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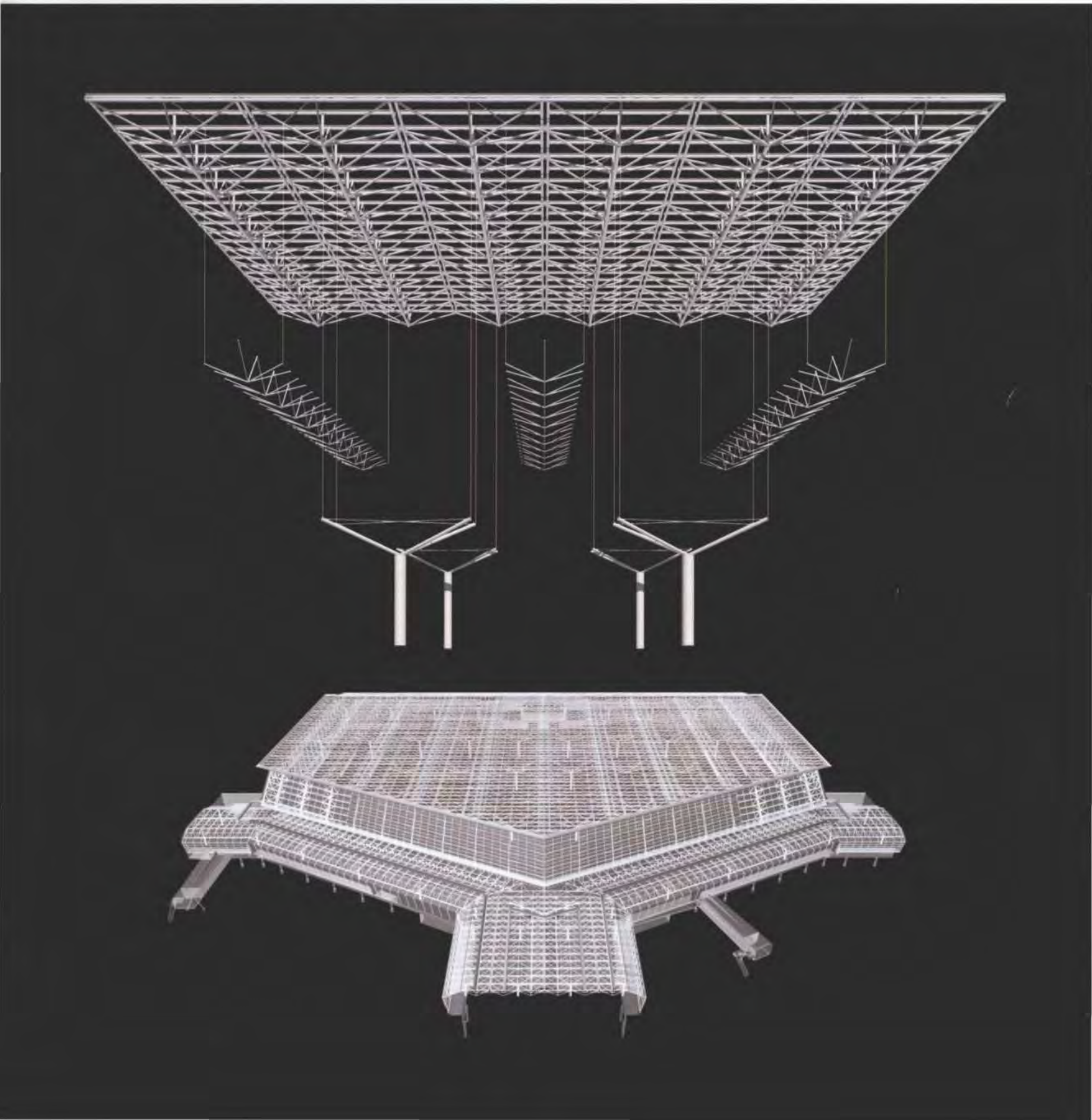

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Vauxhall Cross bus station, London

Kenneth Fraser Robert Pugh Daniel J Wong

This new £4.5M bus station in South London is a symbol of regeneration in a run down area, and a landmark structure to enhance the local environment and amenity.

1. Architectural elevation.

Introduction

The new £4.5M bus station designed by Arup Associates at Vauxhall Cross, South London, is a symbol of regeneration in a run down area previously notorious for its domination by traffic. The project was commissioned through Transport for London (TfL) to create a coherent and efficient interchange for bus, rail, and Underground users - to promote the use of public transport - and be a landmark structure to enhance the local environment and amenity.

In an earlier phase, this major road junction near an important crossing of the River Thames, and one of the strategic entrances to the new congestion charging zone, was reconfigured into a gyratory system. This liberated a section of highway to provide a site for bringing together previously dispersed and inconveniently accessible bus stops.

Client ambitions

The project was initiated and influenced through the desires and ambitions of a stakeholder client body. A key player was the Office of the Mayor of London, Ken Livingstone. The Mayor's strategic transport objectives promote greater use and accessibility of public transport, greater emphasis on walking and cycling, and a reduction in traffic congestion, whilst the Mayor's Energy Strategy, a set of objectives introduced in 2004, aims to reduce London's contribution to climate change, eradicate fuel poverty, and promote and deliver sustainable energy for public projects.

TfL, the Mayor's strategic transport authority, identified the need for a rationalized road layout and integrated public transport interchange at Vauxhall to reduce the impact of traffic, and in parallel, the London Development Agency encouraged regeneration by strengthening Vauxhall's role as a sub-regional transport node.

2. A well-lit, safe environment for bus passengers.

A landmark structure was needed to put it on the map, and to stimulate investment and commercial activity by enhancing and making safe the street environment. These objectives were managed through the Cross River Partnership, in consultation with the Mayor's Architecture and Urbanism Unit, and through the planning implementation of the London Borough of Lambeth.

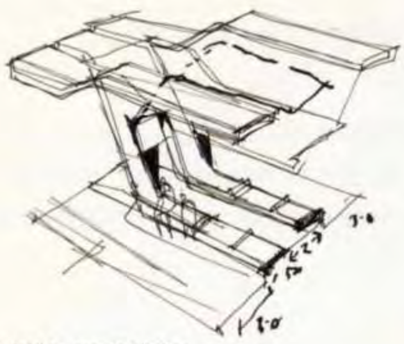
The public was widely consulted through the briefing process, as were TfL's London Buses division and the Metropolitan Police.

Design competition

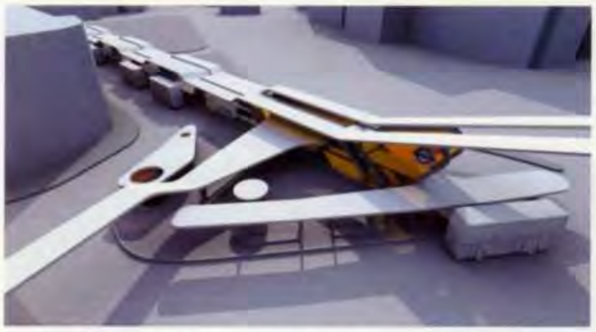
The roadworks were initiated as a separate first phase. This contract introduced the gyratory, giving priority to buses and improving the area for cyclists and pedestrians, as well as creating the site for the proposed new bus station. A limited design competition was held for the bus station project while this work was ongoing.

The site was a linear former highway, with its north end close to connections with the Underground and surface railway stations and subways. The northern end also marked the confluence of all the primary axes of roads and views and, being a former highway, included a significant presence of buried mains services and sewers.

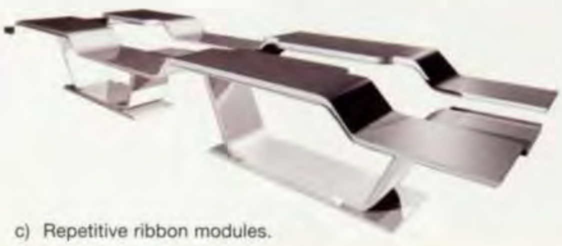
The competition submissions were reviewed by all the stakeholders, as well as being displayed at an exhibition for a public vote. The design by Arup Associates was announced as the winner in February 2002.



a) Ribbon fold to create shelter.



b) Continuous ribbon terminating with 'super long' cantilever.



c) Repetitive ribbon modules.

3. Aspects of design development.

Design principles

The bus station has been realised as a 200m long, 12m wide, undulating stainless steel 'ribbon', which rises as a 'super-long' cantilever at its northern nodal end. The development of this as an idea is a functional response to the aspirations and constraints of the brief and site.

The undulations along the length of the canopy reflect the frequency of bus stands. Each dip of the canopy provides a seating refuge and raking support for the canopy above, which rises over the height of double-decker buses. The folds in the layered ribbon also echo London's iconic bus and Tube route maps, dating back to the 1930s.

The open canopy, rather than an enclosing building, offers free and safe access through permeability and visibility, not obstruction.
The emphasis along the concourse is on movement rather than occupation. Equally, the undulating structure has minimal contact with the ground and potential obstructions.

The principal intermodal circulation and the key operational accommodation are at the canopy's northern end, the accommodation structure being used as a springing point to launch the ribbon's dramatic elevating twin cantilevers. Theses oversail the circulation area and underground obstructions, and project over the most prominent vista of the site to demark the interchange location.

The cantilevers combine their urban role with a functional purpose. The arms are at a 20° inclination facing south and covered with a photovoltaic array to generate power for the building operation, and to actively display the application of the Mayor's Energy Strategy policies to a new public building.

Structure and fabric

The linear undulating form was configured into a repetitive modular arrangement of stainless steel-clad, paint-protected, mild steel portal framing. This comprises a longitudinal spine of two parallel 'I'-beams on raking box section columns supporting cantilevered cross-rafters – on plan appearing much like a toy rail track. The long span of the typical module minimized the frequency of foundations and potential impact of buried obstructions.

The roof sheeting and soffit lining formed a sandwich-like structure within which services and drainage could be discretely distributed, and the typical module was then modified geometrically at the northern end to provide the steel box section springing frame for the two projecting tapered cantilevers.

The cladding system comprises 1.6mm thick linen-finished stainless steel sheets, fixed to a cold-formed purlin subframe, increasing to 2.0mm thick at the lower level of the raking column legs to enhance resistance to accidental damage and vandalism.

Regeneration and urban context

The public prominence of the project required an in-depth and wide-ranging consultative process at key stages of the design programme. Critical input from this was incorporated into the design, including increased shelter, extended CCTV coverage, additional public toilet facilities (including a French-style *pissoir* for revellers from local nightclubs), and more retail; input also extended to choices of materials, fabric, and colour.

The brief called for the project to draw together an integrated visual approach to the area around the interchange, and so the design pulled together lighting, signage, materials, graphics, furniture, and public art, cohering with the architecture to create a contemporary interchange that expresses itself as a catalyst for urban regeneration. The project has thus become a community focal point, facilitating appropriate pedestrian access to future high density mixed use development opportunities as identified in the local authority's plan for the surrounding area.

4. Steel framing to typical module.

5. View from the apex down the 'Ribbon' concourse.

As urban design, the project forms a sculptural marker for significant new corridors whose axes intersect at the soaring cantilevers. By day, the ribbon allows daylight to enter throughout the circulation area and displays itself in its bold choice of material and sculptural form. By night it becomes an animated floodlit beacon, offering both visual excitement and a well-lit safe environment.

Photovoltaics

To fulfil the Mayor's Energy Strategy to promote the use of renewable energy in public buildings, a grant for incorporating photovoltaic cells was provided through the DTI's Major PV Demonstration Programme, following a submission by the design team. State of the art high-efficiency hybrid PV technology has been used, combining ultra-thin amorphous silicon with monocrystalline technology in the one cell – an optimum solution for London's cloudy skies. Covering over 200m^2 of the upper surface of the long cantilevers - at near ideal orientation and inclination – the PV cladding offers 30kWph generation of carbon-free electricity, handling a significant proportion of the bus station's demand. Additionally the angle and prominence of the cantilevers make the PV cells visible from the surrounding area, an important public demonstration of renewable energy use.

Operations

London Buses started operations at Vauxhall Cross interchange in December 2004, with a formal opening by Ken Livingstone as Mayor of London in February 2005. The initial estimate of travel frequency was 2000 bus movements per day. Underground and surface rail services each generate 700 movements daily, so that over 45 000 commuters use the interchange precinct every day. It is understood that bus services have increased by up to 40%, demonstrating the success of the project in promoting the use of public transport, as envisaged in the initial brief. The bus station is now the second busiest in London after Victoria, and its presence has stimulated local business and planning development, and brought forward the upgrading of other transport facilities in the area.

6. PV cells on upper surface of cantilevers.

Credits

Client and project manager: Transport for London **Stakeholder client body:** TfL Street Management, London Development Agency, Mayor's Office Architecture & Urbanism Unit, Cross River Partnership, London Borough of Lambeth **Architect and SME engineer:** Arup Associates – Annelise Penton, Yomi Bola, Mark Boyle, Dan Daly, Nicola du Pisanie, John Edgar, Geoff Farnham, Kenneth Fraser, Ed Hoare, Marek Monczakowski, Mark Oxbrough, Lizzie Pomeroy, Karl Pratt, Robert Pugh, Graham Redman, Caroline Sohie, James Ward, Daniel Wong, Roger Wood, Vincent Young **Security and acoustic consultant, and planning supervisor:** Arup – Jeff Green, Rory Huston, Barbara Marino, Gil Van Buuren **Quantity surveyor:** E C Harris **Main contractor:** Norwest Holst Construction Ltd **Structural steel:** Hawk Engineering **Stainless steel cladding:** ECL Contracts Ltd **Glazing:** Optima Architectural Glass **Photovoltaic installation:** SolarCentury **Mechanical and electrical installation:** McMillan and Co **Signage:** Browse Bion **Illustrations:** 1, 3, 4 ©Arup Associates; 2, 5, 6 ©Arup Associates/Christian Richters

A sustainable business model for GRI

Andrea Fernandez Jean Rogers

GRI is facing a critical time in its evolution: how to stay independent while funding development of a new set of sustainability reporting guidelines. Arup explored what could be learned from other international standards-setting organizations to help GRI achieve a sustainable business model.

Introduction

A recent article[1] about the emerging importance of non-financial reporting stated: 'the big problem is that the genre's development so far has been haphazard. No one powerful organization has taken responsibility for its progress... more discipline needs to be brought to bear on its standards.'

A 'powerful organization' in this role needs to be well-funded, intellectually sound, free of conflicts of interest, and command the respect of a diverse set of constituents in the international community, both financial and non-financial. The Global Reporting Initiative (GRI) could become this one powerful organization. It is revising its 2002 sustainability reporting guidelines to bring more discipline and rigour to them: addressing materiality, improving comparability, and developing performance-based indicators are all innovations planned for what have been dubbed 'G3'.

But only if GRI can sustain itself until then. The irony that this body produces sustainability reporting guidelines and yet does not have a sustainable business model is not lost on its constituents. Its early supporters - foundations, corporations, and governments alike - all want to know how GRI will ensure its own economic viability in the future.

Achieving a sustainable business model without conflicts of interest is essential for maintaining the trust of stakeholders and ensuring successful development of its next generation of reporting guidelines. Both aspects are critical to the future viability of GRI.

Easy money?

Over 2000 companies currently produce non-financial reports, and analysts have noted that no company serious about reporting on its social and environmental performance embarks on this task without first taking a look at the GRI guidelines. If each of these companies paid just $650 for the guidelines, GRI's operating budget ($1.3M in 2003) would be easily covered, maintaining as it does a small staff of only about 20 people in Amsterdam, co-ordinating the development of the guidelines, sector supplements and technical protocols, and managing stakeholder input. The budget includes administrative and overhead expenses, but not programme-related costs, which generate income.

What is GRI?

The Global Reporting Initiative 'is a multi-stakeholder process and independent institution whose mission is... to support global progress towards sustainable development[.] The GRI Sustainability Reporting Guidelines will become the generally accepted, broadly adopted worldwide framework for preparing, communicating and requesting information about corporate performance... These guidelines are for voluntary use by organizations for reporting on the economic, environmental, and social dimensions of their activities, products, and services... Started in 1997, GRI became independent in 2002, and is an official collaborating centre of the United Nations Environment Programme (UNEP) and works in co-operation with UN Secretary-General Kofi Annan's Global Compact.'[2]

GRI's first set of guidelines, published in 2000, are now used by over 600 companies. A second generation has been publicly available, free of charge, since 2002. They were produced through an exhaustive multi-stakeholder process, bringing together experts on a broad range of environmental and social topics.

But the path to a sustainable business model for GRI is not as simple as charging reporters for the value of using the guidelines. This could interfere with some of its basic goals of improving the quality and quantity of sustainability reporting. GRI believes that the guidelines should remain free and in the public domain, to encourage uptake and eliminate barriers to use, in particular for small and medium-sized enterprises and non-governmental organizations.

Conflicts of interest lurk behind every attractive revenue stream: offering accreditation/certification of consultants, taking contributions from those to whom the standards apply, engaging in consulting activities, and even providing education to stakeholders, can all potentially bias the work products or the organization itself. Navigating these minefields while remaining true to the vision and still generating a solid revenue base is a significant challenge.

GRI is not alone in facing this conundrum. All standards-setting organizations grapple with maintaining independence and neutrality, especially while offering a public service, in the face of pressure to generate revenue rather than rely on handouts.

'We would like to engage with Arup'

In January 2004 GRI invited some experts, including Arup, to explore ways to optimize the value and ease of non-financial reporting by developing software-based reporting tools for use by reporters. The Arup team presented GRI with ideas on developing tools such as SpeAR®, and creating performance-based indicators from the guidelines.

The same month GRI issued a request for proposal (RfP) with the stated objective of developing software-based tools based on its 2002 reporting guidelines. However, Arup's prior experience with software development, and the fact that new guidelines were anticipated for 2006, engendered concerns about the risks of tool development, the competition GRI would face, the funding required for such an initiative, and the potential obsolescence of such a tool in 2006. Also, this was a significant deviation from GRI's core mission of developing reporting standards. It might create confusion, if not suspicion of conflict of interest, in reporters' minds.

For these reasons, Arup did not propose software-based tool development, but instead a strategic engagement for GRI to minimize the risks associated with such a venture. Arup could assess the competitive landscape and market conditions, gauge the potential features and functionality of such a tool based on user research and demand, and determine the corresponding price points and the business model for such a venture which, if profitable, could be funded by outside venture capital firms. Rather than partner with a technology provider, Arup would remain independent and 'technology agnostic' so as to provide the best strategy possible.

A call from GRI in May 2004 came as a surprise. It had received 34 other responses to the RfP (all proposing to build a tool and partner with GRI to bring it to market) but, though concerned about pushing the timeline back to conduct strategy, GRI decided that these questions had to be addressed before embarking on a technology project: 'We would like to engage with Arup.'

The team's response was two direct questions: what was the motivation behind this project, and why did GRI want to develop software tools when it was essentially a standards-setting body? The answer was not the expected concern about reducing transaction costs for reporters, or responding to stakeholder demands, but a simple, pressing, need to make money. GRI was in 'a desperate situation' from giving its guidelines away for free. It would not make it to 2006 unless it developed revenue streams.

The crux of the issue was therefore, how could GRI sustain itself, and still produce guidelines that could be offered for free as a public good?

One project became two. Arup did evaluate the potential for GRI software, but quickly learned that reporters wanted better guidelines from GRI, not better digital tools. Arup's global network of sustainability consultants conducted stakeholder research, interviewing NGOs, financial analysts, reporters, non-reporters, and business schools to understand how the guidelines could be improved to address stakeholder needs. Based on this research, the team developed the conceptual approach to innovations required for the guidelines, such as a flexible framework, incorporation of materiality into indicator selection, performance-based metrics, and benchmarking, as well as the technology strategy for delivering the new guidelines on line.

