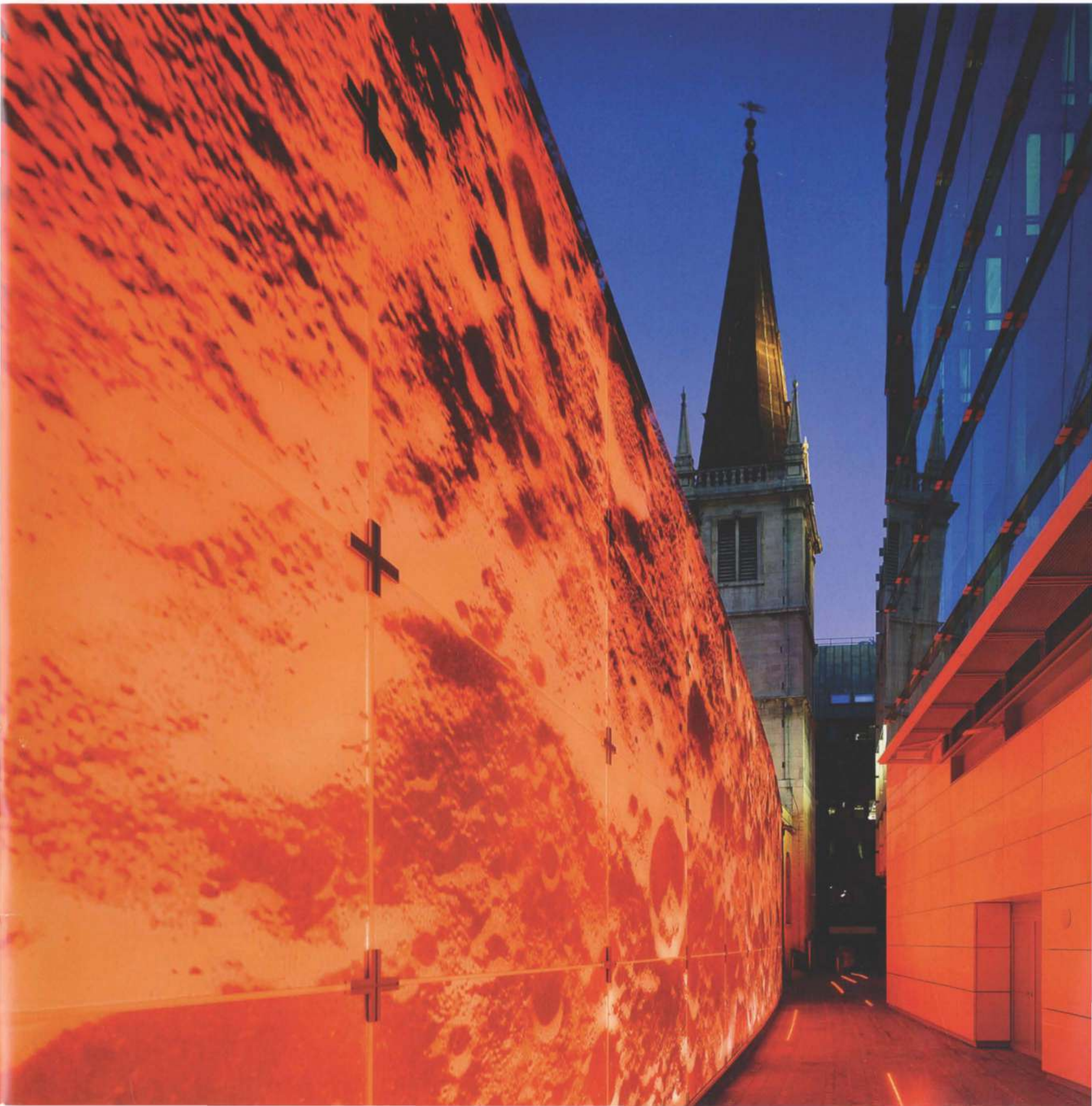
2/2005

The Arup Journal



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CCTV Headquarters, Beijing, China:

Structural engineering design and approvals

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Introduction

Growth in China is happening at an historically unparalleled rate. China Central Television (CCTV), the principal state-run broadcaster, currently has 13 channels, but by 2008 it plans to be operating over 200 channels and competing successfully with CNN, NBC, Sky, and the BBC in the global market. To enable this expansion, and to place CCTV firmly on the global map, a new headquarters facility was needed, with the entire television-making process housed in one location within Beijing's newly-designated Central Business District (Fig 1).

In early 2002, CCTV organized an international design competition, which attracted some of the biggest names in architecture. After much effort it was won in August 2002 by Rem Koolhaas's practice Office for Metropolitan Architecture (OMA), based in Rotterdam, working with Arup. To secure the project, OMA formed an alliance with the East China Architecture and Design Institute (ECADI), which would act as the local design institute (LDI) of record for both architecture and engineering. Working with an LDI is a statutory stipulation for all projects in China, and the LDI's local knowledge and contacts can make the relationship very beneficial.

'Who says that structure should not be reinvented? ... Who says that reinventing structure cannot be creative?'

Rem Koolhaas, from a discussion at Tsinghua University, 5 August 2003.

The design team

When the SD (scheme design) started, the project was divided between Arup offices in Hong Kong and London. The core team, including six staff seconded from Hong Kong and one from Beijing, was located in London to work closely with OMA in Rotterdam. Given the many engineering disciplines involved, and the need for dedicated project teams for each of the three buildings on the site, Arup had a near-permanent presence in OMA's offices. Four of ECADI's engineers joined the Arup team in London for most of the EPD (extended preliminary design) phase, while their architectural colleagues worked alongside OMA in Rotterdam.

Another Arup team in Hong Kong provided information and guidance on Chinese design and procedures, maintained contact with local authorities and the client, and offered specialist input such as wind and fire engineering. As the design progressed, additional input was received from Arup offices in Beijing and Shenzhen.

This close co-operation proved invaluable in delivering a scheme design within four months and the EPD and EPR (expert panel review) approvals within a further six.

Arup provided engineering and consultancy input for structural, building services, geotechnical, fire, communications, and security design, leading the engineering design through SD, EPD including the associated approvals processes to tender, working with ECADI engineers. ECADI currently leads the production of the final construction information and is to provide site assistance with support from Arup.

1. CCTV in the new Beijing CBD.

Architectural concept

The client stipulated in the competition brief that the facility should all be housed on one site, but not necessarily constrained to one building. In his architectural response, however, OMA decided that by doing just this, it should be possible to break down the 'ghettoes' that tend to form in a complex and compartmentalized process like the making of TV programmes and create a building whose layout in three dimensions would force all those involved – the creative people, the producers, the technicians, the administrators – to mix and produce a better end-product more economically and efficiently.

The winning design thus combines administration and offices, news and broadcasting, programme production and services – the entire process – in a single loop of interconnected activities. The specifics of the structure evolved in tandem with the specifics of the building as they in turn evolved, a notable example being the placement of double-height studios within the Towers and Base, which significantly influenced the structural form.

The public facilities included in the project are located in a second building, the Television Cultural Centre (TVCC); both buildings are serviced from a single support building which houses major plant as well as the site security.

Progress to construction

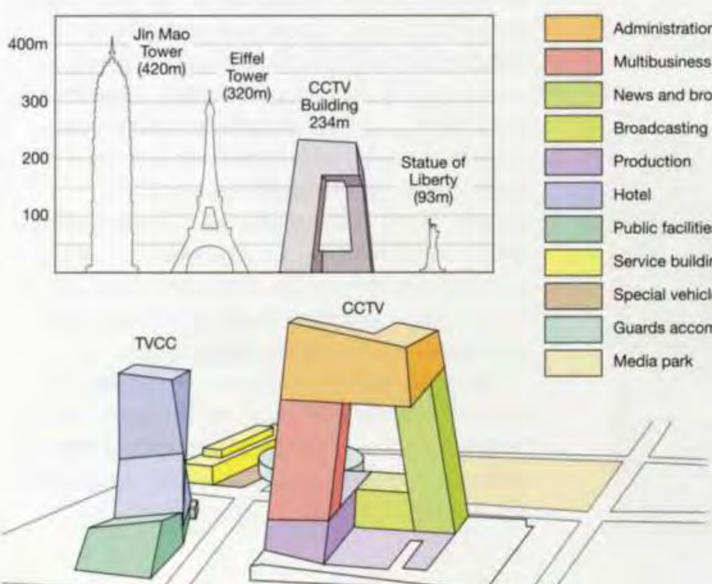
Given the challenging and unprecedented nature of the winning design, the competition was followed by a further period of justification and persuasion, during which Arup applied considerable effort at substantial risk. During the next four months, feasibility studies were made and two key proof-of-concept meetings held between the client's technical advisors and key members of the Arup team. These primarily addressed the safety, buildability, and overall cost of the scheme, and concluded that though there was no precedent for such a building, it could be achieved. Once the client was convinced of this, contracts were signed and the experienced international design team required to deliver the project was mobilized. The official ground-breaking ceremony took place on 22 September 2004, but although construction started relatively recently, it is felt that rather than wait more than three years until completion, the fantastic story of the realization of CCTV should start to be told now. This first article is principally a description of the structural design, analysis, and approvals process for the main CCTV building. Subsequent editions of *The Arup Journal* will contain episodes on the building services and security engineering for the main building, on the TVCC and support buildings, and on the construction process to completion and opening.

The new CCTV headquarters development

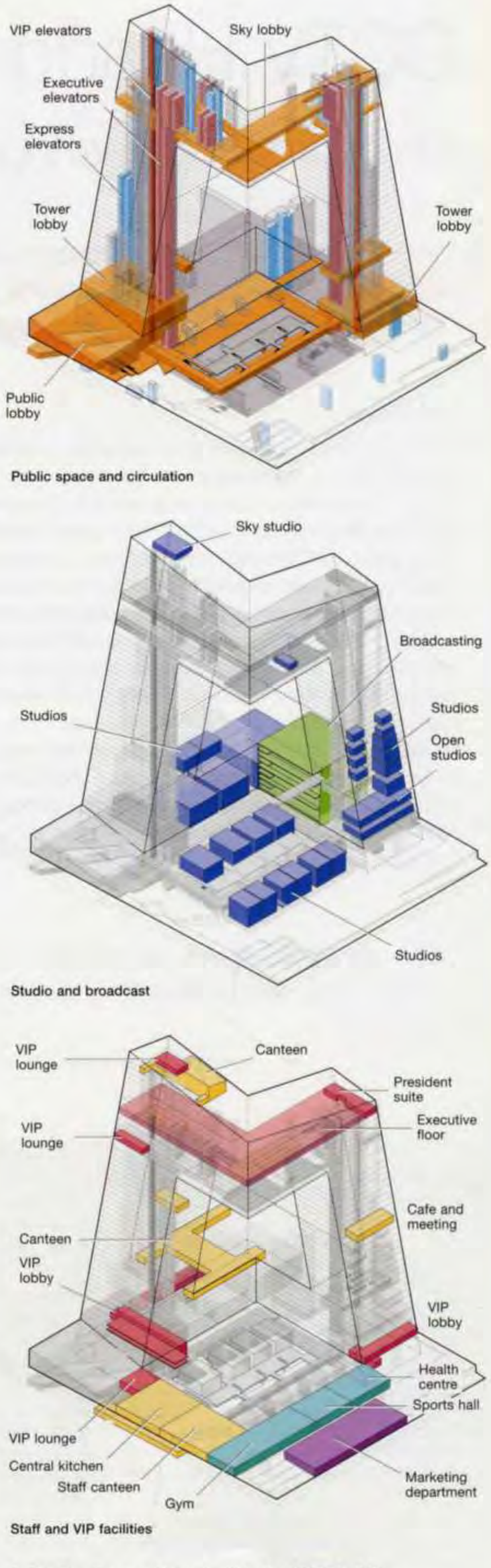
The entire CCTV development has a site area of 187 000m^2 and will provide a total of 550 000m^2 gross floor area. The estimated construction cost is around 5bn RMB (or $US600M), and the project as a whole (Fig 2) includes:

- the China Central Television headquarters building (CCTV building)
- the Television Cultural Centre (TVCC)
- a service and security building
- a landscaped media park with external features.

The 450 000m^2, 234m tall (Fig 3), CCTV building consists of a nine-storey 'Base' and three-storey basement, two leaning Towers that slope at 6° in each direction, and a nine to 13-storey 'Overhang', suspended 36 storeys in the air, all combining to form a 'continuous tube'. Viewed in other terms,the total building form can be seen as four distinct volumes, each approximately the size of One Canada Square in London's Canary Wharf, two of them leaning towards each other from opposite corners of the site, and joined at the top and bottom by the other two, both horizontal and with opposite 90° angles in their middles.



2. The site layout, showing programme distribution.



3. The functions and layout within the CCTV building.

Structural form

Superstructure – the 'continuous tube'

Early on, the team determined that the only way to deliver the desired architectural form of the CCTV building was to engage the entire façade structure, creating in essence an external continuous tube system. Adopting this approach gave proportions that could resist the huge forces generated by the cranked and leaning form, as well as extreme seismic and wind events.

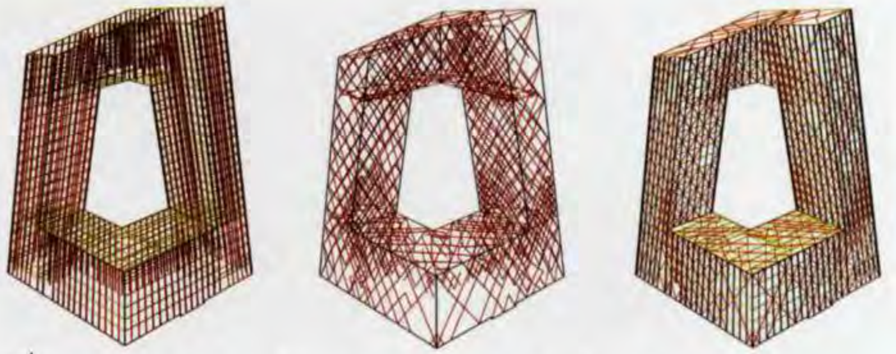
This 'tube' is formed by fully bracing all sides of the façade (Fig 4). The planes of bracing are continuous through the building volume in order to reinforce and stiffen the corners. The continuous tube system is ideally suited to deal with the nature and intensity of permanent and temporary loading on the building, and is a versatile, efficient structure which can bridge in bending and torsion between the Towers, provide enough strength and stiffness in the Towers to deliver loads to the Base, and stiffen up the Base to reinforce the lower Tower levels and deliver loads to the foundations in the most favourable possible distribution, given the geometry.

Vertical cores housing lifts, stairs, and risers are oriented and stepped so that they always sit within the footprint of the sloping Towers. Sloping cores, to allow consistency of floor plate layout, were considered but ruled out due to constraints on the procurement of the lift systems.

In addition to the cores, the floor plates of the Towers take support from many vertical columns. Given the nature of the sloping Towers it is not possible to continue vertical column lines from top to bottom, so a two-storey deep system of transfer trusses is used at approximately mid-height. The floor plates of the Overhang are also supported by vertical columns that are transferred to the external tube structure via a two-storey deep transfer deck (Fig 5).

The continuous tube structure has behind its final irregular arrangement a regular base pattern of perimeter steel or steel-reinforced concrete (SRC) columns, perimeter beams, and diagonal steel braces set out on a typically two-storey module. The regular base pattern was tuned or optimized by adding or removing diagonals and changing brace plate thickness to match the strength and stiffness requirements of the design.

The two-storey base pattern was chosen to coincide with the location of several two-storey high studios within the Towers. A stiff floor plate diaphragm can only be relied on every two storeys, hence lateral loads from intermediate levels are transferred back to the principal diaphragm levels via the internal core and the columns.



4.
Principles of the tube structure: regular grid of columns and edge beams + patterned diagonal bracing = braced tube system.

The braced tube structure gives the leaning Towers ample stiffness during construction, allowing them to be built safely within tight tolerances before they are connected and propped off each other. The tube system also suits the construction of the Overhang, as its two halves will cantilever temporarily from the Towers.

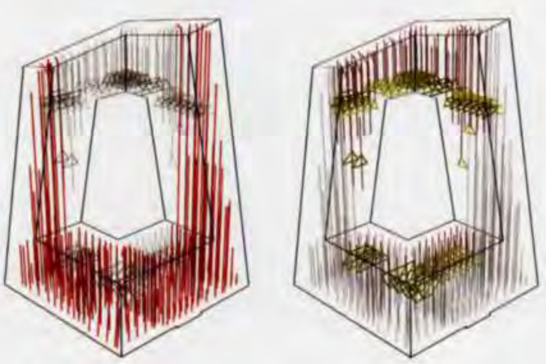
Robustness

The continuous tube has a high degree of inherent robustness and redundancy, and offers the potential for adopting alternative load paths in the unlikely event that key elements are removed. This was studied in detail and provides the building with a further level of safety.

Substructure and foundations

The main Towers stand on piled raft foundations. The piles are typically 1.2m in diameter, and about 52m long. Given the magnitude and distribution of the forces to be transferred to the ground, the raft is up to 7.5m thick in places and extends beyond the footprint of the Towers to act as a toe, distributing forces more favourably into the ground. The foundation system is arranged so that the centre of the raft is close to the centre of load at the bottom of each Tower, and no permanent tension is allowed in the piles. Limited tensions in some piles are only permitted in major seismic events.

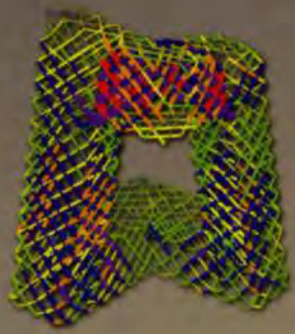
For the Base plus three-storey basement, a traditional raft foundation is used, with tension piles between column locations to resist uplift from water pressure acting on the deep basement. 15-20m long, 600mm diameter tension piles will be arranged under the raft with additional 1.2m diameter piles under secondary cores and columns supporting large transfer trusses from the studio areas (Fig 6).



5.
(a) Internal columns starting from pilecap level.
(b) Internal columns supported on transfer structures.

6.
The foundation system.

7.
Brace stresses for a uniform grid.



8.
Unfolded view of the structure, showing areas to densify or rarefy the mesh.

9.
Models illustrating the development of the façade pattern.

Developing and optimizing the bracing pattern

The diagonal braces within the continuous tube structure visually express the pattern of forces within the structure and are an important aesthetic aspect of the cladding system. The bracing pattern was determined through an intense iterative analysis and in close collaboration with the architect.

The principal structure of the building was modelled in Oasys GSA and representative loading applied, including a static equivalent load for a level 1 earthquake. Initially, a uniform bracing pattern (Fig 7) was adopted, and the SRC and steel columns sized appropriately. The distribution of forces within the braces was then investigated, and the results categorized into three groups with an appropriate action applied to the braces within a particular group:

- densify the mesh by adding braces; 'doubling'
- keep the same
- rarefy the mesh by removing braces: 'halving'.

The structure is highly indeterminate, so changing the bracing pattern resulted in a new distribution of forces within the columns, braces, and edge-beams. Changes in stiffness also changed the dynamic behaviour of the structure and hence the seismic forces that are attracted. Patterning became an extremely involved iterative process.

An unfolded stress pattern view of the structure was developed (Fig 8) to clearly display the results of the whole building in one view, or alternatively folded up into a 3-D model (Fig 9). This enabled the design team to visually process the results quickly, while keeping the architect up-to-date and involved in the development of the pattern.

A performance-based design approach

Chinese approvals process

The legal framework in China governing building design practice is similar to those of Japan and some continental European countries where the design codes are legal documents published and enforced by the state government. Design engineers must comply with the codes when designing buildings and structures covered by their scope, but equally the codes provide legal protection to the design engineers who are relieved of any legal responsibilities by virtue of compliance. The Chinese code for seismic design of buildings (*GB50011 – 2001*), sets out its own scope of applicability, limiting the height of various systems and the degree of plan and vertical irregularities. Design of buildings exceeding the code must go through a project-specific seismic design expert panel review (EPR) and approval process as set out by the Ministry of Construction.

Although the 234m height of the CCTV building is within the code's height limit of 260m for steel tubular structural systems (framed-tube, tube-in-tube, truss-tube, etc) in Beijing, its geometry is non-compliant. The Seismic Administration Office of the Beijing Municipal Government appointed an expert panel of 12 eminent Chinese engineers and academics to closely examine the structural design, focusing on its seismic resistance, seismic structural damage control, and life safety aspects.

Arup realised the importance of engaging the expert panel early in the design process, and three informal meetings were held to solicit feedback and gain trust before the final formal presentation. The panel was under enormous public and state scrutiny to closely examine Arup's design, the rigorous nature of which - aided by successful collaboration with ECADI - was of vital importance. From day one the building received wide publicity in China, and concerns were voiced by both the general public and the government over the safety of the adventurous design - indeed it came to be referred to by the public and the media as 'Wei Fang' (the dangerous building): an indicator of the scrutiny the project and hence Arup were under.

Seismic requirements

As the seismic design lay outside the scope of the prescriptive Chinese codes of practice, Arup proposed a performance-based design approach from the outset, adopting first principles and state-of-the-art methods and guidelines to achieve set performance targets at different levels of seismic event. Explicit and quantitative design checks using appropriate linear and non-linear seismic analysis were made to verify the performance for all three levels of design earthquake.

The criteria for this performance-based design are beyond those usually applied to such buildings in China, and were set by the Arup design team in consultation with the expert panel to reflect the importance of the building both to the client and to the Chinese Government. The basic qualitative performance objectives were:

- no structural damage when subjected to a level 1 earthquake with an average return period of 50 years (63% probability of exceedance in 50 years)
- repairable structural damage when subjected to a level 2 earthquake with an average return period of 475 years (10% probability of exceedance in 50 years)
- severe structural damage permitted but collapse prevented when subjected to a level 3 earthquake with an average return period of 2500 years (2% probability of exceedance in 50 years)

For the CCTV development site, the peak horizontal ground acceleration values associated with the three levels of design earthquake are 7%, 20% and 40% of gravity respectively.

Elastic superstructure design

With the bracing pattern determined from the initial concept work, a full set of linear elastic verification analyses were performed, covering all loading combinations including level 1 seismic loading, for which modal response spectrum analyses were used. All individual elements were extensively checked and the building's global performance verified. Selected elements were also initially assessed under a level 2 earthquake by elastic analysis, thus ensuring key elements such as columns remained elastic.

The elastic analysis and design was principally performed using SAP2000 and a custom-written Chinese steelwork code post-processor, which automatically took the individual load cases applied to the building and combined them for the limit state design. Capacity ratios were then visually displayed, allowing detailed inspection of the critical cases for each member. Due to the vast number of elements in the model – 10 060 elements representing nearly 90 000m of steel and SRC sections – and the multitude of load cases, four post-processors were run in parallel, one for steel columns, one for SRC columns, one for braces, and another for the edge beams that together form the continuous tube. The SRC columns used a modified post-processor to account for the differences between the steel and SRC codes; section properties of these columns were determined using XTract, which also computed the properties for the subsequent non-linear analyses.

Software

Many software packages were used to deliver the CCTV structural design, some developed in house by Arup:

CSI SAP2000: limited non-linear structural analysis and design with static, dynamic and push-over capability

Oasys LS-DYNA Environment: non-linear explicit time history analysis

Oasys GSA: linear structural analysis with static and response spectrum analysis dynamic capability

Oasys Vdisp: plug-in for GSA to analyze non-linear soil stiffness

Oasys GSRaft: iterative non-linear soil-structure interaction analysis

Oasys Compos: composite steel beam and concrete slab analysis and design

Oasys Adsec: composite (SRC) cross-section analysis

Oasys ADC: reinforced concrete design package

Xtract: non-linear large strain composite (SRC) cross-section analysis

MSC/Nastran: heavy duty finite element analysis package

Xsteel: 3-D CAD package.

10. Non-linear finite element simulation model showing local buckling of a typical steel brace.

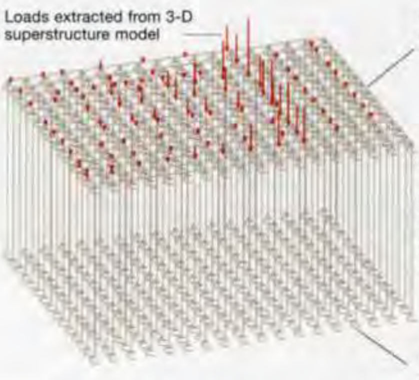
The post-processor provided a revised element list which was imported back into SAP2000, and the analysis and post-processing repeated until all the design criteria were met. As the structure is highly indeterminate and the load paths are heavily influenced by stiffness, each small change in element property moves load around locally. Optimizing the elements only for capacity would result in the entire load gradually being attracted to the inside corner columns, making them prohibitively large, so careful control had to be made of when an element's section size could be reduced and when there was a minimum size required to maintain the stiffness of the tube at the back face.

To further validate the multi-directional modal response spectrum analyses, level 1 time-history checks were also made using real and artificially-generated seismic records.

Non-linear superstructure seismic design and performance verification

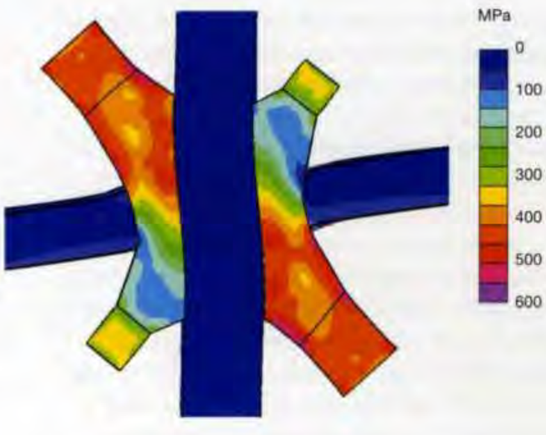
For the performance-based design, a set of project-specific 'design rules' were proposed by the design team and reviewed and approved by the expert panel, creating a 'road map' to achieve the stated seismic performance objectives. Appropriate linear and non-linear seismic response simulation methods were selected to verify the performance of the building under all three levels of design earthquake. Seismic force and deformation demands were compared with the acceptance limits established earlier to rigorously demonstrate that all three qualitative performance objectives were achieved.

Inelastic deformation acceptance limits for the key structural brace members in the continuous tube were determined by non-linear numerical simulation of the post-buckling behaviour. LS-DYNA, commonly used to simulate car crash behaviour, was used for this work. The braces are critical to both the lateral as well as the gravity systems of the building and are also the primary sources of ductility and seismic energy dissipation. Non-linear numerical simulation of the braces was needed to establish the post-buckling axial force/axial deformation degradation relationship to be used in the global 3-D non-linear simulation model. It was also used to determine the inelastic deformation (axial shortening) acceptance limit in relation to the stated performance criteria. Post-buckling inelastic degradation relationship curves illustrate the strength degradation as the axial shortening increases under cyclic axial displacement time history loading. The acceptable inelastic deformation was then determined from the strength degradation 'backbone' curve to ensure that there was sufficient residual strength to support the gravity loads after a severe earthquake event.



11. GSRaft model of the piled foundation.

Having established the inelastic global structure and local member deformation acceptance limits, the next step was to carry out non-linear numerical seismic response simulation of the entire 3-D building subjected to level 2 and level 3 design earthquakes. Both the non-linear static pushover analysis method and the non-linear dynamic time history analysis method were used to determine the seismic deformation demands in terms of the maximum inelastic inter-storey drifts and the maximum inelastic member deformation. These deformation demands were compared against the structure's deformation capacities storey-by-storey and member-by-member to verify the seismic performance of the entire building. All global and local seismic deformation demands were shown to be within their respective acceptance limits, demonstrating that the building achieves the quantitative and hence qualitative performance objectives when subjected to level 2 or level 3 earthquakes.



12.
The von Mises stress distribution of a large connection plate under the most unfavourable loading combination.

Foundation design

The design of the foundations required that the applied superstructure loads be redistributed across the pilecap (raft) so as to engage enough piles to provide adequate strength and stiffness. To validate the load spread to the pile group, a complex iterative analysis process was used adopting a non-linear soil model.

