diameter, 12m deep chamber formed of precast segmental concrete rings. Upstream of the wet well, only limited attenuation was possible and so to accommodate a 1:50-year storm, the well contains four pumps, each with a capacity of over 1100 litres/sec. Water is pumped to a header tank at the top of an adjacent earth mound, from where it flows down a 1350mm diameter gravity main to an attenuation pond prior to discharge into Crane Brook.

13. New ecological pond.

14. Shenstone pumping station.

15. Balancing pond near Junction T5.

Environmental considerations were applied during geotechnical work and almost all aggregates used during construction were won from within or immediately adjacent to the site. This helped minimize disruption to traffic and disturbance of local communities. Careful positioning of stockpiled topsoil assisted in screening construction activity, even before the permanent screening bunds were constructed.

Geotechnics

Stewart Jarvis

Arup's geotechnics team applied a wide range of measures to enable reuse of materials. By processing site-won materials, pavement quality aggregate, concrete aggregate, drainage stone, building sand, selected granular materials, and cement-bound material aggregates were produced for the project. This ensured a minimal import of materials and a largely balanced earthwork. Despite early concerns about the need for some 'selective' working to be done within glacial deposits, the use of motorized scrapers proved to be a great success, helped considerably by relatively good weather during the construction period.

The route crosses a variety of geological materials typical of the UK Midlands: the Sherwood Sandstone, Mercia Mudstone and Coal Measures strata. Overlying these strata, a variable thickness of superficial deposits relating to past glacial periods was present. Generally, ground conditions were good, but deep 'sub-glacial' channels infilled by a variety of poorer materials were present in places. In addition, 16 areas of potentially contaminated land had to be dealt with. Quantitative risk assessments were carried out on the contaminated materials and in general the team was able to prove that most of it could be reused within the works.

In a significant number of areas, reinforced soil abutments proved a more cost-effective solution than piling, particularly since the specified class of granular backfill to the reinforcing straps was site-won. Elsewhere, both piled and conventional shallow foundation solutions were adopted.

Part of the route corridor had to contend with shallow mineworkings and deep backfilled opencast excavations. Again, a range of measures was required - including drilling and grouting, surcharging, and structural solutions - to deal with these issues.

Pavement design

Geoff Griffiths

The team designed a range of pavement options for use at different locations, so as to suit existing ground conditions and traffic loadings, and provide the most cost-effective solutions. Two principal options were selected for the main carriageway: continuously-reinforced concrete pavement (CRCP) with thin wearing course overlay, and fully-flexible bituminous construction. As well as ground conditions, the choice of option was based to a large extent on the availability of site-won materials, and the variability in width of the carriageway.

It was fortunate that the route traverses a very large quantity of glacial sand and gravel that could be, and was, processed to form a substantial portion of the motorway pavement. Approximately 50% of the length is constructed in CRCP using site-won aggregates, including all of the concrete, the cement-bound material, and capping. The pavement construction platforms of subbase and capping material were made stronger than the standard design in order to cope with the heavy construction traffic loading and reduce the risk of a premature, construction traffic-induced failure.

A 'concrete train' was used for the concrete pavement, laying the full 14.3m carriageway width in a single pass. The reinforcement was fixed in position in advance of the concrete train by an innovative Australian method, used for the first time in the UK on this project; then the 220mm thick CRCP was overlaid with 35mm of thin wearing course to provide a quiet and smooth running surface.

The fully flexible pavement option was adopted for the M42 southern end, where modifications to existing carriageway of varying widths and depths were required, and at the northern end of the project where ground conditions were variable and generally much poorer. Conventional paving plant was used for laying the various pavement layers in single-lane widths.

The earthworks and pavement were key elements in the construction of the works, representing the largest single elements of cost to the contractor as well as being vital to the work programming for early completion.

Site team

Colin Copeman

As previously noted, the contractor CAMBBA divided the site into four geographical sections for construction purposes. Each was staffed by a mixture of personnel from the four parent contractor companies, based in site offices within the individual sections. AAJV provided a team of usually six design and inspection staff to each of these section offices.

CAMBBA senior management and staff, who had the remit for overall site responsibility, were based in a 'core office' on the project route at Shenstone, near Lichfield. AAJV reflected this arrangement and located its site design management team, and specialists for buildings, environmental works, and motorway communications, at the core office. At its peak, AAJV's overall site team was 40-strong. The concessionaire, its technical advisors, and the Highways Agency's technical advisors were also based in offices at Shenstone.

AAJV had two distinct roles on site: firstly, to provide technical advice and support to CAMBBA, and secondly, to monitor the quality of the works to ensure that they were constructed in accordance with the design.

The technical support role consisted primarily of responding to technical queries and processing design changes. These - required for example to suit changed circumstances, resolve construction problems, or resulting from value engineering - were reviewed by the concessionaire's technical advisors in a similar way to the primary design. Arup's Integration tool enabled instant access to all drawings and other documents from desktop computers in all offices throughout the site.