Separately, from August 2004 Arup looked at the business model for GRI as an organization. The goal was to make the transition from a philanthropy-based model toward a self-sustaining model that would continue to allow GRI to innovate and promote its guidelines and serve its constituents' needs while remaining independent. A sustainable business model for GRI would enable it to:

- create stable, diversified revenue streams
- reduce or eliminate its dependence on grant income and corporate contributions
- generate sufficient income to cover its operating expenditures and future investments in product development
- expand its geographical and business reach cost-effectively
- avoid conflicts of interest.

To begin to develop such a model, Arup reviewed those of other standards-setting organizations, and interviewed over 70 GRI stakeholders to understand what kinds of products and services GRI can and should offer to meet their needs.

2. GRI's 2002 guidelines, and 2003-2005 business plan document.

Table 1: Comparison of business models for international standards-setting organizations.

	International Accounting Standards Board	Financial Accounting Standards Board	Social Accountability International	International Organization for Standardization	US Green Building Council	AccountAbility	Global Reporting Initiative
Website	www.iasb.org	www.fasb.org	www.sa-intl.org	www.iso.org	www.usgbc.org	www.accountability.org.uk	www.globalreporting.org
Year established	1973	1973	1996	1947	1993	1995	1997
Mission	To develop a single set of high-quality, understandable, and enforceable global accounting standards that require transparent and comparable information in financial statements and to achieve convergence in accounting standards around the world.	To establish and improve standards of financial accounting and reporting for the guidance and education of the public, including issuers, auditors, and users of financial information.	To improve workplaces and combat sweatshops through expansion and further development of the currently operative international workplace standard, *SA8000*, and its associated verification system.	To develop and disseminate international voluntary standards in the fields of engineering, industry and technology.	To promote the design and construction of buildings that are environmentally responsible, profitable, and healthy places to live and work.	To promote accountability for sustainable development by: • creating a credible assurance standard and underlying accountability framework • providing quality professional development and certification • influencing public policy for organizational accountability.	To develop and disseminate globally applicable Sustainability Reporting Guidelines for voluntary use by organizations for reporting on the economic, environmental, and social dimensions of their activities, products, and services; GRI aims to make sustainability reporting as transparent and ubiquitous as financial reporting.
Voluntary compliance?	Yes	No	Yes	Yes	Yes	Yes	Yes
Stakeholder involvement	The public is invited to meetings and to comment on draft documents. Different regions and diverse stakeholders are represented in governance structure.	FASB follows an extensive 'due process', open to public observation and participation, and co-operating with other national standards bodies.	Convenes stakeholders from diverse backgrounds to develop standards.	Each country has a standards body represented in ISO; other stakeholders can take part in ISO by becoming involved with ISO members from their own country or serving on their country's national delegation to ISO.	USGBC is a consensus-driven, stakeholder-based organization; Members are from diverse backgrounds in the building industry and are active participants in developing the LEED rating system.	As part of the revision process for the AA1000 Assurance Standard, AA has been running a series of consultation meetings with key stakeholder groups: small assurance providers, large assurance providers, company users, investors, large reporting organizations, and NGOs.	GRI produces its Guidelines and sector supplements through an intensive multi-stakeholder collaboration involving international members of civil society, NGOs, corporations, the financial community, academics, intermediaries, and others.
Certification and accreditation schemes	None	None	Accredits certification bodies that certify facility compliance with social accountability standards, and accredits training organizations that provide education.	ISO does not directly audit/certify; Member organizations serve as accreditation bodies which can then 'accredit' other organizations to serve as 'certification' bodies to conduct auditing and certification of management systems (*ISO 9000, ISO 14000*).	Types offered: (1) Certification of buildings against the LEED rating system (2) Accreditation of professionals from various disciplines in the field of green building with respect to their knowledge of the LEED standard.	Jointly with IRCA, AA has developed a Certified Sustainability Assurance Practitioner Programme for business managers, internal auditors, internal practitioners, external assurance providers, trainers, and consultants. AA provides consulting to evaluate the quality of assurance processes.	No formal programmes. GRI verifies all 'in accordance' reports - a small number of the total reports that are voluntarily submitted to GRI.
Memberships	No formal membership programme.	No formal membership programme.	No formal membership programme.	Open to national standards institutes and restricted to one member per country.	Organizational members only; trade associations cannot become members; individuals can participate through membership in local chapters.	AA has developed a series of membership levels accessible to both large and small organizations, academic institutions, NGOs, and individuals.	GRI has a membership scheme for 'Organizational Stakeholders' who pay an annual fee to be involved in its governance.
Education programmes	Publications and question data bank; no courses offered.	Only publications and reports.	Undertakes public education through outreach, consultative workshops, conferences, research, publications, training, and conferences.	No courses offered by ISO; training under ISO standards provided by outside parties.	A wide variety of courses and training seminars, extensive resources via its website, and an annual conference; local chapters help organize training sessions.	AA has developed a suite of training programs to support organizations in building their competencies and capacities in the field of accountability-related policies, systems and standards.	No formal education or training programmes beyond what is in the guidelines and sector supplements, available on GRI's website.
Funding sources	Grants from public/private sources, primarily accounting firms (76% revenue); publications and subscription service (23%).	Accounting support fees from SOX (60%); licensing/royalties (17%); subscription services (14%); publications (7%); contributions, seminar revenue and other (1%).	Government grants (53% revenues); accreditation fees (10%); course fees (11%); conference revenue (26%) and publications (<1%).	National membership dues (65% revenue); royalties for purchase/ reproduction of standards documents (18%); publications (15%).	Conferences and training programmes (45%), membership dues (28%), accreditation of professionals (8%), publications (7%), sponsorships (5%), grants (4%), and certification of buildings (1%).	Projects (48.9%); membership (15.4%); grants (11.2%); conference/events (6.5%); (14.3%), publications/other (3.8%).	Grants (96%) and other (fees for membership programme launched in 2003 and guidelines sales). GRI accepts contributions from foundations (30% revenues), governments/ public agencies (35%), and corporations (31%).
Revenue and costs, 2003 except where noted ($M)	Operating revenue: 21.9 Operating expenses: 22.7 Net operating loss: 0.23	Net operating revenue (for FASB and GASB): 34.2; Total expenses: 26.2; Net operating profit: 8.0	Total revenue (2002): 1.7 Total expenses (2002): 1.95 Net operating loss: 0.26	Total revenue: 23.7 Total expenses: 24.2 Net operating loss: 0.5	Total revenue (2002) 6.4 Total expenses: 5 Operating profit: 1.4	Total revenues 1.42 Total expenses 1.38 Net operating profit 0.04	Total revenue: 3.82 Total expenses: 3.79 Net operating surplus:0.03
Notes on viability of business model	IASB relies primarily on support from grants. Each of the 'big four' accounting firms contributes $1M pa.	FASB's business model radically changed after the Sarbanes-Oxley Act, which charges issuers of securities mandatory fees to fund FASB. As a result, FASB's 2003 revenue increased 74% over 2002, with 22% operating profit.	Relying heavily on government grants, SAI operated at a loss in 2002.	ISO has a solid membership base with broad government support, but operated at a slight loss in 2003.	USGBC has much the most successful business model studied, with 22% operating profit margin in 2002; 96% of revenue is based on fees for services, with grants contributing only 4%. Diversified stable revenue streams include a successful annual conference and strong educational programmes. Certification of green buildings, their *raison d'être*, provides only 1% of revenue.	AA has a diverse model, operating at 2.8% profit in 2003; AA expects revenues to increase dramatically (84.3% from 2004 to 2005), due to its new joint venture programme with IRCA. AA derives close to 50% of its revenue from consulting projects. AA is the only organization that sets standards and offers consulting.	GRI finances took a turn for the worse in 2004 due to heavy reliance on grants, resulting in an operating loss. It needs to diversify its revenue streams and increase membership revenue.
Data source	IASCF Annual Report 2003	Financial Accounting Foundation 2003 IRS Form 990	Social Accountability International IRS Form 990	ISO Annual Report 2003	Financial Accounting Foundation 2003 Annual Report	Financial Accounts 2002/2003 fiscal year	Annual Accounts 2002/2003 fiscal year

Learning from others – a view into standards-setting bodies

In its third-generation 'G3' GRI aims to produce globally applicable guidelines that enable sustainability reporting to be as rigorous, comprehensive, and ubiquitous as financial reporting. In a sense, it aims to become the non-financial reporting equivalent of the International Accounting Standards Board (IASB).

Much can be learned from standards-setting organizations because they all face the challenge of creating a sustainable business model while avoiding conflicts of interest. Many also are committed to offering their 'core product' for free, as a public good. Arup reviewed the business models of several international standards-setting bodies to understand the essential elements as a basis for informing GRI's business model.

Other types of business model were also reviewed, but are not presented here. The process of evaluating alternative business models helped GRI to hone its mission and commit to producing its core products and services centred on the guidelines, rather than diversifying into other areas, such as offering software tools to assist with the process of reporting. The organizations that offered the most relevant case studies for GRI were International Accounting Standards Board (IASB), Financial Accounting Standards Board (FASB), Social Accountability International (SAI), International Organization for Standards (ISO), US Green Building Council (USGBC), and AccountAbility (AA) (see Table 1 opposite).

They were chosen because they all offer generally accepted standards created through a multi-stakeholder process relevant to a broad (if not international) constituency. They also provide a mix: some have been around for quite a while, others are relatively new on the standards-setting scene. ISO boasts the greatest longevity with 57 years to date. FASB and IASB were both introduced in 1973, and the rest in the 1990s, GRI included.

The types of standards these organizations produce are also relatively varied: IASB and FASB produce accounting standards, AA promotes assurance activities, SAI develops standards related to human rights in the workplace, ISO generates a broad array of standards for intra-government adoption, and USGBC was the first to establish principles for the design and construction of green buildings in the US. All the organizations establish standards that are adopted voluntarily except FASB, which is mandated by the Securities and Exchange Commission in the US.

3. GRI stakeholders: Elvis Au (China), Lewis Hawke (Australia), Giusy Chiovato-Rambaldo (Italy)

Highlights of the analysis

With two notable exceptions (FASB and USGBC), these organizations are generally unsuccessful in generating cash to support their ongoing activities without relying upon grants or donations.

Conflict of interest challenges present the major difficulty in developing sustainable business models, and each organization handles them differently. Only USGBC both certifies and accredits under its standard. SAI and ISO accredit organizations which can then certify other organizations under the standards, whilst AA has just launched a new Practitioner certification programme in partnership with the International Register of Certified Auditors for professional certification in assurance against the *AA1000* Assurance Standard; neither of the two financial accounting-related bodies undertakes any certification/accreditation. AA couches its consulting revenue as 'project-related'. No other organizations engage in consulting, which can affect non-profit status and present a conflict of interest. IASB accepts equal contributions, $1M annually, from each of the 'big four' accounting firms: KPMG, Deloitte, PricewaterhouseCoopers, and Ernst & Young.

New-found profitability – FASB benefits from SOX

FASB's business model changed radically following the US Sarbanes-Oxley Act of 2002 (SOX), which as part of its tightening-up of financial and accounting disclosure mandated that all issuers of securities pay a fee to the organization. This fee helped FASB to increase its revenues 74% in one year, and become financially self-sufficient.

FASB's accounting support fee is collected from all publicly traded companies, based on market capitalization, and by sales of publications. The Securities and Exchange Commission (SEC) approves FASB's annual budget, prohibits contributions to maintain independence, and requires an annual audit. The SEC continues to require FASB standards to be adhered to by its registrants. Document sales continue as a major source of funding, but its Accounting Standards and Concept Statements are now available at its website free of charge, benefiting investors by enabling and encouraging transparent financial reporting and removing another possible FASB conflict of interest by eliminating the requirement for purchase of FASB publications. Allowing FASB publications to reside in the public domain and eliminating specific corporate contributions will help restore public confidence in financial reporting.

The cash infusion for FASB came none too soon. The annual reports of the Financial Accounting Foundation, FAF (FASB's parent organization) indicate an operating deficit of $4.3M in 2002 and $1.1M in 2001. FAF incurred operating deficits for the past five years because contributions and publications sales did not match expenses[3].

Viability considerations: USGBC leads the way

The one organization with a truly self-sustaining business model is USGBC. With diversified revenue streams, a solid membership base of individuals and organizations, and strong demand for its educational workshops and annual conference, USGBC has become a strong, independent, self-sustaining organization in just 11 years. Today, it includes over 5300 member companies and organizations, representing more than 1000% growth in the past four years alone.

USGBC's *raison d'être* is green buildings - it writes the standards for design and construction and certifies buildings according to the standards. However, this core activity generates only 1% of revenue, partly because the building process is protracted and the review process complex. Only 121 buildings were certified by USGBC in 2004. USGBC's revenue-generating mainstays are the one-day LEED training workshops given around the US and the professional accreditation programme open to architects, engineers, and green building professionals. These products are brilliantly synergistic, driving traffic to one another. A successful chapter model ensures broad reach and access to customers (over 40 local chapters in the US). USGBC has both benefited from and contributed to the recent boom in the $5.8bn US green building products and services market. Not just a case of being in the right place at the right time, USGBC has intentionally crafted a sustainable business model that creates and supplies the market demand for education and professional validation, while allowing it to continue its core mission of promoting green buildings as healthy places to live and work.

Table 2: Potential revenue streams for GRI.

Revenue stream	Comments
Membership programmes GRI will revamp its membership programmes to better meet stakeholder needs, and leverage technology to keep costs down. Benefits will include greater interaction with GRI and discounts on programmes and services. Fees will be on a sliding scale, and highly competitive with other organizations.	GRI is currently under-performing on membership. Its OS programme represents both a greater commitment (governance of GRI) and expense than most are looking for. A lower-cost programme with more relevant benefits will better serve stakeholders.
Educational programmes GRI will develop educational programmes for launch in 2006, including fee-based workshops offered regionally, and technical manuals.	GRI has amassed a vast pool of intellectual property that can be mined for educational programmes. By 2007, education will form its largest revenue stream. The trick will be to leverage their extended global network for trainers and delivery venues, similar to USGBC. This will keep distribution costs low and revenue in house.
Professional accreditation GRI is considering a programme to accredit professionals on their knowledge of the G3 guidelines. Demand for accreditation will parallel growth in the thriving consulting market.	This is the most controversial proposed revenue stream, but GRI will avoid problems by following a similar accreditation model to USGBC. It would not cover professional practice, only knowledge of the reporting guidelines as evidenced in an exam.
Report registration GRI will require self-declared GRI reporters to meet minimum requirements for reporting, and register their reports with GRI for a nominal fee.	While not a significant revenue stream, this protects the reputations of GRI and reporters4. GRI will not validate report data or content, only check that minimum reporting requirements have been met.
Publications and advertising GRI will develop 'thought leadership' publications related to trends in reporting, and consider peer-to-peer advertising of resources, related to sustainability reporting on their website.	To avoid conflicts of interest, GRI will not engage in rating or ranking reports.
Strategic partnerships GRI will develop a strategic partnership programme using XBRL (eXtensible Business Reporting Language) which is becoming the standard for financial reporting. Advance copies of the code will be offered to technical partners, allowing them to reduce time to market for G3 tools. The open source code will be free to the public after G3 launch.	A technology partner programme will provide a small revenue stream and allow GRI greater control over use of their guidelines in reporting tools. Through this programme, GRI can meet stakeholder needs and facilitate development of reporting tools without becoming a software provider.

Parallels to GRI

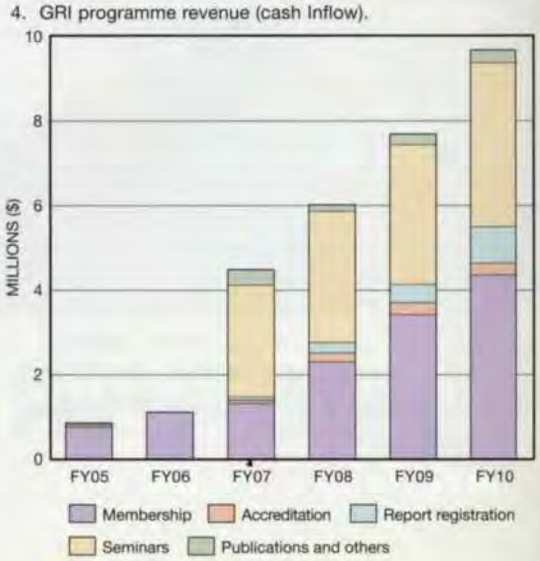
Because most organizations studied were on the brink of financial instability, and/or heavily reliant on unsustainable forms of income such as grants and contributions, they did not, except for USGBC, represent aspirational business models for GRI. But FASB's situation also raises interesting questions about support for GRI from those attempting to restore public confidence in corporations through better reporting.

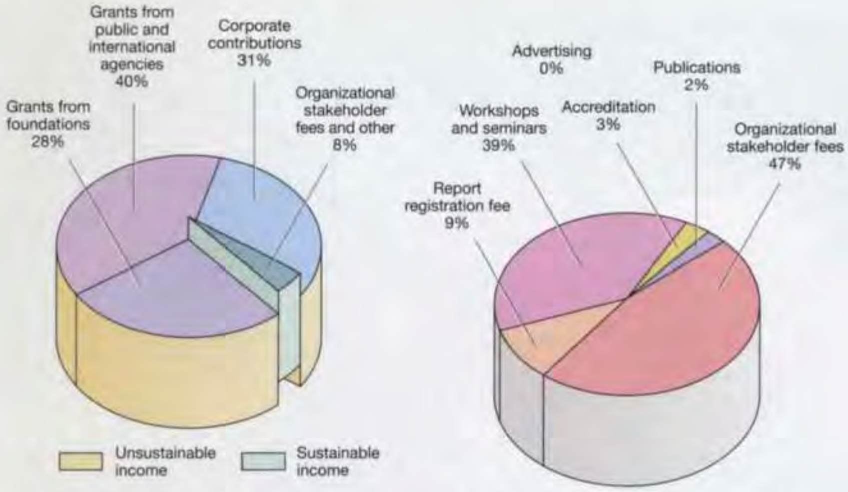
Like USGBC, GRI enjoys a dedicated, even zealous global following and has amassed a vast reservoir of intellectual property that it can draw upon. GRI could learn much from USGBC about creating a small number of educational programmes to meet stakeholder demands and developing a network of local chapters to facilitate delivery - this keeps costs low and the revenue in-house.

Like FASB, GRI is working to promote transparency and comparability in reporting. GRI takes a broader and longer view of risk by setting standards for disclosure of environmental and social parameters with material implications. Securities regulators and exchanges are beginning to take note: the Johannesburg exchange already requires sustainability reporting for its listed companies. As non-financial reporting becomes mainstream, a funding scenario like the SEC/FASB model may be possible for GRI. The challenge will be to demonstrate the utility of GRI reports to the financial community and to the public. GRI will also need to be prepared to accept the impact that such a relationship would have on its independence. In this scenario, not all stakeholders will be created equal.

In the meantime, GRI will need to focus on developing stable, diverse revenue streams based on providing valuable products and services to stakeholders.

4. GRI programme revenue (cash Inflow).





Breakdown of GRI income in FY03 **Breakdown of GRI expected revenue in FY10**

5. Diversification of revenue streams, current and projected.

Making the transition

GRI will be best able to meet the needs of its stakeholders, remain free of conflicts of interest, and generate revenue from its activities, by developing programmes to benefit stakeholders (Table 2).

GRI's programme revenue is expected to rise from under $1M in fiscal year (FY) 2005 to nearly $10M in 2010 with the launch of the new products and services (Fig 4). These numbers are based on conservative projects for market growth and capture. Revenue from membership and educational services will form most of GRI's income streams in the future.