The superstructure loads were applied to a discrete model of the piled raft system. Several hundred directional load case combinations were automated in a spreadsheet controlling the GSRaft soil-structure interaction solver (Fig 11). This procedure iteratively changed the input data in response to the analysis results to model the redistribution of load between piles when their safe working load was reached. The analysis was then repeated until the results converged and all piles were within the allowable capacities. The envelope of these several-hundred analyses was then used to design the reinforcement in the raft itself.

Connections

The force from the braces and edge-beams must be transferred through and into the column sections with minimal disruption to the stresses already present in the column. The connection is formed by replacing the flanges of the steel column with large 'butterfly' plates, which pass through the face of the column and then connect with the braces and the edge-beams. No connection is made to the web of the column to simplify the detailing and construction of the concrete around the steel section.

The joints are required to behave with the braces, beams, and columns as 'strong joint/weak component'. The connections must resist the maximum probable load delivered to them from the braces with minimal yielding and a relatively low degree of stress concentration. High stress concentrations could lead to brittle fracture at the welds under cyclic seismic loading, a common cause of failure in connections observed after the 1994 Northridge earthquake in Los Angeles. Two connections, representing the typical and the largest cases, were modelled from the original AutoCAD drawings using MSC/NASTRAN. The models were analyzed, subjected to the full range of forces that can be developed before the braces buckle or yield - assuming the maximum probable material properties - to evaluate the stress magnitude and degree of stress concentration in the joints. The shape of the butterfly plate was then adapted by smoothing out corners and notches until potential regions of yielding were minimized and the degree of stress concentration reduced to levels typically permitted in civil and mechanical engineering practice. CAD files of the resulting geometry of the joints were exported from the finite element models and used for further drawing production (Fig 12).

Transfer structures

Whilst the external tube structure slopes to give the unique geometry, the internal steel columns and cores are kept straight for functional layout and to house lift and services shafts. This resulted in a different configuration for every floor - the spans from core to façade, and internal column to façade, change on each. Consequently, internal columns can be removed where the floor span decreases sufficiently on one side of the core. Similarly, additional columns are needed up the building height where the floor spans increase significantly on the other side of the core. Transfer trusses support these additional columns, spanning between the internal core and the external tube structure. They are typically two storeys deep and located in plant floors so as to be hidden from view and to minimize the impact on floor planning.

The sizes of the transfer trusses mean that they could potentially act as outriggers linking the external tube to the internal steel cores - undesirable as this would introduce seismic forces into the relatively slender internal cores. The design preference is to keep all the seismic forces in the more robust diagrid framing of the continuous tube. The transfer trusses are thus connected to the internal cores and the external columns at singular 'pin-joint' locations only. Detailed analyses were made to ascertain that no outrigger effects result from the transfer truss geometry.

13. One of several construction sequence loading arrangements considered.

The floors cantilevered from the two leaning Towers to form the Overhang are enclosed by the continuous tube structure on the outside. This supports a two-way transfer deck in the bottom two storeys of the Overhang, carrying the columns for the floors above.

The Base also contains major transfer trusses, spanning over the principal studios to support the columns and floors above.

Construction issues

The building's unique form necessitated careful consideration of the construction method throughout the design process. Both the method and sequencing of the works (Fig 13) will affect the permanent distribution of dead load through the continuous tube.

To allow the contractor some flexibility in method and programme, upper and lower bound analyses were performed, using staged construction and loading to build up the final dead load incrementally. The lowest bound of loading when the two Towers are connected puts the highest stresses into the Overhang structure since it acts as a prop between the Towers, while the upper bound puts the largest stresses into the Towers since they carry more of the load in bending as a cantilever. Between these two extremes there is scope for the contractor to choose his programme, and to propose alternative erection procedures.

The timing of the connection between the Towers is also important, so as to minimize the relative movement between them from thermal and wind effects. It is also important to minimize future thermal movements between the Towers that could put large stresses into the Overhang where it is restrained by the Towers.

14. Site work begins, September 2004.

Conclusion

The structural design of CCTV posed many technical challenges to the large international team. They were successfully overcome, within a very tight programme. Arup's unique global depth of experience and knowledge made this possible, enabling the right people to be involved at the right stages of the project. The Arup team delivered the design through a seamless global collaboration, transcending time zones, physical distance, cultures, cost centres, and even the SARS outbreak. Foremost in the team's collective mind was the need to deliver the complex design on time for the client and in so doing win the approval of the Chinese Ministry of Construction expert panel.

Credits

Client: China Central Television **Architect:** OMA Stedebouw BV **Geotechnical, structural, MEP, fire, and security consultant:** Arup - Abdel Ahmed, Chuan-Zhi Bai, Cecil Balmond, Carolina Bartram, Chris Carroll, Wayne Chan, Mark Choi, Dean Clabrough, Paul Cross, Roy Denoon, Omar Diallo, Mimmy Dino, Xiaonian Duan, Gary Ge, Craig Gibbons, Sam Hatch, Guo-Bo He, Xue-Mei He, Colin Ho, Goman Ho, Yi Jin, Jonathan Kerry, Michael Kwok, Francis Lam, Peter Lam, Richard Lawson, Alexis Lee, Jing-Yu Li, Zhao-Fan Li, Ge-Qing Liu, Peng Liu, Quan Liu, Pierre Lui, Man-Kit Luk, Andrew Luong, John McArthur, Rory McGowan, Hamish Nevile, Gordon Ng, Xiao-Chao Pang, Jack Pappin, Steve Peet, Bill Peng, Dan Pook, Chas Pope, Qun Shi, Andrew Smith, Stuart Smith, Derek So, G Y Sun, George Thimont, Alex To, Fei Tong, Paul Tonkin, Ben Urick, Bai-Qian Wan, Yang Wang, Will Whitby, Robin Wilkinson, Michael Willford, Michelle Wong, Stella Wong, Eric Wu, Jian-Feng Yao, Angela Yeung, Kenneth Yeung, Terence Yip, George Zhao, Julian Zheng (analysis, geotechnical, structural) **Illustrations:** 1, 9 ©OMA; 2 Nigel Whale; 3 -14 Arup

The next article in this series, discussing the building services design of the CCTV development, will appear in *The Arup Journal* 3/2005.

The Scottish Parliament Building, Edinburgh

David Hadden Don Henning Patricia Johnstone
David Lewis Duncan Richards Alan Tweedie
Simon Webster Robin Wilkinson

From the contemplative seating in the façade to the innovative shape of the debating chamber, this is a building for the people.

2. Window seat in MSP's office.

1. The debating chamber.

Project background

HM The Queen officially opened the Scottish Parliament Building (SPB) in October 2004 after six years' design, construction, and debate - principally about time and cost. The end result has received much acclaim from critics and journalists, as well as many thousands of visitors, supporting the intention for the SPB to be a building for the people. From the innovative shape of the main debating chamber (Fig 1) to the contemplative seating in the façade of the MSPs' (Members of the Scottish Parliament) offices (Fig 2), the vision of the Spanish architect Enric Miralles has been realized, despite his untimely death.

Located at the opposite end of the Royal Mile from Edinburgh Castle, and close to Holyrood Palace, the site encompasses an area of 1.45ha within the old road boundaries that houses the new buildings, plus a further 1.86ha of new landscaping. It also contains the listed Category A Queensberry House, where the original 1706 articles of the Union between England and Scotland were established. It is poignant that self-determination for Scotland has now been established and will be practised here, within an ensemble of individual buildings (Figs 4 & 5) that contain offices and support for the MSPs, committee rooms, media facilities, and the debating chamber, all above a common basement area.

In a referendum on 11 September 1997, almost 75% of Scottish voters agreed that there should be a Scottish Parliament, and this result led to the search for a permanent home. Holyrood was selected, and an international competition launched by the UK government Scottish Office on

26 January 1998 to select a design team. From over 70 expressions of interest, five were short-listed and asked to produce indicative design ideas. The contenders were Rafael Vinoly, Michael Wilford, Richard Meier and Keppie Design, Glass Murray & Denton Corker Marshall International, and Enric Miralles Benedetta Tagliabue (EMBT). On 6 July 1998 the team headed by the latter was chosen. Later, after the Scottish Parliamentary elections, the Parliament itself became the client.

After the initial competition rounds, the architectural practice RMJM joined EMBT in a joint venture to provide local expertise. Arup supported EMBT/RMJM throughout the competition and was appointed as structural engineer. Later, this was supplemented by additional consultancy commissions in blast, well water studies, façade engineering, and civil engineering/landscaping. In January 1999, Bovis Lendlease was appointed as construction manager.

4. Computer image of main buildings.

Working partnerships

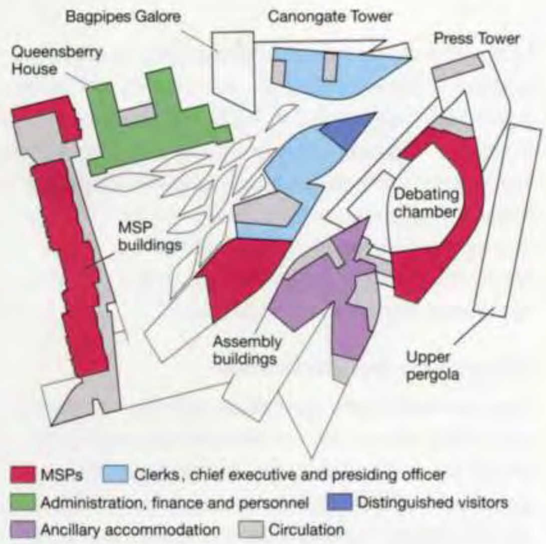
A joint venture company was formed between EMBT and RMJM in Edinburgh, with the intention of carrying out the design in Edinburgh, but in practice Miralles created it from his studio in Barcelona. Throughout the first year, Arup team members travelled regularly to Barcelona to visit him and discuss the structural designs. His chosen way of working, which suited the complex shapes he was intent on creating, was to produce physical models, ranging from the whole site at small scale in polystyrene to large-scale details in balsa wood.

Although frustratingly difficult to pin down, Enric Miralles was a very charming man, who constantly sought to improve his designs despite programme pressures. It was with great shock that the team learnt of his death from a brain tumour in summer 2000. By then he had established the arrangements, the massing, and the feel of the buildings – the use of fair-faced concrete throughout, the carefully configured sightlines through the seemingly complex arrangements – and Joan Callis, his right-hand man, defended these principles throughout the remainder of the project.

Arup's Edinburgh office and a London group collaborated closely on the structural design. The former was mainly responsible for the geotechnical work and basement design, the refurbishment of Queensberry House, 'Bagpipes Galore' (a former shop whose retained façade would front a new building behind), and the roads and landscaping. The London group designed the superstructure for the new buildings – The MSP office building, the Assembly buildings, the debating chamber, a further new building along Canongate, the road that bounds the site to the north, and the decorative canopies, as well as the scheme design for the glazed MSPs' foyer linking the buildings (Fig 3). Both teams also liaised closely with Arup Security Consulting.

Whilst London staff travelled to Edinburgh for scheduled meetings and day-long design sessions, it was of great value that the Edinburgh office and the resident engineer could cover all other meetings, on site or with the architects, and deal with site and design issues at short notice.

3. Architect's image of the MSPs' foyer.

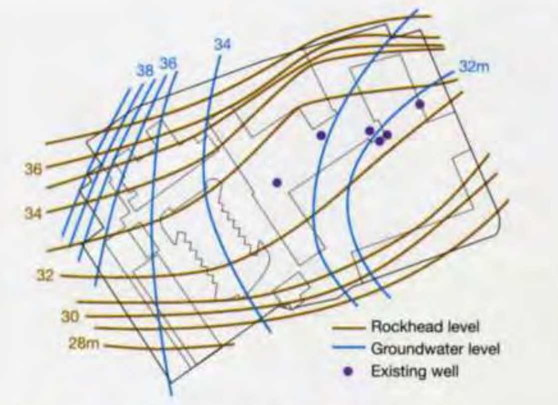


5. Site plan.

The site

Site history

Prior to the SPB, the site was divided into two distinct areas, the Scottish & Newcastle Brewery to the east and Queensberry House and its gardens to the west. The east area had long been associated with brewing, with William Younger II purchasing part it in 1825 for £5000. By the late 1870s five wells were extracting groundwater for brewing, and records indicate that water was pumped at a rate of 4000 –14 000 litres/hour in 1938. Extraction ceased in the 1960s. Queensberry House itself was built around 1670. After a series of alterations and changes of ownership it was bought in 1801 by William Aitchison, who stripped it of its fittings and fixtures. Two years later it was sold to the Board of Ordnance and the site was developed as a barracks and hospital block with a parade ground on the site of the former garden. It was then that another storey was added.



6. Conjectured rockhead levels, groundwater levels, and existing wells across the site.

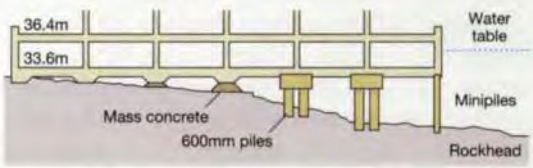
From 1815 onwards it was successively a public hospital, a House of Refuge, and a geriatric hospital until it was finally closed in 1996 and bought by Scottish & Newcastle Breweries. Its varied life had a significant impact on the building fabric's structural integrity, and it was in poor condition when handed over to the Parliament. In 1997 Scottish & Newcastle made Queensberry House and the land to the east available for the new SPB.

Site geology and groundwater

The site stratigraphy comprises drift deposits (sand, gravel, silt) above rock; to the west lies sandstone and to the east volcanic basalt. Rockhead levels generally fall from Canongate to Holyrood Road, and particularly significant for the foundation design was the sharp dip in rockhead level in the south-west corner, down to 6m below foundation level.

Conjectured groundwater levels were plotted and taken as the base values for design and construction. During the site investigation, groundwater levels were recorded and subsequently confirmed during regular monitoring of water levels within standpipes located strategically throughout the site. Design groundwater levels are taken in the long term to be 2m above the current measured values to allow a factor of safety against future rises in groundwater level; the high levels in parts of the site influenced the structural design, in particular requiring the use of tension piles where buoyancy exceeded the applied dead loads.

7. Foundation strategy.



Existing and new wells

Out of 20 wells found on the main brewery site (Fig 6), six main ones, up to 3m in diameter, had shafts up to 44m deep with bores up to 100m deep. To enhance water extraction rates for brewing, these wells were connected to each other, mostly by headers (horizontal culverts) 6m deep, though two were linked by horizontal mines at 18m and 23m depth respectively. As they were concentrated beneath the new debating chamber, great care was taken to expose and infill the wells and co-ordinate foundations to avoid them.

Given the site's successful extraction history, Arup proposed to the client that well water might provide a sustainable supply for the SPB. The firm was appointed to produce a feasibility study and hydrogeology report to assess the viability of this proposal, and analyze the impact of any groundwater extraction on the surrounding area. As a result, two new boreholes were sunk which yield around 5000 litres/hour each. Together with a buffer tank, they provide cooling water and grey water for building services.

Basement and foundation construction

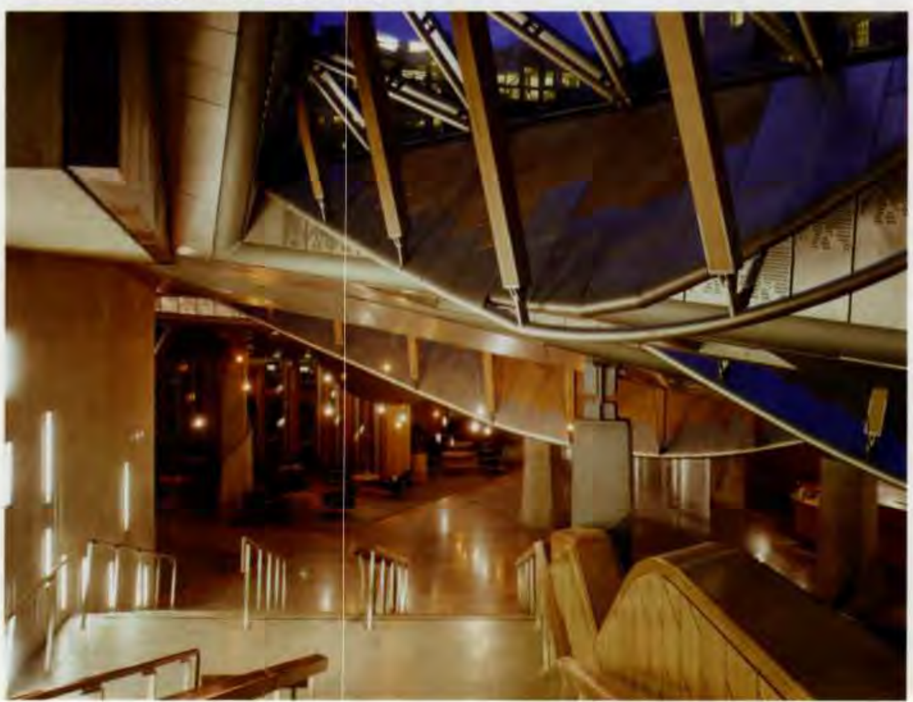
This involved excavation to depths of around 4m in the west and 7m in the east, where the plantroom areas below the debating chamber and Assembly towers are located. A hard/soft secant piled wall was used for much of the excavation perimeter to minimize movement felt by surrounding structures and to prevent groundwater entering. To the east, an open battered excavation sufficed, as groundwater levels are lower and there are no adjacent structures.

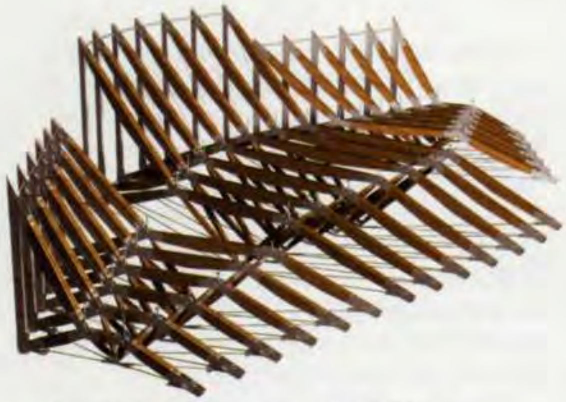
Piled walls retaining Queensberry House were designed to limit movement behind to 10mm horizontally and 5mm vertically, due to the listed building's sensitivity. During excavation a programme of regular monitoring was established to record any movements.

The foundations are typically pad footings, bearing on rock exposed during excavation. Where rock levels lie up to 2m below the underside of the pad foundations, mass concrete was infilled between pad and rock. Only in the south-west corner were piles used, due to the low rockhead level (Fig 7).

The basements, which lie below the water table, are defined in the client brief as a Grade 2 (better utility) space, in line with *BS8102*. This requires no water penetration and to achieve this, the basement slabs were designed as a watertight concrete structure with crack widths limited to <0.2mm. The external retaining walls are not designed as watertight concrete but as a drained cavity wall.

8. Stairs leading down to the MSPs' foyer.





9. Computer model of the debating chamber roof.

11. Committee room.

The new buildings

The public entrance and debating chamber

The main public foyer is on the east side, opposite Holyrood Palace, and contains an exhibition, information facilities, and a retail outlet. As the 'parliament of the people', the SPB opened its public areas in September 2004, complete with guided tours. By the end of November more than 130 000 people had visited the building, making it a considerable tourist attraction in its own right.

The foyer is characterized by its high quality fair-faced concrete finishes and, in particular, three in situ reinforced concrete vaults with random saltire crosses and irregular light wells, each having an individual geometry with a tapered plan section, making it unique in construction terms. They form a dramatic ceiling (Fig 14), and contrast with the light and airy spaces beyond. The vaults rest on three main steel beams supported by high quality precast columns, also of unique shape and form, which required them to be cast offsite and upside down. All the concrete, whether precast or in situ, was produced from consistent materials to ensure a correct colour match.

10. Model of the Assembly buildings.

The debating chamber (Fig 1), some 49m long and 25m maximum width, is immediately above the public foyer. The floor is a major steel grillage that both acts as a transfer structure to cope with the variable column positions above and below this level, and allows the chamber to cantilever beyond the ground floor structure and support the heavy façade and its finishes, designed to withstand terrorist action. This floor is stepped and integrates the supply air systems and complex electrical installations within its depth, as well as supporting various mezzanine levels and the public galleries. All finishes are in oak and this theme is extended upwards to the roof structure and ceiling arrangements.

Spanning across the entire space is a roof supported on major three-dimensional timber trusses with stainless steel ties and connections (Fig 9). This structure is entirely sculptured and its geometry required unique nodes and bracing systems. The roof extends further skyward on its western boundary, forming large roof-lights that allow in considerable natural daylight. In keeping with Parliamentary strength and longevity, the roof materials are of the highest quality - European oak for the glu-lam compression members, and stainless steel for all other elements.

The roof geometry coheres with the chamber shape by having the trusses arranged in three distinct groups, separated by discontinuity zones with changes of ceiling level. This ceiling level is set above the trusses, with a steel purlin roof again above, carrying the final roof finishes. The trusses are supported on a tri-girder at the rear of the chamber and on external concrete-clad steel columns at the inner façade. These columns extend like cathedral buttresses from the bottom of a basement light well to the top of the structure. The combination of exposed structure and high quality finishes forms a dramatic space for the Parliament to conduct its business publicly and openly.

Assembly buildings

The Assembly buildings (Fig 10) accommodate the committee rooms and support facilities where most Parliamentary business is carried out - an ensemble through which the MSPs pass at first floor level from their garden to the debating chamber. Miralles likened the Assembly buildings' external appearance to upturned boats on a Scottish shore; their geometry and interaction with each other is subtly complex and the roofs especially so, with stepped double curvatures, achieved by structural steelwork, reflected in the internal ceilings to give an ecclesiastical ambience (Fig 11). These spaces contribute to encouraging collaboration rather than confrontation.

The buildings are designed in post-tensioned reinforced concrete, principally to achieve clear spans of up to 14m with structural depths of 350mm, thus providing column-free spaces with minimum floor heights allowing integration of the building services. The leading points of the buildings are truncated at the lower levels and cantilever significantly from the main body. The floor structures and shear walls act together to achieve these cantilevers, which enhance the spaces thus formed at the ground floor.

12. Entrance to the Canongate building showing the first floor cantilever and the Zen Garden.

The Canongate buildings

The Canongate buildings abut the formal entrance that allows the public to view the buildings and look into the MSPs' foyer, and complete the perimeter of the northern boundary. The wall is of precast concrete elements embodying several scribed panels, masonry units from the original buildings, and a reproduction of a drawing of Edinburgh Old Town made by Miralles during his first visit to the city.

Above the entrance the building cantilevers by up to 14m, achieved by integrating a double-storey height vierendeel truss on both sides into the façades. The trusses are in steel to minimize creep deflections, and also support secondary steel beams spanning between them to provide column-free space inside. The steel I-sections forming the trusses have concrete cast into and between their flanges to create a high quality exposed finish between the windows on the interior side, consistent with the concrete finishes throughout the rest of the Parliament. Post-tensioned anchorages secure the steel structure to the reinforced frame behind, controlling deflection and dynamic movement. The roof comprises steel beams, close-centred purlins, and profiled metal decking designed for blast protection.

At first floor level on the Canongate side, a balcony known as the Zen Garden is supported by steel beams cantilevering from the north vierendeel, with posts for the balcony wall in turn cantilevering vertically.

The Canongate building is directly adjacent to the road and has therefore been designed for bomb-resistance. Arup Security Consulting provided equivalent static forces for the design after assessing the building's stiffness. The forces are resisted by plate action of the slab, and thick reinforced concrete core walls. The building is founded on large pad foundations bearing directly on rock, and under the cores, the mass of concrete has been increased to resist uplift from high lateral loads.

The MSP building

The 129 MSPs work in a six-storey linear building parallel to Reid's Close along the site's western edge. Their cell-like offices (Fig 13), each with a protruding window seat, are along the western façade, and corridors along the eastern edge, with views of the garden and the MSPs' foyer, connect them to cores at each end of the building. An additional escape stair, cantilevering from the building side at its midpoint, links the top three floors to an escape corridor at the third floor connecting to the south core. The cores also give access to the garden level and the basement car park below.

The office structure comprises in situ reinforced concrete portal frames supporting precast concrete vault units that form the ceilings and support the floor finishes. Alternate portal frame beams cantilever beyond the office columns by up to 3.5m to support the 300mm deep in situ reinforced concrete corridor slab. The vault cross-section has surface recesses for services distribution and soffit recesses at the bearings, to achieve the architect's desired effect of the vault seeming to hang in mid-air rather than bear onto its supports.

The client preferred in situ concrete to precast for a more robust building, so the precast vault details include an in situ stitch allowing full anchorage and ties, so as to achieve the necessary robustness. The south core is close to the road, exposed to the risk of blast, and designed for lateral forces far greater than normal, with the outer wall specially reinforced to prevent a local breaching. Blast also influenced the design of the western façade's precast backing panels, which needed careful reinforcement detailing to achieve the required degree of blast resistance in thin panels with a large irregular opening.

13. Computer-generated view of an MSP's office.

14. The public foyer concrete vault seems to hang in mid-air.

15. Upper and lower pergolas and the north-east canopy.

Canopies and pergolas

The main public entrance is framed by a complex of three structures, the upper and lower pergolas and the north-east canopy (Fig 15). Both pergolas are supported by conical 'flame-shaped' columns that match others in the SPB. Their stocky forms act as cantilevers and resist moments from the upper pergola. The columns are carried on pad footings designed to resist overturning moments.

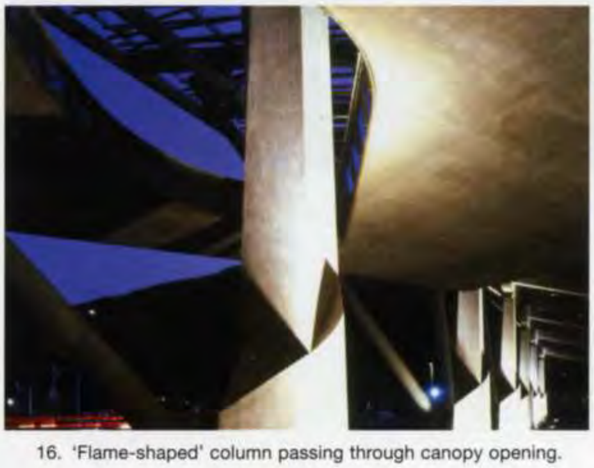
The upper pergola is a 58m x 9m grillage of stainless steel hollow sections covered by a random arrangement of 'bamboo' (actually Scottish oak), suspended 6m - 8m above ground by raking stainless steel hollow sections. The pergola acts as a vierendeel on plan to take the horizontal forces to the flame-shaped columns and the raking props cast into them. Ties from the tips of the flame-shaped columns to the tips of the raking columns were introduced to control the deflections at the extreme ends of the pergola, where the cantilever length is around 9m.

The 'lower pergola' is a grillage of fair-faced concrete beams running along the whole east façade of the SPB, approximately 5m above ground level. This was designed to be constructed in situ but was re-designed in conjunction with the contractor as precast beams.

The north-east canopy is a concrete slab, curved in section and cantilevering up to 9m from the building, taking its principal support by hanging from the pergola above it and with its backspan disappearing into the main building. It is further complicated by the presence of an opening, through which one of the flame-shaped columns passes, thus preventing the canopy taking direct support from the column (Fig 16).

Although the canopy would deflect significantly under dead load, this was not seen as a problem as no partitions, cladding, or other fittings were affected, and the already curved shape made the deflection visually insignificant. The canopy was designed for a live load of 1.5kN/m^2, with a deflection limit of span/500 in case of unintentional pedestrian loading, perhaps from political protesters!

The architect required the canopy and the lower pergola to have exposed concrete to all faces. This had to be considered in conjunction with the requirement for a 100-year design life, and concerns about the long-term appearance of the concrete when viewed from overlooking windows finally led the architect to agree to cladding the upper surface of the canopy. For the lower pergola beams stainless steel reinforcement was specified, to reduce the risk of unsightly staining in this highly visible structure.



16. 'Flame-shaped' column passing through canopy opening.

Façades

Introduction

Arup Façade Engineering (AFE) was initially appointed for three months to support EMBT/RMJM on two critical cladding packages, the foyer roof and the specialist glazing, but its involvement grew into other areas of the project. Ultimately three separate teams were contracted for the MSP building elevations, the precast concrete elements, and the next phase of the specialist glazing and foyer roof packages.