16. Materials processing plant at Weeford Quarry.

17. Curved roofs and a strong visual identity: toll booths at Weeford Park.

CAMBBA's IT system also permitted shared access by all parties, including the client and advisors, to documents, procedures etc.

The contractor operated a self-certification scheme for the quality assurance of the works; there was no third party supervision of construction. AAJV's role was to audit the contractor's quality procedures and construction activities to gain confidence and enable signing of construction certificates; each section of works had to be separately certified prior to the issue of completion Certificate. The concessionaire's and the Highways Agency's technical advisors fulfilled a similar role for their respective organizations. The level of inspection and auditing by each party was defined at the start of the works in inspection and test plans. Management of the quality monitoring process by AAJV to ensure that specified targets were achieved was facilitated by the development of a records database, which permitted rapid and selective interrogation against each construction certificate.

The contract completion date for construction was January 2004. The contractor targeted to complete early, and the M6 Toll opened to traffic almost two months early in early December 2003.

The M6 Toll road is the first of its kind in this country. To support this method of transport, toll plazas - a common sight in continental Europe - are a necessity. As the concept was new to the UK, Arup was keen for the plazas to have maximum impact, and designed practical yet aesthetically pleasing structures that fit within their semi-rural environment.

Toll plazas

Rob Greenwood

The multidisciplinary team of architects and engineers designed a total of 28 buildings for eight different needs at six toll station sites. The aim was to satisfy the functional requirements with integrated designs that emphasize corporate styling and value for investment, as well as safety and security. Close working relationships with the tolling systems' commissioners and suppliers were essential to ensure that all technical systems and building services were fully co-ordinated and integrated.

A strong styling theme of curved roofs was developed for the main buildings, with particular attention given to the colour selection to satisfy the concessionaires and planning authorities. Value engineering, involving users, builders and designers, was a feature of the design development, so as to ensure that the functional needs were achieved and investment wisely used. The priority of achieving safe and secure places that delight and are familiar to both toll users and operators' employees was maintained throughout the subsequent detail design stage. The buildings team remained in place throughout construction, working with contractors and subcontractors to ensure that the design principles and quality standards were achieved.

Building Summary	Great Wyrley (T7)	Burntwood (T6)	Shenstone (T5)	Weeford (T4)	Weeford Park (near T4)	Langley Mill (T3)	Coleshill MMA* (M6 J8)	Saredon MMA (M6 J11a)
Toll canopies and booths (number of toll lanes)	10	4	4	4	10	3+3	-	-
Toll station buildings (m^2) and underground access tunnels	245	205	205	205	245	205	-	-
Electricity supply buildings ($40m^2$)	✓	✓	✓	✓	✓	✓	-	-
Operations management centre ($1000m^2$)	-	-	-	✓	-	-	-	-
Police security building ($90m^2$)	-	-	-	✓	-	-	-	-
Maintenance, personnel and equipment building ($560m^2$)	-	-	-	✓	✓	✓	(1)	(1)
Salt stores (tonnes)	-	-	-	5000	-	-	2500	2500
Snowplough shelters ($95m^2$)	-	-	-	✓	-	-	✓	✓

(1) Provision made for satellite maintenance building if required later.

*MMA (Motorway Maintenance Area)

18. Summary of the number and nature of the buildings on the M6 Toll.

Conclusion

Tony Jones

There is no doubt that the M6 Toll is one of the most exciting developments in British road transport for many years. Under the scrutiny of industry and the media, there were high expectations of its performance, and studies following the opening of the 44km route show that the toll has been welcomed by a diverse range of road users. In summer 2004 the concession company, MEL, reported that the road was used by an average of 55 000 vehicles per day - an increase of 80% since January 2004, the first full month of operation. A major milestone was reached in August 2004 when the 10Mth customer using the route was logged.

Arup is proud to have been involved in the development and delivery of this project, the first toll motorway in the UK. Throughout its life, the project has engaged the full range of Arup's multidisciplinary skills involved in a highway scheme. Many engineers, planners, environmentalists, scientists, quantity surveyors, specialists, computer programmers, and support staff have contributed over the years, and good teamwork has always been a feature of the many stages of the work.

Developing the route and taking the scheme through the public inquiry presented many challenges to the Arup team, and delivering the design for the UK's largest design-and-build road project was a huge logistical challenge met and overcome. Throughout, the intention was to make the completed road a testament to good design, sympathetically fitting into the landscape to minimize its environmental effect, and presenting a smooth, pleasant, and safe alignment for the motorist.