GRI's operating expenses will grow relatively steadily from $1.3M per year in 2005 to $2.0M in 2010. A significant investment* for transition to the sustainable business model will be required concurrent with the development of G3, but with release of the new guidelines and rollout of the new programmes and services in 2006, GRI will have achieved a sustainable business model by 2008. Diversity is the key to its stable financial future (Fig 5).

By 2010, GRI will have improved its reliance on sustainable forms of income from 3% to 100%, and no longer be dependent on grants or contributions to fund its activities. It will have achieved a diverse and robust business model based on providing fee-based services that meet stakeholder needs, while ensuring that the guidelines remain free and in the public domain.

A call to action

A recent publication[5] rated the Top 50 non-financial reports produced in 2004, and no less than 47 of them used GRI's guidelines in their preparation. *The Economist*, commenting on this[1], highlighted the problems with even the best sustainability reports - lack of comparability, departure from material issues, and absence of key performance indicators. It even disparaged GRI for offering a 'one size fits all' approach. Ironically, these are all innovations planned for GRI's next release.

It is in the best interest of everyone who benefits from the guidelines to support GRI's transition to a sustainable business model. From asking the right questions, Arup developed with GRI and its board of directors such a business model that should enable it to regain solid financial footing and become a self-sustaining organization, as opposed to being reliant on grants and philanthropy.

Since then GRI has been putting in place the machinery to begin developing the programmes associated with the new revenue streams. The new programmes and services are slated to be rolled out concurrent with the new reporting guidelines, scheduled for late 2006. Maybe then GRI will be recognized internationally as the one 'powerful organization' leading the field of non-financial reporting.

Global Reporting Initiative™

'Arup's work with the GRI has been distinctive on three fronts:

- *Strategic: the Arup team developed quickly a good understanding of the GRI's sustainability mission and multi-stakeholder organization. Building on this, the team moved quickly to add significantly to the GRI's understanding of its technical and strategic opportunities.*
- *Inspiring: the Arup approach is a wonderful blend of can-do, matter-of-fact, and aiming-for-excellence.*
- *Teamwork: Arup proved ready to make a journey with the GRI. Learning and risk-taking could be a two-way process as Arup became a stakeholder in the GRI's sustainability mission.'*

Ernst Ligteringen, Chief Executive Officer, Global Reporting Initiative

*GRI is currently raising funds for the development of G3 and transition to a sustainable business model. Funds raised will be allocated to development of the following programme areas:

• $2.3M G3 standards development • $0.1M Report registration process • $2.2M Educational programmes • $5.3M Technology platform (significant in-kind funding for development of the technology platform has already been committed) • $0.9M New membership programmes • $1.2M Accreditation.

Credits

Client: Global Reporting Initiative **Consultant:** Arup **Business framework project team:** Andrea Fernandez, Jean Rogers (Arup), James Murphy, Ralph Thurm (GRI)

Digital guidelines evaluation project
Client team: Sean Gilbert, Ernst Ligteringen, James Murphy, Alyson Slater, Ralph Thurm **Arup team:** Katharine Adams, Cody Andresen, Lucy Avery, Sara Bordoley, Andrea Fernandez, Caroline Fricke, Aidan Hughes, Gary Lawrence, Georgina Legoe, Yoshiyuke Mori, Stephane N'Diaye, Samantha Plourde, Jean Rogers, Amy Westervelt **Subconsultants:** Renee Andersen (information architecture and content), Ara Avakian (technology), Suzanne Abele Ebanks (funding), Dominic Lusinchi (statistical analysis), Noreen Santini (visual design) **Illustrations:** 1-3 GRI; 4-5 Nigel Whale

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1. The new community route alongside the improved road.

The A470 Lledr Valley Improvement, Wales

Described by the media as 'possibly the "greenest" road in Britain', the new A470 was designed to provide a safe and reliable route for all users with a minimum of adverse ecological impact.

Nick Higgs Dan Saville

Introduction and background

Snowdonia National Park is one of the UK's most beautiful areas. A road improvement scheme in such a highly sensitive environment clearly needs a very sympathetic design and demonstrably sustainable credentials. These factors inspired the design and construction of the recently completed on-line improvements to the A470 between Dolwyddelan and Pont-yr-Afanc in North Wales, for which Arup acted as principal designer.

The A470, a strategic link between north and south Wales, and a primary route into mid-Wales, forms part of the trunk road network that falls under the remit of the Welsh Assembly Government ('The Assembly'). The Assembly has long recognized the route's importance and has been undertaking a series of projects to upgrade and improve it.

Between Dolwyddelan and Pont-yr-Afanc the A470 follows the steep and wooded valley sides of the Afon (River) Lledr. The original route (Fig 2) was narrow and tortuous, with largely non-existent verges, and poor visibility made it difficult for large vehicles to pass and impossible for pedestrians, cyclists and equestrians to use safely. All these factors contributed to an above-average accident rate, frequent delays, and congestion.

The scheme was to improve safety and journey time reliability by upgrading to modern trunk road standards, but balanced with the effective mitigation of environmental impacts. Indeed, any opportunities to enhance the environment were to be grasped. Fitting the road carefully into the landscape was The Assembly's prime goal and great emphasis was placed on the need for environmental mitigation measures to be both comprehensive and effective.

2. The original tortuous alignment.

Overall improvement options to 19.5km of the A470 were first considered in the 1986 Welsh Office A470 Route Study Report, and draft Orders and an Environmental Statement were published in 1995. Following a Public Inquiry, Scheme Orders were made in October 2001 and later that year advanced tree felling work commenced to clear the critical areas of land required for the improvement. During this period, Halcrow acted for the Assembly in developing the Illustrative Design.

Partnering approach

The A470 improvement scheme was let as a design-and-build contract (valued at £17.5M). Arup tendered with Laing O'Rourke and in August 2002 The Assembly awarded the contract to the team. Construction began in November 2002.

From the outset a collaborative approach was adopted by the project partners: Arup, Laing O'Rourke, Halcrow, and The Assembly. This built on the non-contractual partnering arrangements encouraged by the scheme documents and discussions on partnering during the tender period. At the outset all key team members agreed and signed a 'Partnering Charter' (Fig 11). This was no token gesture: regular workshops reviewed the charter and its aims, and enabled feedback and evaluation of team relationships. These were reinforced by regular social activities, eg climbing Snowdon, Wales' highest peak.

Before construction, a public exhibition helped establish a good rapport with the local community and this was maintained during the works through site visits and a well-managed liaison programme that dealt effectively with public queries, leading to positive feedback. Involvement with charity organizations and local events promoted a strong spirit and culture of co-operation between the local community and the site team.

An Environmental Liaison Group, with representatives from statutory bodies such as the Countryside Council for Wales, the Environment Agency, and the Snowdonia National Park Authority, was established early in the project. The group met regularly to review the effectiveness of mitigation and design measures.

This liaison strategy effectively extended the project partnering ethos to the wider stakeholder group. Without this approach and its active management, delivering the scheme effectively would have been extremely difficult.

Design features

Roadworks

Primarily the 7.2km scheme involved road widening and upgrading, but compliance with full design standards would have had undesirable environmental impacts along the route corridor. This was avoided by adopting principles outlined in the design guide 'Roads in upland areas'[1], which requires good quality detailing and a balance between the engineering needs of alignments, visibility, and environmental aspects. Applying these principles resulted in lower design speeds for the carriageway alignment as appropriate, and reduced verge widths. Nevertheless, the improved carriageway width is generally 7.3m except at Pont-y-Pant and under Gethin Viaduct where it is narrower for environmental reasons.

Kerbs were only used where essential for road drainage and safety reasons, ie to control surface water run-off and/or where narrow verges keep traffic clear of the adjacent road boundary. All kerbs have a dark grey exposed aggregate finish to blend into the surroundings.

A new footway was built between Dolwyddelan and Pont-y-Pant with only small sections paved to replace existing sections. All other lengths of footway have a grey crushed slate finish to match adjacent walls. A community route was also constructed between Pont-yr-Afanc and Pont ar Lledr as part of the Conwy Valley Cycle Route (Fig 1).

Traffic signs were kept to a minimum and their locations carefully considered to reduce visual impact whilst still complying with safety requirements. Public footpath signs were saved and re-erected or renewed where they were disturbed by the works. Other features like milestones and name signs were also salvaged and carefully incorporated.

To maximize sustainability and minimize transport of materials, as much of the existing road pavement as possible was retained. Where pavement material had to be removed it was extensively reused within the lower layers of the new road, whose surface generally gives reduced traffic noise.

3. Constructing boundary walls.

Retaining walls

Where there was a safety requirement to contain vehicles, masonry or masonry-faced reinforced concrete walls and parapets were built rather than metal safety fences and parapets, which might have looked too urban.

Stone removed from existing walls was salvaged and incorporated into the new or refurbished walls. Other facing masonry was won from waste stone at local quarries. Overall, the scheme includes some 3.5km of new retaining walls.

Where there was no requirement for vehicle containment, traditional stone walls (Fig 3) were provided using relatively soft mortar which eliminated the need for joints. Where design standards required, they became traffic containment parapets with a reinforced concrete core (Fig 4). All the concrete walls are faced with local stone masonry and incorporate refuges for reptiles, bats, and birds.

Mass concrete walls were constructed for retained heights up to about 2m because they are simple, robust, durable, and economic. For heights up to about 5m, reinforced concrete cantilever stem walls were used.

4. Stone-clad containment parapet.

The middle 2.8km of the scheme, between Pont-y-Pant and Pont Gethin, was the most challenging and required innovative and adaptable solutions to accommodate the variable nature of the ground and the height to be retained by walls, up to about 7m. Walls were founded on rock where it was near the surface; elsewhere they were supported on small diameter piles 2m-10m long socketed into the rock. Thin steel permanent casings were provided from cut-off level to rockhead to stop the pile bores being contaminated with debris prior to or during concreting on the steeply sloping sidelong ground. Although non-structural, the casings also enabled the cover to reinforcement to be reduced, resulting in more efficient use of reinforcement cages.

The walls through this area were mainly constructed of in situ reinforced concrete panels (Fig 5), restrained against lateral movement and rotation by rows of rock anchors between 5m and 20m long depending on the ground encountered. They were inclined at 30° so as to reach competent rock more quickly - generally reducing length - and to avoid passing through the loose rockfill embankment that supports the highway.

This avoided any problems of collapsing drill holes, lost bits, or excessive grout consumption. At Pont-y-Pant, a 13m high retaining wall was constructed directly onto the rock in the river bed and against the original masonry wall (Fig 6).

In several areas the design team improved significantly on the Illustrative Design, by:

- adjusting earthworks profiles either to completely delete retaining walls or replace a vehicle containment wall with a masonry boundary wall

5. Anchored panel wall.

6. Constructing retaining wall No. 6 at Pont-y-Pant.

- using mass concrete rather than reinforced concrete walls where the programme was critical, speeding construction and reducing traffic management/delay costs
- minimizing disturbance to existing walls and so not requiring permanent anchors to stabilize them temporarily; backfill was placed before anchors were installed, avoiding the need to compact the backfill around them
- deleting positive back-of-wall drainage by providing permeable backfill and flow paths through and below wall panels
- building the Pont-y-Pant wall in situ rather than in precast panels – this would have been difficult to construct without road closures.

Geotechnics

The geology comprises mainly closely cleaved siltstones and slatey mudstones with impersistent sandstone horizons. The hardest sandstones form ridges and crags, the most prominent of which narrow the valley at Pont-y-Pant, where an anticlinal fold axis crossed by a major sandstone unit coincides with the valley axis. Near the centre of the route, outcrops of tuffs occur, formed from volcanic ash and dust dating from Caradocian times.

Cuttings into the weathered and more fractured rock near the surface were typically excavated at 45°, with this steepened to 70° or so in the less weathered and more intact rock found in deeper cuttings. Where possible, rock cuts were excavated along joint lines for a natural appearance.

Rock falls can occur at Pont-y-Pant, where the ground above the road is a mass of large boulders, resulting from toppling of the oversteepened glacially scoured crags as the glaciers retreated. To reduce the risk, protection measures in the form of traps and dentition work were provided.

Geotechnical input contributed to many of the successful value engineering initiatives. Soil nails were included in the Illustrative Design and contractor's tendered solution, but additional investigation (both during the tender period and afterwards), analysis, and risk assessments showed them to be unnecessary. The team processed a value engineering change to omit soil nails throughout the project, delivering benefits to all.

Drainage and pollution control

Existing road drainage was uncontrolled, running into roadside ditches and through 'scuppers' before tumbling down the heavily vegetated valley sides into the Afon Lledr and Afon Conwy. In places only yards from the Afon Lledr, a high-quality salmon and trout stream, the project's highway drainage was always going to be an environmental challenge.

The team identified ways to refine the illustrative drainage layouts, rationalized pipe runs, and combined some highway and verge filter drains. This eased some of the traffic management demands in the tightly-defined works corridor but still left potentially challenging excavations for oil interceptors - large tanks that use differences in specific gravity to trap hydrocarbons (usually oil and fuel), preventing them from reaching receiving watercourses.

The Environment Agency understood the difficulties of installing and maintaining oil interceptors in such a challenging location, and were open to alternative solutions for pollution prevention. After considering theirs and the Fire Service's views, and conducting detailed risk assessments into the likelihood of a serious pollution spill, the team designed and implemented a much smaller and easier to construct alternative isolation facility that allows individual outfalls to be closed manually by releasing a flap valve (Fig 7). Procedures for operating the isolation facilities are included in the project maintenance manuals, so that the maintaining authority and emergency services know how to respond in an emergency.

Out of the 19 oil interceptors originally planned, only one was eventually needed.

Treatment of existing watercourses crossing the route also presented challenges, given the near precipitous valley sides and tumbling rocky channels. Wide culverts were built to carry even the most intense storm flows safely beneath the road and down to the Afon Lledr. Large slate blocks found during construction were saved and used to line the stream channels, returning them to their original appearance of natural upland watercourses.

Environmental Management System (EMS)

Key to the effective delivery of the project was the EMS, of which a major part was the Environmental Action Plan (EAP) that detailed the project's commitments to environmental mitigation measures. All sections of the plan were targeted and monitored daily, with formal audits conducted for compliance with the EMS, and continual improvements implemented on site. The EMS was overseen by an Environmental Co-ordinator with a dedicated deputy stationed permanently on site to ensure all EAP commitments were implemented and appropriate mitigation measures provided.

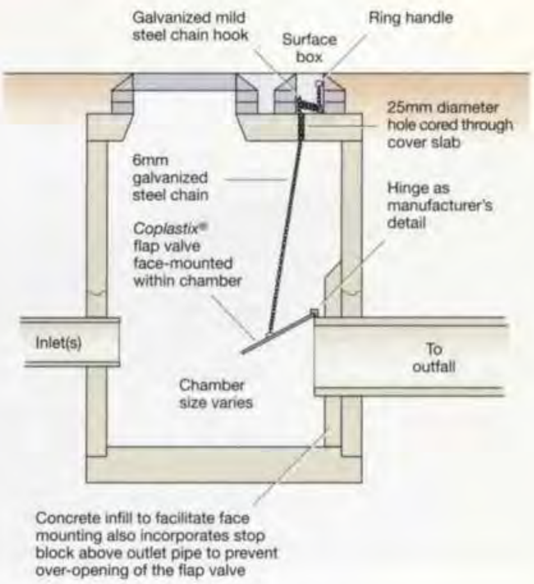
Ecology

The Lledr Valley is blessed with diverse flora and fauna, and from the outset, the importance of the valley for bats, otters, and reptiles was recognized. The Illustrative Design contained several conservation features, including an artificial hibernaculum for Lesser Horseshoe bats; gaps in walls for reptiles, birds, and bats to nest and roost; and culverts with ledges (Fig 8) to help reduce otter mortality from traffic.

Several areas of floristically rich meadow and woodland were translocated to prevent their loss, whilst the construction team protected other habitats, including a Site of Special Scientific Interest and many areas of woodland/upland soils. The Afon Lledr featured constantly in early discussions on construction methodology, due to the need to protect its water quality and associated aquatic flora and fauna.

The team further developed the contract's ecological requirements during construction. The bat hibernaculum - known as the 'bat hotel' on site (Fig 9) - was redesigned to improve its bat 'attractiveness' as well as facilitating easier and cheaper construction, whilst a more cost-effective way to translocate the floristically-rich topsoils was developed with the Countryside Council for Wales. This was a particularly significant success in its first year of new growth.

Throughout construction, Arup's ecological specialists regularly surveyed and monitored the nature conservation in the Lledr Valley. Trees that might contain bats were only felled following detailed inspections and, if necessary, obtaining the appropriate protected species licences. Sites were cleared and walls/buildings demolished only after extensive review of the area for nesting birds, bats, or hibernating reptiles.



7. Drainage isolation valve.

8. Provision for otters.

9. The 'Bat Hotel'.

10. Retaining the landscape setting.

Llywodraeth Cynulliad Cymru
Welsh Assembly Government

A470 DOLWYDDELAN TO PONT-YR-AFANC

PARTNERING CHARTER

The A470 Lledr Valley, Dolwyddelan to Pont-yr-Afanc Project Team will work together in a spirit of mutual trust, openness and co-operation to deliver a quality scheme, which will enhance the reputation of all parties, deliver the intended benefit to the partners and the community and to respect the environment and the needs of all affected by the Project. The team will monitor and measure its success by the degree to which it achieves the following goals:

- Zero accidents
- Zero adverse environmental incidents
- No negative feedback from stakeholders
- Adhere to the agreed communication system
- An enjoyable and rewarding working environment
- Adhere to the agreed problem resolution procedure with 'no blame' culture
- Complete the Project on time
- Complete the Project within the respective budgets of the Parties
- Positive recognition of others for the Project
- Help each other to perform our roles efficiently

Halcrow LAING ARUP

11.

'The entire project team on Lledr worked towards a common goal of delivering the road improvement in an environmentally sensitive way. The fact that this was achieved some five months early, within a partnering framework and that the project is now receiving awards demonstrates that the team got it right.'

Mike Gilbert, A470 Lledr Valley Improvement Project Director, Transport Wales, Welsh Assembly Government

The Environment Agency removed fish safely by electrofishing before the works to some culverts were carried out.

The effectiveness of the wildlife measures will be monitored for five years beyond project completion and comprehensive reports prepared to inform future trunk road schemes in Wales as part of The Assembly's commitment to continuous improvement. Areas of land disturbed by the scheme but not planted/seeded or covered by hard engineering works will be allowed to regenerate naturally, particularly in the most upland sections. This should ensure an appropriate mix of natural flora, benefiting local biodiversity and integrating the scheme into the wider landscape.

Landscape

The landscape setting was carefully considered during design development, care being taken to limit the impact on important rock outcrops, trees and streams, as well as man-made features such as stone walls and the bridges Pont Gethin and Pont ar Lledr. The retention and protection of these features, along with landscape mitigation such as shaping side slopes for return to agriculture, the 'dry stone wall' appearance of new walls, riven oak post and wire fencing, and re-use of salvaged stone, has integrated the new road into the landscape much as the former was. This approach enabled much of the area's special landscape character to be preserved (Fig 10).

Conclusion

The sensitive environment, the design-and-build form of contract, and the demanding timescale - not to mention the weather - made the A470 Lledr Valley Improvement a difficult challenge. By using Arup's technical expertise, developing innovative thinking into deliverable solutions, and fully and enthusiastically subscribing to the non-adversarial partnering approach, the team overcame these challenges and delivered what has been described by the media as 'possibly the "greenest" road in Britain' to the client five months early and within budget. It has achieved its objectives of providing a safer and more reliable route for the travelling public and other users, whilst minimizing its environmental impact.