Foyer roof

Previous work on Portcullis House, Westminster, with its many similarities in design life requirements and bomb blast protection, was extremely valuable, whilst designs developed for the 'lens' at City Hall, London, also proved useful in achieving the required flush outer glazed face that would also deliver good panel retention against lateral loads. The design principles progressed through workshops with Mero, the specialist glazing subcontractor, and were then developed through detailed design with Arup Security Consulting. The installed cladding (Fig 17) is largely unchanged from these initial principles.

17. External view of foyer roof.

18. Feature panels on the façade of the Assembly tower.

Specialist glazing

This had a much wider scope than the foyer roof package, including glazing to the debating chamber, the bridge that links it with the Assembly towers, and the complex shapes enclosing the public stair from the foyer to the end of the bridge. In addition to specific blast requirements for the specialist glazing, the walls and rooflights to the debating chamber also had very onerous acoustic performance criteria to limit road noise penetration. The eventual design employed double-glazed units, with acoustic damping and blast protection performance, built into the laminated unit construction, combined with acoustically enhanced curtain-walling profiles. This system is one of the best performing double-glazed walls yet developed, and was empirically tested prior to manufacture, to demonstrate performance in practice.

MSP building

Originally tendered as one package, the east and west façades were repackaged into different elements including the timber windows, structural steelwork, stainless steel, concrete mullions, timber louvres, and stone. Interfaces between the packages and the wide palette of materials were further complicated by variations in detailing throughout the façade, which affected the weathering line of the envelope. Combining the demanding bomb blast requirements with effective thermal performance involved extensive use of condensation risk analysis. The team also advised on other features, including rooflights and the tower windows.

Precast concrete

The cladding to the debating chamber, press tower, and boundary walls was technically very challenging, and required AFE involvement throughout. A key issue was its behaviour in the event of a blast - the panels have to stay on the building! Others included the complex geometry, fixing, buildability (and handling), and many intricate interfaces with other façade elements. Aspects considered in the designs included durability, robustness, weathertightness and interface with the weathering envelope, and thermal performance. The cladding also includes fenestration elements such as large feature panels (3.5m to 5.5m high) of granite and oak louvre grills (Fig 18), and bamboo panels fixed onto steel carrier frames that stand proud of the precast cladding (Fig 19). Bespoke concealed brackets and fixings were designed and fabricated to accommodate the different tolerance requirements,

19. The complex façade assemblies dramatically contrast with the rugged natural backdrop.

dimensional variations, and movements between the precast and steel elements. Other features include cast-in natural stone, and intricate architectural face mouldings, formed with rubber mats. AFE worked closely with the architects in assisting to review the sub-contractors' design development, production, installation and quality control, all aiming to achieve a high quality, architectural precast cladding envelope.

Canongate walls

At several places in the Canongate boundary walls, the architect designed panels of natural stone inset, and in places recessed, into the precast faces. Some were cast in, which required care to avoid blemishes. The other method was to post-fix the stones into cast recesses, where the challenge was to ensure secure and robust fixings. Many of the natural stones were hand-carved with inscriptions or patterns (Fig 20), and the Canongate boundary walls as a whole, with these intricately shaped and sculpted inserts, required complex structural support and casting techniques.

20. The Canongate boundary wall.

Blast consultancy

Introduction

In December 1998 a meeting took place between the architect, Arup's structural team, and the Government Buildings Counter-Terrorist Protection Advisor to discuss how protection against terrorist bomb attack could be incorporated into the design. The need to add a blast consultant to the project team was subsequently agreed with the client, who noted Arup's capability in this field and asked for a proposal to advise the design team.

In March 1999 a two-stage blast consultancy appointment was added to Arup's involvement. Initially this work was centred in another of the London groups, where experience of blast effects had been enhanced by extensive involvement in the aftermath of the city's major vehicle bomb attacks of the early 1990s[1]. The later stages of the blast consultancy were conducted under the banner of Arup Security Consulting (ASC), formally launched in July 2001.

The initial blast consultancy scope included:

- liaison with Government security advisors
- outline guidance to the design team on blast-resistant design
- review of scheme design proposals with respect to blast protection
- working sessions with the design team on blast-related issues
- advice on blast-resistant design for incorporation into the architect's design intent drawings and specifications for elements of the façade.

Subsequently the following were added:

- ongoing reviews of the design team's developing design and tender documentation
- review of tenderers' and contractors' submissions with respect to blast issues
- site inspection of selected elements of the building envelope with respect to blast protection.

In due course ASC's involvement extended to include regular onsite workshops with the architect, construction manager, and subcontractors whose work packages included blast protection measures.

Application of blast protection measures

Government security advisors identified zones of the complex in which 'standard measures' for blast would apply and others where 'enhanced measures' were deemed necessary. In the former, the initial approach was to adopt, where possible, relatively straightforward design rules for structures and façades without the need for complex blast analyses. In 'enhanced measures' areas, these

21. Test arrangement for MSP building west elevation window.

design rules were to be augmented by explicit analysis of structures and façades under blast loading, which itself was to be derived from a specified weight of explosive material and a stand-off distance appropriate to the element under consideration. While for a more conventional building the prescriptive 'standard measures' approach might ensure an acceptable degree of occupant protection, the challenging geometry and palette of materials of the SPB meant that a more rigorous approach was often necessary, and not only in the 'enhanced measures' zones.

To evaluate the intense but very short-lived airblast pressures created by a high explosive detonation, extensive use was made of ConWep[2], a US military program to which ASC has access through its involvement in UK Government projects. ConWep's blast pressure time-histories were used to analyze dynamically the global behaviour of complete structures, or local effects on individual building elements or areas.

The approach was not to seek to avoid damage entirely under these extreme conditions, but to ensure that it was within acceptable limits that would still provide appropriate protection to building occupants. The analysis and design of structural elements in steel and concrete was based on US methods[3], while assessment of glazing behaviour under blast load drew on the analytical procedures and extensive database of test results built up by the UK Government's own explosion protection team.

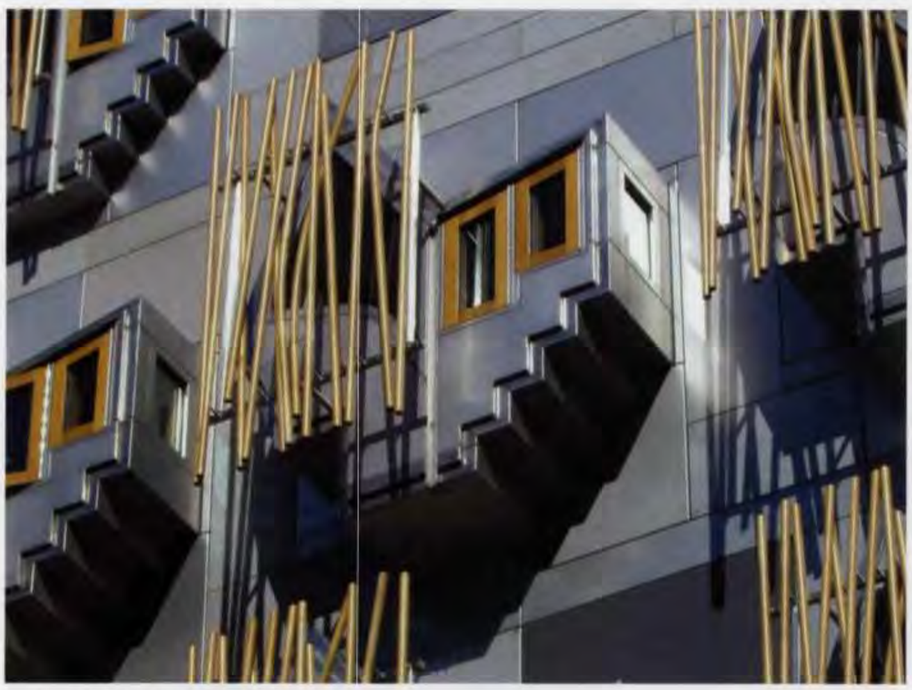
Windows

In buildings for which blast protection is a design criterion, glazing is often the most critical issue in mitigating potential hazard to occupants. At distances from an explosion where human bodies may survive airblast effects without serious harm, glass fragments can cause severe, even lethal injuries. The value of laminated glass in mitigating fragmentation is well established and its use in the innermost leaf of all external windows is now mandatory for new UK Government buildings. A library of proven blast-resistant glazing configurations exists for conventional fixed windows over a limited range of sizes, but the challenge at SPB was to achieve similar levels of performance in windows with unique geometries or which used natural materials and in some cases had to be openable for maintenance or to provide natural ventilation. Through close collaboration with the architect, trade contractors and AFE, solutions were developed to match these apparently conflicting requirements with EMBT/RMJM's aesthetic objectives.

Conceptually, openable windows seem contradictory to blast protection. However, as natural ventilation was fundamental to the design of certain parts of the building, workable solutions had to be found. 'Slam-shut' windows, which can be opened outwards a limited amount for ventilation, were developed in which the openable casement would be forced to close by the blast shockfront. Leakage studies were made of the likely internal pressures from the external design explosion should the casement somehow be prevented from closing. These showed that although internal pressures immediately inside the windows would inevitably be high, they would quickly fall to values below the recognized threshold for eardrum rupture. In the few locations where this criterion could not be achieved, mechanical ventilation was introduced.

Blast testing of windows

Designs for many of the windows and other glazed elements of the building envelope were developed with confidence in their performance under blast loading. In certain cases, for example windows with irregular glazing shapes or timber frames or 'slam-shut' configuration, full-scale physical trials were carried out to prove their blast resistance.



22. MSP building west elevation window.

The arrangements generally adopted for such range tests involve attaching the test sample to the open front of a closed cubicle to prevent the blast wave from wrapping around the target and applying a relieving load on its rear face (Fig 21). The SPB trials, which ASC supervised, identified weaknesses in certain localized details but ultimately through successful tests proved the 'blastworthiness' of the final designs (Fig 22).

9/11 and The Holyrood Inquiry

The attacks on the World Trade Center and the Pentagon on 11 September 2001 were undeniably defining moments in the history of terrorism. They, and subsequent world events, have profoundly influenced perceptions of risk and concerns about security. The UK has a lengthy history of terrorist attacks, not least against government-related facilities and, as noted earlier, the requirement to provide blast protection was included in the 1998 brief for SPB and the blast consultant's role was established well before 9/11. After it, the principles of occupant protection against terrorist attack remained fundamentally unchanged – a point recognized by Lord Fraser in his Inquiry[4]: '*...I am persuaded by the evidence that the events of 11 September 2001 were not the catalyst to a wholesale review of the security requirements on the site nor were they responsible for an escalation in the standards of protection required to meet a previously unforeseen terrorist threat.*'

In his Inquiry Lord Fraser decided to consider security issues but elected to do so by taking evidence in camera from those most closely involved in this aspect of the project, including ASC. Commenting on how the blast consultant's task was fulfilled, Lord Fraser was '*satisfied as to the thoroughness and professionalism with which this work was undertaken by those involved*'.

23. Wall stitching with grouted anchors: length, number, and position dependent on structural condition.

24. Queensberry House after refurbishment.

Refurbishment and landscaping

Queensberry House

Because of the age and history of Queensberry House, Historic Scotland wished to retain and incorporate as many existing floors and joists in the refurbishment as possible. However, its poor condition, the many alterations, and the need to carry modern office loads and provide blast resistance, resulted in just two timber floor areas being retained. All others were replaced with a modern concrete and steel floor system, as thin as possible to allow finished floors to match existing door thresholds and stairs without the ceiling dropping below the tops of the windows. Holes in the beam web allow service ducts and pipes to pass through to avoid providing a separate service zone beneath. The new floors provide robustness and diaphragm action as well as acoustic and fire separation, and add strength, durability, and dynamic performance.

The walls within Queensberry House are generally stone-built, rubble-filled, and up to 700mm thick, but in many places alterations had resulted in brick and blockwork being introduced as new openings were formed or existing ones closed off. This also led to a variety of lintels, with precast concrete or steel joists alongside the original timber ones, or openings without lintels at all. Cracks became evident once plaster and finishes were removed. Some had formed during earlier additions, and unbridged butt joints had opened up due to settlement and movement.

Major remedial works were needed. The outer and inner wall leaves were tied together with special grouted anchors for local strengthening, and wall panels were similarly connected into return walls to ensure overall stability. The latter was mostly where later extensions were built with no ties to the original frame; the new anchors bridge the old butt joints, tying the various elements together (Fig 23).

Such major works on Queensberry House were not originally intended, and additionally the team was instructed fairly late to design the new/old roof (Fig 24). The final appearance of the roof was based on a contemporary sketch of the Edinburgh skyline discovered after extensive archaeological research, together with other old artworks, further buildings of the era by the same architect, and anecdotal evidence.

25. The SPB in its setting of new landscaping.

Landscaping

Landscaping spills out from the built area of the site into the park south of Holyrood Road. As well as roadworks within the park, upgrading two roundabouts and Queens Drive to cater for increased traffic flow once Holyrood Road was closed to public traffic, significant earthworks were needed to establish new topography south of the site and east of the neighbouring Dynamic Earth building. The result is publicly accessible landscape, with embankments, canopies, water features, cycle paths, footpaths, hard areas, newly-planted trees, and indigenous flora (Fig 25).

Level differences within the new landscaped areas were of paramount architectural importance and were achieved using stone encased behind a steel mesh. Corrosion, weathering, durability, and structural stability all had to be addressed in developing a solution for the Scottish climate. Dressed stone in properly designed, specified, and constructed gabion baskets met all the design criteria for retaining purposes.

26. The garden landscape.

Conclusion

These fascinating and highly varied buildings are characterized by two common themes: high quality, fair-faced concrete and complex geometrical shapes, both in the overall building outlines and in individual elements such as the 'flame-shaped' columns and the boundary wall.

Already popular with visitors and set to become a major landmark in Edinburgh, the Scottish Parliament was a major challenge for Arup in its complexity, its scale, and its ever-changing requirements. The firm helped to deliver a unique project that includes 11 buildings - each with its own individual character - contains more than three times the area compared with the competition, and was presided over by five different clients during the six years since it was won. The same period also saw the untimely death of the Scottish leader Donald Dewar, very much a driving force behind the Parliament, as well as Enric Miralles. It is hoped that both would have been satisfied with the reality of their vision.

Credits

Architect: EMBT/RMJM **Construction manager:** Bovis Lendlease **Quantity surveyor:** Davis Langdon **Structural, civil, façade, geotechnical, blast and landscaping engineer:** Arup - Joan Anderson, Francis Archer, Tom Barr, Monika Beyersdorff, Daniele Bosia, Mark Bowman, Geoffrey Burns, Sam Cook, Rob Davis, Brian Edie, David Guild, Tony Gulston, Arjan Habraken, David Hadden, Don Henning, Graeme Herd, Mark Holst, Fred Ilidio, Patricia Johnstone, Hiroshi Kawamura, Gavin Kerr, Rob Kinch, Ken Knowles, David Lewis, Joan Lindsay, John McDonald, Andrew Millar, Stewart Millar, Astrid Muenzinger, Hamish Nevile, Steve Peet, Chas Pope, Stephen Ratchye, Mark Reed, Duncan Richards, Volker Schmid, Annalisa Simonella, David C Smith, Peter Stevenson, Alan Tweedie, Simon Webster, Gary Wilkie, Robin Wilkinson **Building services engineer:** RMJM **Specialist glazing subcontractor:** Mero Structures Inc **Illustrations:** 1, 2, 11, 18, 19 Arup/Adam Elder/Scottish Parliamentary corporate body; 3, 4, 10, 13 EMBT/RMJM; 5-7, 23 Arup/Nigel Whale; 8, 12, 20, 25, 26 Arup/Roland Halbe; 9 Cowley Structural Timberwork; 14, 16 Arup/Peter Cook/VIEW; 15 Arup/Paul Raftery/VIEW; 17 Arup; 21 David Hadden/Arup; 22 Don Henning/Arup; 24 Ken Knowles/Arup

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Constitutional Court, Johannesburg

Alistair Avern-Taplin

On 21 March 2004 South Africa celebrated 10 years of democracy, and to mark the occasion President Thabo Mbeki officially opened the new Constitutional Court in Johannesburg.

Introduction

The Constitution of the Republic of South Africa is the new democracy's supreme authority, and passed into law in 1996. It includes a Bill of Rights and serves to ensure that political powers are exercised within a framework of constitutional constraints, irrespective of what might be intended by the Parliament. To safeguard the Constitution, widely considered the most progressive in the world, 11 judges were sworn in.

The process to construct the Court started in late 1997 when the Department of Public Works launched an open international design competition for an appropriate architectural expression of the new democratic institution. The brief was to develop the entire precinct of the chosen site as 'Constitutional Hill' - a public space for the city and a symbolic place for the nation where the Constitutional Court and various other aligned institutions such as the Human Rights Commission would be accommodated alongside museums, appropriate retail, and residential accommodation, some of which would be accommodated in the historic prison buildings. While the competition focused on the Court building, an appropriate setting for the new elements within the entire site was also called for.

The winner, a joint venture between OMM Design Workshop and Urban Solutions, was announced in April 1998. They were asked to recommend the remainder of the professional team and chose Arup as civil, structural, and mechanical engineer. Key reasons were Arup's reputation for innovative structural design and experience in sustainable building; the Zimbabwe practice was to fulfil a key role in designing a passive cooling system. Arup was also appointed as project manager to provide strategic advice to the client only, and subsequently the firm was engaged for the full project management and civil and structural engineering roles for the entire Constitutional Hill precinct.

1.
Looking south-east: The library's precast façade is on the left, and the Rex Welsh Library tower prominent in the foreground. The Great African Stairs rise towards Constitutional Square and the Court entrance, with the exhibition Gallery to their left and Sections 4 and 5 on the right. On the far left is Hillbrow Tower, an Arup project from the 1960s.

The historical area

The precinct contains several historically significant buildings, including The Fort and ramparts, The Awaiting Trial Block, Sections 4 and 5 'Number Four', and the Women's Goal.

The Fort and ramparts

At the centre of Constitution Hill is The Fort surrounded by its ramparts, originally built between 1896 and 1899 by the Boer president, Paul Kruger, as an act of defiance against the might of imperial Britain, and a way to keep watch over the *uitlanders* (foreigners) in the mining village of Johannesburg, who were plotting an overthrow of the Boers. In 1900, during the Anglo-Boer War, the British took Johannesburg, and imprisoned Boer soldiers in The Fort. A group of Cape Afrikaners who had fought on the side of the Boers were executed at The Fort, killings that marked the beginning of its long history as a place of punishment, confinement and abuse, and Johannesburg's main place of incarceration for eight decades.

The Fort is entered from the south through a set of huge doors that lead through a tunnel. Prisoners passed into a reception area and were then sent to a 'delousing room' where they were stripped and sprayed with cold water, before being moved to the Awaiting Trail Block. Once convicted, they were incarcerated in The Fort if they were white men, in the Native Gaol if they were black men, and in the Women's Gaol if they were female.

The Awaiting Trial Block

All prisoners went through the Awaiting Trial Block. For two weeks, the 156 Treason Trialists of 1956, led by Nelson Mandela, were held there, as were the scores of activists held for three months during the 1960 State of Emergency, and hundreds of teenagers held after the Soweto Uprising of 1976. All these groups were kept in special communal cells. In these horribly overcrowded cells for common criminals, new inmates were inducted into the brutal life of prison. They were often robbed, attacked and even raped by members of the 'Numbers' gangs who exist to this day. A visitors' room was connected to the Awaiting Trial Block, the only place of comfort for the prisoners. This has also been dismantled to make way for Constitution Square, but will be rebuilt, perhaps as a visitors' centre for the precinct.

2.

Section 4 and 5 'Number Four'

Most South Africans know the whole prison complex simply as 'Number Four', a term which symbolized courage and fear, the cruelties and indignities of colonialism and apartheid, and the prison system in general. In 1902, Section 4 and 5 of the prison replaced the native gaol built in 1893. 'Number Four' is to the north of the ramparts and west of the new Constitutional Court. It contained the general cells for black male prisoners where violent criminals, pass-offenders and political prisoners were incarcerated side-by-side. At the extreme north of Number 4 are 24 punishment cells, which contained men who had committed an offence inside the prison such as trying to escape. These cells also held men with infectious diseases like smallpox, juveniles, and men with mental illnesses.

Section 4 and 5 is in a state of extreme disrepair, the paint peeling off its walls, and its courtyards covered in elephant grass and weeds. It forms a vital heritage component of Constitution Hill, and will not be tampered with or renovated. It is the dark heart of the precinct, giving visitors a salutary sense of what prison life must have been like.

The Women's Gaol

In 1909, a new Women's Gaol was built directly east of The Fort, the handsome red brick building that remains today. It held both black and white women, but in separate sections. The vast majority of inmates were neither murderers nor freedom fighters, but ordinary women arrested mainly for pass offences or for making an independent income from beer brewing - illegal because the state controlled the sale of liquor to blacks through its beer halls. Sometimes they had small children or babies with them. This was especially true during the late 1950s, when black women were arrested in large numbers when they deliberately presented themselves to the police without passes.

The Commission on Gender Equality, an official body that looks after the rights of women, took offices in the Women's Gaol in 2003. An exhibition detailing the lives and experiences of three very different women who were incarcerated in the gaol is on display in the oval atrium that is at the centre of the building.

Constitution Hill in a nutshell

The old Fort area bordered by Sam Hancock, Hospital, Kotze and Joubert streets will become an anchor and a symbol of Johannesburg's inner city regeneration. Apart from the Constitutional Court, the new precinct will also house statutory bodies and a thriving complex of heritage sites and museums, exhibition and performance spaces, offices, shops, restaurants and other tourist facilities. It will be an engine of growth and transformation for downtown Johannesburg – and a place where visitors can feel safely the heartbeat of this vibrant city. The precinct will also be home to one of South Africa's major public art collections. To this end an Artworks Project for acquisition of art for the Court and public environment has been initiated.

The entire precinct will, in fact, become a 'living' museum. Visitors will be able to visit The Fort. At the entrance, off Kotze Street, one exhibition already being staged depicts a short history of the prison complex, whilst another shows a society in transition, looking back at the difficulties of the past and the possibilities of the future.

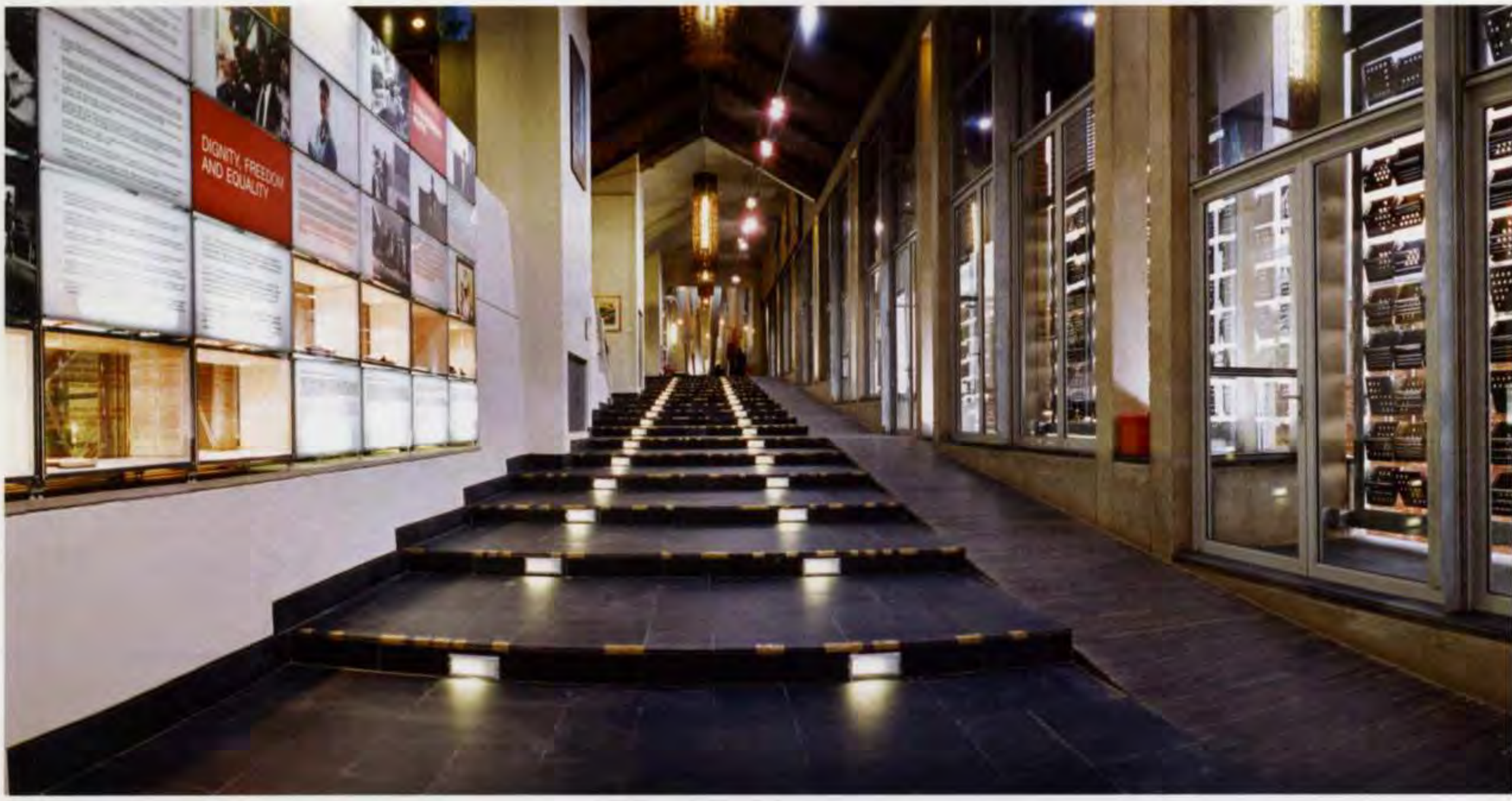
A law library with IT links to the world

The Constitutional Court library of 40 000 books is set to grow by 10 000 a year until it reaches 400 000 volumes, making it Africa's most important law reference site, and one of the most significant in the world. It has also launched the most comprehensive legal virtual library in Africa, which will carry the full text of every major court in South Africa and later all courts in sub-Saharan Africa that carry the electronic text of court judgements.

The library subscribes to all major English law reports, and to those of the German Constitutional Court, three of the German Federal Supreme Courts, and certain French public law reports. The court holds 130 different law report series.

The virtual library has an Internet portal that provides a single point of access to the library's resources. Materials can be searched for and viewed online, and printed or downloaded.

3.
The library, showing its ramped floors; the entire structure is suspended from a portal at roof level to avoid columns in the basement.



4.
The stairs in the exhibition gallery, leading to the foyer in the distance. The Great African Stairs are outside the glass doors on the right and the administration area to the left behind the wall.

Site selection and history

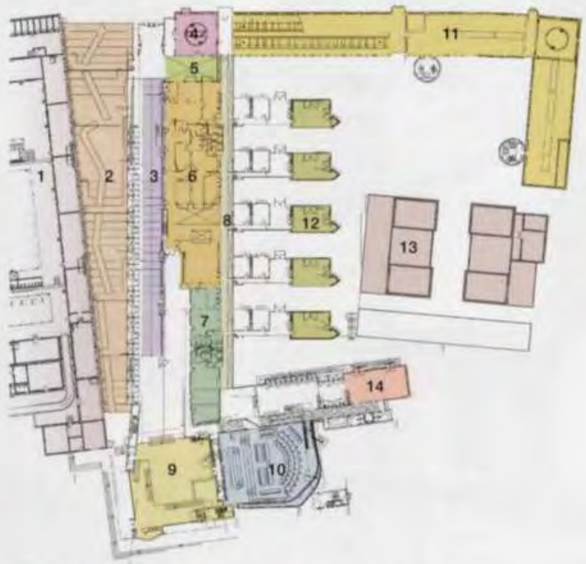
All 11 Constitutional Court judges were from the start actively involved in the site selection. Enabling the eventual building users to choose its location was an act of empowerment, and contributed greatly towards feelings of inclusivity and ownership. The judges warmed to the opportunity and considered several potential sites, in Pretoria and Midrand as well as Johannesburg, but eventually settled on the run-down The Fort precinct on the northern face of Braamfontein ridge in Johannesburg, the apex of the Witwatersrand region and bordered by the inner-city neighbourhoods of Hillbrow and Johannesburg.