Credits

Project client: Highways Agency **Technical advisor:** Owen Williams Ltd **Concession company:** Midland Expressway Ltd (MEL) **Technical advisor:** Babtie Group Ltd **Client/contractor:** CAMBBA **Design JV:** Arup/Atkins **Arup design team:** Justin Abbott, Kim Abbott, George Acuna, Mark Adams, Keith Ali, Sally Allen, Barbara Ancliff, Antonio Antonelli, Clive Aubrey, Hannah Babor, Mike Baldwin, Doug Balmer, Martin Barber, Giles Barker, Lindsay Barnard, Iain Bell, Sam Bellanoff, Christine Blanch, Sue Blanch, Joanne Bole, John Border, Jean-Marie Bordier, Sarah Bowden Jake Brindley, Carol Brownridge, Dick Burge, Ebrima Cham, Paul Chatwin, Lucio Chiodi, Thomas Chyung, Phil Clay, Ed Colgan, Adrian Collings, Steven Cook, Colin Copeman, Paul Cruise, Wilma Cruz, Ben Cryon, Jo Cubbage, Mia Cullino, Mark Darlow, Kim Davey, Ian Davis, Alan Dean, Simon Dean, Mike Dickens, Paul Dickens, Ian Doble, Joseph Donohue, Paul Drinkall, Stephen Dunn, Stephen Dunstone, Patrick Elliott, Barrie Ellis, Frederick Engmann, Karl Fitzgerald, John Gabryliszyn, Lindsay Gauntlett, Steven Gazeley, Alistair Giffen, Lee Gill, Eugene Golshtein, Anna Gracey, Dan Grealey, Tony Greenstock, Rob Greenwood, Geoffrey Griffiths, Helen Groat, Roger Gutteridge, Kate Hall, Peter Handley, Neil Harrison, Andi Hawes, John Henderson, Luke Hookway, Rob Houmoller, John House, Dave Hughes, Gareth Hughes, Tai Hwang, Myra Iererua, Stewart Jarvis, Teresa Jeffcoat, Alice Jenkins, Paul Johnson, Scott Johnson, Tony Jones, Chisung Kang, Svetlana Kelly, Claire Kimber, Michael Kimberley, James Kirby, Jeremy Kruger, Michael Lal, James Lancaster, Paul Larcher, Mike Larvin, Benjamin Lau, Conor Lavery, Robert Lindsay, King Ling, Jason Lloyd, Mike Long, David Lowes, Kevin Lucht, Jon Mabbett, Colin Magner, Benoit Marais, Tony Marshall, Graham Martin, Iain McCulloch, Rory McEwan, Alan McFarland, Carol Mears, Philip Morgan, Jeremy Morris, Peter Morris, Carol Mozuraitis, Neal Mumford, Neil Nicholson, Christopher Nixon, Paul Noble, Katharine Olley, Elaine Owen, Simon Owen, Ronnie Palmer, Joanna Pandeli, Robert Paris, Hemal Patel, Allen Paul, Vikram Paul, Shokrollah Pilwar, Danielle Pollok, Mark Praciak, Adrian Pragas, David Preece, Mark Presswood, Richard Price, Peter Quarmby, Mario Querol, Cliff Richards, Gary Riley, Brian Rogers, Nathan Rollason, Jenny Rough, John Salter, Mick Shield, Ben Sibert, Nick Sidhu, Will Sims, Trevor Skelding, Daniel Smith, Vicky Smith, James Sowden, Paul Stephens, Colin Stewart, Scott Stewart, John Stowell, Paul Summers, Rob Talby, Philip Taylor, Graham Thomas, Richard Thomas, Derya Thompson, Gordon Thompson, Lucinda Thornton, David Tigani, Cliff Topham-Steele, Andreas Tsindos, Alan Turner, Andrew Turner, Michael Tyrrell, Chris Uzzell, Martin Vanicek, Gil Vucetic, Tim Walker, Jared Waugh, Mel West, Peter Weston, Paul White, Craig Wiggins, Eric Wilde, Gavin Williams, Mike Woodcroft, Richard Wren, Katherine Yalden, Tulga Yaran, Jeffrey Yee; **Subconsultants:** Benaim Group, Cooper Partnership **Illustrations:** 1, 10-11, 15, 17, 19: ©Arup/David Griffiths Photography; 2: Nigel Whale; 3-6, 18: Arup/Nigel Whale; 7-9, 12-14, 16: Arup

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Vital statistics

- UK's first toll motorway
- UK's first privately-financed motorway
- UK's largest single motorway contract
- £485.5M lump sum design-and-build contract
- 173 weeks design-and-build contract period
- 44km of dual three-lane motorway
- 1.3Mm^3 topsoil strip
- 9.2Mm^3 excavation
- 7.5Mm^3 fill
- 1.6 Mm^3 processed material
- 800 000 tonnes asphalt
- 190 structures
- 63 000m^3 structural concrete
- 9600 tonnes structural steel
- 139km carrier drains
- 130km safety fencing
- 165km fencing and hedges
- 4.43Mm^2 landscaping
- over 1M trees

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