Awards

ICE George Gibby Award: Highly Commended; Conwy Civic Trust Award (for the quality of the stone walling); CEEQUAL 'Excellent' rating; British Construction Industry Awards 2005: Major Projects Finalist; Prime Minister's Better Public Building: Finalist

Credits

Client: National Assembly for Wales **Client's agent:** Halcrow **Client's environmental advisor:** Wyn Thomas Gordon Lewis **Contractor:** Laing O'Rourke **Principal designer:** Arup - Kambiz Ayoubkhani, Charlie Baldwin, Paul Baralos, Geraint Bowen, Ross Cullen, Ioan Evans, Andrew Gardner, Robert Gordon, Chris Haines, Mike Hayes, Hywel James, Geraint Jones, Claire Kimber, Simon Lawrence, Heather Mitchell, Phil Morgan, Aled Phillips, Simon Power, Linda Pring, Lucy Rackley, Peter Richardson, Richard Sanders, Dan Saville, Debbie Scott, Daniel Smith, Ian Statham, Richard Thomas, Gabe Treharne, Theodosia Tsoumba, Martin Vanicek, Roy Walker, Keith Williams **Landscape architect:** TACP **Ecologist:** Cresswell Associates **Arboriculturist:** Amenity Tree Care **Archaeologist:** Gwynedd Archaeological Trust **Illustrations:** 1, 8-10 Rob Watkins; 2-6, 11 Dan Saville - Arup; 7 Nigel Whale

Reference

(1) Roads in upland areas. Welsh Office Highways Directorate, 1990.

1.

CDO:

Computational design + optimization in building practice

Chris Luebkeman Kristina Shea

Introduction

Computers continue to change the world of engineering and design, increasing the complexity of what can be designed and built as well as enhancing our imaginations and understanding. In today's competitive global market, exploring and exploiting new ways to use computing is key to creating and fabricating innovative designs that expand the perceived boundaries of possibilities.

Imagine a team working on a large-scale building project with complex geometry. Many design parameters can be varied, and their impact on balancing different design performances is not always predictable. Using a new approach to design, the team creates an optimization model that computationally encodes client, architectural, engineering, fabrication, and construction-related parameters and desired performances. Making use of the considerable computer power across the Arup network, a computational optimization process rapidly generates, evaluates, and mediates among thousands of design variations. The result is a set or 'point cloud' of optimized designs from which good designs can be selected based on preferences among performances, or viewpoints on the design.

Navigating the performance space promotes lateral thinking among designers and illustrates the relation between design variations and complex performance trade-offs. The optimization model can then be adjusted and the process rerun with little extra effort to study impacts of parameter changes. Such studies can help designers to determine the best trade-off among performance and cost regions for the design as well as aiding multidisciplinary negotiations. This new design process enables improved design quality in less time with reduced cost, and can make new levels of complexity and new aesthetics possible.

To move towards this future design process scenario, Arup is incubating expertise in computational design + optimization (CDO) within its Foresight, Innovation and Incubation (FII) group in London. CDO is about formalizing aspects of design tasks as computational models so that iterative computation, both interactive and automated, can be used to find feasible and performance-driven design alternatives that would be difficult to arrive at using conventional computing and design processes alone. CDO builds on and incorporates other emerging design computing technologies, including algorithmic design, 3-D parametric and associative geometry, performance-based design, integrated design tools, and design automation.

The primary focus of the CDO incubation period over the past three years has been to ask: with clients demanding high-quality engineering solutions for more and more complex projects, can CDO provide competitive edge in meeting and exceeding increasing demands? The current focus is on engineering design tasks within building projects.

Motivation for CDO

In industries like automotive, aerospace, and boating, CDO is an essential component of the design process in performance-critical applications. It has led to lighter, stronger, stiffer, and often cheaper automotive bodies, aeroplane wings, and ship keels. In building and infrastructure projects, however, it is only applied in small pockets and mostly for detail design tasks, eg automating the sizing of steel and concrete members for tall buildings, which have enabled both cost and design time savings.

To explore current Arup experience in CDO and future benefits, a half-day 'Arup Explores' event was held in March 2004 involving 53 delegates across four international sites and several sectors. One general conclusion related to building projects was that applying CDO early in design opens up the potential to influence performance-driven changes in building form.

Drivers for increasing expertise in CDO include gaining marketing edge due to increased competition, desire for improved quality, shorter design time and cost, increased complexity (eg geometric) of projects, and to foster improved collaboration among multidisciplinary design teams. In addition to drivers, it is timely to expand expertise and the scope for CDO now since it is enabled by increased computing power in both hardware and software capabilities, and increased computer fluency of young designers.

2. Rendering of the proposed Bishopsgate Tower for DIFA in its City of London setting.

Bridging the gap between research and practice

The CDO field is vast, and comprises research in mathematics, operations research, architecture, aerospace, mechanical engineering, and civil engineering. However, a large gap still exists between research and practice in CDO, especially within the building industry.

The reasons for this relate to methods, tools, and people. First, optimization methods are often only tested on small-scale benchmark tasks and do not often include practical design considerations and constraints, some of which can be difficult to model and are project-specific. Potential optimization tasks that could benefit from CDO generally have anything from five to 25 000 variables, from one to millions of design constraints, and from one to as many independent design performance objectives as can be incorporated.

There is also often a mismatch between the areas where CDO can benefit projects most, ie in early design stages, and where it is straightforward to formulate computational optimization models, ie in detail design stages.

Further, current commercial software for CDO, which most often is developed for the automotive and aerospace industries, does not often match the needs of the building industry (eg taking into account country-specific design codes), requiring in-house customization and development of new tools. This is true apart from some building industry-specific software for structural member section sizing, and application of other software to individual building components that strongly resemble mechanical components.

The final reason relates to people, since CDO requires them to think and work differently. Making step changes in design processes is generally difficult. CDO requires new ways to model design tasks in terms of quantifiable design variables, constraints, and performance objectives, as well as giving up direct control of some design variables to a computational process that will determine their best values based on an optimization model formulated by the design team. CDO has been used most extensively so far on projects whose complexity has driven the need to adopt new computational processes. For example, on the Aquatics Centre project for the 2008 Beijing Olympics, without a new automated approach to selecting section sizes and checking them to design codes for all 25 000 steel sections, it would not have been possible for the team to find a working solution, and one that was near the targeted roof weight.

Work within Arup's FII group is addressing these challenges to help bridge the gap between research and practice. Application to live projects is the priority, to raise understanding of how CDO can best be integrated within design processes to improve and extend service to clients. Arup is now using CDO on projects in London, the Solihull Campus, Manchester, Hong Kong, Detroit, Los Angeles, and Sydney.

A good design optimization task is one where there are design variables to work with and the designer needs to better understand the influences of their changes on one or more performances, to both meet design constraints and improve performances. The number of design variables and trade-offs among performances should be meaningful enough to justify the effort involved in creating an optimization model, finding or developing an integrated CDO tool, and carrying out optimization studies. This justification can be through sheer number of design variables, or potential gains in performance, or limited knowledge of how design variables and performances, especially multi-disciplinary performances, interact.

Through direct project work and many discussions about beneficial CDO applications on Arup building projects, three areas with high potential are emerging: structures, façades and building physics applications.

3. Complex canopy entrance to the Bishopsgate Tower.

Generating optimal structures

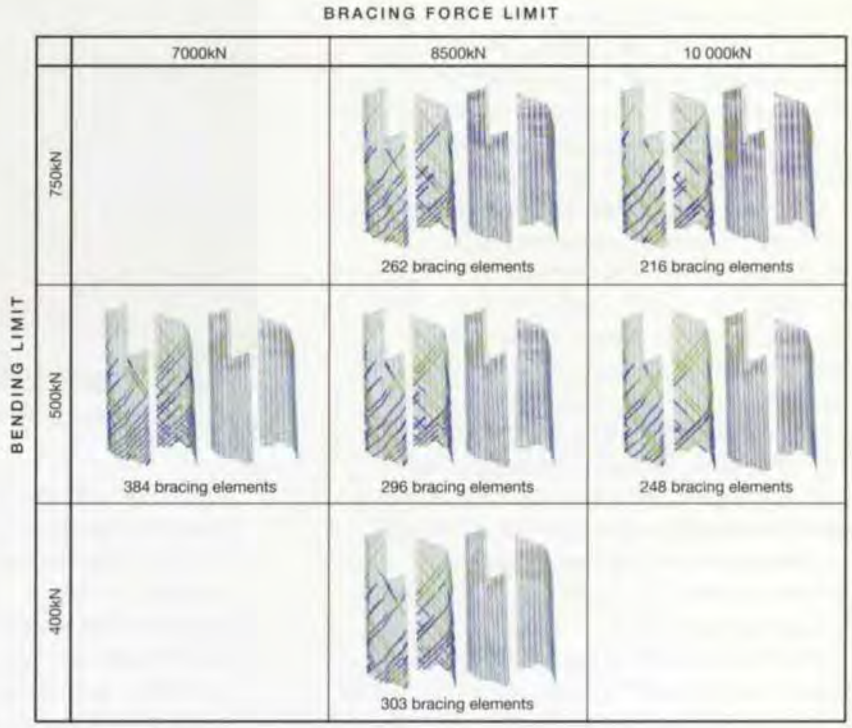
With regard to structures, CDO has been used to generate efficient and aesthetically-pleasing bracing systems for the proposed Bishopsgate Tower in London for Deutsche Immobilien-Fonds AG (DIFA), in collaboration with Arup's Building London Group 4 and working with architects Kohn Pedersen Fox Associates (International) PA (KPF) (Fig 2 & 3).

This curved tower, some 307m tall, required a lightly braced, randomized layout for the steel tubular stability system - 'spirals' of fixed inclination wrapping around the irregular building envelope, emanating from column bases and terminating at varying heights up the building. A variable density bracing pattern was desired with more bracing elements at the bottom of the tower transitioning to fewer at the top.

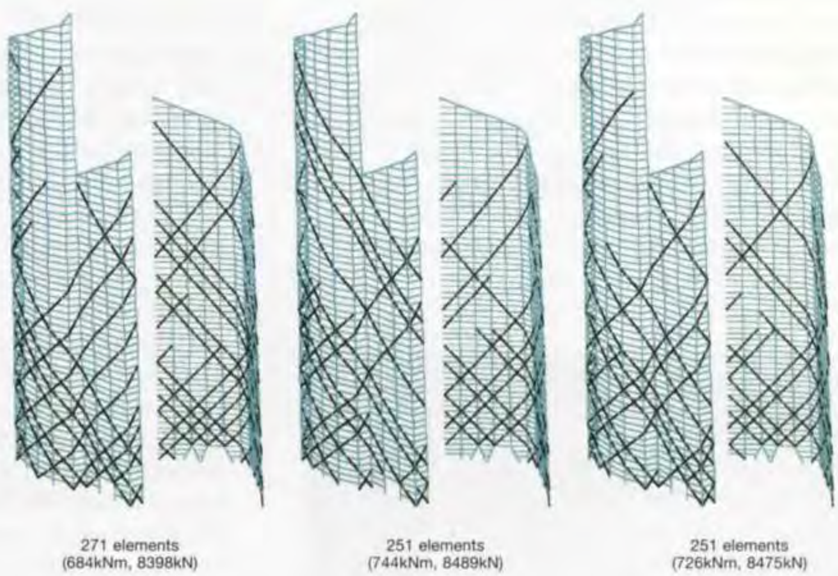
The optimization model for this task encoded 3×10^{48} possible designs, a large number of design variants compared to what can be considered by hand. The objective was to minimize the number of bracing elements while meeting structural limits on maximum axial force in them, and maximum bending moment in the horizontal beams of the perimeter framework (Fig 4).

A new CDO tool was developed initially to automate the manual, collaborative process carried out by the architects and engineers for generating, analyzing, and understanding design alternatives. The search method employed is a variation of pattern search, originally proposed in 1961[1], that evolves efficient bracing patterns through iterative element removal and addition from fully-braced and random starting patterns. This approach would not be possible using traditional numerical, or gradient-based, optimization methods. The 'intelligent' search method, compared with basic automated iterative analysis and removal of under-utilized elements, gave improved designs in terms of reducing the number of required bracing elements for similar structural performance. It also needed substantially less computing time - three hours compared to 14 hours for basic design automation.

Adding a random component to the search procedure and stochastic variation of the starting pattern enable a wide range of design alternatives to be generated from the same process, all with similar structural performance. This benefits a team looking to select designs based on aesthetics, which are difficult to model explicitly within the CDO method itself. Parametric studies were carried out to explore the influence of structural limits on the minimum number of bracing elements in the system, allowing the team to make a more informed decision about which design performance region provided the best trade-off between the bracing pattern and structural limits (Fig 4).



4. Parametric design study of bracing patterns for the Bishopsgate Tower.

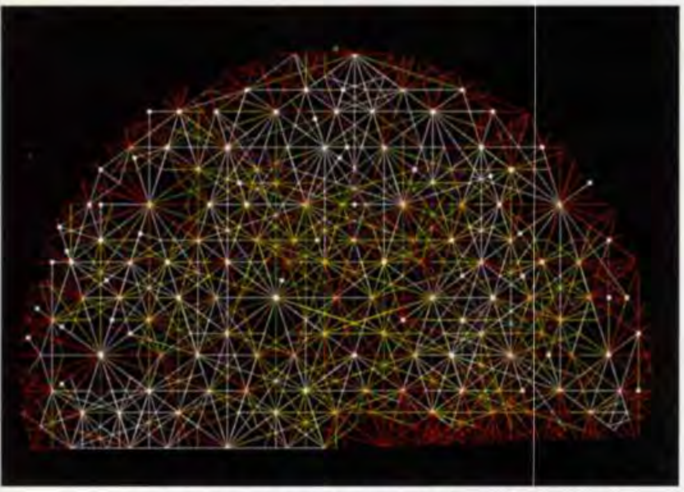


5. Planning application schemes for the bracing system of the Bishopsgate Tower.

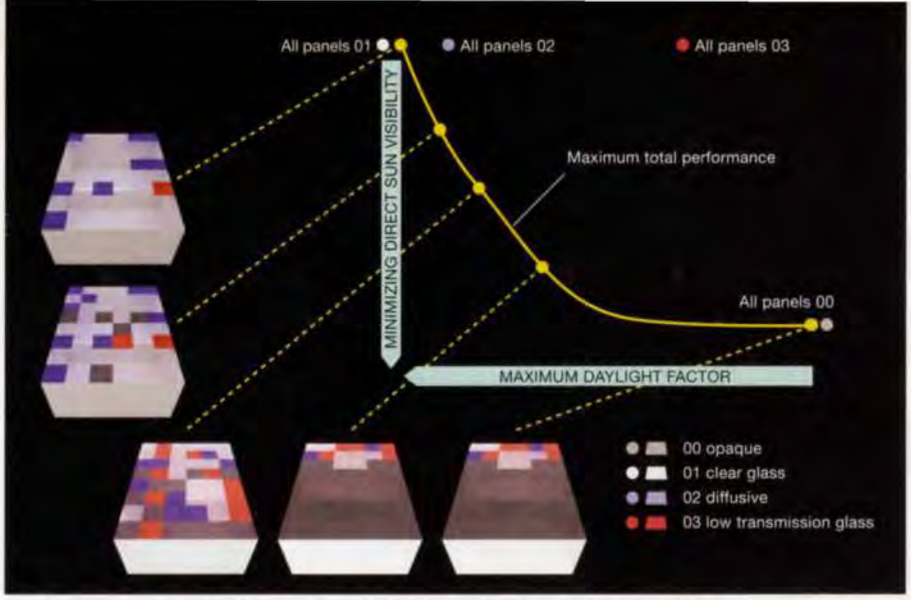
The results of this study were presented to the architects who were enthusiastic and interested in both the bracing schemes generated and the novel design optimization process. Final bracing schemes for the planning application were submitted to the Corporation of London in June 2005 (Fig 5).

The final bracing pattern generated was modified slightly for the planning application, so as to improve the reading at the entrance to the building only. CDO tools may be used again as the design develops, both to investigate the possibility of refining the bracing pattern further and to incorporate, within the same process, parallel studies into the effects of varying individual steel member sizes on the overall efficiency of the building structure. This successful application of an established search method, tailored and extended, provides a valuable case study in applying structural optimization effectively, beyond section sizes alone, on a live building project[2].

Other CDO projects in the area of structures include development of a Rhino CDO toolkit and an application to a steel spaceframe stadium roof. Both involve developing automatic links between CAD tools and GSA, also called integrated design tools. The first project links Rhino and GSA to evolve novel frame structures, whilst the second links a parametric model in CATIA with GSA to optimize section sizes for the steel spaceframe roof according to design codes. Integration of CAD tools and GSA enables automatic creation of GSA models from CAD geometry and structural attributes attached to geometry as well as the potential for gaining fast structural feedback within a CAD environment.



6. Generating an intriguing network of acrylic tubes for a proposed installation by combining a spatial tiling with evolutionary structural optimization (ESO). Colours indicate the iterations of the structural erosion process.



7. Exploring the tradeoff between daylight factor and sun hours for a simple two-room scenario.

The Rhino CDO toolkit was motivated by an installation comprising a unique network of acrylic tubes. The approach taken combines spatial tilings, which are 3-D space-filling algorithms, with performance-driven structural erosion methods, in this case evolutionary structural optimization[3]. Since spatial tilings are not often efficient structures, the aim is to find optimal networks of members within a given spatial tiling driven by the force or utilization in each member, while checking constraints such as strength, buckling, and displacement. The scale of the erosion takes starting designs consisting of thousands of members and erodes them down into a network of the most highly utilized of 500-800 members and support locations (Fig 6).

Panelizing curvy surfaces

Another promising area for CDO addresses the task of panelizing and rationalizing curvy surfaces. Typically panelization of so-called 'freeform' surfaces with flat or limited warp panels, triangular or rectangular, requires all the panels to be of unique dimensions. While it is possible to manufacture using state-of-the-art CAD/CAM capabilities, the fabrication and construction costs can be significant.

CDO can be used to inform and negotiate building form rationalization to navigate the spectrum between extreme free-form surfaces and over-rationalization. A proof-of-concept investigation was carried out using a sample curvy surface for two scenarios:

1) panel joints allowed anywhere on the surface assuming that the outer surface is disconnected from the floor plates, and

2) panel joints required to remain at floor plate heights.

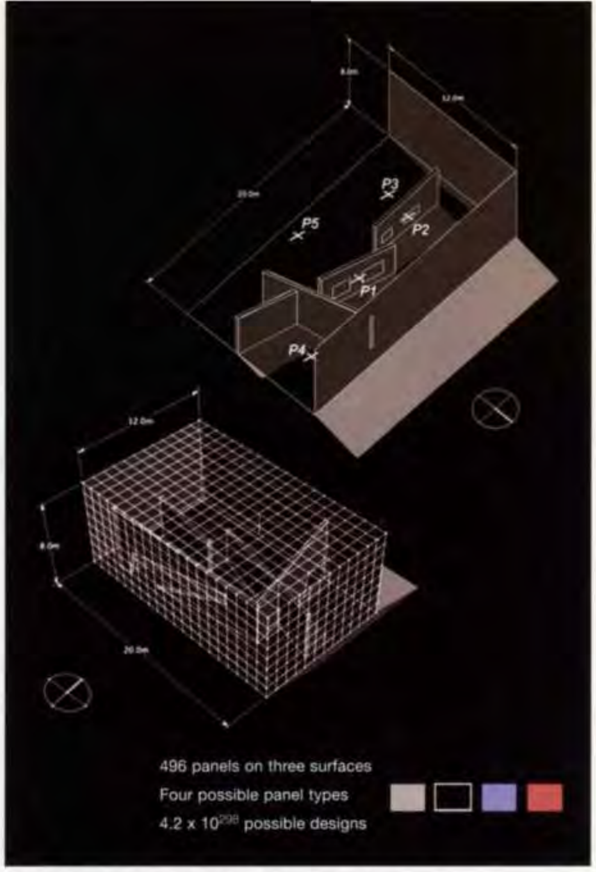
The design objectives include matching the original surface within a chosen tolerance, using only flat panels and achieving some repetition in panel geometry. A purpose-built CDO tool was developed as a Rhino plug-in to operate on any defined surface in Rhino, given initial panelization defined as a mesh. The tool uses the stochastic optimization method of simulated annealing[4] to carry out tens of thousands of iterations in about 15 minutes, trying to improve geometric uniformity among the panels while maintaining defined geometric constraints. CDO was successful in reducing the number of unique panels for the two scenarios described by 10% and 18% respectively. Relaxing the tolerance on surface fit can then be used to guide surface rationalization. As architects' desire for curvy building forms continues to grow, CDO can enable more cost-effective panelization solutions that preserve design intent.