How the site was chosen set the tone for the whole project. The judges would be actively involved throughout, and the design team welcomed this. As the project unfolded, the design's success rested less and less on pure technical ability and increasingly on responsive relationships established across professional and disciplinary boundaries. Thus South Africa's most prominent symbol of democracy was born out of a largely democratic process.

The 12.5ha site is physically accessible and prominently situated, and was seen to have the potential to catalyze the regeneration of Johannesburg's central business district, but the judges selected it above all because of its rich symbolism. Originally built in 1893 as a military defence outpost, it developed into a penal institution - significantly designed by Sytze Wierda, official architect of the South African Republic, who also designed the parliament and supreme court building on Church Square, Pretoria. Over the years, many of those fighting political and social oppression were incarcerated in the The Fort prison, the history of political struggle bestowing on it the doubtful honour of being the only prison in the world in which both Ghandi and Mandela were locked up.

The Fort was thus an ideally symbolic site for the Constitutional Court. To transform the prison would physically and visually dramatize the contrast between a past of 'untold suffering and injustice' and the future of 'democracy and peaceful co-existence', as the postamble to the Constitution puts it. More importantly, the decision to house the Court in inner-city Johannesburg also signifies confidence in the idea of a truly shared democratic public space arising in urban post-apartheid South Africa.

After the site was selected and secured, it was decided that a public competition would be the most appropriate and democratic way of choosing a design; after negotiations, The Fort precinct was donated by the Greater Johannesburg Metropolitan Council to the Department of Public Works. Constitutional Hill will also house the Museum of the Constitution, a constitutional library, and various democratic institutions like the Human Right Commission, the Gender Commission, and the Public Protector. In accordance with mixed use design principles, Constitution Hill will also include market, work, and living spaces.



1	Existing 4 & 5 gaols	8	Internal walkway
2	Great African Stairs	9	Foyer
3	Exhibition arcade	10	Court
4	Rex Welsh collection	11	Reference library
5	Public auditorium	12	Judges' chambers
6	Administration	13	Existing sub-station
7	Council robing and meeting rooms	14	Judges' lounge, conference and comitee room

6.

The winning concept

Though right in the heart of the city, from its inception the site had been insular and deliberately inaccessible, so it had to be connected to the neighbouring precincts, with emphasis on pedestrian movement. Another priority was to design a building that would benefit from the rich and complex legacy of the site, and also important was the notion that in a democratic society civic buildings 'can either gain their symbolic value by expressing the openness they present' or they can be 'alienating monuments' (*SA Architect*, August 1998). OMM Design Workshop and Urban Solutions sought 'the power of a pre-eminent building, without monumentality'.

The result was a series of terraces stepping down the steeply-falling site, facing due north and thus misaligned with both the Fort and the other prison buildings. The topography and the misalignment generate the 'Great African Stairs', which taper as they ascend southward to the foyer and Court at the head of the complex, aligned parallel to the Fort. Paved with bricks from the demolished Awaiting Trial Block, the Stairs are like a stitched seam between the new Court building and Sections 4 and 5 of the old prison to the west.To fulfil the architects' own objective of interweaving past with future, stair towers of the former prison buildings were retained and incorporated in the new complex, and materials like bricks were retrieved and recycled. This approach is echoed in the principles for energy conservation, whereby interior comfort in the building is largely achieved by harnessing the advantages of the high diurnal range experienced in Johannesburg. Apart from the Court chamber, which is air-conditioned, an internal summer temperature no higher than 26°C is achieved, 6-7°C below the ambient temperature. Similarly the Court is designed not to need acoustic amplification.

The public faces of the building engage with passers-by through the various artworks and mosaic cladding. Sun-baffles and screens too are endowed artistically, and shelter is provided by indigenous trees.

5.
Detail of artwork screens on the exhibition gallery elevation, by the top of the Great African Stairs; Constitutional Square and the Court entrance are immediately ahead, and Sections 4 and 5 on the left.

7.
Looking east on the north side of the site, with the library on the right behind its precast façade, and the first of the judges chambers wings on the left. Between is the link between the administration building and the library.

The Constitutional Court building

The building has six main zones:

- the Court foyer - the public entrance into the building and an extension of the most public area of the site, Constitution Square
- the Court chamber, where the judges sit, and judicial debate is conducted in public
- the Judges' chambers, the private area where the judges, their secretaries and researchers have their offices; these areas are in a cloistered courtyard, not accessible to the public
- the administration wing, where most of the Court staff work
- the library, where most of the Court's research is undertaken in what will be the most advanced and largest collection of human rights material on the African continent
- the exhibition gallery, where permanent and temporary art exhibitions will be on display in an extension of the public areas of the building.

The Court chamber and foyer, in the south wing, are directly accessible to the public from Constitution Square, whilst the library, forming the north wing, is also partly open to the public. The two most public functions are therefore the most visible, and located to enable easy access.

8.
The Court chamber: a glazed acoustic reflector is suspended over the judges' and counsel benches. The bricks forming the dry-stack wall were salvaged from the demolished Awaiting Trial Block.

9.
From The Fort's ramparts: In the foreground is the foyer, with the 'light tower' built over a staircase retained from the Awaiting Trial Bock. The Court chamber is right of the foyer.

The administration wing links the foyer, Court chamber and library on a north-south axis. The exhibition gallery doubles as an internal public walkway that parallels this wing immediately to the west. It is enclosed but largely transparent internally to the administration offices and externally to the Great African Stairs.

The Judges'chambers are east of the administration wing in a series of office suites on three floor levels. All north-facing and overlooking a courtyard to the east (which is framed by the Court building and the Hillbrow substation on the eastern boundary of the site), these suites are separated from the administration wing by an inner walkway, a light, triple-height space with timber decked bridges at different floor levels that afford the judges private access to each other's rooms and to the Court chamber and the library.

10.
The entrance foyer to the Court, showing sloping columns, 'bar code' openings in the roof slab, and the curved concrete wall with triangular openings, all in off-shutter concrete.

Language

In the Court building the architects sought to communicate through the language of its form what it is about. And this expression shifts, with the different functions accommodated.

The timber entrance doors to the foyer of the court building stand 8m high. The space is formed in concrete, though largely transparent to the exterior, populated by slanting columns, and alert to the movement of the sun with skylights cast as slots at various angles into the concrete roof slab and closed by projecting glass boxes externally. One of the stairwells of the old Awaiting Trial Block projects into the space, unrestored and a direct reminder of what this place used to be. A small area of the basement level of the old building is exposed below the foyer floor level.

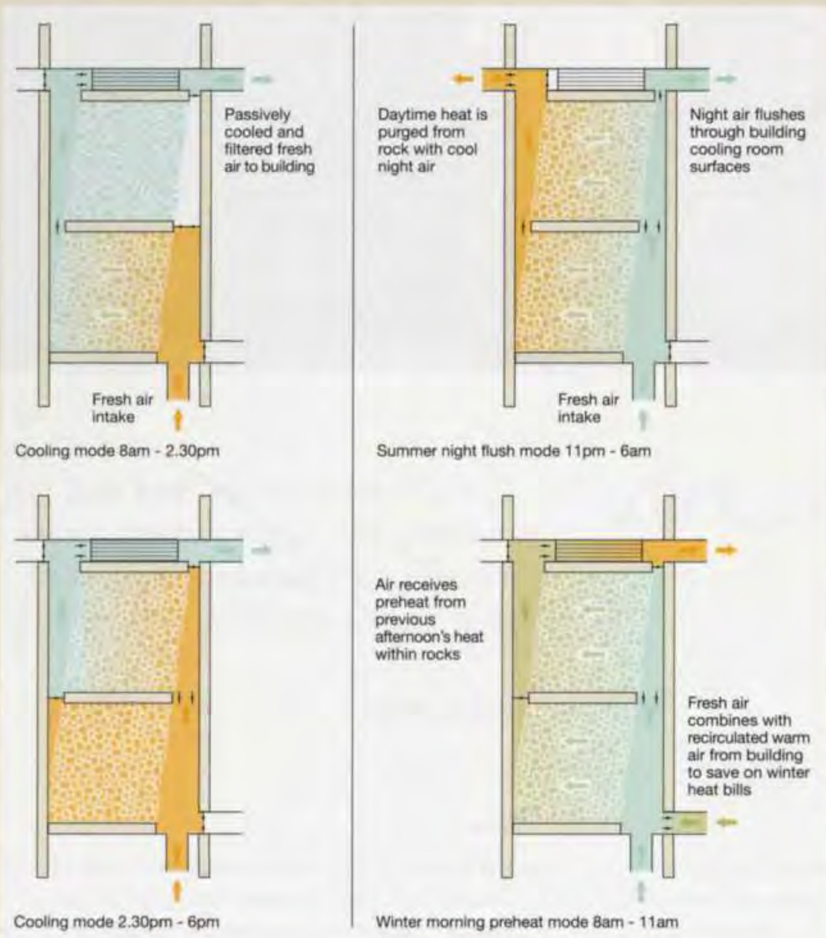
A second set of tall timber double-doors, detailed with hand-worked brass inlays, lead to the Court chamber. Here the internal space is completely open and undivided, using changes in floor level to define the areas for the judges, counsel, and the public – on open terraced seating. Galleries are also provided for the press and for visiting judges. The enclosing walls are substantial and, towards the south-east corner where the first of the old Awaiting Trial Block stair towers shapes the chamber, are packed with bricks removed from this demolished building and set aside for reuse. At the street level of Constitution Square externally, a narrow ribbon of glass, about 30mm high, is inserted into the south and east walls of the chamber.

The people of the Court can be seen going about their business from both the internal public walkway/gallery along the western edge of the building and the Great African Stairs outside. A ramped pathway set within the Stairs zigzags between the contours of the site – a meandering but easier alternative walk. Celtis africana is being planted along the pathway to shade people on the Stairs. The internal walkway/gallery is also ramped in part, and stepped, to negotiate the gradient of the site. The entire west façade is glazed, and protected by steel screens, with doorways all along it. People can choose to walk outside or to go in to shelter from the weather or to view the art.

The twin-roofed north wing, which houses the library, is expressed as 'a box of filtered light'. With its concrete screened façade, modulated by vertical timber-clad bays, and rising three storeys internally - though standing five storeys high from ground level at this point on the site - it is the most visible component of the Court building from the north. The library symbolizes knowledge, wisdom and enlightenment, and this idea is emphasized in the 'tower of light' that forms its north-west corner, where the Rex Welsh Library of antiquarian law books will be housed.

The judges' chambers, by contrast, are on a domestic scale. Each suite includes office space for the judge, a secretary, and two legal clerks.

Sustainability



11. Rockstore operation modes.

While the north/south orientation of the main public spaces of the Court building and of the judges' chambers is most appropriate for passive or low energy climate controls, the east/west orientation of the administration wing (which suited the urban design requirement for a perimeter building) necessitated some climate mitigation. This is evident in the screens to the glazed west façade, and in the layering of the internal space that sets the administration services back from the west wall, inside the temperature mediating zone of the public walkway.

In consultation with the mechanical engineers and the client, it was decided that a rock store system should be used to provide a low energy means to control the building's interior climate. In principle, this increases a building's thermal storage capacity, enabling it to store coolness (absorbed from the cold night air in summer) or heat (from warm day air in winter), which can then be transferred to the interior spaces. It relies on a climate which has a high diurnal temperature range – as exists in the Highveld.

About 550m^3 of packed rocks are held in 14 separate subterranean systems extending 200m along two sides of the basement car-park perimeter. Shallow ponds outside the judges' chambers and a wider, deeper water trough along the library wing also contribute (minimally) to cooling the intake air. Mechanical fans drive cooler air in summer or warmer air in winter from the rock chambers through channels in the floor plenum to floor-mounted outlet vents, to moderate the internal temperature. The system works in conjunction with steel ventilation chimneys on the roof of the administration wing.

These extract hot air from the interior by natural stack effect, and are fitted with fans to accelerate its release. (The internal ventilation shafts also house rainwater downpipes and electrical cabling.)

The rock store system can take 6-7° off the extremes of outdoor temperatures to create a more moderate interior climate. Internal temperatures are then generally within the 26°C maximum defined by international office standards; commonly remaining at around 23°C.

It should be noted that some supplementary provisions were required. Conventional mechanical air-conditioning services the basement archives (to ensure a stable environment for archival material) as well as the court chamber, auditorium, and training room. These latter spaces are designed for gatherings of people and a passive climate control system would be inadequate to manage the physical body heat generated by such numbers.

Materials

The architectural concept is expressed both through the structure and deliberate choice and use of materials. With extensive use of off-shutter concrete in slabs, soffits and columns (a choice initiated by the mechanical requirement that almost all surfaces be radiant so as to contribute to thermal storage) particular attention was paid to the quality of shuttering and consistency of concrete. There is also a good deal of exposed timber and steel, in the form of composite roof trusses and suspended walkways and decks. Merbau timber was chosen as it is the world's only commercially grown and harvested hardwood with the required coloration. It is used not only as a finish for floors, handrails and ceilings, but also as a composite member of the roof timbers and walkway support structure.

Extensive glazing maintains a sense of openness and transparency, a special system being developed where bespoke extruded glazed aluminium frames are bolted to galvanized structural steel members. Bricks from the demolished structures were used both for dry pack and straight-jointed panels, and black African slate floors were installed in homage to the many other government buildings that have over the years used the same material for this purpose.

Credits

Client: South Africa Department of Public Works **Client project manager:** Johannesburg Development Agency **Architects:** OMM Design Workshop and Urban Solutions **Multidisciplinary engineer and project manager:** Arup - Alistair Avern-Taplin, Peter Basson, Colin Chanraya, Trevor Chetty, Errol Davison, Safiya Desai, Shaun Dixon, Anthea du Preez, Nicholas Featherston, Clive Fick, Ingrid Gardner, Krish Govender, Lee-Zane Greyling, Roger Hayim, Andy Howard, Jack Jaza, Roy Jones, Kim Leach, Rob Leach, Roy Morris, Ephraim Mzimase, Linda Ness, Jayanti Odhav, Michelle Pakes, Ash Parshotam, Mike Rainbow, Martin Schindler, James Senior, Errol Shak, Rael Smith, Con Strydom, Liesl Strydom, Elvira Tessa **Quantity surveyor:** Hamlyn Gebhardt, Koor Dindar **Main contractor:** Wilson Bayly Holmes (PTY) Ltd, Rainbow Construction **Structural engineer:** Sibanye Consulting Engineers **Mechanical engineer:** Toon Herman Associates **Electrical engineer:** Van Der Walt Barry **Wet services:** DSB Consulting Civil Engineer **Acoustic consultant:** Acuslov **Landscape architect:** African Environmental Design **Fire consultant:** LJK Fire Engineering Consultants **Illustrations:** 1, 3, 5, 8 Hi Shots; 2, 6, 11 Nigel Whale; 4, 7, 9, 10 Angela Buckland

1. 'The Hub' in its urban South London setting.

'The Hub', Community Resource Centre, London

The client's brief required that the building should be inviting, user-friendly, with universal appeal to help create vitality in its function.

Chris Trott

Introduction

'New Deal for Communities' (NDC) is a UK Government programme designed to tackle social exclusion and renew some of the country's poorest and most deprived neighbourhoods. A central feature of the plan is to put communities themselves at the heart of decision-making, and to this end 39 NDC partnerships have been established in England, 10 of them in London. One of these, in the borough of Newham, is the West Ham and Plaistow NDC, and an early outcome of its delivery plan was to identify the need for three new community resource centres (CRCs).

Arup has been engaged for all three. 'The Hub' in Eastlea is the first; it opened in October 2004, with Woodlands CRC following in mid-2005. The third is intended for North Plaistow. For 'The Hub' Arup was appointed as business planning, structural, building services and building physics consultant, working with Eger Architects.

The projects are all strongly community-oriented and designed on sustainable principles. They are innovative and, together with the other elements of their delivery plan, have helped this particular NDC to become one of the most highly-rated of the 39.

The brief

The client wanted the design to 'be of a high quality standard, inviting and user-friendly, with universal appeal to help create vitality in its function. The design should include the following elements as a guideline:

- be an imaginative landmark scheme
- be innovative in types of materials used
- include energy efficiency in terms of external and internal design functions
- use materials for self-sufficient energy and/or to sell on energy
- have flexible and spacious internal floor space standards
- embody internal and external security measures.'

Team response

The first thing was to hold a socially inclusive public consultation, which identified the needs to be fulfilled. The resulting programme focused on providing space to support the economic situation and community facilities in the area, and the subsequent conceptual design prioritized the project's environmental responsiveness. In parallel, the team evolved a business plan to ensure that 'The Hub' remains economically viable throughout its life.

Building form and layout

The site is some 100m long by 20m wide. The need for an appropriate scale to the building in the context of the surrounding residential area, together with a 'right to light' envelope, constrained its height. This proved quite challenging, particularly in view of the amount of new accommodation that was required. The site had previously accommodated garages which, together with their hard-standings, were removed, as was an existing derelict house.

The building form was also driven by the need for significant and very diverse areas to accommodate business start-up units (BSUs), a café, a pharmacy, a nursery, and a multi-purpose community hall, as well as being significantly influenced by energy and renewable materials considerations.

Carbon optimization of form

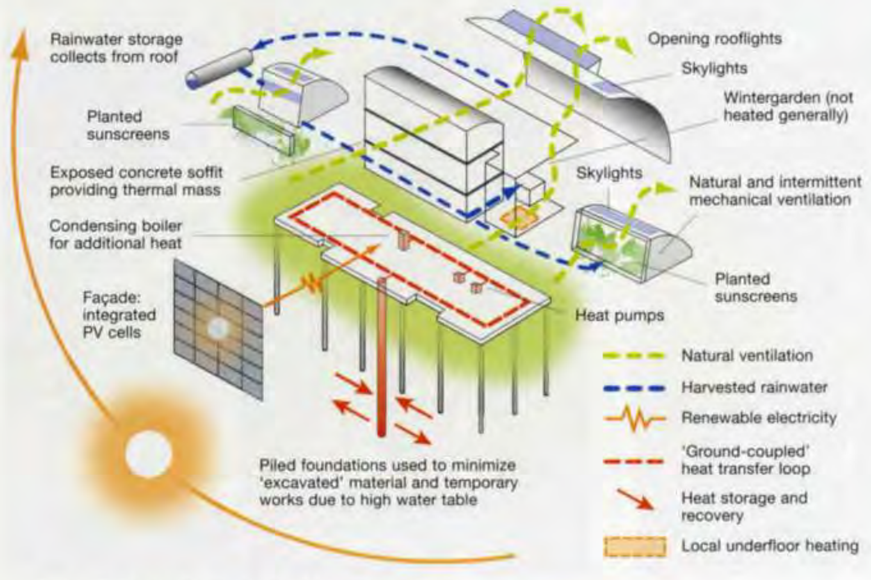
Early in the design, studies were made of how this could be constructed as an environmentally responsive, carbon-optimized building. This process addressed the simultaneous beneficial use of daylight and solar gain to warm the building by using well-positioned windows, glazed elements, and wintergarden zones. The analysis led to recommendations for the orientation and size of windows, and setting appropriate levels of insulation to minimize carbon impact.

This allowed the form, orientation, and overall mass of the building to be developed within a rigorous conceptual framework designed to ensure optimum user comfort, excellent daylight, and minimized energy use. The resulting design gives high levels of insulation to the permanently occupied accommodation, which surrounds a transiently occupied wintergarden that is partially heated in winter. An ETFE (ethylene tetrafluoroethylene) roof covering to the wintergarden was felt to be justified because the space below is not heated fully and because the material used is fully recyclable.

Choice of structural and services systems

Having ensured that the building's passive design was optimized, the building systems were then chosen with the aim of further reducing carbon impact, via both carbon in use and embodied carbon.

3. Upper level walkway and offices beneath skylights.



2. Energy-saving structural and services concepts.

Structural systems

After considering the merits of a concrete structure with thermal storage properties that could have provided further passive cooling and heating, and which would have been designed for extended life, the team decided that the nature of the site and the building required a more lightweight treatment. A structure that could be demounted and reused (or recycled) was therefore adopted, though it was recognized that the potential for reuse elsewhere (or if this proves not possible, reuse of parts or recycling) was only possible for the superstructure.

As the site was overlain by 2.5m to 3m of moderately contaminated fill, the safe working practice of capping and leaving in situ was adopted. Methane was detected during the site investigation, and this required mitigation through suitable ground slab design and following the best practice guidance in *CIRIA Report 149*[1].

A pile solution was adopted, which allowed all the fill material on site to be retained and avoided the environmental penalties of considerable muck-shift and the associated embodiment of carbon in the sub-structure. Should the site again be redeveloped, the piles could be reused for residential or similar buildings. The ground-bearing slabs contain 30% of cement replacement material to reduce the quantity of cement required.

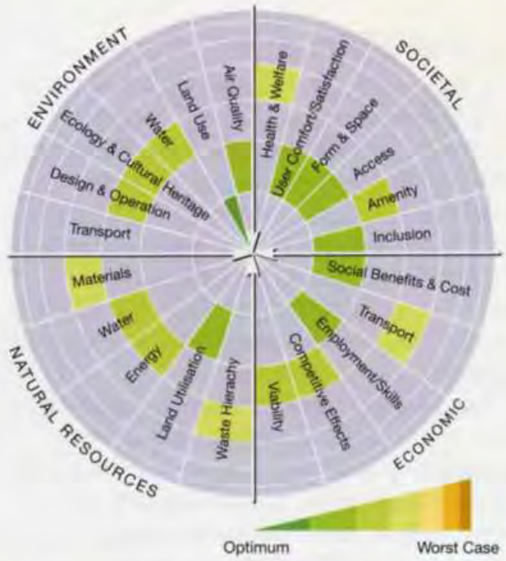
The structural frame is in steel, with suspended slabs of precast concrete; encased floor beams were avoided, and a minimal concrete cover to the precast slabs was used to simplify future dismantling. The steelwork is punched with its designated size and grade, and jointed by bolting to allow it to be easily identified and dismantled in the future.

Services systems

The ventilation is mixed mode. When weather permits, occupants can use natural ventilation, drawn in through the external windows and passing via internal windows to the wintergarden, from which it exits at high level. At other times modest levels of fresh air are introduced via heat pumps.

As well as having windows, the south façade is clad with photovoltaic (PV) elements. This has several merits. It provides a renewable electrical supply to the ground-coupled heat pumps, nominally sufficient for their annual supply, and also acts as a rainscreen with a cavity behind, allowing air to be drawn into the heat pumps in cold weather, having recovered waste heat from the PV elements. In addition, it provides shade in summer to the business start-up units. The windows have retractable shades so that the occupants can harvest useful solar gain in winter when the sun is low.

4. The public face of 'The Hub': street entrance to the café.



5. SPeAR® diagram showing 'The Hub's 'green credentials'.

Because the BSUs were developed to allow for a high degree of cellularization, and IT-intensive users were expected, a modest level of cooling was deemed appropriate in those areas, albeit only to limit internal temperatures to a maximum 28?C on design days. Various heating and cooling systems were considered, and a ground-coupled heat pump system was chosen as it offered minimum carbon impact and also allows the BSUs to be heated as required. Eight 150mm ground bores along the northern border of the site were drilled 80m deep to take heat from and discharge to the surrounding ground.

The remaining areas of the building have no mechanical cooling, and are heated either by radiators, or in the case of the partially-heated wintergarden, via underfloor units in the café's seated area. A condensing boiler provides boost and back-up heating.

Water conservation features include low consumption fixtures and fittings in toilet areas, with a root irrigation system for the planted walls. A rainwater storage tank is provided below the children's external play area to the nursery and is expected to contribute to a saving in mains water of around 50% pa. Harvested rainwater is used for toilet flushing and plant irrigation.

Electrical systems include the PV arrays on the south façade, which feed the building's main distribution board with power, offsetting around 20% of the total demand. Metering arrangements allow for export of power to the local grid when demand is below the building's requirements. Low-energy luminaires are used throughout.

Business planning and photovoltaic funding application

The functional planning was informed by a business plan which Arup developed to ensure that 'The Hub' has a sustainable future post-handover. By an iterative process, spatial planning focused on maximizing the higher-value areas of the project. Capital costs, rental incomes, operating costs, and consumables costs, together with appropriate risk profiling, were built into the business plan at concept sign-off stage, after which the client took over detailed development of the business planning framework directly.

The building systems design described above contributed to making the business plan sustainable, and it is anticipated that energy and water consumption costs will be reduced by around 50% as a result.

On behalf of the client, Arup also compiled the funding application for the PV installation to the UK Department of Trade and Industry-funded major PV grant scheme. The project was awarded the maximum possible grant of 70%.

Sustainability assessment

In support of the PV funding application, a sustainability assessment was carried out, using Arup's SPeAR® methodology to demonstrate its sustainable credentials. The building's primary foci on strengthening the local community's economic base through the provision of business start-up opportunities and providing a wide range of services to the community are clearly evident from the assessment, where the socio-economic indicators demonstrate that the project priorities have been successfully met.

Summary

'The Hub' began with a clear vision, and the brief and design process flowed directly from that. It opened to the public in October 2004, following four months of fitting out by various tenants. It is operating successfully and its design and development have produced useful feedback for the subsequent CRCs in the delivery plan.

Credits

Client: New Deal for Communities **Architect:** Eger Architects **Multidisciplinary engineer:** Arup - Simon Bourne, Dave Clarke, Ed Clarke, Ulrike Elbers, Andrew Fraser, Lesley Graham, Richard Harpin, Inka Heile, Stephen Hill, Carole Large, Wolfgang Muller, Vicky Potts, Les Stokes, Gareth Thyer, Cyrus Toms, Chris Trott, Julie Wood **Illustrations:** 1, 3, 4 Arup/ Dennis Gilbert/VIEW; 2, 5 Lesley Graham

Reference

(1) CONSTRUCTION INDUSTRY RESEARCH AND INFORMATION ASSOCIATION. *Report R149*. Protecting development from methane, by GB Card. CIRIA, 1996.

Making knowledge work

Dominique Poole Tony Sheehan

'Mistakes are valuable guides, they should not be forgotten or concealed. Rocks and reefs are charted on maps as a warning to sailors, shouldn't we do the same with our mistakes and failures?'

Ove Arup, Doodles & Doggerel

Introduction

Managing knowledge within organizations has become increasingly difficult in recent years. Decisions must now be made at greater speed, against more aggressive global competitors, and in the face of greater volumes of information than ever before. In this context, appropriate knowledge must be applied consistently, to avoid the increasing threat of litigation and to deliver increased value to clients. The potential rewards are considerable; when knowledge is managed successfully, organizations create value in the market-place through their ability to deliver the best of the firm, drawing on the most appropriate skills.

'If I have seen further it is by standing on the shoulders of Giants', wrote Isaac Newton to fellow scientist Robert Hooke in 1676. What Newton meant was that his own scientific and mathematical advances owed much to the knowledge and discoveries that had been made by others before him. The challenge is not to repeat, but to learn from the past and to improve on it with each iteration. The same is true for today's organization, where one key resource is derived from an ability to learn from one project to the next. At the same time, organizations must offer something extra, and must develop new solutions faster than competitors so as to innovate from a position of confidence and informed judgement.

Within Arup, the goal of mobilizing expert knowledge occurs in two ways:

- Individual experts can be found through 'Arup People,' an award-winning tool which provides access to the declared expertise of individuals together with documents such as their CV.
- Networks and communities of experts in various fields help to provide a focus, sharing knowledge and responding to questions in a range of technical areas, and helping to ensure that knowledge flows readily across the firm.

Approaches to managing knowledge

Knowledge Management (KM) requires the integration of expertise in people, process and technology to create business benefit. It applies skills drawn from areas as diverse as business strategy, IT, information science and organizational effectiveness. As a result successful KM is difficult to achieve. Many organizations have struggled with the selection of appropriate KM tactics amidst a maze of potential solutions.

In practice, the choice is relatively straightforward: Firms seeking to innovate will focus more on KM techniques that support creativity by creating strong networks between people, whilst firms seeking to deliver standardized products will tend to focus more on systems and processes (Fig 1).

At Caunton Engineering, a UK-based steelwork fabricator, managing knowledge through strong adherence to procedure enabled by technology enables good productivity. By contrast, the US-based design consultancy IDEO has a culture of freedom and empowerment which allows individuals to apply their knowledge as effectively as possible in order to support innovation with minimal constraint by procedure. Arup combines both approaches to ensure that knowledge which supports both innovation and standardization processes is shared and reused effectively.

1. Innovation vs standardization.

Types of knowledge

When managing knowledge, a distinction is commonly drawn between knowledge that is tacit (associated with skills and experience in people's heads) and that which is explicit (in documents or databases). Both must be managed if organizations are to be successful, but the emphasis will vary according to the business focus. Explicit knowledge to support standardization needs to be captured, articulated, documented, and stored in electronic databases for reuse at a later date. Tacit knowledge, by contrast, is highly personal; it is the skills and expertise acquired through experience, and thus is strongly linked to the context in which the knowledge exists. It is difficult, if not impossible to capture and reuse tacit knowledge, but using it effectively is nevertheless essential for companies seeking to maintain a competitive edge.

In Arup the challenge of storing and accessing basic data about its ever-growing number of projects has been met for decades by a searchable project records system, initially founded in the 1960s using physical methods like edge-punched cards. This system has subsequently employed ever-more sophisticated computerized techniques to keep pace with user needs and demands, which now enable it to embrace a far wider range of explicit knowledge about the firm's projects by integrating existing systems such as the image library.

To emphasize the greater potential value of tacit versus explicit knowledge, consider a recent study of a firm of 6000 people. The storage capacity of the firm's databases amounted to some 40TB (terabytes) of explicit knowledge: data and information (1TB = 1000GB). By contrast, the storage capacity of an individual's brain exceeds 4TB of tacit knowledge with context. Effectively the information and data stored in the firm's database is equivalent to only 10 people, illustrating the potential power of an organization that can fully mobilize its tacit knowledge in practice.

2
The effect of information growth on our capacity and desire to learn.

The combination of explicit knowledge in databases, and the recruitment of the best staff with exceptional tacit knowledge, are both key KM goals. The additional challenge for any organization seeking to manage knowledge effectively is to ensure consistent application of the right knowledge at the right time in a way that creates value for clients. It is about making knowledge work; enabling people to make the right decisions, combining the best of their own knowledge with the best knowledge of the organization and wider industry at any given time.

Working effectively

Whilst the goal of knowledge work seems relatively simple, increasing pressure on individuals has made the effectiveness of today's knowledge worker questionable.

A key skill for designers has always been the need to balance urgency in decision-making with the ability to pause, reflect, consult, and deliver the best possible quality of response to clients. Perhaps the greatest challenge to effectiveness in this type of work is that the rapid growth of information in recent years has started to exceed the capacity - and indeed the desire - of individuals to learn.

Many people have become too busy to reflect, overloaded with information to the extent that they are forced to rely instead on the information at hand (Fig 2).

This gap must be closed if people are to work more effectively and deliver their full potential. To thrive, organizations must combine three key activities in a way that supports business needs:

- embed explicit knowledge into processes
- mobilize tacit knowledge through people finders, networks, and communities
- create the right environment for decision-making through effective team-building, decision support tools, and training.

Embedding explicit knowledge into processes recognizes that, to be competitive, organizations must deliver good practice and comply with certain basic procedures. In some cases these procedures can also be a legal requirement – compliance with health and safety and other legal obligations, for example. Capturing and embedding such explicit knowledge can be achieved by various methods – for example, through Word macros, letter templates and standard letters of appointment – all requiring expert knowledge to be translated into rules and procedures that can be applied across organizations. Technical knowledge can be integrated into processes through calculation plans, standard details or spreadsheets – a simple example in the corrosion protection field is the translation of a 30-page British Standard into a two-line interactive spreadsheet. This translation allows a less-experienced engineer to benefit from the knowledge of an expert, minimizing the chances for mistakes on a project, and enabling people to reuse templates, sound in the knowledge that they are building on past experience rather than reinventing the wheel.

Whilst application of standardized knowledge is valuable, mobilizing tacit knowledge is essential for more innovative projects and organizations to ensure that creativity is not curtailed. In today's increasingly dispersed organizations, it is essential to network effectively to ensure that clients receive the best knowledge of the firm, rather than the best available in a given location. This may be by finding experts or by networking people together by communities of practice; groups of individuals working on separate projects but united by common interests. The potential value of communities is immense, as they provide a powerful means of knowledge exchange, allowing people to ask questions, search for answers, and receive training from experts in their chosen field.

Having created a knowledge base, the challenge is then to create the right environment to ensure consistent and appropriate application of this knowledge. How do we encourage individuals to make the right decisions at the right place and time? The answer ultimately lies in such factors as an organization's culture, its ways of working, and knowledge sharing. In many ways, this requires attention to factors that are rooted in the past; mentoring, coaching, teaching and learning.

3

Young engineers working alongside their more experienced peers need the opportunity to learn by observing, by listening. By doing this, they can acquire valuable skills, such as managing risk and learning from failure, progressive problem-solving, self-organization, and interpersonal skills. In the present economic environment all this is becoming harder to achieve, as increasing workloads and tighter budgets drive many firms towards ways of optimizing performance, increasing productivity, and eliminating unnecessary activities. There is a danger that increasing workloads prevent senior staff from devoting sufficient time to junior staff. In the short term, this may achieve cost savings and improve efficiency, but the long-term consequences are alarming – lack of knowledge transfer runs the risk of repeating mistakes that are well known to experienced staff.

Looking to the future

Effective KM demands that organizations consider:

- how best to recruit, develop, and retain the best people
- how best to combine the skills of individuals
- how to create distinct capabilities in an increasingly competitive business environment
- how to create value for clients and communicate it effectively.

Recruiting the best people is essential to sustain competitive advantage, yet remains a particular challenge in the engineering sector where increasingly talented individuals are being lured into purely commercial and financial firms where better-paid careers may be on offer. In the face of such competition for talent, organizations must recognize the need to engage individuals, recognize their needs, and respond to these to ensure people are happy to work for the organization rather than merely being employed to do so. In recent years, the difficulty in recruiting good staff has put individuals in a much stronger position. People are now more likely to hire organizations than vice versa.

People expect to be involved in interesting work, to achieve an appropriate balance between work and home life, and to be treated fairly in terms of rewards of recognition. Ultimately a split has emerged between individual and organizational priorities resulting in the need to strike a balance.

The future will see people as increasingly key to effective KM and business performance. Organizational pressures to achieve increased productivity, greater agility, and competitiveness in the marketplace can only be achieved if knowledge is managed and applied in ways that complement the needs of the individual. The knowledge challenge is to successfully achieve this balance between organizational needs and individual motivations (Fig 3).

Organizations must, therefore, consider how to get the best from the people they recruit, addressing such diverse issues as culture, motivation, and the workplace itself. The physical space in which people work offers opportunities to encourage creative thought and knowledge exchange. The metaphor of the mediaeval monastery is a good example of customized space, providing a variety of environments for different knowledge needs. Cloisters were spaces geared to accidental contact, and certain conventions were adopted in their use. For example, monks would walk in pairs to discuss issues, but an individual walking alone holding an open breviary was understood by others to be meditating. Similarly the UK Government Communications Headquarters (GCHQ) building in Cheltenham, England, has been designed to promote the exchange of knowledge to aid the global 'war against terrorism'. The threats of terrorism require different ways of working, with a new emphasis on knowledge sharing and the ability to create serendipitous links and to form multidisciplinary quick-response teams. Open-plan offices, hot desking, spaces with comfortable sofas, artwork, and statues have all been incorporated to stimulate creative thinking and encourage open talk.

Conclusion

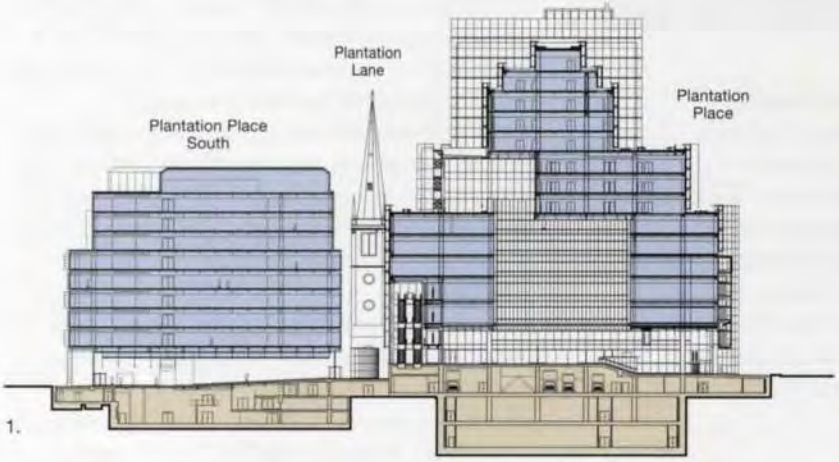
Successful organizations of the future will make knowledge work for their clients better than ever before. Clients will come to organizations demanding access to the best experience rather than merely the best available. They will expect people to deliver current good practice through appropriate processes, supplementing this with an ethos of improvement and innovation. Client expectations will continue to rise, and organizations that fail to match these standards will not survive.

To thrive in the future, organizations must manage knowledge strategically, developing an ability to recognize and exploit new market needs through effective combinations of skills and interests. Arup, for example, has already applied expertise developed in the germ warfare sector to address the spread of disease in hospitals, and finite element analysis developed in the building sector to car design. The key challenge will be responsiveness, and the ability to combine existing skills and interests from unexpected sources in ways that create client value. Knowledge will still have to be managed - not just to solve today's business problems, but to ensure that organizations continue to generate new capabilities for the future.

Credits

Tony Sheehan is Group Knowledge Manager for Arup.
Dominique Poole is Knowledge Project Manager at Arup.
Illustrations: 1, 2 Nigel Whale; 3 Ng Choon Boon;
4 Philippe Pellerin

Plantation Place development, City of London



1.


2. Plantation Place and St Margaret Pattens viewed from Eastcheap.

One of the largest new projects in the heart of the City offers over 100 000m² of internal floor space and yet avoids overwhelming the adjacent historical buildings.

Plantation Place, designed by Arup Associates for the British Land Company, is one of the largest new projects in the heart of the City. Comprising almost an entire block, the 1ha site is bounded by Fenchurch Street (north), Mincing Lane (east), Rood Lane (west) and Eastcheap/Great Tower Street (south). Christopher Wren's grade 1 listed church of St Margaret Pattens occupies the south-west corner, together with an 18th century town house now used as an office. Another office building, 51 Eastcheap, remains on this part of the site, adjacent to the church.

The Plantation Place development comprises two buildings. The larger, itself known as Plantation Place, and built along Fenchurch Street, has 15 storeys plus three basement levels, giving a total of 78 300m² gross internal area above ground, including 2300m² of net retail at ground level. It has various floor plate sizes and uses; levels 2 and 3 may be fitted out as trading floors providing 4900m² net of contiguous office area on each floor. The second building, Plantation Place South, is 10 storeys high and provides some 22 500m² gross internal area.

The development also incorporates a new pedestrian route, Plantation Lane, which cuts east-west from Wren's church to Mincing Lane. The creation of this route – a combination of art, architecture and urban design – embeds the new building into the grain of the ancient city and enhances the urban context. One side is marked by an integrated artwork, also designed by Arup Associates in collaboration with artist Simon Patterson, depicting the surface of the moon, while the natural stone pavement is inscribed with text. This newly-created route acknowledges the City of London's rich historic fabric, reflecting the medieval street pattern.

The proximity of the site to the River Thames and its location outside the City's cluster of tall buildings set the maximum height. This, coupled with various view studies and rights of light agreements, defined the envelope profile of both buildings. Of special concern were the close views of the tower and spire of St Margaret Pattens from Great Tower Street. Here the upper mass of the building is set back and this, together with the glass cladding reflecting the sky, avoids overwhelming Wren's design.

Plantation Place

Mick Brundle

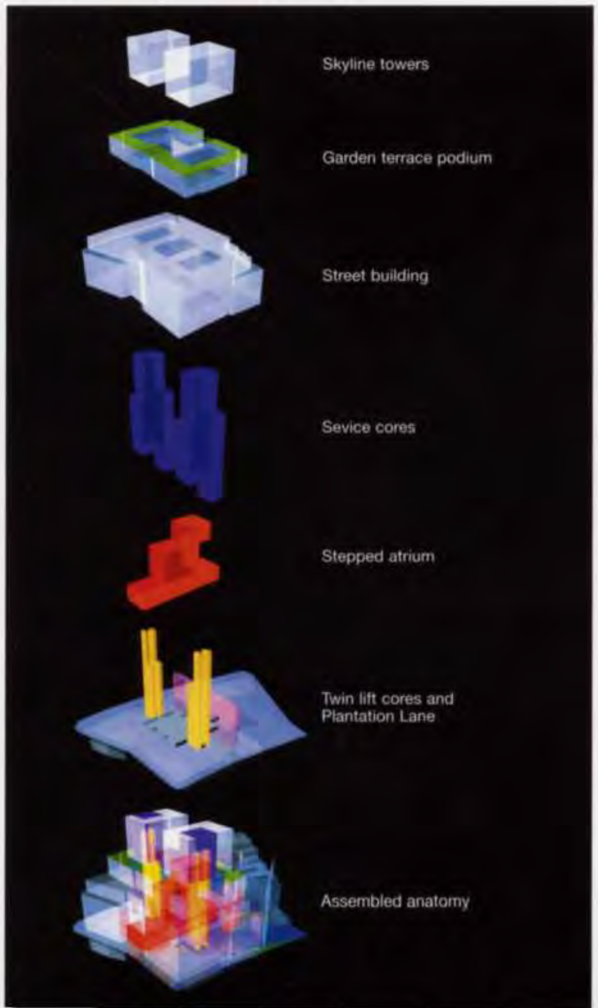
The overall form

The overall architectural form developed in response to the site's complex constraints, but was also conceived as a positive contribution to the civic realm in this part of the City. Through a series of adjustments in plan, angled cuts and set-backs, the building transforms itself from the street-defining base and reinvents and fragments its form as it ascends, culminating in a pair of glass cube forms in the skyline. The resulting composition, while accommodating the very considerable programme, disseminates its volume into its immediate surroundings. It is seen from the surrounding streets not as a single object but a series of vignettes.

The stratification of the building vertically, into street architecture below and deep setback terraces of smaller office floors above, suggests two façade types and provides the opportunity for opening windows for fresh air and garden terraces at the upper levels.

4. The Plantation Place atrium.

3. Plantation Place building anatomy.



The internal anatomy

The Fenchurch Street entrance is defined by a change of alignment of the existing street pattern, which together with the recycled and critically-acclaimed Marketing Suite Beacon[1], establishes the building's presence when viewed from the Gracechurch and Lombard Street part of the City.

A pair of Jura limestone-clad towers framing the glass entrance screen provide a *cordon sanitaire* between the office entrance and retail areas, which occupy most of the ground plan. A double-height entrance hall leads via a wide Jura limestone staircase to a 43m high central atrium. A dematerialized glass bridge connects together the first floor levels and provides a dramatic threshold before entering the atrium interior.

The offices are on either side of the atrium, with two cores to each side containing lifts that serve all floors and escalators at the rear to the lower levels. The cores also contain services risers, staircases and washrooms, and allow easy access to all parts, particularly the larger floors, so walking distances are minimized.

In section the atrium is stepped towards the south on the upper levels, bringing daylight and sunlight deep into the lower level. This configuration provides a more usable contiguous floor plate arrangement at the upper levels; the atrium forms the centre of a U-shaped office floor at levels 7 to 9 and is bridged over completely at levels 10 to 14.

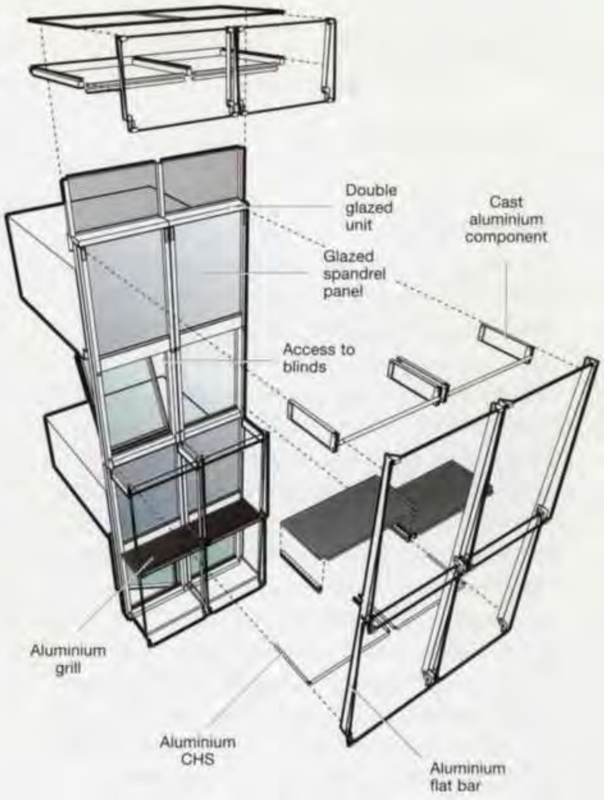
Service access for both buildings is from a vehicle entrance in Rood Lane. A two-way ramp provides access to an upper basement level with head clearance for large trucks and refuse vehicles. There is parking for 46 cars at this level. Two further basement levels, the middle and lower basements, contain plantrooms and tenant storage. An additional plant room is provided at level 15.

The façades

The cladding design represents a long-standing interest by Arup Associates in environmental design, occupant comfort, and a 'layered' approach to architectural façades. The two main types described combine these aspects, incorporating various passive and active solar control devices and simultaneously creating a distinct architecture. The façades have high thermal performance, exceeding the requirements of the new part 'L' of the *Building Regulations*, with solar shading and high insulation standards increasing comfort levels and minimizing energy consumption. A balance between highly insulated cladding and high performance glass maintains internal comfort conditions.

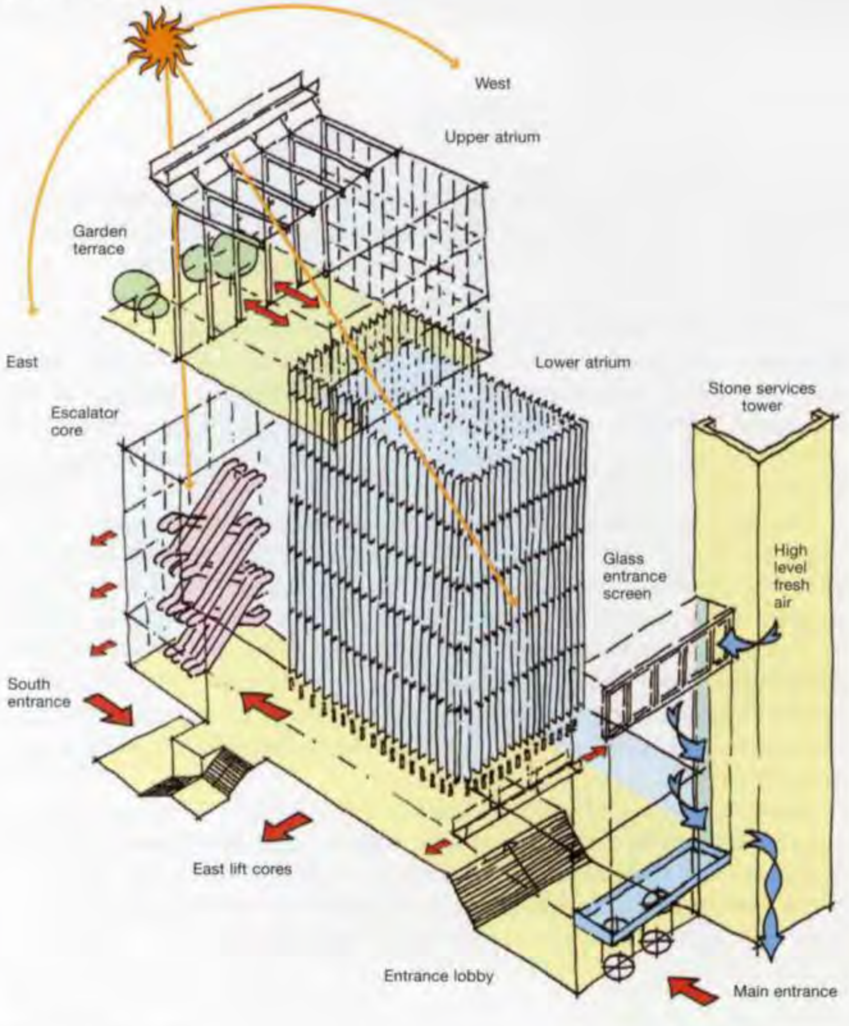
The street base responds in height and façade treatment to the character of the surrounding City buildings. As the streets here are narrow, the façades are designed for oblique viewing. Heavy modelling in stone, glass and metalwork maximizes the effects of light and shade and provides an urbane presence, while maintaining a fully glazed perimeter to the deep floors.

The upper-level floors are smaller, and enjoy enhanced daylight, a more open aspect, panoramic views of the City, and fresh air. Innovative technology can enhance the workplace environment; the whole building offers a high quality, fully air-conditioned environment but the environmental solution also goes much further. The upper levels can be partly operated without air-conditioning. The air at this level is less polluted, giving the opportunity to naturally ventilate the offices from opening windows in the façades, in conjunction with air-conditioning when required.



6. Upper level double-skin cladding.

5. The atrium concept.



Upper level double-skin cladding

A double skin of glass, the outer a wind and rain screen of frameless clear tiles tilted at 3°, acts as an open-jointed thermal flue, rain screen, and wind baffle. The inner skin of high performance glass cladding, with opening windows and heavily insulated glass spandrels, allows occupiers the choice of natural ventilation or air-conditioning for much of the year. Both skins were based on a 1.5m wide module and assembled on site as a series of 600mm deep prefabricated cassettes, complete with blinds, glazing, and maintenance walkways.

The zone between the skins contains active solar blinds on the outside of the inner cladding while deep maintenance walkways act as passive solar shading, reducing the need for descending blinds on sunny days. These walkways provide maximum access to the cladding and blinds without disturbing the office activity within, essential for a typical densely-occupied City floor plate.

Sensors mounted on the inner façade for every tenancy zone detect solar conditions for that part of the building, while controllers inside raise and lower the blinds accordingly. The façade thus responds locally to solar conditions. The outer skin allows windows to be opened for ventilation in rainy and windy conditions, and protects the solar control blinds from wind damage when deployed in all but extreme situations.

7. The atrium at podium level.

The architectural expression of the upper building massing provides a distinctive silhouette on the City skyline. This, in combination with the layered façade of the reflective glass tiles, active solar blinds and metal filigree, enhances the skyline presence and positively locates the development in the City context.

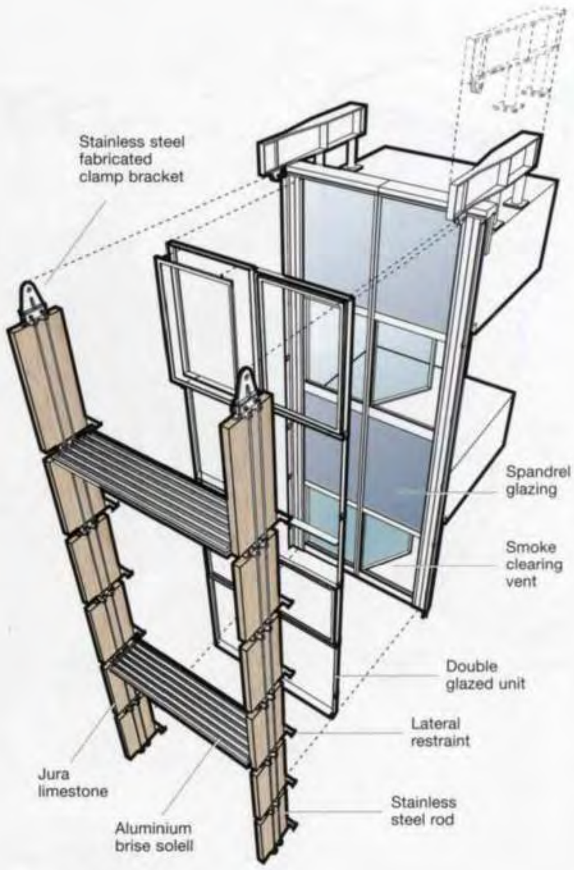
Lower level cladding

As the lower floors, with their deep-plan offices, are large and close to noise and pollution from vehicles, natural ventilation is not appropriate. Instead a curtain of linked Jura limestone fins on a 3m horizontal module 600mm deep orthogonal to the façade replaces the outer glass screen of the upper level cladding.

The reason for this is part contextual and part environmental. The building replaced a collection of stone buildings including the neoclassical commodity trading building Plantation House. Although none were of great architectural merit, it was a condition of planning that the new building should present itself to the City as one clad largely in stone.

The stone fins form a three-dimensional curtain which, together with horizontal fixed metal louvres and heavily insulated glass spandrels, provides sun shading to the office floors and a suitable architectural composition to the urban setting. Though the façades are fully glazed, the mostly oblique views from the narrow streets show the fins closing up to conceal the glass and forming a more solid elevational expression. This also benefits occupiers, as the fin screen and glass insulated spandrel provide an element of privacy in the manner of an Ottoman jalousie, whilst the fins themselves, similar to a conventional stone reveal, act as light reflectors into the interior.

To maximize the street retail presence around most of the building, the stone curtain stops at first floor level, the ground plane with the exception of the main and service entrances being expressed as metal clad columns with glass shop windows and entrance screens between.



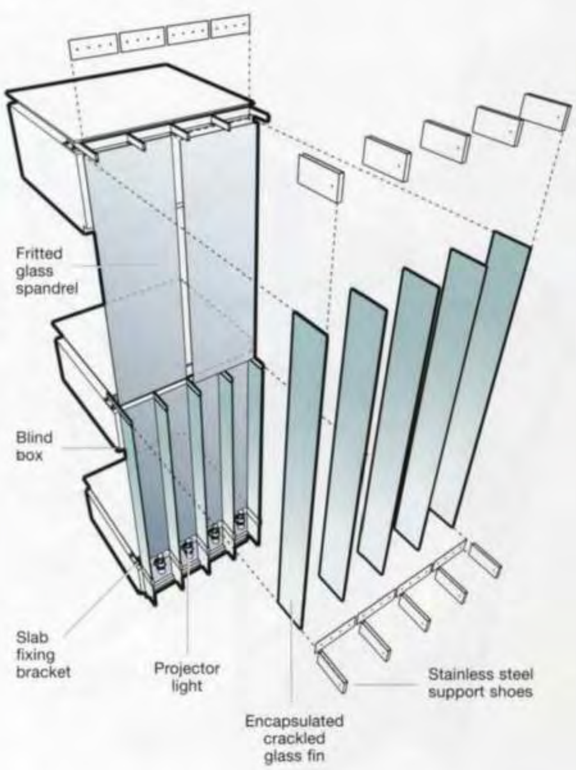
8. The lower level cladding.

The atrium cladding

The skin defining the atrium's spatial envelope continues the theme of manipulating light. Resonating with the principle of the external curtain of stone fins, the atrium cladding is designed as a series of projecting vertical glass fins on a 750mm horizontal module within the atrium supporting the glass perimeter cladding. The layer of fins forms a screen between the occupiers of the office floors, allowing some privacy and visually defining the seven-storey atrium as a large 'room'.

The fins are fabricated from shattered toughened glass, encapsulated between two sheets of low iron glass. They transform ambient light from various natural and artificial sources into coruscating light, an optical device similar to a cut glass chandelier. Stainless steel 'shoes' spanning between floor levels continuously support the fins, which are edge-bonded to the atrium glass cladding with structural silicone, providing stiffness and reduced glass thickness to the whole cladding assembly. With the varying external light entering from the southern sky, a dramatic and ever-changing interior is created at the heart of the building.