Building envelope optimization

CDO also links with Arup's increasing interest and expertise in designing with building physics. The goal here is to develop new CDO tools that facilitate the design of optimized building envelopes in response to lighting and energy criteria (Fig 7).

As a starting example, CDO has been used to generate optimized design alternatives for a scenario involving a media centre in Paris that includes a gallery space, meeting room, reception area, and director's office, all with different lighting requirements. The façade comprises 496 panels (design variables) chosen from four types (opaque, clear, diffused, shaded) that combine to produce 4.2×10^{298} possible designs (Fig 9). The internal walls do not reach the ceiling, allowing light to pass between the spaces. Design performance is assessed by evaluating five response points in the space for daylight factor and sun hours, two points for view, and the entire space for cost and thermal performance, thus defining 15 independent performance objectives in total. Optimization is carried out using a multi-objective 'ant colony' optimization method[5]. The result of one optimization process consists of a set or point cloud of 'Pareto optimal' designs (ie where no improvement in one performance is possible without damage to another performance[6]) that can be browsed using a graphical interface developed for this project. There are no predefined weightings among performance objectives and all designs in the optimal set are 'optimal' with respect to a certain viewpoint.

By setting preferences among performances, designers can tune the design to best meet and balance their combined goals (Figs 7 & 8). Many extensions to this work now exist, including expanding energy and cost models as well as aesthetic models. Greater benefits will be achieved by allowing the building envelope to change form in addition to changing the envelope panel layout.



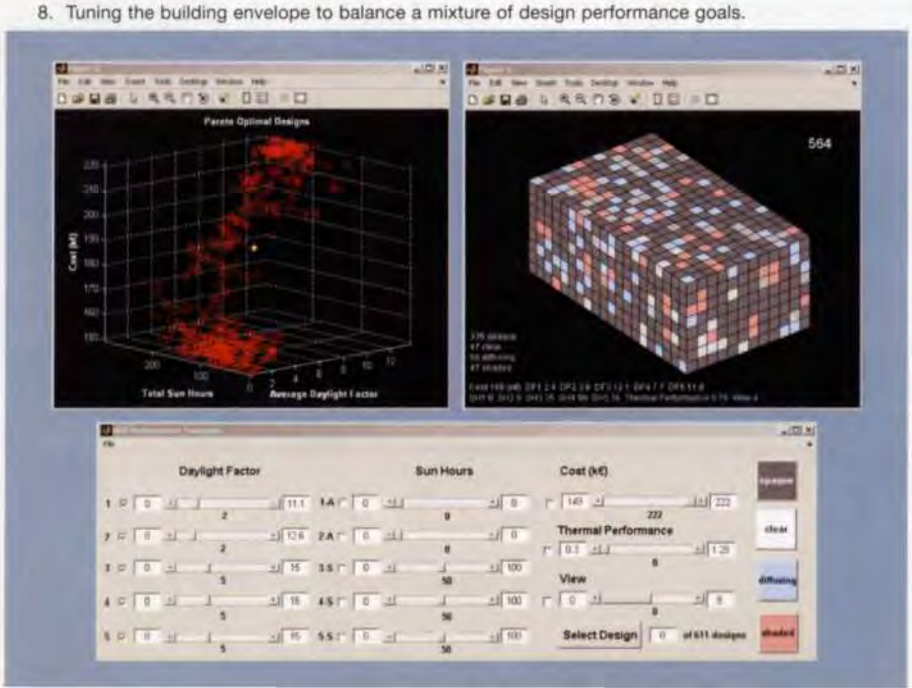
9. Scenario for optimizing a panelized façade for a multi-purpose room within a media centre.

CDO futures

Extending expertise in CDO involves successfully combining modelling, methods, tools, and people. Recent progress in applying CDO in practice has extended the state-of-the-art of use in Arup as well as contributions to academia. Benefits starting to be realized include extending what designers can currently do, enhancing design understanding, and improving design quality, time, and cost. Design time savings are often realized through the design automation component of CDO.

Successful applications require designers who are willing to think outside the box in terms of both the design variants they are willing to consider and embracing new design processes that take advantage of emerging computational methods and tools. The next opportunities for CDO at Arup, which will increase the potential benefits, include incorporating multidisciplinary viewpoints within CDO models and widening the scope to optimizing building form through collaboration with like-minded architects, and perhaps clients, to apply CDO at earlier design stages.

8. Tuning the building envelope to balance a mixture of design performance goals.



Dr Chris Luebkeman is Director of Arup's Foresight, Innovation and Incubation (FII) Group.

Dr Kristina Shea is a senior engineer in FII.

Projects

Bishopsgate Tower: with Arup's BEL4 group (Damian Eley, Chris Neighbour) with Cambridge University Engineering Design Centre (Rob Baldock)

Building envelope optimization: with Arup's BEL5 group (Andy Sedgwick, Jeff Shaw, Arfon Davies, Giulio Antonutto-Foi) with Gianni Botsford Architects (Gianni Botsford)

Rhino CDO toolkit: with Arup's Advanced Geometry Unit (Cecil Balmond, Daniel Bosia, Tristan Simmonds)

Illustrations: 1 Stefan Klein/iStockphoto; 2, 3 Images by Cityscape Digital Ltd (architects: KPF); 4-9 Arup/Cambridge University Engineering Design Centre

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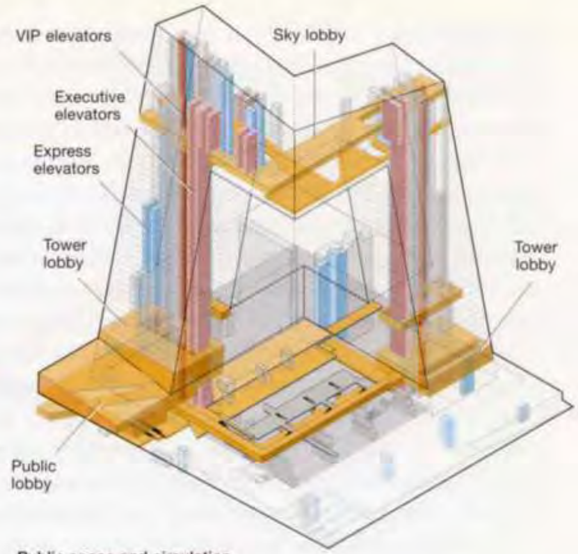
CCTV Headquarters, Beijing, China:

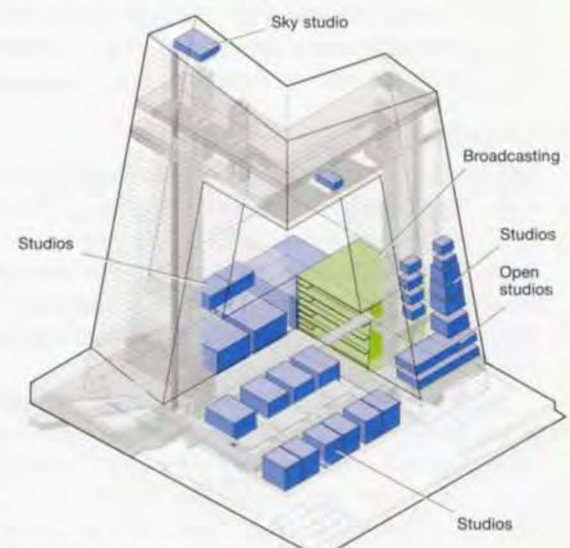
Services engineering design

**Dane Green Bob Lau Iain Lyall David Pritchard
John Pullen Clodagh Ryan**

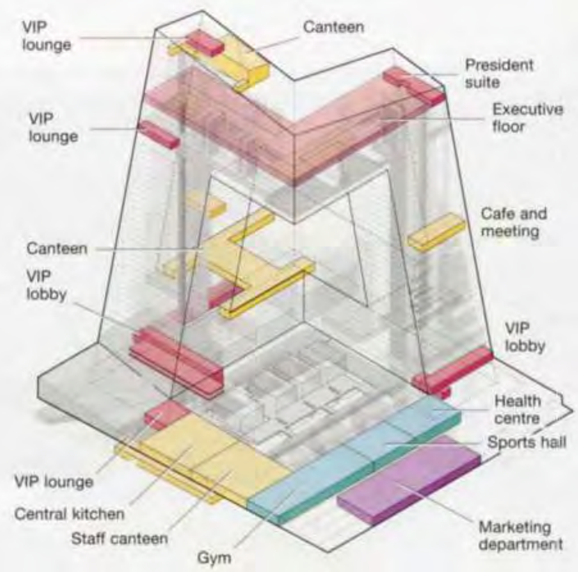
The CCTV Headquarters' three-dimensional layout is designed to break down the 'ghettoes' that tend to form in the process of making TV programmes. The building's 'loop' form encourages staff to mix, creating a better end-product more economically and efficiently.



Public space and circulation



Studio and broadcast



Staff and VIP facilities

1. The functions and layout within the CCTV building.

Introduction and architectural concept

The first article in this series[1] began with the evolution to date of this unique project. China Central Television (CCTV) has been expanding greatly, in competition with major international TV and news service providers, and so organized an international design competition early in 2002 for a new headquarters. This was won by the team of Rem Koolhaas's OMA (Office of Metropolitan Architecture) and Arup, which subsequently allied with the East China Design Institute (ECADI) to act as the essential local design institute (LDI) for both architecture and engineering. The previous article outlined the design collaboration process.

The unusual brief, in television terms, was that all the functions for production, management, and administration would be contained on the chosen site in the new Beijing Central Business District (CBD), but not necessarily in one building. In his architectural response, however, Rem Koolhaas 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 making TV programmes, and create a building whose layout in three dimensions would force all those involved to mix and produce a better end-product more economically and efficiently.

The winning design for the 450 000m^2, 234m tall, CCTV building thus combines administration and offices, news and broadcasting, programme production and services – the entire process of Chinese TV – in a single loop of interconnected activities around the four elements of the building: the nine-storey 'Base', the two leaning Towers that slope at 6° in each direction, and the nine to 13-storey 'Overhang', suspended 36 storeys in the air (Fig 1).

The public facilities are in a second building, the Television Cultural Centre (TVCC), and both are serviced from a support building that houses major plant as well as security. The whole development will provide 550 000m^2 gross floor area and covers 187 000m^2, including a landscaped media park with external features. Work began on site in September 2004.

CCTV briefing

CCTV's competition brief was very detailed, setting out the requirements for the organization's main departments and their relationships with each other, but on the assumption that each major grouping would be in adjoining but separate buildings. To their great credit, when CCTV chose the OMA/Arup competition entry, they completely rewrote their original brief and populated the competition building to make best use of the winning concept.

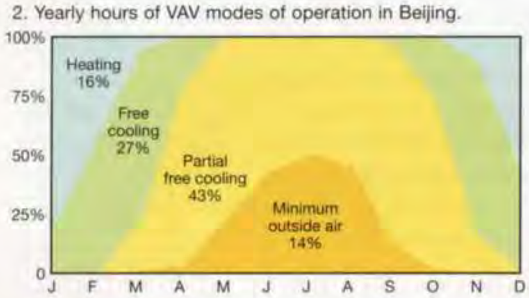
This revised brief stayed remarkably intact throughout the design, with few changes as it evolved. To have such detail at competition stage and subsequently at the commencement of design was very beneficial for the swift development of the MEP services, as CCTV had given thought to every individual space and defined its services needs. In addition, CCTV made it clear at the outset that the latest modern services hardware for the project could be sourced from within China, and this was found to be true with few exceptions.

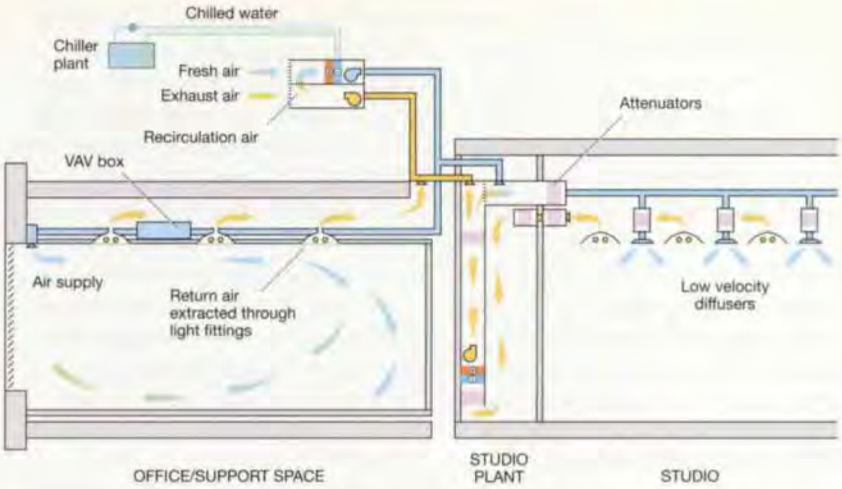
Services provisions

Continuity of operation is essential for TV; consequently two 63MVA secure independent electrical supplies at 110kV serve the site. These operate simultaneously, sharing the load, but each can support the full site load should the other fail. A third separate 10kV special use supply is also provided. 13MVA standby generator capacity backs up the secure high voltage supplies, providing essential power for broadcasting and life safety systems in the event of catastrophic failure of all incoming supplies. Key broadcasting systems also have UPS (uninterruptible power supply). Cooling of broadcasting areas, their support rooms, and the substations that serve them is also critical for continuity. A hierarchy of cooling load shedding and circuitry gives priority to these areas.

The Beijing CBD is well provided with district heating systems as well as city steam, so there is no boiler installation on site. The district heating provides all the heating needs, and the steam system gives humidification and heating backup during district heating maintenance shutdowns.

2. Yearly hours of VAV modes of operation in Beijing.





3. Schematic of studio VAV air supply.

HVAC system selection

The CCTV building

From operating experience in their existing buildings, CCTV preferred variable air volume (VAV) systems. Arup's review of Beijing climate data indicated that there were long periods when substantial free cooling through the VAV system would be economically beneficial (Fig 2). Significant areas of the building operate continuously and others for extended evening times, enhancing the benefits of free cooling via the VAV system. The internal cooling loads in most areas were beyond the capacity of chilled ceilings and passive chilled beams, but active chilled beams and four-pipe fan coil units were possible options.

CCTV had poor experience with ceiling-mounted fan coil units: leaks, condensation, and regular maintenance of filters and fans at high level were among their concerns. Also, chilled water and condensate drains were unacceptable above ceilings or anywhere at high level, except in mechanical plantrooms, to reduce the risk of drips or leaks damaging broadcast equipment.

VAV systems with terminal reheat were agreed as the preferred option. As the structure is all steel, the ceiling voids are deep enough to accommodate large supply ring ducts, the void being a plenum return path. Long and repeated discussions were held over the amount of 'porosity' acceptable in the beams to allow services to pass through structure. It was a complex situation, as the sloping façade and vertical core meant that both the structural and the HVAC layouts changed every few floors, resulting in many different solutions dependent on location. Having the HVAC supply and exhaust risers inside the steel core structure also generated some interesting integrated solutions.

The TV studios vary in size from 2000m² with a large audience to less than 100m² with low occupancy. They range from the lowest basement levels up to the 50th floor, and the HVAC solutions vary with size and location. The larger studios were zoned and had dedicated air-handling plants with direct connection to outside air. Higher up the building this was not feasible, so small plantrooms were located on the floor adjacent to the studio, with ventilation air from the VAV system (Fig 3).

Having agreed the system concept, the location and size of air plant was reviewed. If floor-by-floor plantrooms were used they would have to be adjacent to the façade to use 100% outside air for free cooling. Initial assessments showed that more than 150 plants would be needed, mostly in prime usable perimeter space and requiring regular maintenance access via operational areas.

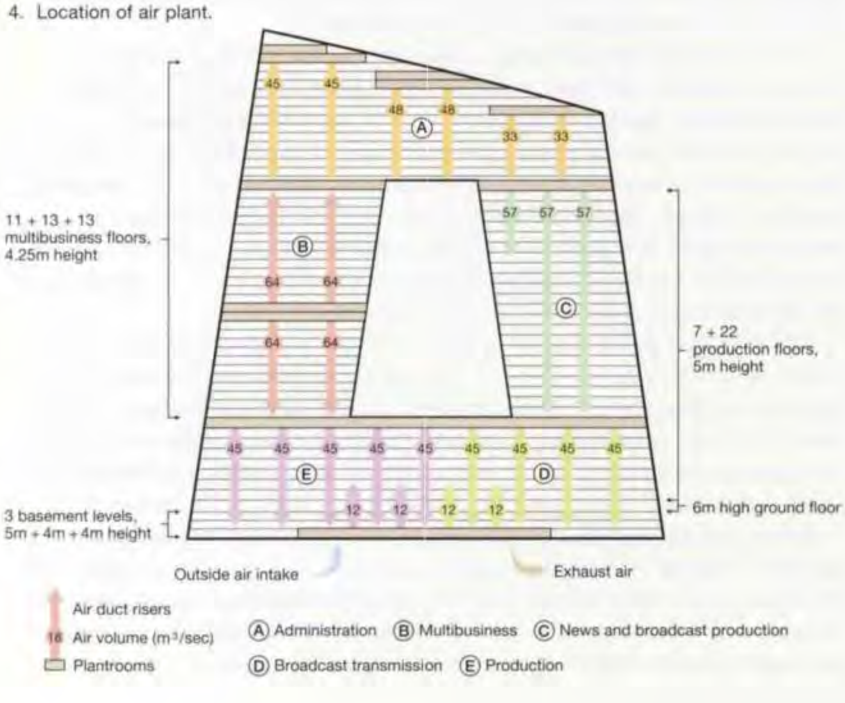
The team settled on nine main air plantrooms, with the unusual solution of several large parallel linked air-handling plants serving large vertical supply and exhaust risers in the central core (Fig 4). Each plantroom serves 10-20 floors, with supply riser velocities starting at 15m/s and exhausting at 12m/s, and lower velocities in floor ring mains and branches. A typical plant arrangement has six air-handling units (AHUs) at 25m^3/sec each. As the air volume required decreases, the control system, continuously calculating the total volume, isolates an AHU and adjusts the fan speed of those remaining. Further reductions in volume allow more units to be isolated, thus keeping the minimum number operating at close to maximum efficiency. On increasing load the reverse cycle occurs and AHUs are sequentially reconnected to the system. Each floor zone can be isolated from the supply and exhaust risers by motorized dampers, allowing unoccupied areas to shut down whilst leaving other zones on the same system in normal operation and control.