9. The atrium cladding.



Atrium glass bridge

Terry Raggett

The client required the first floor plates bisected by the atrium to be linked by a bridge, which Arup Associates desired to be as light and ephemeral as possible. It was thus built substantially of glass, the glazed floor providing both visual lightness and significant lateral stability. The spanning elements are integrated with the floor structure above and are not visible in the finished enclosure.

A ladder chassis of stainless steel flats is suspended by stainless steel rods attached to the floor beams above. The interaction between the suspending and suspended structures was checked for overall dynamic performance. Laminated glass floor panels were laid laterally with a continuous silicone seal into the ladder structure using an EPDM separating strip. This ensured that they contribute to the lateral stiffness of the frame over the full 18m span.

The critical structural element is the coupling piece that connects the ladder chassis to the suspension rods. This element supports the glass wall panels via cantilevered brackets and resists the lateral balustrade and kick rail loads.

10. The glass bridge interior.

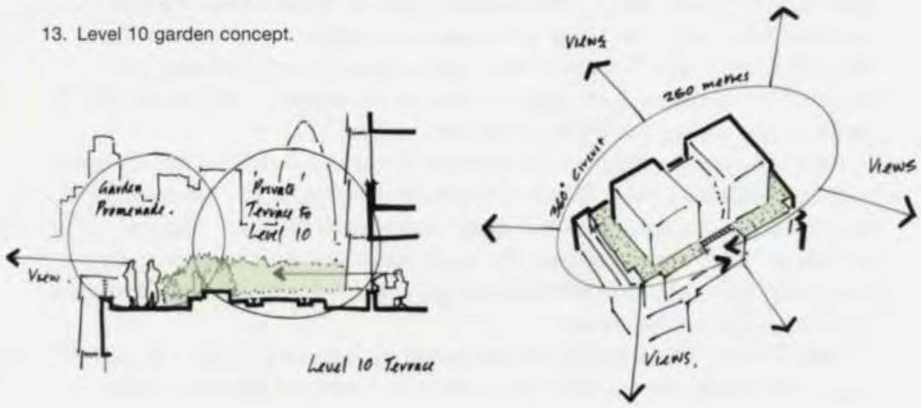
The laminated glass wall panels are supported via neoprene pads on these brackets and restrained laterally at their corners using EPDM shims to avoid glass-to-metal contact. There is an allowance for vertical alignment at either end of the tie rods, and the structure is restrained longitudinally by connection to the floor structure at one end only.

The ladder chassis came to site as one piece and was slid into position on a moving platform. The rods were then attached and adjusted for alignment and subsequently for load equalization prior to glass installation.

11. The atrium cladding: corner detail.

12. Level 10 garden terrace.

13. Level 10 garden concept.



'Time and Tide' artwork: Plantation Lane

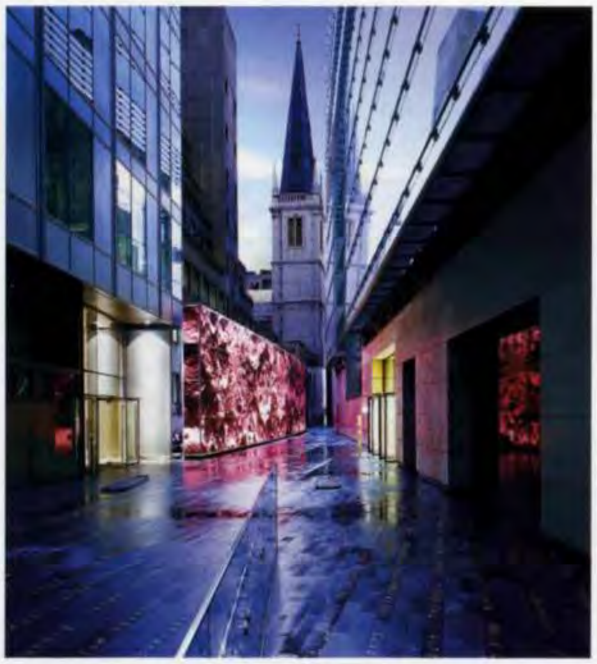
Lee Hosking Declan O'Carroll

Artistic vision

This close collaboration between the artist Simon Patterson and Arup Associates, funded by developers British Land, is part of an initiative to 'put something back' into the City of London. The artwork is integral to Arup Associates' public realm concept, and crucially was developed hand-in-hand with the design of the new public space, rather than commissioned separately.

The work, 41m long and 6m high, was conceived to suggest constancy during times of change, and Patterson also devised a collection of texts to be inset into the stone of the new pavement. The text sits along a series of great arcs, which appear to slide underneath the mass of the new buildings. Each curve of text represents a different timeline, beginning with Roman gods and goddesses, and moving through miscellaneous information such as the City Guilds, the Livery Companies and the different membership degrees of the Freemasons. 'The visitor can either follow a particular timeline, or choose a more random but equally fascinating reading by cross-referencing the different timelines', says art critic Andrea Schlieker[2].

14. Plantation Lane looking west.

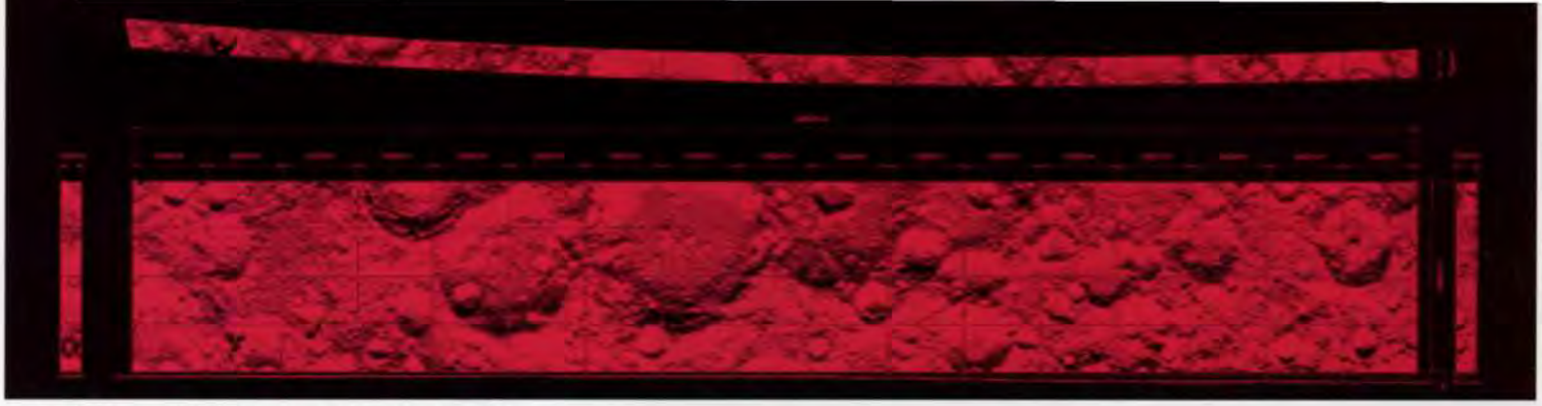


The garden terraces

The step between the upper and lower atrium chambers occurs at level 7, corresponding to a garden terrace level. A south-facing wintergarden on the floor of the upper atrium has direct access to the outside garden terrace. As the building steps back, other terraces are formed, culminating in the main large garden terrace at level 10 with direct access for occupiers from the two main lift cores through the upper façades.

This garden was designed as a series of arboreal chambers of soft and hard landscape linked to a main pedestrian route around the building perimeter, giving occupiers a sheltered, private and attractive amenity. A maintenance railway for cleaning cranes occupies the inner part of the terrace. By designing the rails flush with the hard paving and providing parking alongside the two cores for the cranes, the sense of 'garden' is maintained when viewed from the level 10 occupied floors.

The terraces are linked to the south by a vertiginous bridge over the glass roof of the atrium, which allows a 360° promenade around the building with exceptional views of the Thames and the City. The gardens have happily provided a habitat for insect and bird life, which surprisingly proliferate at this level in the City, when given the opportunity.



15. The illuminated Moon screen: orthogonal projections.

Patterson settled on an image of the Moon to counterpoint the difficult, rapid and often violent changes that have imposed themselves on the people of London across the ages. Londinium's Roman inhabitants used the Moon's cycles to underpin their calendar, and today it is a symbol of scientific progress.

'As the same hemisphere of the Moon always faces the Earth, people will have witnessed the identical sight in the night sky throughout history, from the first settlers in Londinium to today's City bankers', says Schlieker. 'The image of the Moon is particularly rich in associations, within the field of pagan and sacred symbolism, as ubiquitous symbol in legends and myths, as locus for romantic yearning, but also as incarnation of scientific progress in the 20th century. Patterson wants to allude to all of these different concepts with this mysterious and emblematic image.'

Engineering

The screen foundations were cast well in advance of the final geometry being resolved. An oversized 1200 x 650mm deep supporting reinforced concrete beam was necessary to give flexibility for the artistic vision, leaving room for some minor deviation in the plan geometry and size.

In its final resolution, the curved geometry of the screen lines the middle of Plantation Lane's south edge, set out east/west using a 2.4m x 750mm module along a radial geometry. The steel frame of the giant light box comprises a series of structural UC sections 6m tall at 2.4m centres, positioned at its rear and attached and levelled to the concrete below by baseplates, with post-drilled bolts.

To maintain the clarity and simplicity of the design vision, the support system had to minimize shadowing inside the screen when illuminated and be positioned far enough behind the artwork to not show through immediately behind the glass. As the structure was never designed to be visible, the lightness of the members was entirely a consequence of the lighting performance.
A simple system of horizontal arms bolted to the column sections supports the glass screen, and provides the first level of vertical adjustment. These arms are in turn supported by threaded diagonal tension rods that carry the glass dead load, and also provide further adjustment. Cruciform stainless steel clamping brackets with no visible external fixings are fixed into threaded ends of these arms. This allows horizontal adjustment to maintain the screen curvature. The glass itself is 1.5m x 2.4m modules in landscape orientation.

The glass and artwork were prototyped in a series of 1m square samples, inspected in a purpose-built lightbox. In all, 24 samples were examined before the final glass build-up and printing technique was chosen. Multiple procedures were involved, including several different methods of ink-jet printing onto both glass and laminate material.

The final glass build-up is a laminate of two sheets of 12mm low iron glass with an anti-reflective acid-etched finish to the outer visible surface. This was to avoid reflections in the surface when viewed obliquely – an important consideration, as the approach is always at an angle along the narrow Lane. The rear of the inner glass pane is covered with a 100% ceramic white frit, which diffuses the light source and eliminates views inside the screen through the 'white' areas of the monochromatic image. The final artwork was produced photographically and laminated with a clear pvb interlayer to complete the sandwich. The completed image can be viewed in daylight as well as by artificial light.

The glass panel installation is finished with a clear silicone joint to reduce particle migration inside the screen, and to minimize maintenance needs. The back of the screen is powder-coated aluminium panels, attached by 'hook-on' cladding technology, which can be removed for maintenance. The joints between them are sealed with gaskets to eliminate light leakage, which would have been a distraction to the offices behind the screen.

Color Kinetics *ColorBlast* LED fittings supply the illumination in rows at the top and bottom of the light box at 800mm centres, fed from two separate control boxes at each end of the screen. The software-controlled lighting enables a constantly changing colour rendering behind the glass. The top row of light fittings is accessed externally via a discreet glazed hinged lid complete with gas struts to allow safe maintenance, and restraining clasps to avoid wind uplift.

16. The Moon screen: colour variations.

Plantation Place South

Graham Goymour

Overall form

As a discreet element in the development, Plantation Place South adheres to many of the design principles developed for the site as a whole, while establishing a clear identity for itself on the southeast corner. It is designed around a central core, with principal south and east-facing frontages onto Great Tower Street and Mincing Lane. It connects at basement level to share servicing facilities with the overall development.

17. Plantation Place South from the junction of Mincing Lane and Great Tower Street.

The building's massing responds to its prominent corner location with set-backs at upper levels to create sympathetic relationships with adjoining buildings and to reinforce the sense of architectural order in the façade, arranged in three tiers. At ground level a double-height colonnade supports the main body of five floors, whose plates extend to the site boundaries to reinforce the surrounding urban pattern and correspond with adjoining parapets and setbacks. Above this, three upper levels are set back in two stages to create terraces and to break down the building's massing.

Entry sequence and integration into urban context

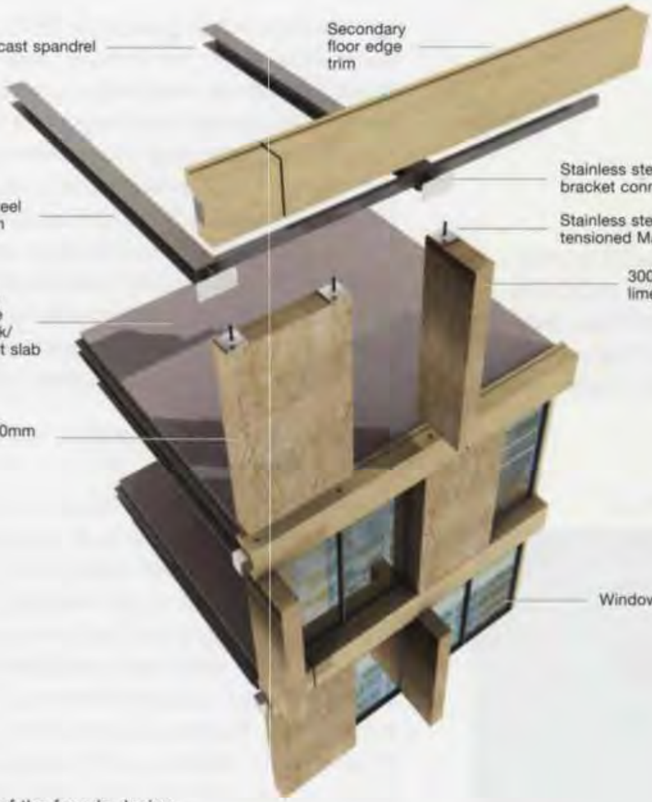
To further augment the public realm on the site, the design of Plantation Place South incorporates its own route at ground level linking Great Tower Street to the new pedestrian route, Plantation Lane. This internal link is designed as part of the building's entry sequence, which takes visitors through an external arcaded space into a large, double-height entrance hall. This leads directly to the ground level lift lobby and is extended northwards, via a gradual incline, to Plantation Place. The entire sequence of spaces is lined on one side by the broad sweep of a curved chain mail screen that finally connects to the external illuminated screen in Plantation Lane.

The intention behind this internal route is to encourage cross-movement though the entire site to the benefit of the greater development and the building itself, which is served by a secondary entrance from Plantation Lane.

Façade design: loadbearing stone

With its proximity to the conservation area, the Wren church and indeed, Plantation Place, the building's architectural identity appropriately relies to a large extent on the use of natural stone. At the same time, compliance with *Building Regulations* suggested a very deliberate approach to limiting the amount of glass. These considerations led to the evolution of a façade where stone transcends its common use as a cladding material to one in which structural, architectural, and environmental concerns could find a common expression.

The façade design for Plantation Place South also evolved from patterns established in the first phase of the project, particularly the use of suspended stone fins. A Jurassic limestone from Bavaria was chosen for its excellent weathering properties and high compressive strength, and in Plantation Place South these properties are utilized in a loadbearing construction.



18. Elements of the façade design.

Instead of cladding components being clipped to the outside of a structural frame, a masonry wall was erected, with openings formed to receive window components in a separate installation. This traditional approach of wall and window construction suggested an economic benefit through greater market competition than the more usual curtainwall solutions.

A modular approach with a 3m grid was adopted, with three basic structural components: a stone fin, a stone wall panel, and a horizontal spandrel panel, each arranged in repetitive bays in a staggered pattern with glazed window openings.

The base pattern on the east elevation places the larger window openings north of the projecting fins to maximize self-shading, which is also enhanced by the deep reveal nature of the façade. Window framing is also hidden behind the masonry panels to minimize heat loss. The fin/panel/window pattern is staggered from floor to floor so that there is always a structural overlap between panels and fins from one floor to the next. Spandrel beams are arranged in 6m lengths, so that perpend joints always occur at the centreline of a wall panel below.

On the south elevation, which receives more direct sun, the arrangement of stone changes so that some fins are turned through 90° to become in-plane panels, thus further limiting the amount of glass on the façade, while still conforming to the established structural module with vertical load paths repeated every 3m.

A giant order at ground level collects this loadbearing construction through a transfer spandrel bearing onto columns at 6m centres around the building's periphery that also form arcaded spaces for the building's main entrance as well as a retail unit alongside Plantation Lane. Between these, office space pushes out to meet perimeter columns in the form of large bay windows.

Finite element analysis of the stone elements, scale load testing, and prototype panel construction all assured the integrity and buildability of the system.

By contrast, the building's upper levels are clad in a unitized system combining glazed and opaque units that maintain the same proportion of clear glass as below for a consistent internal appearance. This lightweight cladding also reinforces the sense of contrast between lower and upper levels.

Structural design

As well as satisfying the normal functional aspects, the structural design aimed to enhance project delivery and value. The key concepts, which define the approach taken, are as follows:

- Arrange the layout to mitigate site constraints in advance of construction.
- Configure the substructure to give an early gain on critical path activity.
- Optimise the structural frame system for efficiency and buildability
- Use an innovative passive approach to the fire protection of structural steelwork.
- Develop a creative and integrated façade design to add character and value.

Bounded by Underground tunnels, highways, and a nearby building on shallow foundations, the site's existing perimeter retaining walls surrounded a zone of undisturbed archaeology. The basement was therefore sited centrally, clear of these constraints to mitigate obstruction disturbance and minimize the effects of excavation ground movements. A central core and the principal columns were arranged to be in this clear zone with only light perimeter loading.

Secant walling and foundation piling progressed unobstructed in the central zone. The outer zone was slabbed over the undisturbed archaeology, and this formed a stiff perimeter waling ring to enable open central zone basement excavation. The avoidance of substructure temporary works allowed a slipformed core to spring directly from the lower basement level. This gave the earliest start to core construction, including prefabricated services risers, lifts, and toilet finishes - the critical path activities in a commercial shell-and-core office building.

19. View from office floor south towards The Monument.

20. The reception hall.

Optimizing the structural frame

The building's planning and floor plate efficiency suited a central core with clear floor spans to the perimeter, and alternative floor framing systems were compared. The normal efficiency of multi-bay concrete construction was eroded without the repetitive bay continuity for the building layout considered here. Additionally, elastic redistribution of two-bay continuous concrete increases load on the central column, but pattern loading still requires the edge columns to carry a full bay reaction. This means that foundations for concrete need to be designed for more than the building actually weighs, with significant impact on foundation cost.

A steel frame, on the other hand, ideally suits simple bay spans, so the chosen approach was UC sections for secondary beams, acting compositely with the lightweight concrete metal deck slab to reduce overall structural depth, and services duct distribution running freely below. Services cross-overs and core entries were organized in the spaces between beams, which meant that, within the same overall floor depth, services space and distribution flexibility actually exceeded the comparable thinnest prestressed concrete flat slab option.

Passive fire protection

An outstanding feature of the structural design is the use of state-of-the-art thermo-mechanical analysis to establish an economical approach to the fire protection of structural steelwork, and determine the strengths and weaknesses of the building structure so that mitigating measures could enhance robustness in the fire limit state. This resulted in the first approved use of this approach for a City of London building. Additionally, the development of specific construction details to help limit the impact of fire on the final structural design provides an additional level of safety.

This approach comes from extensive research carried out with the University of Edinburgh, validated on the Cardington Large Building Test Frame Program.

After agreement on the approach was obtained from the client, his insurer, and the local authorities, the fire team developed the design basis fires for input to the structural models with the City of London, the London Fire and Emergency Planning Authority, and a third-party reviewer. Following detailed and extensive non-linear finite element analysis of the composite steel frame structure in the various agreed design fires, the team undertook a comprehensive review of the structural fire responses.

This demonstrated what structural elements required fireproofing to ensure a major load-carrying mechanism in fire could take place – tensile membrane action. In addition, various changes to the cold temperature design were made including redirecting the rebar within the concrete core to limit heat transfer to this anchoring mechanism, and providing specific fireproofing to key connections. Progressive collapse checks in the fire limit state were carried out on the basis of the recommendations in Part A of the *Building Regulations*.

As severe fires were assumed, on the basis of total sprinkler failure and full floor engulfment in fire, plus multiple areas of broken glazing for venting in the design fires, no limits were required to be placed on the building design for future changes.

This approach has been nominated for the Structural Steel Design Award 2005.

Credits

Client: The British Land Company PLC **Architect, structural, and M&E engineer:** Arup Associates - Nicola Adams, Gert Andresen, Mark Arkinstall, Rachel Atthis, Simon Barden, Graham Bardsley-Smith, Mike Beaven, George Bowman, James Bown, Mark Boyle, Anita Bramfitt, Paul Brislin, Tony Broomhead, Mick Brundle, Peter Caller, Glen Carney, Jason Clark, Steve Clarke, Peter Connell, Chris Cowell, Paul Dickenson, John Edgar, Geoff Farnham, Paul Felix, Kevin Fellingham, Martin Finch, Richard Gargaro, Matt Gilliver, Maureen Godbold, Darren Goodman, Graham Goymour, Ian Hazzard, Matthew Higgs, Ed Hoare, Tony Hoban, Lee Hosking, David Hymas, Jacqueline Jiang-Haines, Lindsay Johnston, Mario Kaiser, Jackie Keegan-Warg, Dan Kelly, Caroline King, Mike King, Mike Kinney, Joanne Larmour, Andrew Lawrence, Pablo Lazo, David Lee, Tommy Lee, Steve Leonard, Benjamin Lim, Sean Macintosh, Teresa Marshall, Luke McAdam, Barry McAulliffe, Richard McCarthy, Daryl McClure, Abi McGillivray, Will McLardy, John E Miles, Cathy Milligan, Marek Monczakowski, Terry Moody, Andrea Nonni, Declan O'Carroll, Jane O'Connor, Mark Oxbrough, David Pearce, Annelise Penton, Lizzie Pomeroy, Robert Pugh, Carolyn Quinn, Terry Raggett, Steve Ratchye, Graham Redman, James Reed, Patrick Regan, Roland Reinardy, John Roberts, Davina Rooney, George Scott, Stephen Setford, Caroline Sohie, Lexy Stevens, Nick Suslak, Matt Vaudin, Malcom Wallace, Jim Warren, Gary Webb, Mark Winter, Ken Wiseman, Roger Wood, Jo Wolbers, Tim Worsfold **Controls, façades, fire, transportation, acoustics, geotechnical, archaeological, materials, security, water and planning consultant:** Arup - Darren Anderson, Simon Barden, Simon Barnes, Simon Brimble, Graham Dodd, Nathan Hewitt, Richard Hughes, Susan Lamont, Barbara Lane, Pein Lee, Tom Linder, Nicola Masters, Silole Menezes, Bruno Miglio, Zedi Nyirenda, Dinesh Patel, Joe Pavely, Jeffrey Pereira, Haico Schepers, Matthew Shinkel, Cyrus Toms, Stephan Von Roon, Simon Webster, Darren Wright, Malcolm Wright, Roddy Wykes, Jason Zawadzki **Project manager:** M3 Consulting **Quantity surveyor:** Gardiner & Theobald **Construction manager:** Bovis Lend Lease **Planning:** Montagu Evans **Rights of light:** Anstey Horne **Party wall surveyor:** Dron & Wright

[Plantation Lane] **Artist:** Simon Patterson **Artist's visualization:** Stephen Kirby **Architectural metalwork & glass balustrades:** Glazzard **Stone flooring:** Gabriel Engineering; Miller Druck International **Stone supplier:** Italmarble Pocai, Neumeyer and Brigl **Illuminated screen & glass gates:** Josef Gartner **Printed interlayer processing:** Concepta Colourglass **Glass supplier:** Eckelt **Stainless steel gates:** Kimber Engineering **Floor lighting:** Zumtobel **Illuminated screen lighting:** Lighting Technology Projects

Illustrations: 1, 3, 5, 6, 8, 9, 13, 15, 18, 21 Arup Associates; 2, 4, 7, 10, 11, 14, 16, 17, 19, 20 Christian Richters; 12 Richard Bryant

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1. The rental car facility from the south-west, with the quick turnaround building in the foreground.

Miami Airport QTA: risk-informed performance-based fire protection

Risk assessment and performance-based fire engineering met the challenge of designing a facility with 120 fuel dispensing stations for the rental car area at Miami Airport's multi-modal transportation hub.

Richard Custer Matthew Johann Brian McLaughlin Brian Meacham Jeffrey Tubbs Christopher Wood Eileen Wood

Introduction

Miami International Airport (MIA) is one of the busiest in the USA, ranking third by passenger numbers in 2003 after New York's JFK and Los Angeles' LAX. A long-term masterplan for comprehensive improvements has been under way since the mid-1990s and, in addition to extended and enhanced terminal facilities and a fourth runway, the current $4.8bn Capital Improvement Program includes a major upgrade to the landside transportation system.

Part of this upgrade is the Miami Intermodal Center (MIC), a transportation hub to facilitate connections and transfers between air, rail, and ground transportation. Its first phase is a five-year programme comprising, firstly, improvements to the currently congested highway system, and secondly, construction of the first phase of the MIC 'core' and of the MIC/MIA Connector, an automated people mover system that will link the MIC with the airport.

The programme's third element is the consolidated rental car facility (RCF), which will occupy slightly more than half of the 53 acre (21.5ha) MIC site. The RCF will house the operations of all rental car companies at the airport and serve as the transportation core for intercity and local buses, heavy rail, retail outlets, and passenger services, with provision for future developments. Within the RCF, a key element is the quick turnaround (QTA) facility, which will be used for vehicle fuelling, cleaning, and light servicing.

The QTA

Typically, QTAs are isolated, on grade facilities. However, the constrained MIA site has led to the unprecedented step of making this QTA a multi-level facility, rather than the conventional grade level or ground floor location. Thus it is essentially an immense reinforced concrete parking garage, comprising four storeys each 660ft x 320ft (201.2m x 97.5m), with 16ft (4.9m) floor-to-floor height. As conceived, the first three levels will contain fuel dispensing (120 stations, 40 on each level), fluid filling (oil and windshield washer), tyre air filling, and washing areas. The fourth floor will be used for additional vehicle storage.

Two fuel farms and storage areas for the QTA liquids (windshield wiper fluid, oil, detergent, etc) will be nearby, with the storage tanks for the gasoline built underground. The gasoline piping to the QTA will be contained within a vertical concrete construction, with entry onto each level.

Unlike the rest of the RCF, the QTA operations present unique hazards and risks. Specifically, the number of gasoline dispensing stations planned in the building greatly exceeds what is allowed by the governing regulations (*NFPA 1*[1] and NFPA *30A*[2]), which also do not allow multi-level indoor fuelling, and only permit indoor fuelling on the ground level within 50ft (18m) of an exterior wall.

The refuelling configuration poses a number of hazards, including:

- a larger uncontrolled fuel release in one place than would occur at a smaller, independent facility, due to increased fuel release rate and/or spill duration
- more sources of potential ignition from the many fuel dispensing stations
- greater challenges in fire detection, suppression, and/or egress than in a smaller facility
- the potential for explosions from the formation of fuel vapour-air mixtures
- more significant spray fires as a result of the higher pressure in fuel supply lines to multiple levels
- fuel fires flowing from a higher to a lower level, due to the elevated fuel dispensing
- increased risks to occupants and responding emergency personnel from multi-level fires and/or explosions.
- increased challenges in fire suppression associated with multi-level fuelling.

A risk-informed performance-based approach

In October 2000 a workshop was held to discuss the fire and life safety issues associated with the RCF's conceptual design. The workshop determined that, given the overall scale of the facility, a performance-based approach would be the most appropriate, informed by a system safety assessment and risk analysis.

This was made possible by the existence of regulatory clauses that allow the use of alternative methods and materials to those specified by the regulations. The Miami Dade Aviation Department Aviation Life Safety Bureau thus allowed for a performance-based approach as appropriate for the facility, given its uniqueness and incompatibility with prescriptive code requirements.

Fire and life safety analyses

As part of a design development team that also includes EarthTech Consulting Inc (project manager), HNTB Architects Engineers Planners (architect), Wolfberg Alvarez (MEP engineer), and Burns & McDonnell (fuel system design), Arup was engaged in 2000 as risk and fire protection consultant.