Welfare and health concerns

CCTV is active in enhancing staff welfare and provides excellent working conditions. Beijing has the usual big city pollution problems, so CCTV required two-stage particulate filtration and also carbon filtration on all air plant to reduce pollution levels entering the building. CCTV also required a minimum 40% level of internal humidity - not to protect broadcasting equipment from static electricity, for which lower levels would suffice, but for occupant comfort. Their experience showed staff to have fewer respiratory problems if humidity levels are higher.

During design, the SARS outbreak caused serious disruption in China and to the performance of CCTV, who raised concerns that air-conditioning systems could distribute infection throughout the building. Arup's review of the World Health Organization and Hong Kong government reports on how the SARS infection spread confirmed that it was via an aerosol particle. Any recirculated air in the building would pass through the AHU filters, trapping aerosols, so air-conditioning would be unlikely to contribute to the spread of this infection; most would occur by close contact within the workplace. The team agreed with CCTV that plants serving broadcast functions would have the heating and humidification capacity to operate in an emergency without recirculation. In a future infection problem, the 100% outside air emergency override would allow these areas to continue operation with reduced dissemination risk, even if other parts of the building had to be shut down.

4. Location of air plant.



TVCC building

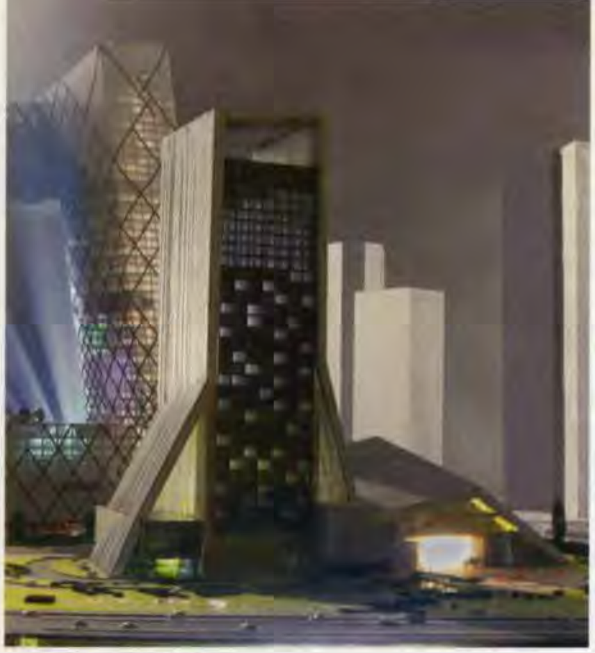
The TVCC tower contains multiple functions, including a 280-room hotel with restaurants, ballroom and spa, a 1500-seat theatre, digital cinemas, and large audio recording studios (Fig 5). The hotel rooms have a conventional four-pipe fan coil system, with other hotel functions served by all-air systems, including displacement. The theatre is a complex space with stage-level moveable seating, a multi-level adjustable stage and orchestra pit, and a large tiered balcony with 1000 seats, so the air-handling system needs to respond to different theatre configurations and audience patterns.

The tiered seating areas have a zoned floor plenum with underseat supply, whilst the lobby, flexible seating, and orchestra pits are served by variable volume displacement systems. As the audio recording studios have exceptionally low noise criteria, heavily attenuated dedicated plants and low velocity distribution ducts serve them via ultra low noise displacement vents at low level.

Mechanical services from the support building

Above ground, the support building will accommodate 200 site security staff plus garage and maintenance space for the TV outside broadcast vehicles. Roof-mounted cooling towers for the chillers and generator coolers require careful acoustic selection to meet the noise requirements at the site boundary. Below ground, the support building is the heart of the CCTV operation, containing the incoming power supplies and main 110/10kV transformers, standby generators, chiller plant including ice storage, and incoming district heating supplies and associated heat exchangers and pumping station.

CCTV was clear about the number and size of chillers it wanted to serve the site. The peak cooling load of 64MW was greater than originally envisaged, so a compromise was needed. To retain competitive bidding to sufficient suppliers, the chiller size was limited to 10MW; so six were needed (one standby), with two smaller 2MW chillers also included for efficient low-load operation. In addition, a further 10MW low temperature glycol chiller will serve a dedicated ice store capable of providing 25 000 ton hours (2110MWH) of storage. Arup's predictive analysis of monthly average cooling loads indicated that this size of ice store could be used efficiently throughout the year.



5. The TVCC building.

Multiple cooling towers (nominally two per large chiller) serve the water-cooled chiller plant, a decision that enables the minimum number of towers to run to meet the load, operating near peak efficiency. A hydraulically separated cooling tower provides free cooling for the chilled water system when outside temperatures are low enough.

By balancing the use of this tower with the ice storage and the smaller chillers, relatively low winter cooling loads are met with very low energy input. These strategies, coupled with variable flow chilled and condenser water pumping systems and the use of staged high efficiency VAV plants, allows CCTV to manage its energy input effectively with very significant reductions in energy input over more conventional approaches.

The chilled water is distributed to the basement of the two main buildings through service tunnels. Secondary chilled water pumps distribute throughout the lower levels and to intermediate level plantrooms, where plate heat exchangers and tertiary pumped circuits provide hydraulic separation to limit system pressures. There are 'critical areas' with a cooling load of 2MW and 'operationally essential areas' with an additional cooling load of about 8MW. Critical areas are served by the main chilled water system and by a second hydraulically separated and parallel system.

This system and its support systems are generator-supported and will use a small chiller or the ice store as the critical cooling source. Provided that a large chiller is available and one of the three incoming electrical supplies is operational, the essential area cooling loads can also be met. This hierarchy of load management allows CCTV to operate its critical broadcasting cooling with limited generator backup and, provided some incoming power is available, normal operation of most of the facility.

Controls and commissioning

Introduction

Each building has its own building automation system (BAS), operated and managed independently, but interconnected via the sitewide IT infrastructure, as both CCTV and TVCC must communicate with the support building. User access is via operator workstations in each building, and a building management system (BMS) provides common user access to the BAS and other building services subsystems throughout the development.

Deliverables

For the BAS Arup provided basic system requirements, instrumentation criteria and sequences for the major and more complicated systems, device schedules for all typical plant and panels, and single line control diagrams that reflected the systems described in the sequences. Control panels were located on floor plans.

The concept of detailing 'typical' plant allowed the team to limit the amount of information it had to produce, but as the end of the extended preliminary design phase approached, the number of variants of each plant type increased, and it was a challenge to detail the information to avoid confusion and to pass on an accurate and useful document to ECADI. For the BMS Arup provided the requirements for the different types of network, and described the type of information that would usefully be exchanged between the BMS and the integrated subsystems.

The heating and cooling systems were based on a variable volume two-port valve concept - a type of system understood to be not common or well understood in China. To assist ECADI in the next stage, Arup therefore provided guidance notes on the selection of differential pressure control valves and two-port control valves as part of its design documents.

Building automation system

Some of the control functionality for the mechanical systems has already been described. On the VAV plant, terminal boxes on the floors were originally designed to have non-intelligent controllers, as there was a significant cost penalty in using intelligent controllers. More than 10 000 terminals would add significantly to the cost, size, and complexity of the control system.

However, following a controls workshop with the client engineering team, it was decided to adopt intelligent controllers for the VAV boxes. These would provide considerable future flexibility in reconfiguring boxes as the building use changed, and be able to monitor and respond to staff requests remotely, outweighing the additional cost. The BAS networks will need to be structured to ensure that system operating speeds are not compromised by this additional network traffic.

The chilled water system in the support building was a particular challenge. It is a typical, but very large, variable volume secondary and staged constant volume primary configuration, with primary pumps sequenced, all based on accurate measurement of the flow rate in the primary bypass. The complexity is in the primary circuit, which comprises medium and large water chillers with different sized primary pumps, used in combination with an ice store, glycol chiller, and free cooling plate heat exchanger.

The ice store utilizes the glycol chiller, and has sets of plate heat exchangers and pumps that operate depending on whether the ice is being made by the chiller, or whether the ice is being melted and providing cooling to the chilled water. Sequences were provided for the ice store to make best advantage of the electrical tariff structure. In simple terms, when electricity is cheap (overnight), the system makes ice and free cooling is utilized if external conditions are favourable. When electricity is expensive (mornings and evenings), ice is melted to assist primary cooling.

Building management system

The CCTV brief specified that there be a BMS to form a common user interface to the building services subsystems and a means of passing information between the different subsystems where there is an operational benefit. The subsystems would operate independently and not rely on the BMS for control.

The types of system deployed are similar to those at an international airport, and the concept here was based on systems integration work at London Heathrow Terminal 5. Interface standardization is a key objective for successful integration, and using international standards reduces system integration costs, eliminates the need for specific vendors, and allows more flexibility in selecting products.

The concept is for each subsystem to have a standard server, interrogated by the BMS. Graphical user interfaces (GUIs) connected to the BMS provide user access. Arup recommended that object linking and embedding for process control (OPC) - an industry standard method for systems to share information and work together - be a preferred solution for the servers. Alternatives such as BACnet (a data communication protocol for building automation and control networks) can also be considered; if a subsystem supplier cannot offer an OPC or BACnet interface, an alternative driver will have to be used or developed, but the intent is to standardize wherever possible.

The BMS software allows users to create and display graphics with data from multiple systems on a single screen, override plant operation, manage alarms, trend historical data, run decision support systems, and manage information between systems. Metered data is transferred to office billing systems and alarms transferred to maintenance management systems. The access levels given to each BMS user define which tasks can be undertaken.

The systems interfaced using the server approach include the lighting control, building automation, fire alarm, electrical network management, and maintenance management. Others, such as security and CCTV, smart cards, emergency lighting, and car park management, are seen as standalone systems that will be monitored for fault via volt-free contacts by the BAS. Critical equipment rooms, which are provided with dedicated downflow units, will be monitored - via a serial interface and an open protocol such as *Modbus*® - by the BAS.

Operator access to the BMS is from workstations in each building and via personal digital assistants (PDAs). These will communicate to the sitewide area network via a wireless web server, and allow maintenance staff to view plant operating conditions and reset alarms when they are not near a workstation.

Commissioning and testing

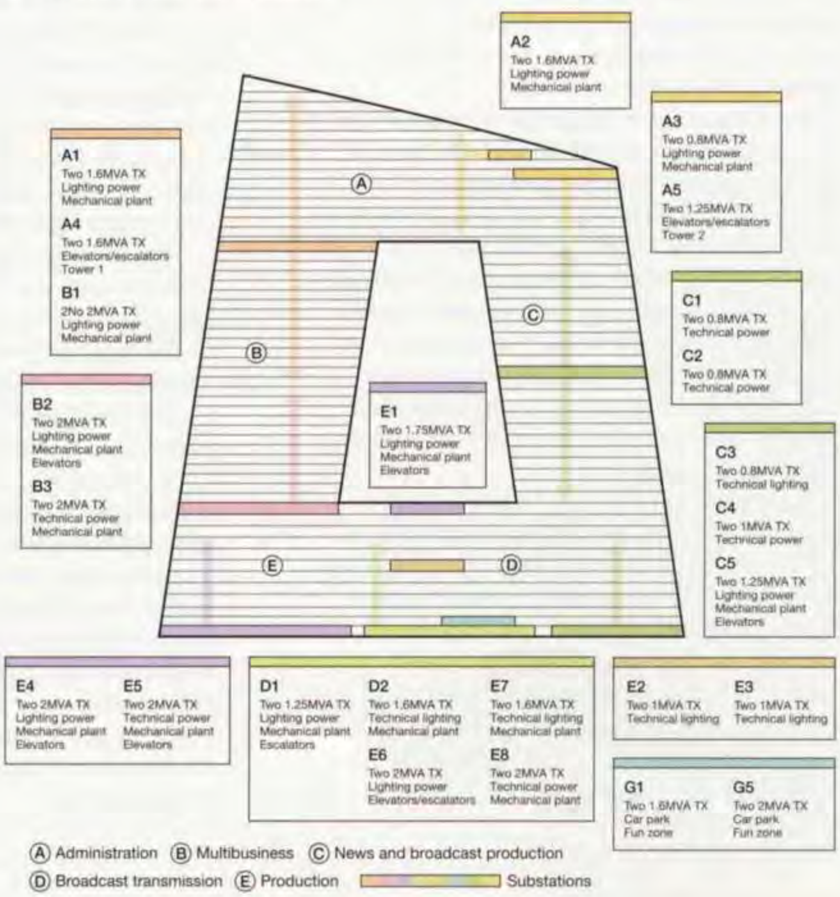
Thorough commissioning and testing of building services are critical to the correct functioning of the systems. Arup established very early on that it was essential that the CCTV systems, though large and complex, be simply and swiftly commissioned once installed. Several features were incorporated into the design to achieve this.

The air-conditioning systems comprise VAV and water systems, and each was subjected to a theoretical commissioning review process, including considerations of maximum and minimum values and the essential components required to allow successful balancing of the systems at all levels of operation. The VAV systems were designed to be highly self-balancing, with low operating noise levels as a priority. Airflow measuring and regulating devices were included on the riser connections, with the VAV terminal units providing the local regulation.

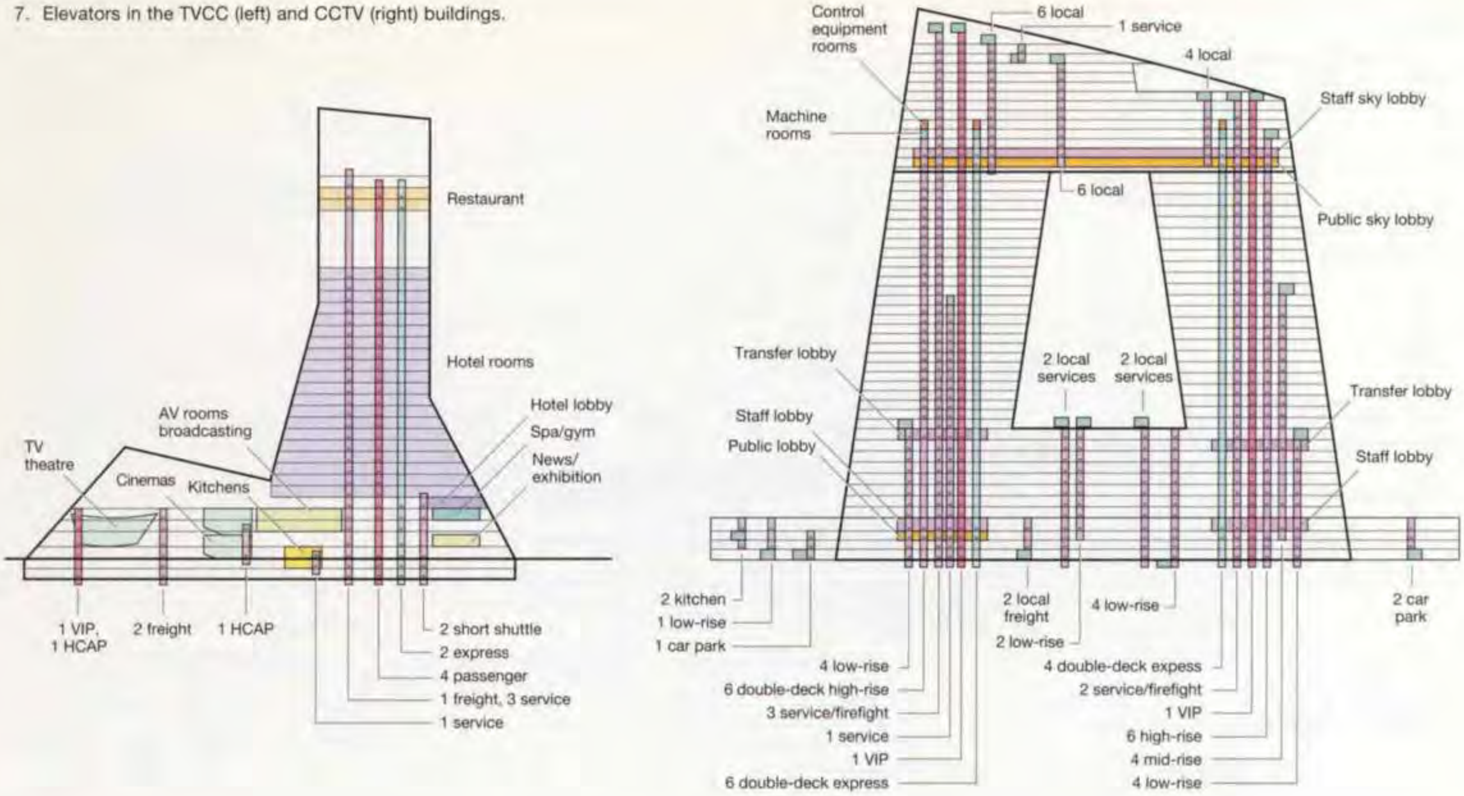
The chilled and hot water heating systems were also designed for minimum on-site balancing, achieved by strategically locating differential pressure control valves (DPCV), generally at each floor level, with orifice plates to allow calibration of them. Once calibrated, and at maximum demand, the DPCVs self-balance the system at all part load conditions. Secondary balancing is still required in some areas through traditional fixed orifice double regulating valves.

To verify pump flow rates, orifice plates are located in each distribution system. The pump speed control is accomplished by measuring system pressures at the approximate index circuits. Pressure test points are near all measuring instruments to ensure correct calibration.

6. Location of 10kV/400V substations.



7. Elevators in the TVCC (left) and CCTV (right) buildings.



The condenser water system incorporates several regulating stations to ensure that each water chiller and cooling tower receives its design volume of water. Particular attention was paid to their operating scenarios, with measuring and regulating stations being included to ensure each chiller receives a matched volume of condenser and chilled water.