As discussed and agreed at the October 2000 workshop, the overall approach addressed the hazards associated with the refuelling stations in two parts - assessing fire and explosion hazards, and assessing the overall risks associated with hazards in the QTA – and following the design and analysis process outlined in the *SFPE Guide*[3].

The first step required a Fire Protection Engineering Design Brief (FP Design Brief) report to be submitted to the stakeholders. In general, this sets forth the scope of the analysis and details the overall performance-based process used, allowing stakeholder and authority input into the process before the bulk of the analysis is performed. This further allows for specific review and approval of the overall level of safety necessary for the facility.

The next step was to quantify the fire scenarios identified in the FP Design Brief in engineering terms. Firstly, the system safety assessment for gasoline used risk and failure analysis techniques to determine the significant scenarios that would need to be addressed through the fire and explosion hazard analyses, and estimated the frequency and sizes of spills.

Secondly, this was updated to include additional fuel island systems deemed necessary by the design/owner team. These were the lubricating oil, windshield washer fluid, and compressed air systems, and the updated system safety assessment outlined and summarized the risks posed by them. (The results concluded that the safety features specified for the refuelling islands for the 120 stations in the QTA's three levels will provide sufficient protection for any hazards from them.)

Thirdly, the performance-based fire protection report gave an overview of the fire protection systems and features proposed for the QTA, using 'performance language' to describe the overall approach to active and passive fire protection features in the facility, critical features, and design options for these features.

Finally, explosion hazard for gasoline fuel spills within the QTA was further reviewed, and documented in the gasoline vapour dispersion and overpressures report. This three-part analysis (vapour development, vapour dispersion, and deflagration overpressure estimation) concluded that significant structural damage was unlikely, but as with large spills in on-grade, open-air gasoline refuelling, persons in the vapour cloud could be seriously injured or killed. Specific recommendations and critical management procedures have thus been developed to address staff and other occupant safety.

Design solution

Based on the performance-based analyses developed for the QTA, the Arup team defined many critical features as being necessary for a successful design. First of all, the overall maintenance and operations requirements included the need for a comprehensive training and maintenance plan, together with an overall security plan to address deliberate events like arson or terrorism.

Beyond these, the team produced detailed sets of design characteristics that addressed overall fire and life safety issues; emergency fuel shut-off; the delivery, dispensing, and storage of fuel, windshield washing fluid, and lube oil; and control room panel features. These are all detailed overleaf.

What is performance-based design?

In contrast to the prescriptive approach which only specifies methods and systems without identifying how these achieve the desired safety goal, performance-based design in the case of fire protection uses an engineering approach based on established fire safety objectives, analysis of fire scenarios, and assessment of design alternatives against the objectives. This allows for more design flexibility and innovation in construction techniques and materials, gives equal or better fire safety, and maximizes the cost/benefit ratio during design and construction.

Critical design features

Fire and life safety

- four-hour rated vertical chases and concrete piping trenches
- fuel island retention area sized to accommodate a 100-gallon (455 litre) spill
- combination ultraviolet and infrared (UV/IR) sensors to detect flame in the fuel dispensing areas and initiate automatic fire suppression
- 212°F (100°C) heat detectors over fuel dispensing areas to back up UV/IR sensors
- overhead and floor-level alcohol-resistant foam system at the fuel dispensing stations to suppress and control fires in the retention area
- automatic sprinkler protection throughout, except directly over the retention basins at the fuel dispensing areas
- water curtain that won't spray into retention basin at the 20ft (6.1m) clear zone
- water curtains at the QTA/RCF interface
- manual fire alarm stations throughout
- standpipe and hose stations at egress stairs and as necessary throughout
- voice communication devices throughout
- visual alarms where required by code or due to ambient noise
- four-hour fire resistance rating for all floor-ceiling assemblies, columns, and other structural components, with tested fire-resistive protection to floors and ceilings directly above the fuel dispensing areas
- properly fire-rated expansion joints
- access for tenant spaces from refuelling areas through a corridor open at the top
- drains for the retention to be raised, like a roof drain, to reduce potential blockage
- minimum 3ft (900mm) free area above the tenant spaces to allow a substantial path for explosion venting.

Fuel delivery and storage

- fuel delivery within a dedicated unloading area having a containment area sized to hold the entire contents of a tanker truck (8000 gallons/36 400 litres)
- containment areas having dedicated drainage to an oil/water separator
- fill connections located within spill containment pads draining to concrete containment area
- integral overfill valves within the tank drop tube
- double-wall steel fuel storage tanks
- tanks provided with integral automatic gauging and leak detection systems, with control panels in the fire command room
- tank gauging system to monitor total product level, product temperature, and water level, designed to alarm at high-level and low level conditions
- monitoring system for tank interstitial space (leak detection) and pump sensors.

Fuel piping

- double-wall welded carbon steel piping, and welded carbon steel containment piping, with 100% radiographic inspection of welds
- nitrogen-filled double-wall interstitial space, with leak detection monitoring
- separate dedicated systems for each of the six piping sections (two per floor, 20 fuelling positions per section)
- systems velocities below recommended maximum to minimize static charge generation
- pipe grounding to provide path for rapid dissipation of static charge
- supply piping drain to low point connections, and gravity discharge, to completely drain system for maintenance.

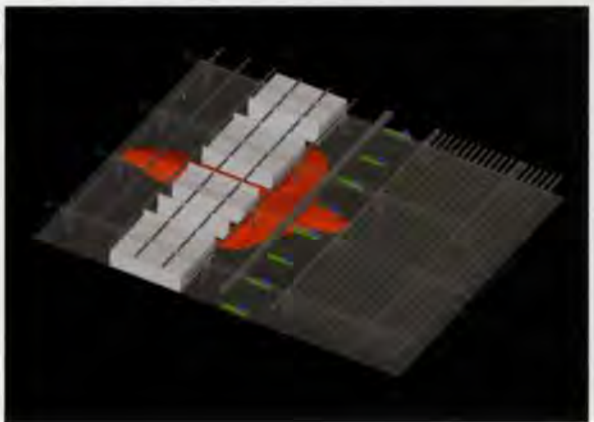
Fuel pumping

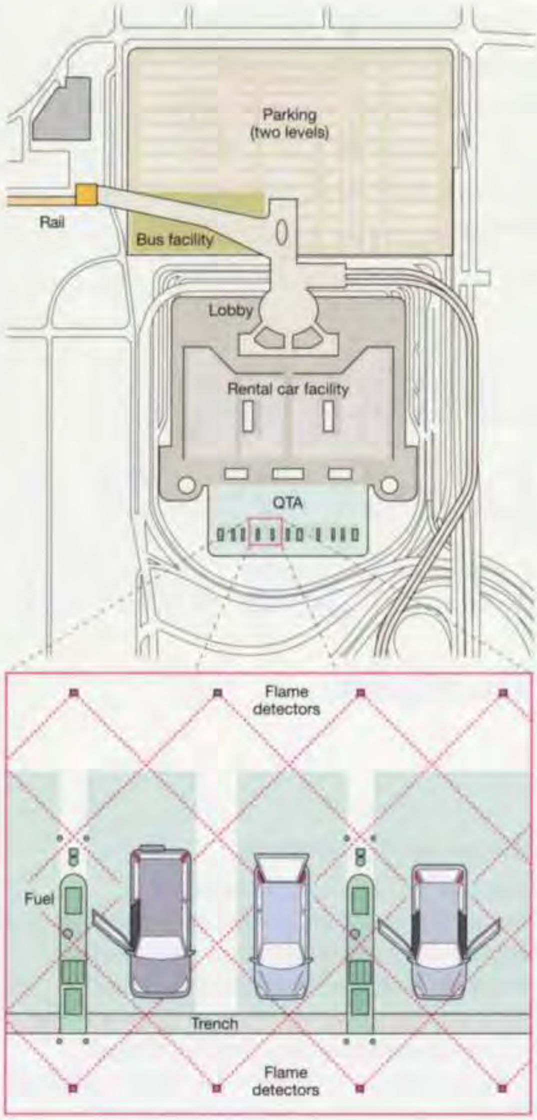
- dedicated tank-mounted vertical turbine pumps for each of the six dedicated piping sections
- pumps sized to provide maximum flow 200gpm (15 litres/sec) (20 positions at 10gpm each)
- pumps to start on signal from one dispenser and time-out after 10 minutes if no additional signals received
- hydraulic control/pressure reducing valves at each service level at QTA entrance for each set of 20 fuelling positions
- control/pressure reducing valves to fail in closed position; to modulate to limit pipe pressure regardless of inlet pressure; to shut off upon excess flow, leak detection alarm, emergency fuel shut-off alarm, or tank low level alarm
- automatic recirculation valves at the pump discharge to recirculate approximately 30% of the design flow back to the tank to prevent the pump from operating at no flow conditions
- thermal relief valves located within each piping segment, actuating to protect each segment from over-pressurization from thermal heat gain, and discharging into a gravity system that drains back to the underground storage tanks
- service level high pressure switches downstream of the control/pressure reducing valves at each service level
- pumps provided with a shut-down feature if service level high pressure switch increases to set maximum pressure.

Emergency fuel shut-off

- stations at each dispenser island and at remote locations within 20ft (6.1m) and 100ft (30m) of the dispensers
- stations to shut off the following components on a 'per-floor' basis: all fuel pumps, all fuel dispensers, all control/pressure reducing valves, and all lube oil and windshield washer systems
- system to shut down upon receipt of alarm from an emergency fuel shut-off station or from the voice communication and fire detection system.

2.
Computer simulation of the explosive range zone of a gasoline leak from a fuelling station after 120 seconds.





3.
Top: plan of RCF and QTA showing the constraints on site area by highways and rail lines.
Above: layout option for UV/IR flame detectors at fuelling islands, configured to prevent fires being hidden from detector view by parked vehicles with doors, hood and trunk open or closed.

Windshield washing fluid and lube oil delivery/storage

- washing fluid stored in two 2000 gallon (9100 litre), vertical, flat bottom polyethylene, above-ground tanks in the fluids storage rooms
- lube oil stored in two 1000 gallon (4550 litre), horizontal, cylindrical, above-ground tanks in the fluids storage rooms
- delivery through a locked pedestal-mounted spill containment box outside fluids storage rooms
- integral pressure-rated overfill prevention valve in the fill drop tube to close, and the high-high level alarm to alarm, when high-high fluid level is reached within storage tanks.

Windshield washing fluid and lube oil: dispensing, piping, and pumping

- dispensing through a spring return hose-reel at each fuelling island
- each dispensing location controlled by a normally-closed, fluid line solenoid valve
- normally-closed, fluid line solenoid valves to close when any fire detection system device or emergency fuel shut-off station is activated
- dispensing reel hoses limited to 30ft (9m), with an aluminum gooseneck, manual fill, hose end control
- washing fluid piping to be 1.5in (38mm) stainless steel tubing
- lube oil piping specified as Schedule 40 carbon steel
- lube oil joints to be weld connections, except at connections to equipment
- separate pumps for each zone on each floor, each pump serving 20 servicing positions
- washing fluid pump valves to shut down when any fire detection systems device or emergency shut-off station is activated.

Control room panel features

- two separate programmable logic controllers for increased reliability, both to operate in parallel or with one in 'hot-standby' mode (ie where one unit controls the operations while the other is kept updated and ready to control operations should the first unit fail)
- programmable logic controller for all fuel systems operations, interacting with the voice communication and fire detection system, emergency fuel shut-off system, leak detection system, and low product level alarm
- fuel delivery systems only to operate when the voice communication and fire detection system is operating and functioning properly, the emergency fuel shut-off and leak detection systems are not in alarm, and the automatic tank gauging system is not in low product level alarm
- programmable logic controllers designed to include an interface panel to display alarms and system information
- control panel designed to alarm if high pressure switch increases to set maximum pressure.

Conclusion

The Arup team's analysis was peer-reviewed and has been ultimately accepted by the authorities. Construction of the QTA and RCF is expected to commence later this year, with the whole facility scheduled to open for use in 2007. Arup provided significant value by demonstrating that this structure could be designed and built safely at an overall reduced operating cost, which made the analysis and protection features well worth the cost.

Credits

Project owner: Miami International Airport **Client and project manager:** EarthTech Consulting Inc **Design architect:** HNTB Architects Engineers Planners **Architect of record:** Sequeira & Gavarrete **Design MEP engineer:** Wolfberg Alvarez **Design fuel system:** Burns & McDonnell **Fire engineer:** Arup – Richard Custer, Matthew Johann, Brian McLaughlin, Brian Meacham, Jeff Tubbs, Christopher Wood, Eileen Wood **Illustrations:** 1 EarthTech; 2 Arup; 3 Nigel Whale

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Can buildings be engineered to allow desired wireless frequencies to enter whilst deflecting others for privacy or security? Frequency selective surfaces (FSS) may be the answer.

Designing buildings for a wireless world

Alan Newbold

Introduction

People at work want both universal access to information, increasingly through mobile communications, and security and privacy for their communications. The challenge is to meet both requirements simultaneously in the workplace. Currently mobile communications infrastructure and systems are designed on the basis of detailed analysis of radio frequency (RF) coverage and capacity requirements. Security and privacy needs can be met through good design, but eavesdropping remains an issue. How can building design and fitout aid the design of wireless communications systems, and reduce the problems of eavesdropping, by using frequency selective surfaces (FSS) and attenuating materials?

Demand for spectrum continues to grow, and hence propagation characteristics within buildings are becoming a more important consideration. Generally, as the frequencies of operation rise from 450MHz, 900MHz, and 1.8GHz, to 2.4GHz and 5.2GHz, the ability to penetrate building materials reduces significantly.

As new wireless systems with limits to the number of available channels and operating at higher frequencies are installed in buildings, it is time to consider selecting different types of material for use in construction, based on their RF characteristics. For example, reflecting material could be used to prevent signals from propagating into rooms; RF-attenuating film could be added to double-glazed windows; and FSS could be deployed to allow certain frequencies to propagate into a room while reflecting other frequencies.

One of the hardest challenges designers face is to predict the frequencies that will be used in the future, as wireless technologies develop and users demand ever-increasing bandwidth. Buildings are constructed to last many years and internal fit-outs occur every few years, but new wireless standards are developed every few months; a detailed understanding of the latest developments in wireless communications standards and products, and an appreciation of the characteristics of the frequencies they use, are required.

Research on FSS for Ofcom

In a team that also included Culham Electromagnetics and Lightning (project managers), the National Physical Laboratory, and Warwick University, Arup Communications and Arup Materials Consulting recently took part in a project for the UK regulatory body Ofcom (Office of Communications) to research the practical potential of FSS in a real office environment to aid in spectrum efficiency. The specific aim was to demonstrate the possibility of reducing the coverage area of a wireless system through the use of FSS and attenuating materials. This would then allow the radio channels to be reused over a shorter distance and result in a more spectrum-efficient system through increasing capacity per m^2.

2. A 5.2GHz bandstop FSS.

A 63m² demonstrator facility was constructed to simulate an office environment, and then partitioned into three electrically isolated areas and equipped with both IEEE802.11b (2.4GHz) and IEEE802.11a (5.2GHz) wireless local area network (WLAN) systems. This particular construction was lined with a reflective material that provided approximately 60dB of attenuation throughout the facility, which allowed the team to benchmark the capability of the FSS.

Defining FSS frequency requirements

Before constructing the FSS panels, the attenuation characteristics and target frequencies were defined. To determine these characteristics, the team analyzed the main in-building requirements for wireless communications, covering wide area network (WAN), local area network (LAN) and personal area network (PAN). In the wide area, the ability to access mobile cellular networks is fundamental for any organization and so coverage into the building is needed at frequencies between 900MHz - 2.2GHz.

In addition, and particularly due to some recent highly publicized problems, the requirement to allow TETRA (terrestrial trunked radio) frequencies into a building for the emergency services is critical, as is allowing PMR (private mobile radio) services to operate for specific client requirements, including IT and security departments. Hence coverage needs to be available from 350-470MHz and from 870-900MHz in a building.

For most organizations, the use of personal wireless communications is assumed to occur within a relatively short distance (<10m) and hence when considering the propagation of radio waves the signals are assumed to work within a restricted area and not as part of LAN or WAN systems.

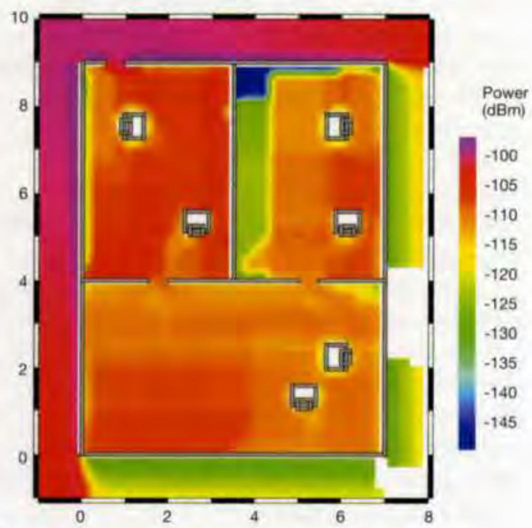
The main RF requirement affected by building design and fit-out today is the deployment of LAN systems, including those developed under the IEEE802.11b/g and IEEE802.11a/h standards at 2.4GHz and 5.2GHz. Most users of the former standard are accustomed to the concept of a wi-fi hotspot, where coverage is provided in a particular predicted high-use area. However with new applications like wireless voice over IP, the ability to achieve roaming coverage, where users can walk from area to area without dropping the connection, will become a minimum requirement in offices.

In the local area, wireless IEEE802.11b systems use the 2.4GHz band with 22MHz channels, limiting the system to three non-overlapping channels, each providing up to about 11Mbps raw data throughput or 5.5Mbps shared data throughput to the users covered by the access point. Where many users are located in a small area, like an airport departure lounge, coverage is often overlapped to provide a higher aggregated throughput. Also, where in the event of an access point failure a minimum level of RF coverage is required, coverage is overlapped to provide resilience. To ensure provision of aggregated throughput and RF resilience the RF design can become very complex and in some cases impossible without some level of inter-access point interference.

New wireless standards and systems are continually being developed to improve performance within these constraints. The ratified IEEE802.11g standard increases the overall throughput up to about 20Mbps. However it still offers only a limited number of non-overlapping channels. Although the IEEE802.11a/h systems aid this particular problem through the provision of eight non-overlapping channels, the 2.4GHz systems are still increasing in popularity and applications like voice have not yet been developed at the 5.2GHz frequency. This will probably result in two radio systems being required for use in buildings, operating at 2.4GHz and 5.2GHz.

Alongside frequency management problems, the security of wireless systems, particularly wi-fi, is poor. Many of the security risks that have been highlighted can be mitigated through careful design, but the radio link will always remain vulnerable as it is difficult to place boundaries on RF transmission. There have been many documented cases of potential hackers eavesdropping open networks from outside the building.

The 2.4GHz and 5.2GHz bands are categorized as licence-exempt industrial, scientific and medical (ISM) bands and are becoming more heavily utilized. These bands are self-regulated and hence any interference between systems needs to be resolved by users. This will become much more of an issue with heavier use of these areas of spectrum. For example, some major hospitals have started to have problems with some of their medical equipment due to utilization of the ISM band, and in some cases agreements have been reached to move medical electronics away from the ISM band and into a dedicated band.



3.
Software modelling results: GSM signals from outside the building.

4.
The Ofcom test installation: the dielectric cladding was polyethylene, the FSS substrate was polyester, and the core was extruded polystyrene.

Given the limited number of non-overlapping channels in the IEEE802.11a/b/g/h systems, it was felt that if a cost-effective FSS could be designed to selectively reflect certain frequencies in the 2.4GHz or 5.2Ghz bands, then buildings could be designed to aid in the efficient use of these frequencies and hence aid RF design. Although research carried out on another Ofcom project shows that it is theoretically possible to achieve the required results, to design a practical example will be very challenging.

The next desirable objective is to design an FSS able to stop or pass 2.4GHz and 5.2GHz bands in their entirety. This would allow an organization to selectively prevent the 5.2GHz band used by staff or operations from being transmitted across a physical boundary and into a common area, but allow the common-use 2.4GHz band to pass across the boundary unaffected and maintain public or voice communications.

Due to the separation between target frequencies, it is relatively easy to provide about 45dB attenuation in the stop band, with only 2-3dB attenuation in the pass band. Software propagation modelling showed that a relatively small FSS panel could be used to provide sufficient signal strength into the appropriate room from the transmitting AP. The FSS were made from two layers, each using a dielectric core of extruded polystyrene separated by a spacer. The total thickness of the structure was about 30mm and the outside of each FSS was clad with a dielectric material.

The project demonstrated that an FSS could allow a 5.2GHz signal to propagate through it whilst preventing a 2.4GHz signal from passing. This meant that through a combination of the appropriate shielding and FSS it is possible to isolate 2.4GHz signals from one room to another whilst allowing a 5.2GHz signal to pass into both rooms. The reverse of this was also demonstrated.

To show that it was possible to meet the requirements of allowing mobile cellular and emergency communications into a building whilst preventing all higher frequencies from passing, a low pass FSS was constructed. This proved that signals up to 1GHz could be allowed to pass into a building, hence allowing TETRA emergency services, PMR signals or 0.9GHz GSM signals in. Currently it is not possible to design an affordable FSS to permit 1.8GHz to pass whilst preventing the transmission of 2.4GHz.

Choice of FSS materials

Bob Cather Edwin Stokes

The practical issues around incorporating FSS materials in a real office/building environment had to be considered - issues of both the inherent suitability of candidate materials and their interaction with construction and building operation. For this project, two general forms of construction were considered as the base. Office buildings are constructed either traditionally, with brick structural walls and lightweight concrete partitions within, or in the more modern combination of concrete and/or steel-framed structure, with lightweight timber or plasterboard partitions. Most prestige City offices are of 'modern' construction, though due to increased desire to reuse or refurbish existing buildings, a significant and possibly increasing number may be of the 'traditional' methods and materials.

The Arup Materials Consulting team analyzed the constraints and requirements arising from building regulations, the compatibility with adjoining materials, and the practicalities of installation and maintenance. When locating FSS within partition walls, these factors include compatibility with adjoining components including junctions and joints, health and safety considerations, acoustic properties, fire performance, the nature of any applied finishes, and durability and maintenance. When incorporated in the façade, there are additional issues of continuity of weathertightness and façade thermal and comfort performance, and accommodation of movement and deflections.

With all these factors in mind, as well as considerations of in-service modification, replacement and maintenance, the next task was to determine the suitability of candidate substrate materials proposed by project partners for installed FSSs. Five materials were proposed: PET (*Melinex*), polyimide (*Kapton*), GRP laminate (*Isola*), polymethacrylimide (*Rohacell*), and extruded polystyrene foam (*Styrofoam*).

Melinex PET is a clear thermoplastic film commonly used as protective film on glazing. It is flexible but vulnerable to tear, and is inherently flammable. However, it has good UV resistance, with typically a 10-year service life exposed on glazing.

Kapton is a translucent yellow thermoset film, typically used in the electronics industry as a flexible substrate. Like *Melinex* PET it is flexible and vulnerable to tear, but it is far less flammable. It has excellent chemical resistance but absorbs moisture easily.

Isola is a thin and rigid glassfibre reinforced plastic (GRP) laminate, typically used as a substrate of printed circuit boards. Like *Kapton* it has good fire resistance and chemical resistance, but its susceptibility to moisture absorption can lead to delamination.

Rohacell is a polymethacrylimide (PMI) foam, and comes in two grades: A (aircraft structural grade) and HF (high frequency antenna grade). It has good resistance to most solvents and fuels (though not to alkalis), low flammability, good high temperature stability, and can be readily shaped and formed.

Styrofoam extruded polystyrene foam is widely used in buildings for thermal insulation in roofs and wall cavities. It is very flammable and has limitations on mechanical damage compared to the other candidate materials. It has good acid and alkali resistance but poor solvent resistance.

The various service requirements and the materials properties were compared, to draw tentative conclusions on the most appropriate basis for further development. Incorporated within the building structure and fabric, the FSS will be impractical to inspect, modify or replace, so it must be robust enough to tolerate site conditions and have confident long-term performance. In interior fit-out, aesthetics, UV, abrasion, fire spread and reaction to cleaning regimes are all important issues; whilst when FSS are incorporated into local workstations, aesthetics and unit cost come to the fore. The material needs to be unobtrusive, and workstation configurations may change many times in the life of a building.

With every issue weighed in the balance, the team concluded that though *Styrofoam* is a viable and cost-effective option for internal partitions, it would need to be encased to meet the fire performance regulations and was too open to damage, so *Rohacell* would probably be the most appropriate due to its robustness, versatility and fire performance. For façade use, *Melinex* PET is probably the best option because of its flexibility and UV resistance.

5. A more familiar use for PET.

6. Terminal 5 at London Heathrow Airport will use the latest technologies to tailor its wireless infrastructure.

Applications in buildings

Most of today's landmark buildings, including airport terminals, major stations and corporate headquarters, use glass façades and are fitted out as open plan office or public spaces. This in itself creates enormous challenges for designers of wireless systems, particularly in resolving coverage vs. capacity, and addressing the issues of frequency management. One of the main security problems for these buildings is preventing unauthorized users from eavesdropping on their wireless networks from outside the building perimeter, but the distance from which a potential eavesdropper can 'sniff' a wireless network can be greatly reduced through the appropriate selection of building materials. It is possible today to procure glass with a significant level of attenuation built into it so that it will reduce the leakage of the radio signal outside the building. When supplemented with special screening material that can be fitted to the inside of windows, this could bring the distance of leaked signal to within the physical perimeter of the site.

A screening solution will also attenuate mobile cellular, PMR and TETRA signals, but by adding a low pass FSS into the walls at appropriate points it is possible to allow the required signals to propagate into the building. These principles can be applied in airports, major stations and trains, and theatres and auditoria as well as offices.

Airports and major stations have many tenants with independent wireless communications requirements. In areas where there are physical boundaries between adjacent tenants it may be possible to physical separate the tenant systems using FSS combined with reflective screening. This would allow the landlord systems to function as normal.

One interesting problem for train operators is ensuring the propagation of mobile cellular signals into the new carriages made with metalized windows, where signal strengths are varied at best. Using a FSS designed for train carriage operation it would be possible to allow the mobile cellular frequencies to propagate into the carriage.

Increasingly clients are requesting that some or all wireless communication is prevented within a specific space, eg operating theatres, auditoria, lecture theatres, and some meeting rooms. Through a combination of careful building planning and the use of special materials it is possible to achieve up to 120dB of attenuation, which could therefore have the desired effect.

Conclusion

In the future, construction firms, landlords, and tenants should take closer interest in RF propagation as wireless communications become more and more critical to business. Consultants and designers will also need to use the building materials, fit-out materials, RF materials, FSS, intelligent antennas, and wireless systems in a combination of ways to achieve the desired results.

Though an FSS really needs to be able to differentiate cost-effectively between individual channels in the 2.4GHz frequency band, the current developments in this technology have many potential applications in industry.

The project was one of 10 funded by Ofcom as part of the Spectrum Efficiency Schemes 2003-2004. The detailed results and findings will be published on the OFcom website, http://www.ofcom.org.uk/research/industry_market_research/technology_research/ses/ses2003-04.

This feature is based in part on the article 'Designing buildings for the wireless age' in IEE Communications Engineer, June/July 2004.

Credits

Client: Ofcom **Team members:** Culham Electromagnetics and Lightning; National Physical Laboratory; Warwick University; Arup - Bob Cather, Ken Kilfedder, Bruce Laidlaw, Alan Newbold, Edwin Stokes **Illustrations:** 1 Tim Pohl; 2 Ofcom; 3, 4 Arup; 5 Todd Smith; 6 Richard Rogers Partnership

The Caltrans District 7 Headquarters, Los Angeles

Eugene DeSouza Andy Howard Teena Videriksen

Taking advantage of the prevailing climate of Southern California, the new headquarters - opened on time and on budget - achieves high standards of energy-efficiency and sustainability.