Electrical power supplies, service strategy, and 10kV infrastructure

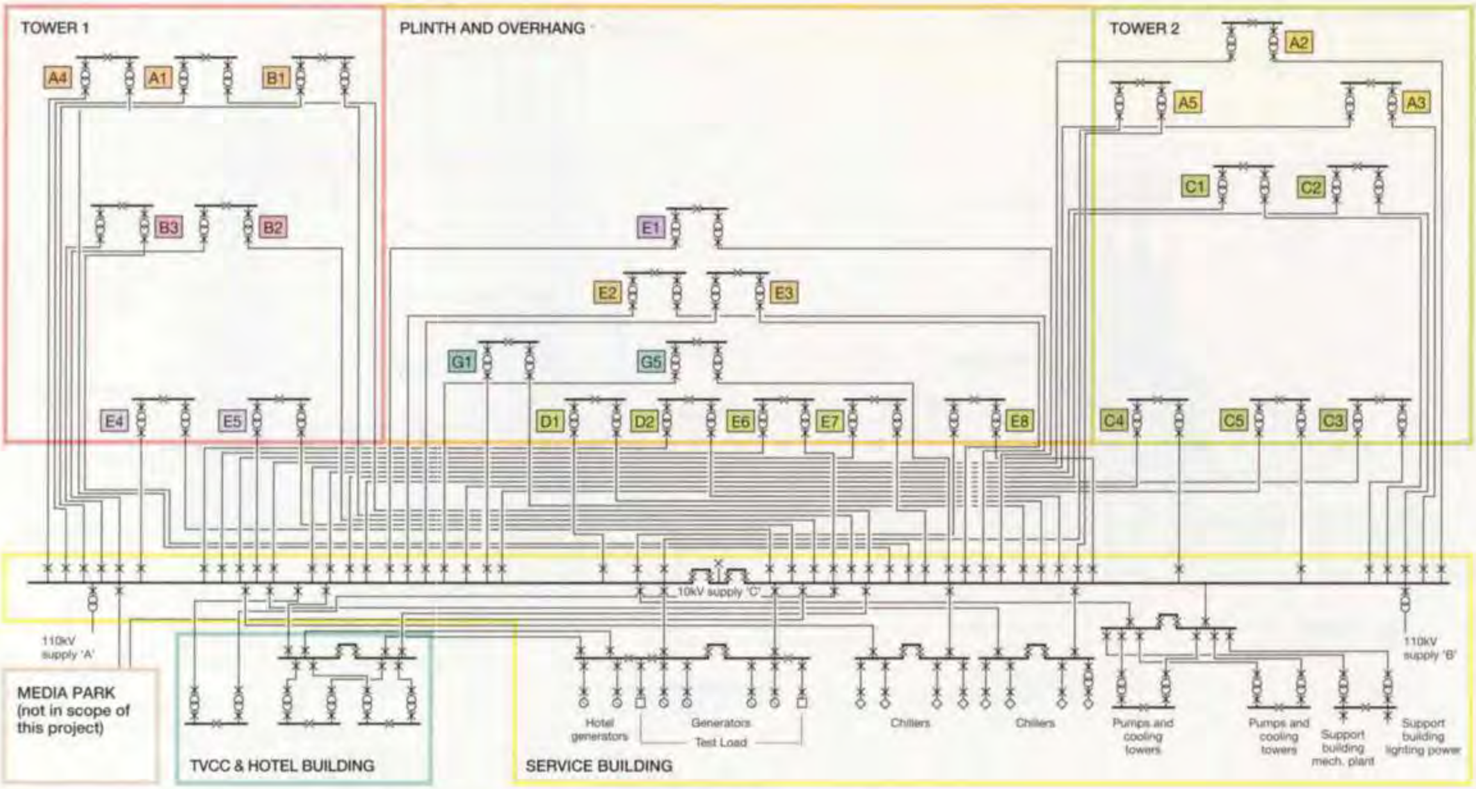
CCTV's comprehensive project assignment and brief documents demonstrated its commitment to and ownership of the project to an extent very rare in early design stages. The scheduled room details for the three buildings, indicating the function, floor level, and area of each space, enabled Arup to convert the data into specific electrical loads and supply needs at an early stage. The brief also included statutory planning dimensions for electrical plantrooms, and categorized the technical loads into priorities, detailing the precise UPS (uninterruptible power supply) configuration for each category.

CCTV had also made initial estimates of the electrical capacity in the brief, and this was confirmed during design development. At the outset, CCTV had secured preliminary agreements for two 110kV city power network feeders routed independently to the site from different 220/110kV substations and a third 10kV network feeder from a local substation. As already noted, the development will be supplied from a duplicated 10kV site distribution system, supported from two separate 110kV/10kV 63MVA oil-cooled transformers, each able to support 100% of the total project load, but sharing it under normal operation as a safeguard. The third 10kV city power network feeder will support priority loads if a failure occurs on both 110kV feeders, when the electrical network management system (ENMS) will disconnect non-essential loads.

All these systems provide considerable reliability for the project's electricity services, but for CCTV this was insufficient for some of their technical power loads and associated mechanical plant. These required further backup from standby generators, which will also support all life safety loads for the project.

The support building houses the Beijing Power Bureau incoming 110kV supply switchgear and their two large 110/10kV transformers, CCTV's 10kV switchgear, 10kV standby generators, 10kV chillers, and other mechanical plant. The 10kV radial feeders of the duplicated site distribution system are run from the consumer's switchboard and routed via separate cable routes in a service tunnel to the building basements. High-voltage risers feed distribution substations with duplicate cast resin transformers, each sharing around 50% of the load. The CCTV building alone has 25 of these, each serving specific technical or departmental loads (Fig 6). Another five serve TVCC and its hotel, and there are five more in the support building.

The elevator consultant specified over 90 elevators and 21 escalators for the whole project (Fig 7), which contribute 8.36MVA to the total connected load. Two substations, one in the top of each Tower, are dedicated to supplying some of this. To limit the size and number of escape stairs in the Towers, the lifts are used in parallel with the stairs. This means that the power supply to the lifts is generator-backed, and cooling to the lift motor rooms is on the 'essential' circuit.



8. Simplified diagram of the electrical supply for the three buildings (see Fig 6 for key to substations).

The overall estimate of maximum electrical demand for the site is in the order of 60MVA, with maximum estimates for the individual buildings being CCTV: 41.46MVA; TVCC/hotel: 8.68MVA; support building: 16.58MVA; plus 2.00MVA allowed for future development of a media park (Fig 8).

The ENMS will control and manage the normal and emergency functions of the duplicate 10kV and 380V infrastructure, with links to the BAS and the generator load management system (GLMS). The ENMS will identify and plan for periods of peak demand, and enable maintenance schedules to be based on actual operating history, identifying and providing diagnostic information on faults to help CCTV take preventative action and avoid forced electrical interruptions.

The switchgear cubicle controller on each 10kV feeder circuit will manage the switching functions of circuit breakers and bus section switches in the various predetermined load scenarios associated with loss of power, generator operation, and load shedding. The system will also enable energy consumption to be monitored at various points, such as incoming supplies, main feeders, and major loads. Each cubicle controller will also be capable of horizontal communications, allowing for pier-to-pier communication for load shedding, recovery of the load, and internal harmonic analysis.

The ENMS is based on a powerful dual redundant SCADA (supervisory control and data acquisition) concept, utilizing a dedicated communication infrastructure based on industrial Ethernet technology to form the backbone to which all ENMS communication equipment will connect.

The network infrastructure will be a dedicated fault-tolerant Ethernet fibre optic sitewide ring; avoiding any single point of failure and loss of availability, it will have industrial Ethernet switch hubs connected at strategic locations. Links to the BAS via a remote terminal unit will report the status of the three power supplies, the generators, and the busbar configuration of the consumer's 10kV switchgear. It will also ensure the planned reconnection sequence of all mechanical plant to suit the third 10kV supply and generator load scenarios.

The brief considered that the standby generators should be arranged for 380V operation, but lack of suitable plant spaces at the appropriate substation locations, and the circuit lengths necessary from centralized plant, resulted in a high voltage solution. Six 10kV 2200kVA generator sets running in parallel under the control of the GLMS will provide optimum use of the available capacity and give ultimate priority to life safety loads, supplying power via the normal duplicated 10kV and 380V infrastructure. The CCTV building's life safety load was considered when determining the likely total capacity, as this is the largest total load of the three buildings and fire in all three simultaneously is extremely unlikely.

The hotel has 100% backup, as required by its operator, but normally across the remainder of the site only the technical and associated loads will be supplied. In a developing emergency, where all incoming city power to the site has been lost and a fire or evacuation scenario occurs causing life safety plant to start, the GLMS/ENMS will start the remaining generators and manage the load in response to the increasing power demand.

On this basis the estimated generator capacity required for the site is 9200kVA for technical, etc, loads/CCTV life safety loads, and 3600kVA for the hotel load (fully-diversified), totalling 12 800kVA.

9.
Site progress, August 2005: TVCC is in the foreground, with piling completed and excavation to the base of the rafts. Piling is complete at CCTV (behind) with excavation under way to the base of the rafts (up to 30m below ground level).

Piped services

Both CCTV and local codes required greywater in addition to cold water and drinking water, giving three cold water systems to integrate into an already complex building.

The main water storage in the basement is transferred and distributed to draw-off points throughout the CCTV building. As for other services, its size and height made special demands, in this case dictating four pressure zones; this was complicated further by the presence of the two Towers. Intermediate break tanks, with variable volume pump sets and sensitive pressure-regulated control, will avoid excessive operating pressure and comply with local plumbing code requirements.

The drinking water will be derived from the incoming domestic main, and then treated with localized particle and UV filtration at each zone before passing into the storage tank. Distribution will be as a pumped circulation main to constantly turn over the supply and avoid stagnation.

To maintain the water systems' integrity, the wastewater will also be separated to collect grey water from wash hand basins, showers, air-conditioning condensate drainage, and waste cooling water. The local authority is proposing to treat and return grey water from a centralized city plant.

Fire suppression

The entire development includes many categories of fire risk, each requiring a different type of fire suppression system. CCTV preference, local fire codes, results from fire engineering analysis, and architectural intent all influenced the choice of system. These include:

- street hydrants around the perimeter of all three buildings to protect external areas and façades
- internal fire hydrants and hosereels on the floors, positioned so that the jet of two fire hydrants or hosereels can reach any point
- water cannon extinguishing systems in CCTV's main entrance lobby and the TVCC atrium, as their height exceeds the effective operating height of the fast response type sprinkler system
- foam cannon extinguishing system to protect the helipad on the CCTV roof
- deluge systems for the CCTV studios and TVCC theatre stage, with open type deluge nozzles installed under the latter's grid
- water sprays for the diesel generator rooms
- sprinklers in offices, hotel rooms, all general areas, corridors, and lobbies (fire hazard classification Medium Hazard II)
- Inergen (mixture of nitrogen, argon and carbon dioxide) gas suppression systems for 'sensitive' rooms where water spray risk was a concern and cleanup of residue can be a problem. These are fed from a centralized supply and are divided into nine zones in CCTV and seven zones in TVCC.

Over 200 'sensitive' rooms containing recording and broadcasting equipment and recorded programme material require special fire suppression, which had to take into account local fire codes and CCTV's design brief. These requirements called for either a gaseous flooding suppression system or a water-based pre-action type. CCTV considered the water-based system unsuitable due to the potential for water damage.

Large gaseous suppression systems require the room construction to be reasonably airtight, and robust enough to survive the rapid discharge of extinguishing gas. Also, pressure relief ducts from each room to the outside are required. These provisions attracted additional cost and construction time, as well as valuable space for relief ducts, so the team investigated other possible solutions.

Arup recommended a water mist extinguishing system, in which mist under high pressure cools the room, reduces oxygen, and scrubs smoke. This system swiftly extinguishes and cools a fire with minimal water, thus reducing the risk of water damage and removing the risk of re-ignition inherent in gas suppression. It has been used in the marine industry for many years and is developing for sensitive building applications. However, CCTV decided to stay with the familiar technology of gas suppression. Of the gases available in China, Inergen was selected as the most environmentally acceptable, with a low safety risk for personnel.

Conclusion

The MEP schematic design was completed in May 2003 and the extended preliminary design (EPD) in February 2004. Handover of the very complex EPD took several months of detailed of correspondence and meetings with CCTV and ECADI. The post-handover Arup role is to answer technical queries and to comment on the ECADI construction stage documents.

Credits

Client: China Central Television **Architect:** OMA Stedebouw BV **MEP, geotechnical, structural, fire, and security consultant:** Arup - Olly Base, Chris Brown, Jun Chen, James Cheung, Kenneth Chong, Chi-Wing Chow, Judy Coleman, John Coppin, Chai Kok Eow, David George, Dane Green, Alistair Guthrie, Maggie Lam, Bob Lau, Iain Lyall, Adam Martin, David Pritchard, John Pullen, Clodagh Ryan, Eddie Scuffell, David Seager, Lewis Shiu, Kenneth Sin, Jodh Singh, Glen Swinney, G B Wang, William Wong, Sabrina Wong, Alba Xiu, Ming Yang (see previous article for Arup analysis, structural, and geotechnical credits) **Illustrations:** 1 Arup/OMA/Nigel Whale; 2-4, 6-8 Nigel Whale; 5 Arup/OMA; 9 Arup

Reference

(1) CARROLL, C *et al.* CCTV Headquarters, Beijing, China: Structural engineering design and approvals. *The Arup Journal*, *40*(1), pp3-9, 2/2005.

The next article in this series, discussing the security systems design of the CCTV development, will appear in *The Arup Journal*, 2/2006.

Gatwick's long haul: a unique air bridge

Neil Carstairs Daniel Powell Stephanos Samaras

Simplicity requires imagination in a world of advanced technologies. The need to satisfy airport, aircraft, and passenger requirements simply but distinctively determined how London Gatwick Airport's new air bridge was designed and built.

1. The completed air bridge in use, at night.

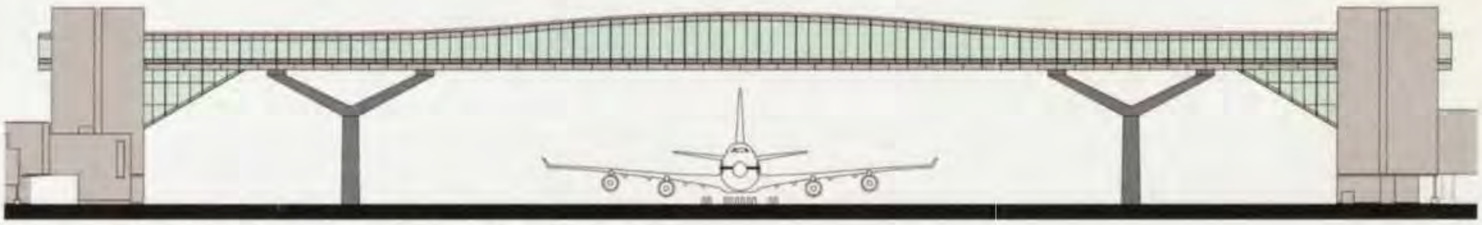
Introduction

Not many pedestrian footbridges provide access to island piers, and give serious plane-spotting opportunities to passengers while maintaining the operational status quo of an airport and its airlines. The new air bridge at London Gatwick Airport does all these things. It is a key component of the North Terminal's new 11-aircraft stand building, Pier 6, Gatwick's biggest development since the North Terminal itself opened back in 1988.

Compulsory purchase of adjoining land could have left long-term scars on both the environment and the local community. The British Airports Authority team at Gatwick realised that the expansion could be achieved through a remote satellite pier built in an area previously used as aircraft parking stands. How to link this island to the main North Terminal was long debated and, having evaluated the two main options, above or beneath the aircraft taxiway, the team chose a bridge.

This was an environmentally friendly solution compared to a tunnel, since it eliminated the disposal of 81 000 tonnes of fill. Equally important, the team wanted to give passengers the truly unique experience of crossing one of Gatwick's busiest taxiways above the aircraft, with panoramic views of the whole airport. The design brief was completed with two other major requirements: the link should have landmark status for the airport, and its construction have minimum impact on operations.

The bridge had to provide sufficient clearance to the 19.4m tall Boeing 747-400. (Any stands that may be redeveloped for use by the 4.7m taller A380 Airbus will not involve the use of this taxiway.) However the size and shape were also dictated by the need to maintain the lowest overall height and minimize obstruction to ground radar. Bridges involving masts or tall piers were thus eliminated. This bridge caters for much larger aircraft than the only previous one of its type, in Denver, Colorado, and its scale and construction method make it unique in engineering terms.



2. Elevation of the 198m-long air bridge with a Boeing 747-400.

Realization of design

A team comprising Arup as bridge engineer and lead designer and WilkinsonEyre Architects was charged with realizing the design brief. The bridge is fully enclosed with all services inside, so external maintenance is minimized. At each end the bridge terminates in vertical circulation cores containing lifts, stairs, and services routes, with escalators providing direct links to the arrivals and departures levels.

Architecture was part of the engineering and vice versa, the form and shape being dictated by the engineering needs of both assembly and completed state. The way it works is simple and effective: the deck was a simply supported beam during assembly, and the whole completed bridge is a continuous frame fixed on piled foundations.

The main structure, entirely of high strength steel, consists of two basic elements, a 198m-long spine beam and a pair of Y-shaped 22m-tall supporting columns (Fig 2). The spine beam comprises a triangular plated box of constant 2.5m depth below and, above, a variable-depth triangulated space truss in the form of inverted pyramids, visible to the passengers. With a total depth of 6m - 9.3m on a gentle curve, the resulting shape emulates a real bending moment diagram. The structural curve was then matched for the cladding and the interior.

The two Y-shaped columns are placed symmetrically about the centre of the taxiway and the bridge, the 128m spacing between them allowing for future taxiway widening. The column shape increases the effectiveness of the main beam by reducing its effective structural span. In cross-section the columns are A-shaped to provide the required strength to the deck in the direction of major loads such as wind.

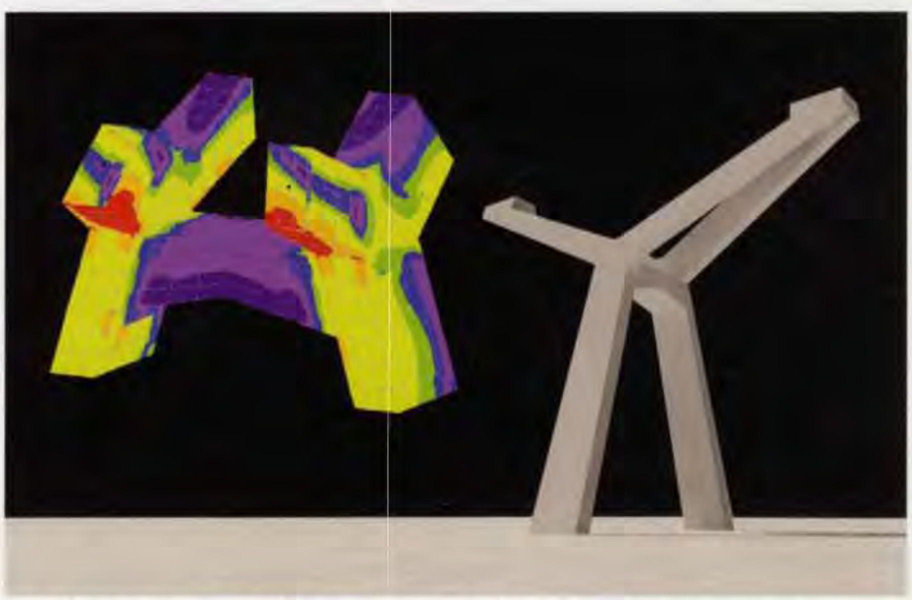
Detailed analysis and design

A truss in the roof plane, and the concrete deck slab at floor level, provide lateral stability. Their edges are connected by vertical glazing support bars that complete the structural system while minimizing interruption of the glazed façade. Since all the deck elements contribute to the structural stability, a full 3-D skeletal model of the deck was developed using Oasys GSA, with the triangular plated box modelled with 2-D shell elements and the legs modelled as simple sticks.

The construction sequence was developed with the contractor early in detailed design and included in a single analysis model: the bridge was 'built on the computer' in seven stages, including the addition and later removal of temporary supports. The stresses locked in by this process were significantly different from those obtained by applying the full dead load to the completed structure. These stresses were then combined within the model with various live load, temperature, wind, and impact loadcases, and the results enveloped to give the design load effects. This model was also used to confirm the bridge's buckling stability and to determine the natural modes of vibration.

For the design of the large nodes where the deck meets the legs and at the junction in the Y, detailed 2-D element models were developed incorporating the various plates. Basic loads were extracted from the main bridge model and manipulated in a spreadsheet to be applied to these models, and then the same combinations as used in the main bridge design were copied across. These confirmed plate thicknesses and weld sizes (Fig 3). Later, the model at the deck connection was modified to allow sizing of the bolts and pin forming the final connection, and also to confirm that the access holes needed to tighten these bolts would not cause unacceptable stress concentrations.

Each leg is supported on six 9m long, 900mm diameter piles, founded in mudstone. Asymmetry in the design moments meant that the legs were placed eccentrically on the pilecaps. A reinforced concrete tie beam joins the pilecaps at the base of each A-frame to reduce horizontal loads on the piles. Independent piled foundations supported the temporary towers for lifting during assembly.