Introduction

In March 2005, Thom Mayne of Morphosis was awarded the 2005 Laureate of the prestigious Pritzker Prize for architecture. The Caltrans District 7 Headquarters, Mayne's most recently completed project, was described as one of his more important projects: 'The design of this building goes beyond merely providing functional spaces. It seeks in every way to actively engage the city and people while blurring the distinction between outside and inside, with the objective of creating a government bureau that works as a truly public building.'

The California Department of Transportation is, in its own words, 'undergoing a transformation from a transportation bureaucracy to a mobility company'. Historically responsible for operating the labyrinth of freeways and highways in California, its scope of responsibility now extends to other transport modes including rail and mass transit, and embraces issues of appropriate land use and environmental responsibility.

1. North-west view from City Hall, featuring the light bar and the Eli & Edythe Broad Plaza.

District 7 is one of the more complex of the 12 districts which Caltrans oversees. Serving the City of Los Angeles as well as the greater Los Angeles and Ventura counties, District 7 sustains a population of 11M. Its existing headquarters building was over 50 years old and, apart from being too small and obsolete for the evolving functions and aspirations of Caltrans, it carried a visible legacy of damage from the January 1994 Northridge earthquake.

The challenge

In 2000 the State of California initiated a competition for a new headquarters building that would incorporate 'world-class design excellence, sustainability, integration of art and architecture, and contribute to the revitalization of the civic center'. The delivery method was 'modified design/build', in which entrants are initially provided with more detailed information about the proposed project than in a conventional design/build approach. The initial 11 developer/contractor-driven teams were reduced to a shortlist of three: Thomas Properties/Morley Construction/NBBJ, with OMA (Rem Koolhaas); Urban Partners/Clark Construction/Gruen, with Morphosis (Thom Mayne); and Koll Construction/Langdon Wilson, with Miralles Tagliabue (Benedetta Tagliabue). Arup contributed to all three teams.

The Urban Partners/Clark Construction/Gruen/ Morphosis entry won, with Arup providing mechanical, electrical, plumbing, and telecommunications engineering, as well as sustainability advice. The team was commissioned in February 2002. The design created 700 000ft^2 (65 000m^2) of useable area, in a 10-storey tower on top of a three-storey podium, together with a 350 000ft^2 (32 500m^2), four-level, subterranean parking garage. The project budget was fixed at a very competitive \$174M against an aggressive 30-month schedule.

The challenge was to design and build over 1Mft^2 (100 000m^2) with full tenant improvement, on a city centre site that was not only restricted but architecturally sensitive. It lies opposite the lofty art deco splendours of Los Angeles' City Hall, which has dominated the area since it was opened in 1928. Also nearby is the Cathedral of Our Lady of the Angels, as well as the city's most striking new public building, the Walt Disney Concert Hall. In addition, the site lies within the '10 minute Diamond' – a plan originally initiated some 20 years ago to restore downtown Los Angeles. By creating an accessible and attractive urban environment, the plan is intended to draw people back downtown to both live and work. Dan Rosenfeld and Ira Yellin of Urban Partners, who led the winning consortium for the District 7 Headquarters, were instrumental in developing the 10 minute Diamond plan for the City of Los Angeles. Sadly Ira Yellin died during the course of the project, but its completion stands as a fitting symbol of his contribution to downtown Los Angeles.

2. Plaza view from entry canopy looking north toward City Hall.

The architectural goals of the project were ambitious, and no less so were its aspirations for sustainability: the building is expected to achieve the US Green Building Council LEED™ (Leadership in Energy and Environmental Design) Silver Rating.

Upon receiving Notice to Proceed, a formidable project team was immediately mobilized. The architects and contractor established a joint project office where teams of engineers and specialists camped during the hectic early weeks of the schedule. Through close collaboration and a tremendous team spirit, the design was developed rapidly to meet the critical structural steel mill order date, only four months into the design process. At this early stage the MEP design had to be sufficiently developed and detailed in order to commit to equipment room locations, equipment sizes and loads, and structural beam penetrations. This early critical milestone demanded tight discipline from the design team and a streamlined and linear design process.

Although Arup was originally contracted to provide schematic and detailed design services only, with construction documents being prepared by the trade subcontractors, the modified design/build contract included a rigorous submission, review, and approval process to ensure design compliance with the bid documents. Based on the value Arup provided in the negotiation of bid alternates and bid clarification requests, and to maintain consistency of the design intent, the general contractor expanded Arup's role.

During the period when design was being transitioned from the design team to the trade subcontractors, and the project was already in construction, MEP equipment ordering became critical to the project schedule. Interaction between designers and builders became intense as the team worked to resolve detailed specification interpretation issues that stalled the ordering of major air-handling and cooling equipment. It was at this particularly demanding stage that the mechanical subcontractor declared bankruptcy, forcing the appointment of a replacement.

3. Interior view from office of scrim pneumatic actuators.

Arup's role was immediately expanded to ensure progress of the construction documents, and provide daily site presence to aid in the rapid orientation of the new mechanical subcontractor. Ultimately Arup's involvement on the project increased to 50% more than originally anticipated.

The general contractor and entire team collaborated in an intense effort to overcome the setback caused by the loss of this key trade subcontractor. Incredibly the project schedule was recovered, and the completed building was handed over to a very happy client at the end of the programmed 30-month concurrent design/build period.

Energy efficiency

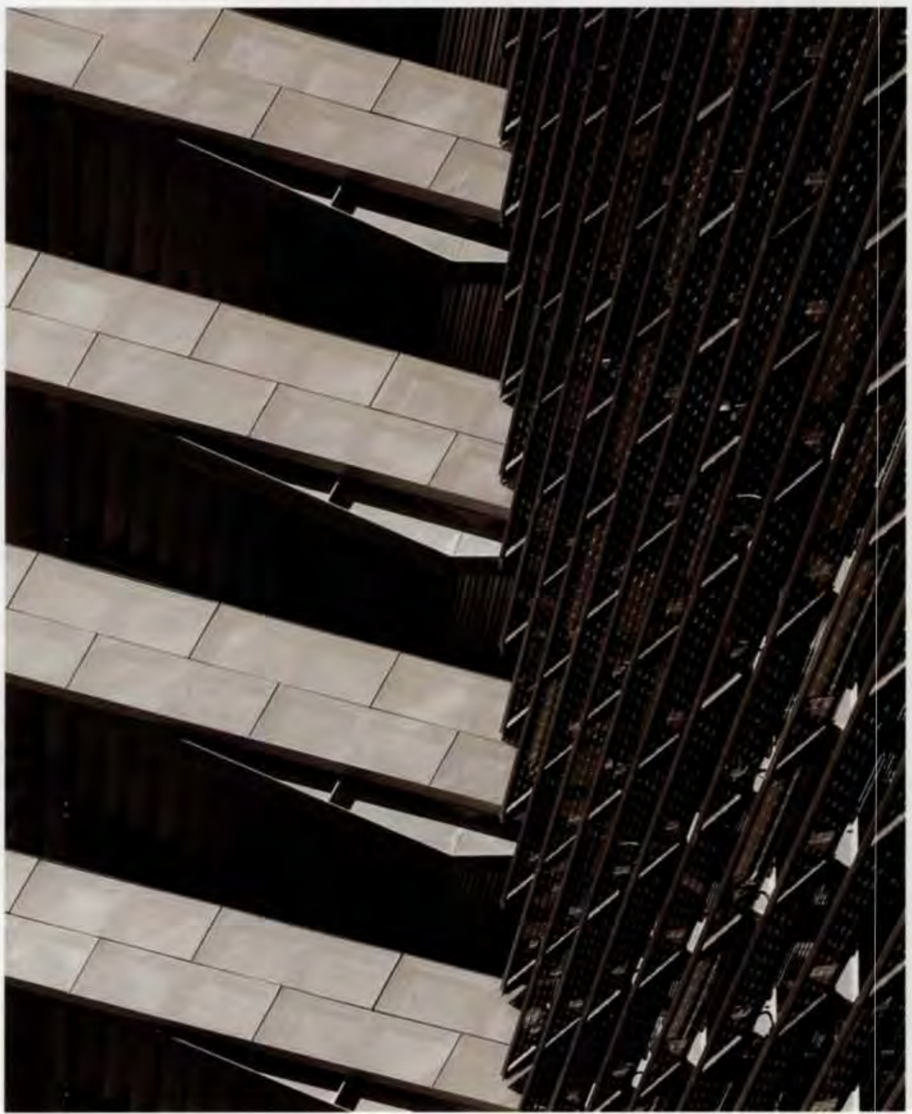
The building orientation evolved in response to functional requirements and the surrounding urban environment, and the resulting form presented extensive east, south, and west façades on a narrow plan designed to maximize occupant views and the use of daylight.

The thermal performance of the façade was identified as critical to achieving the aggressive energy conservation targets set forth in the design/build brief. The client specified that the measured building performance should better the energy efficiency requirements of the California Energy Commission Title 24 by 20%. This equated to about a 30% improvement on *ASHRAE 90.1*, which is adopted in many states as an energy usage benchmark. The team exceeded this goal by documenting 30% savings on Title 24 (equating to 40% improvement on *ASHRAE 90.1*).

The design/build process against such an aggressive schedule demanded that cost and value engineering be strong and continual components of the design process. The façades became the focus of detailed costing, value, and constructability review early in the process. Arup developed façade modelling using ROOM and NATFAC to determine the thermal performance and internal comfort conditions produced by a range of façade options. ROOM is part of the E+TA (environmental and thermal analysis) software suite developed by OASYS, Arup's software development and sales company. The team selected for detailed evaluation, a semi-active solution incorporating an exterior 'scrim' of perforated sheet metal. The lifecycle value of the façade was then assessed and compared with other more traditional solutions. The modelling demonstrated capital cost savings derived from reduction in the HVAC system capacity and, more importantly to Caltrans, a significant lifecycle benefit that helped gain support for the unconventional approach.

The scrim comprises framed aluminum panels punched with holes of varying sizes to provide 48% openness, and allow for clear vision and natural light. The scrim acts as a second skin 10in (250mm) away from the inner façade, while also contributing significantly to the character of the building and its presence on the LA skyline. In addition to its clean, hi-tech aesthetic, the scrim reduces energy consumption effectively while maintaining a bright working environment and providing views of the city. It also acts as a shade, reducing solar heat gains and limiting infiltration of unconditioned outside air by reducing wind pressure on the inner façade.

4. Detail of photovoltaic panels and south escape stairway.



To further reduce heat gain, the east and west façades have been designed as thermal flues, using the building height and hot sun on the external face of the scrim to generate high air change rates between the outer and inner façades. This serves to keep the driver of conductive heat exchange close to the ambient air temperature. Many of the scrim panels are powered to open automatically in response to the position of the sun, playfully punctuating the otherwise clean lines and flat planes of the building's outer skin.

Balancing cost and façade performance was a continual challenge, particularly as the team explored options for some form of protection for the south elevation that would provide contrast with the east and west façades. A range of solutions that met the architectural objectives and engineering performance criteria was quickly developed, however delivering these solutions within the contractor's budget demanded a more innovative approach to design and procurement. Ultimately, the team went up-market for a cheaper solution, leveraging the financial incentives offered by the State and utility providers to promote alternative energy generation.

On the south façade the aluminum scrim is replaced with an open lattice framework that supports a vision glass wall incorporating a 14 000ft^2 (1300m^2) array of 895 building integrated photovoltaic (BIPV) panels. The panels harvest solar energy and convert it to electricity during peak hours when cooling demands are at their highest, providing significant energy savings due to the punitive peak demand energy tariff structure. The direct current power generated by the BIPV cells flows through power conversion equipment and into the building's electrical distribution system, contributing 92kW of peak power.

In addition to its energy saving properties, the south façade behaves similarly to the east and west, reducing the heat load by shading from the opaque, monocrystalline BIPV cells, reducing infiltration, and promoting natural ventilation between the two vertical layers of façade.

Detailed sunpath studies were undertaken to determine:

- the optimum power output angle of the panels
- their vertical spacing to prevent self-shading
- the optimum cell density in the panels to achieve the required output and maximize natural light in the offices
- their positioning relative to each other in order to balance aesthetic with the occupant lines of sight.

Savings by Design

This programme, funded by California utility customers under the auspices of the Public Utilities Commission and administered through four utilities - the Pacific Gas and Electric Company (PG&E), San Diego Gas and Electric (SDG&E), Southern California Edison Company (Edison or SCE) and Southern California Gas Company (SoCal Gas) - exists to encourage high-performance non-residential building design and construction.

Financial incentives are available to owners when a new building's efficiency exceeds the minimum Savings by Design thresholds, generally 10% better than Title 24 standards. These incentives encourage owners to make energy efficiency a major goal in their new buildings, and help to defray some of the costs of energy-efficient building components.

To support the extra effort for integrated energy design and to reward exceptional design accomplishments, Savings by Design also offers financial incentives to design teams. In its Whole Building Approach, a computer simulation model calculates the energy savings of the building compared to the Title 24 baseline. The design team qualifies for incentives when the building design saves at least 15%.

http://www.savingsbydesign.com

5. View from behind photovoltaic panels.

Through extensive computational modeling of the sun path across the annual cycle, a balance was struck between the BIPV summer and winter applications. This resulted in a panel angle of 50° off the horizontal and a spacing between panels of 5ft (1.5m).

The design/build team was able to reduce the cost of the unique multifunctional façade system by securing $800 000 in rebates from Savings by Design, the Southern California Gas Company, and the Los Angeles Department of Water and Power.

In addition to the effective performance of the composite façade, the energy conservation target was exceeded through a combination of measures including:

- control of minimum outside air supply using CO_2 measurement (demand ventilation)
- premium efficiency motors for all equipment
- extensive use of variable speed drives interfacing with the building management system (BMS)
- variable volume pumping
- increased chiller efficiency
- equipment sizing to maintain efficiency at actual operating points (ie high peak and part load efficiencies)
- improved control system accuracy and performance
- the building control and automation systems
- system commissioning
- appropriate minimum thicknesses for pipe and duct insulation
- optimized thermal insulation performance for building envelope
- use of dual-pane, low-E, and low solar heat gain coefficient glazing
- external environmental control in the form of the scrim on the east and west façades
- angled photovoltaic panels over the entire south façade fenestration.

6. View of maintenance walkway on the south façade between glazing and photovoltaic panels.

Energy modelling shows the envelope performance to be very good; overall the system was designed to achieve approximately 1 ton of refrigeration per 400ft^2 (94.6W/m^2) in the hot southern California climate.

The chiller plant was designed to operate with an annual energy efficiency of no more than 0.55kWh of energy consumed per ton-hour (0.156kW per kWh) of cooling capacity delivered to the air distribution system. This includes the chillers, chilled water pumps, condenser water pumps, and the cooling tower fans. In practice, the variable frequency drive (VFD) centrifugal chillers have a full load efficiency of <0.5kW/ton and part load efficiency of <0.36kW per ton.

Similarly, the air distribution system was designed to deliver air at an annual energy consumption of no greater than 0.40kWh of power consumed per ton-hour (0.114kW per kWh) of cooling delivered.

All major HVAC equipment and driving motor efficiencies were selected to minimize effective operating costs. California Energy Commission standards were used to determine the minimum acceptable level of efficiency for analysis.

Building automation

A comprehensive DDC (direct digital control) BMS serves the building, based on individual microprocessor-based controls for separate subsystems such as the lighting and mechanical controls.

The control parameters are presented on a conventional PC workstation allowing monitoring and adjustment of all building environmental functions. This allows the client to provide a comprehensive 'help desk' type of service for responding to staff problems or equipment failures. The automatic controls establish and monitor the principal environmental control criteria, while still allowing for a degree of user control over their local environments. The control system is optimized for energy conservation, utilizing free energy, such as economizer cycle cool air and daylight whenever available.

The control parameters are as follows:

- occupancy sensors
- light level sensors to optimize the use of daylighting
- free cooling, ventilation, cooling tower economizer cycles
- energy and demand monitoring
- CO_2 monitoring for demand ventilation
- CO monitoring for car park exhaust
- chiller optimization
- boiler optimization.

Mechanical systems

The building is cooled by three water-cooled VFD centrifugal chillers, utilizing non-HCFC refrigerant; one sized to handle the base cooling load, while the other two are each sized to handle 50% of the peak cooling load. They provide a total cooling capacity of 1800 tons of refrigeration (6.33MW) - 120% of peak load - and are in a basement mechanical equipment room, served by four open-cell, induced-draft cooling towers of equal size for heat rejection.

The cooling towers were selected to cool 120% of the peak chiller capacity, equating to 144% of the peak design load. A constant volume primary and variable flow secondary chilled water system is provided. Part of the cooling system can operate on emergency power, providing 350 tons of refrigeration (1.2MW) under standby power scenario.

Three equal-sized natural gas-fired boilers located in a basement level mechanical equipment room discharge flue gases into a common header flue that runs up a dedicated riser shaft to vent at

7. View of south-east corner from Second Street, incorporating photovoltaic panels.

8. View of plaza featuring plaza artwork and signage.

roof level, 14 floors up. These boilers supply 150% of the building heating load required by the client, ie 50% standby/redundancy. The total installed heating capacity is 8925MBH (2.6MW).

Eight exterior AHUs, each supplying about 45 000ft^3/min (21m^3/sec) of air, are at upper roof level and serve levels 4-13. Seven more AHUs in basement mechanical equipment rooms, and on the lower roof, serve all spaces from ground level to level 3. All AHUs serving office areas are equipped with airside economizers controlled on dry bulb temperature.

The mechanical rooms are strategically located to take into account the wind direction around the building and to ensure that the intake louvres, for the full outside air economizers, avoid excessive wind pressures, entrainment of noxious pollutants, toilet exhaust fan discharge, and discharge effluent from the cooling tower systems. A combination of smaller AHUs and fan coil units (FCUs) serve the elevator machine rooms and electrical closets, which contain transformers and communication closets on each floor. The AHUs can supply up to 523 000ft^3/min (246m^3/sec) of air into the building.

The AHUs are sized to optimize the air velocity through the filters and over the cooling coils, thereby optimizing the system static pressure requirements. Belt-driven plenum (plug) fans are used to achieve the most effective fan selection to satisfy the system characteristics, and to provide optimum acoustic performance. Each AHU has the capability for full airside economizer operation, using the return fan as exhaust fans in this application, through the articulation of the damper systems. The turndown operating characteristics of the individual AHUs has been evaluated to ensure acceptable performance at lower air flow quantities.

Kitchenettes and core toilets are connected to the general exhaust air system within the two common risers, extending through the building core. In the event of a fire, this riser doubles for smoke exhaust, drawing air off the fire floor and negatively pressurizing the space.

In the data centre, close control CRAC (computer room air-conditioning) units with filters, chilled water coil and electric steam humidifiers, meet the room loads. These units, together with part of the chilled water system, operate on emergency power to maintain conditions if the main power fails.

The four basement levels of parking are ventilated by a mechanically-driven push-pull system, in which supply shafts drop down at the north end of the parking levels and exhaust shafts rise up at the south end. Fans are located at each of these riser shafts, and supply air is brought in via elevated external air intake openings within architectural structures. A common header connects the air inlet points to the top of each supply air dropper.

On the south façade, a plenum tower discharges exhaust air more than 15ft (4.5m) above ground via external louvres, and away from populated areas such as the sidewalk, open plaza and exterior playground. Sensors control variable speed supply and exhaust fans to maintain acceptable levels of CO within the parking garage. Utilizing VFDs ensures that substantial energy is saved when operating the garage ventilation system. The exhaust fans are rated to work at 250°F as they also serve as smoke exhaust fans for the parking levels. Up to 623 000ft^3/min (294m^3/sec) of air is exhausted from the parking garage.

Telephone services and communication rooms housing sensitive electronic components are conditioned by ceiling-mounted chilled water FCUs, served by part of the building's 24/7 air-conditioning system.

The design includes an additional 10% capacity for future use on all the building systems, including but not limited to all of the air systems and the chilled water and heating hot water systems. All equipment, ducting and piping meets this requirement by being sized to accommodate this future load. The equipment sizes were determined based on the highest air flow rate obtained from computer-generated heat gain calculations to offset each room's load at the time of the building's peak block load.

9. Aerial view from the north-west.

Fire engineering

The high rise smoke management is provided by rated exhaust fans on the upper roof. There are two fans at the top of two dedicated riser shafts, one per full building height core, and each sized at a capacity of 35 000ft^3/min (16.5m^3/sec). Fire-rated shafts extend down the full building height. Under a fire scenario, the smoke dampers off these rising shafts will open on the fire floor and the fans on the roof will ramp up as required for the particular smoke/fire zone. These smoke exhaust fans are provided with emergency power from the emergency generators for this purpose. Fire fighting/escape stairwells are provided with stairwell pressurization systems, with the ability to introduce 12 000ft^3/min (5.6m^3/sec) of outside air into the stairwells, distributed over the full height of the building.

Lighting

The open office spaces are illuminated by pendant direct/indirect three-lamp fluorescent luminaries with state-of-the-art control to create a visually dynamic environment. The fixtures are unique in that they are provided with digital addressable ballasts and are controlled both via a network lighting control system and locally. These ballasts are based on the DALI (digital addressable lighting interface) communication protocol and are compatible with other open protocols used in building automation systems, thus presenting opportunities for total building system integration.

The indirect lighting provides general ambient lighting and is controlled through the building automation system. The direct lighting is primarily used to enhance the working environment for staff and their performance. The luminaries at each workstation are equipped with integral occupancy sensors that control the operation of direct lighting component to reduce the amount of energy wasted. The perimeter fixtures are furnished with integral photocell/occupancy sensors, which automatically dim when there is sufficient natural daylight available or when someone leaves the space, thereby creating a functional and energy efficient environment.

Communications

The data communications cabling infrastructure is supported by two completely redundant incoming service routes. One is designed to support local service providers and the Caltrans fibre optic ring, while the second supports other tenants, and serves as the building's redundant pathway to the outside world. The pathways for incoming services are designed to support current cabling infrastructure with an allowance of 25% for future expansion. Both routes serve the main incoming service room (MPOE). Through various pathways (conduit and cable tray), the MPOE is connected to the main distribution frame (MDF).

The 900ft^2 (84m^2) main computer room, or data centre, is adjacent to the MDF. Two sets of telecom rooms, vertically stacked, are designed to provide riser pathways to connect all 14 floors to the MDF and data centre. A fully redundant fibre optic ring connects all telecom rooms to the data centre.

The data cabling system comprises a network of copper cable supported by fibre optic cable. The data centre houses the electronics that support a network of cameras throughout the Los Angeles metropolitan area, as well as Caltrans data and voice networks. Multiple radio systems are installed in this building to communicate with incoming helicopters, various Caltrans departments, police and Caltrans satellite offices.

State raises the bar

Through a design/build process that promoted and placed emphasis on design excellence through the unique bidding procedure, the State of California has procured an outstanding piece of urban architecture within an aggressive budget and to an ambitious schedule. The project has already won several awards and is expected to receive the US Green Building Council's LEED™ Silver Rating for its demonstrable achievement of exemplary sustainability goals. The building is a credit to those involved and raises the bar for future public projects in the City of Los Angeles.

Credits

Owner: Department of General Services, California; **User:** District 7, California Department of Transportation; **Design/build team:** Main and First Design/Build Associates, Inc., which consists of: Urban Partners, LLC (Developer); The Clark Construction Group, Inc. (General Contractor); Morphosis (Design Architect); and Gruen Associates (Executive Architect); **Mechanical, electrical, plumbing and telecommunications engineers:** Arup – Peter Alspach, Robert Buckley, Joe Ceballos, Susan Chen, Vahik Davoudi, Eugene de Souza, Steve Done, Keith Franklin, Kathleen Hannon, Andy Howard, Rick Lasser, Craig Macadang, Julian Mamro, Anait Manjikian, Vahan Margaryan, Maurya McClintock, Bruce McKinlay, Ildiko Mezei, Josef Nejat, Morad Pajouhan, Jonathan Phillips, Fernando Rivas, Jerry Rodriguez, Lisamarie Roed, Massoud Safaee, Helen Sinanyan, Raymond Tam, Armen Topakian; **Construction manager:** O'Brien Kreitzberg/URS Corporation; **Structural engineer:** John A. Martin Associates, Inc **Illustrations:** 1, 7, 10 John Linden; 2, Benny Chan/Fotoworks; 3, 6, 8, 9, Roland Halbe; 4, 5 Jim Sinsheimer

'The new Caltrans District 7 Headquarters is the fastest, most affordable, and most innovative public building ever developed in California, and Arup's contribution to this project was significant. They were able to maintain their creativity, while working within tight budget and schedule restraints, and with a demanding client.'

Dan Rosenfeld, Principal, Urban Partners LLC

10. The plaza viewed from the north, incorporating plaza artwork from Los Angeles' Public Art Program.

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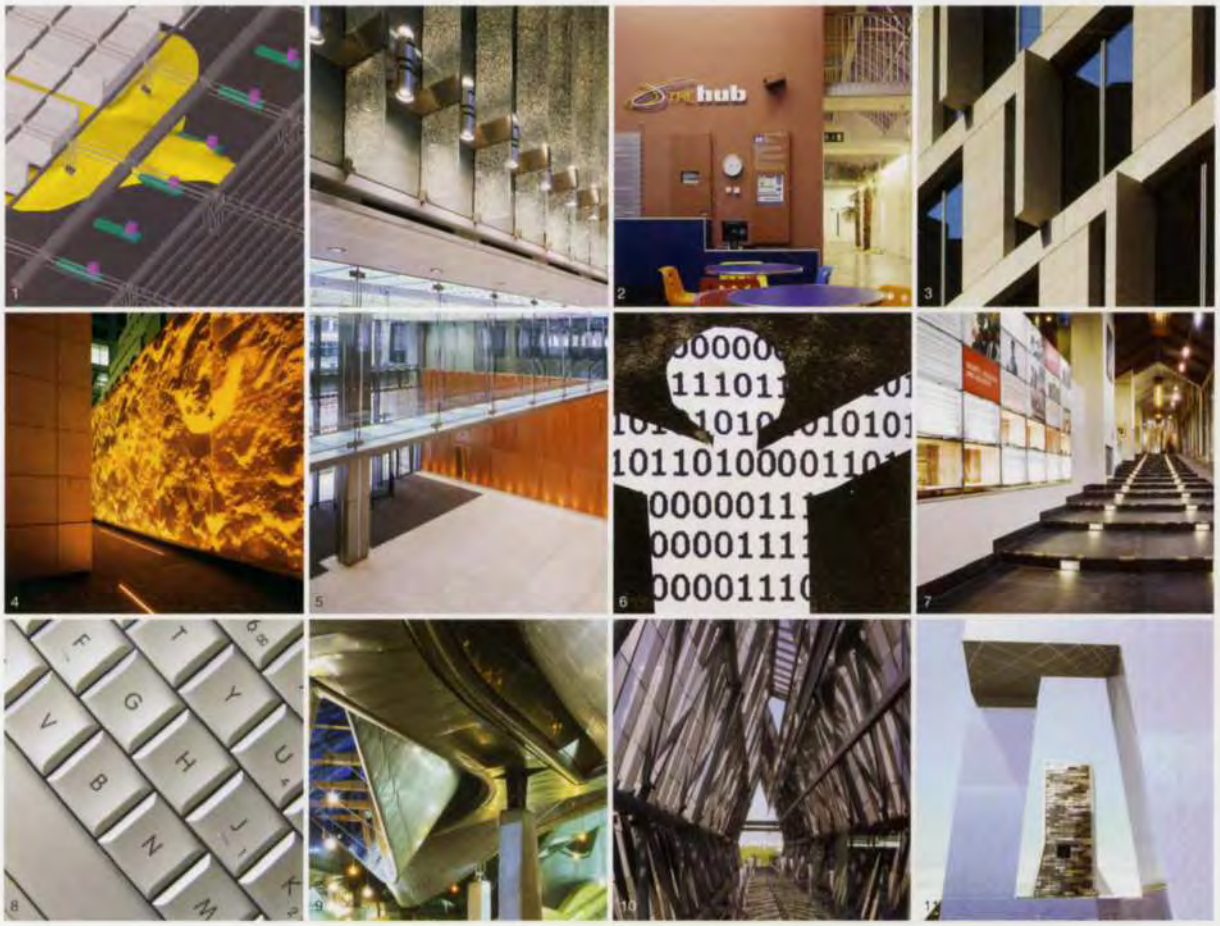

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