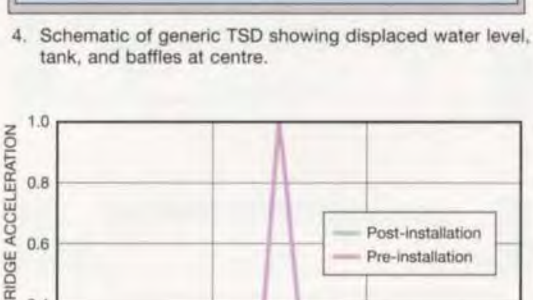
3. One of the 22m tall steel Y-shaped columns, with 3-D analysis model of the 'knee' junction using 2-D finite plate elements.

Dampers

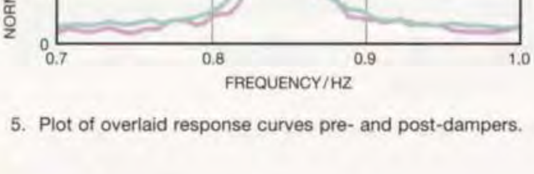
Dynamic analysis indicated that if more than 1200 people crossed the bridge at one time (the capacity of three fully-loaded 747s), it could exhibit excessive lateral response due to dynamic instability, like the London Millennium Bridge. Tuned slosh dampers (TSDs) were therefore installed.

In TSDs, the tuned moving mass is provided by a sloshing liquid in a tank rigidly attached to the structure (Fig 4). The geometry of the tank, and the liquid's density and depth, govern the active mass and frequency of the damper. Baffles at the centre of the tank control internal energy dissipation by applying drag forces to the sloshing liquid. TSDs can be a cost-effective alternative to mechanical tuned damping systems for some applications, particularly if the main contractor supplies the tanks as part of the structure.

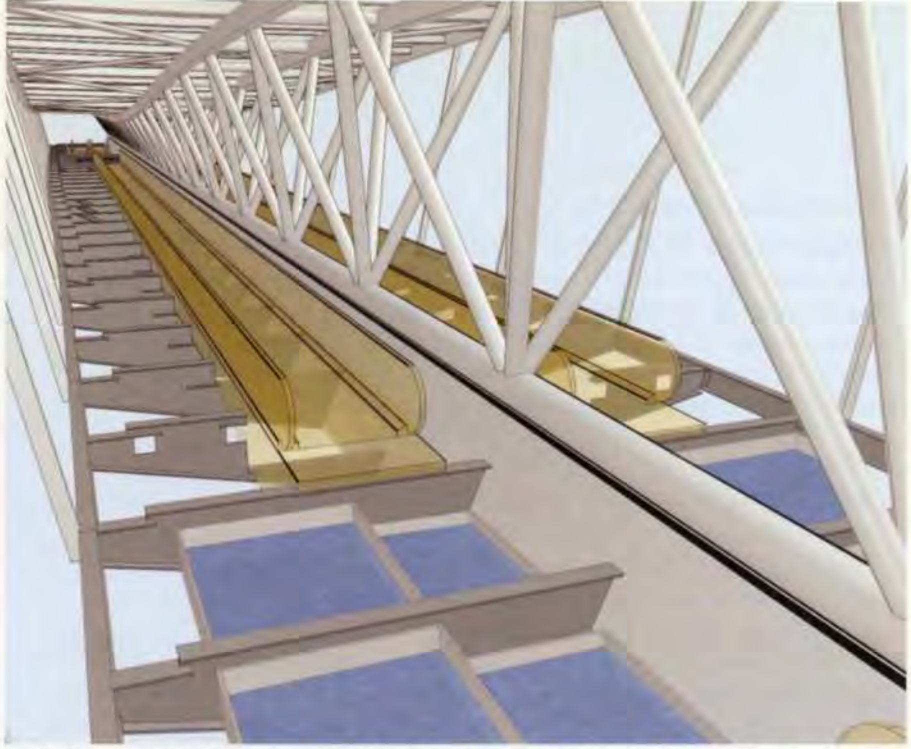
Prior to completion, there was some uncertainty over the bridge's exact dynamic characteristics because sliding connections at the base of the glazing were expected to provide additional, but analytically unpredictable, dynamic stiffness. Thus a range of dynamic properties had to be considered for the two lateral modes potentially susceptible to pedestrian excitation; across this range, the frequency and damping requirement of the modes varied significantly. The damping system therefore needed a relatively large tuning range and the capacity, if required, to be tuned to two different modes.



4. Schematic of generic TSD showing displaced water level, tank, and baffles at centre.



5. Plot of overlaid response curves pre- and post-dampers.



6. Four pairs of tanks are placed at midspan beneath floor level, each pair between a pair of transverse beams on both sides of the central spine.

The system comprises eight sealed stainless steel tanks below the deck at mid-span (Fig 6), each partially filled with water, providing a total of some 8 tonnes of active damper mass. Each tank has adjustable internal divider plates, allowing an approximately constant active mass across a broad range of frequencies; multiple tanks allow tuning to multiple modes.

A concept design was developed from existing theory and data for sloshing tanks, and a prototype was laboratory tested on a shake-table. When the bridge was close to completion it was dynamically tested by a pair of synchronous electro-dynamic shakers, which applied a force equivalent to several hundred people walking in step. The results indicated an insignificant shift in the natural frequencies at higher response levels and that the higher lateral mode remained above the range of frequencies excitable by pedestrians. The optimum tank configurations for the lower mode were therefore derived, and the tanks commissioned by the contractor under Arup's direction. Tests after commissioning showed damping in the lower mode to have increased more than three-fold to about 2.7% of critical (Fig 5) - very close to the prediction. This level of damping increased the theoretical number of pedestrians required for excessive lateral response to over 3500, well above what is practically achievable on the bridge.

The passenger experience

In creating the passenger tube, the concept of the human spine and ribs was adopted. The central spine beam supports the floor and roof rib beams, and the tube is completed by struts between roof and floor ribs supporting the full-height glazed façade. This is inclined inwards by 11° from the constant width roof towards the floor, thus creating a curved deck floor that narrows at mid-span. The spine beam separates departing and arriving passengers with a glass screen along the middle of its inverted truss pyramids, together with a high-level bulkhead concealing the ductwork. The glass screen is the only vertical planar surface inside the bridge (Fig 7 overleaf).

The continuously varying and curved form makes a dynamic and interesting space, with visible lines as elegantly smooth curves. As pedestrians negotiate the four 61m autowalks, the gently curved planes give the feeling that the bridge moves along with them, and plane-spotters can pause at the lofty 10m-long mid-span space to examine the aircraft moving beneath.

Specification and maintenance

The elements and materials were carefully selected for quality and type, based upon airport requirements for standardization and maintenance, aircraft safety, and the desire to give passengers an exciting and distinctive environment. Although the bridge appears to consist almost entirely of curved planes and lines, the individual elements are planar or straight - standard components that not only were cost-efficient to start with but also can be efficiently maintained.

How it was built

Airports are extremely busy environments, even at night when runways are shut. To build anything above a taxiway without disrupting operations requires a high degree of planning and technology and the collective contribution of many individuals and organizations, especially when it involves building a 2700 tonne structure complete with internal and external glazing.

The principle was simple - design, build, move, and then erect (Fig 7) – but rarely is this scale of prefabrication seen outside the offshore industry and certainly it was a pioneering process for a UK airport environment, a sequence impossible to execute without modern heavy moving and lifting equipment.

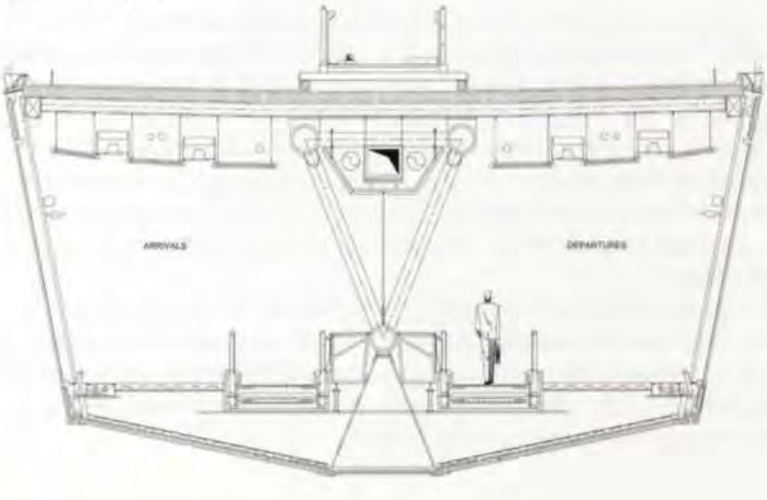
Key to success on such occasions is that the build/move/erect process is known in advance and pre-coordinated with all the other airport activities. Inevitably pitfalls can occur, but an operational safety case encompassed the whole design and delivery process, and its implementation was ensured through rigorous quality assurance. All perceived risks were meticulously assessed, and mitigation measures put in place and ready, with both backup equipment and resources on standby.

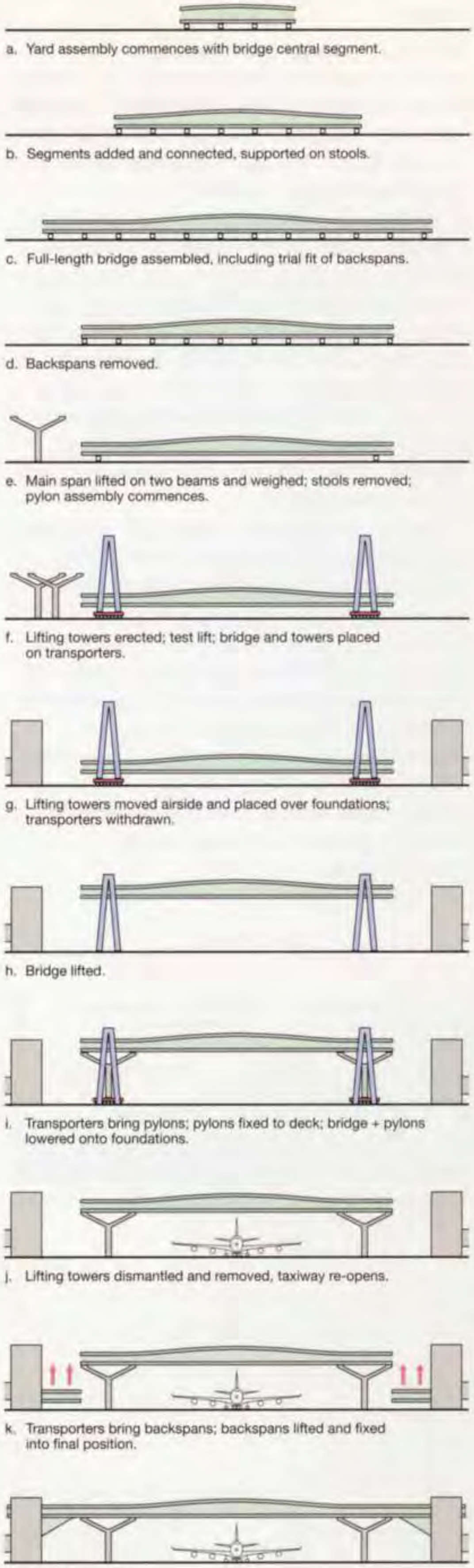
Build

The build employed traditional techniques and took place 1.5km from the airport in a yard specially equipped with all necessary infrastructure. The bridge was built in five component parts; the 164m-long central deck section, the two Y-shaped columns, and the two 17m-long end deck sections that were to be erected last and connect the bridge with the cores.

The challenge was to ensure that these five would geometrically fit together when brought into their final position. Fit-up is influenced, especially for steel structures, by the quality procedures during build, by the weather conditions, and by the way prefabricated structures are handled. Problems with fit-up could have caused major disruption to airport operations, so the quality assurance procedures were paramount for successfully implementing the next two phases. These also included testing all equipment under more severe conditions than expected later.

7. Typical cross-section.





a. Yard assembly commences with bridge central segment.

b. Segments added and connected, supported on stools.

c. Full-length bridge assembled, including trial fit of backspans.

d. Backspans removed.

e. Main span lifted on two beams and weighed; stools removed; pylon assembly commences.

f. Lifting towers erected; test lift; bridge and towers placed on transporters.

g. Lifting towers moved airside and placed over foundations; transporters withdrawn.

h. Bridge lifted.

i. Transporters bring pylons; pylons fixed to deck; bridge + pylons lowered onto foundations.

j. Lifting towers dismantled and removed, taxiway re-opens.

k. Transporters bring backspans; backspans lifted and fixed into final position.

l. Bridge complete.

8. Fabrication and erection sequence.

Regular detailed surveys of control points on the deck and legs confirmed the geometry and that movements were as predicted, and the final fit-up pieces below the deck were made to match the as-built geometry.

The deck was stressed down onto temporary supports in the yard before glazing commenced, so that movements as the weight of glazing, concrete deck and other secondary loading was added would be minimized. On completion of this operation, the tie-downs became slack and could be removed. All this fit-out work was done in the yard to minimize the taxiway closure required for erection.

Connection details between the five components were developed jointly by Arup and the contractor. Making large structural welds in situ over the taxiway was ruled out, but the forces to be transferred between deck and legs were large. Also, large temporary loads while the legs were hung from the deck acted in the opposite direction to the permanent loads. A 350mm diameter pin projecting up from the top of each leg into a machined hole in the deck plate transferred permanent horizontal loads, a machined strip round the perimeter of the 3.0m x 700mm plate transferred the weight of the bridge in the permanent condition, and 68 high strength friction grip bolts, each 24mm in diameter, round the perimeter carried the weight of the legs during erection and tension due to bending in the permanent condition.

The end sections were connected to the main deck by conventional bolted splices, with access holes in the tubes and triangular box to avoid the need for captive nuts.

The connection of the legs to the foundation also needed much design development. The fixed bases of the legs meant that bending moments induced tension in this connection, so 50 holding-down bolts 40mm in diameter were needed in each foundation. To ensure their correct layout, these were cast in to the concrete foundation using substantial templates. The final solution used a slotted 130mm thick base plate and large washer plates to give as much tolerance as possible for placing the four legs on a 128m by 14.7m grid.

9. The 164m-long deck section with the lifting towers, on the transporters at the prefabrication yard.

10. On the move inside the airport.

11. In their final position, the scale of the supporting columns is clearly apparent.

Move

Placing the 2000 tonne main span of a bridge on wheels and moving it is highly ambitious, but when that structure is fully glazed it also becomes sensitive to movement variations. The answer lay in the design of the air bridge and its components and the technology of controlling movements. The principle of SPMT (self-propelled modular transporter) units is simple: add any number together to give the required load capacity and the wheels will share the load equally and precisely move the whole as a unit (Fig 9).

Two beams, 128m apart, carried the 164m section of the air bridge, while two groups of 10 transporter units supported these beams and the lifting towers: 2400 tonnes in total. The bridge at that stage was a simply-supported structure with the bending moment diagram as echoed in the curved roof profile.

The electronic controls of the electro-hydraulic steering, and suspension of the 240 pairs of rubber-tyred wheels, ensured that terrain imperfections along the 1.5km travel distance could be minimized whilst the cargo was kept level and undisturbed.

Moving the bridge was a spectacular overnight event, particularly for pilots using the taxiway just before and after it crossed (Fig 10). The gentle roar of the SPMT power units and the single driver, controlling all the moves remotely, were the only evidence of this technology in action.

12. The completed bridge interior, where passengers can pause and enjoy the 'surreal experience' of a 747-400 passing beneath them.

13. The first 747-400 to pass underneath the air bridge.

Erect

At a stately 0.5km/hour the cargo reached its destination on time. Then the transporters rotated the whole assembly 120°, manoeuvred, and placed it exactly above its permanent foundations. The weight was then transferred to the 36m lifting towers, thanks to the transporters' ability to lift and lower their bed by +/-300mm. The scene was set. The pair of lifting towers then raised the bridge 24.5m above the taxiway, some 2.5m above its final soffit level, in just a few hours by remote electronic control of hydraulically operated strand jacks.

Meanwhile the transporters returned to the yard and brought the pair of Y-shaped columns. These were driven underneath the bridge, and by simultaneous lowering of the bridge and raising of the transporters' platform, the tops of the columns were connected to the bridge deck. That was one of the most critical milestones, since the pin connections were designed to accommodate a tolerance of only 5mm, an indication of the accurate manoeuvrability of all this heavy equipment, and a tribute to the accuracy of the fabrication. Technology had its greatest moment.

The air bridge had taken shape - hanging by the lifting towers. Together with its columns, it was lowered onto specially-prepared foundations to be connected and become a fully stable and safe structure (Fig 11 previous page). After only 10 days, the taxiway re-opened and aircraft pilots and passengers were witnessing the uniqueness of taxiing underneath a structure (Fig 13). In subsequent lifting operations, the two 17m-long end spans were erected to complete the bridge and connect it to the adjacent buildings.

Conclusion

The air bridge is both an architectural statement of engineering and an engineering statement of architecture: two disciplines in harmony. The main curve on the deck, related to a simple bending moment diagram, reveals most elegantly how it was built. This arching profile is echoed internally, generating a dynamic volume that rises to 6m high at the centre of the bridge (Fig 12). A landmark, and a new experience for Gatwick users, has been created: in the words of a passenger: 'A surreal experience, being above a jumbo jet as it moves'. The bridge opened to the travelling public in May 2005.

Credits

Client: BAA Gatwick Ltd **Architect:** WilkinsonEyre Architects Ltd **Bridge engineer:** Arup – Mike Banfi, Jon Bell, David Bennett, Ben Bridgens, Alison Butcher, Simon Cardwell, Neil Carstairs, Neil Chadwick, Martin Doherty, Len Griffin, Kathy Gubbins, Yoshikazu Ichimaru, Neil Jones, Mike Long, Stuart McClymont, Ed Mendes, Strachan Mitchell, Chris Murgatroyd, Mike Oldham, Daniel Powell, Stephanos Samaras, Roger Ridsdill Smith, Graeme Taylor, Sally Turnbull, Michael Willford, Duncan Wilkinson, Richard Wilkinson, Paul Wilson, Peter Young **M&E engineer:** N G Bailey & Co Ltd **Principal contractor:** Mace Ltd **Steelwork fabricator:** Watson Steel Structures Ltd **Illustrations:** 1, 11-13 ©Arup/WilkinsonEyre/Nick Wood; 2, 3, 6, 7 Arup; 4, 5, 8 Arup/Nigel Whale; 9, 10 ©Arup/BAA plc

Why rails crack

Gauge corner cracking on the British network: Investigation

Robert Care Steve Clark
Mark Dembosky Andy Doherty

Gauge corner cracking caused the fatal Hatfield rail crash. Few had ever heard of the phenomenon, and no-one knew why it was suddenly occurring. Arup, with TTCI, was asked to investigate the cause.

1. The Hatfield crash.

Background

On 17 October 2000, a high-speed *Intercity* train from Leeds to London on the East Coast Main Line derailed at Hatfield, Hertfordshire (Fig 1), resulting in four deaths and over 30 injuries. It soon became clear that a break in the high rail on a 1500m curve was to blame.

Investigations concluded that there were numerous cracks on the running surface, and when one of these penetrated to the base, multiple fractures of the railhead led to disintegration over some 30m (see Fig 2 for nomenclature). The potential for gauge corner cracking (GCC), as the phenomenon was initially called, to lead to railhead break-up made the then UK rail infrastructure operator, Railtrack, begin a rigorous system-wide inspection programme. Few in the UK had ever heard of GCC and no-one knew why it suddenly occurred. The search began for the cause.

Arup's role: November 2000 to date

Phase 1

The large number of locations damaged by GCC led to many temporary speed restrictions, and a major effort to replace affected rails, switches, and crossings (S&C). All this caused train delays and cancellations, and early work was directed towards treating the symptoms rather than addressing the causes. The cracking at Hatfield was caused by rolling contact fatigue (RCF), something familiar in branches of engineering focused on bodies in rolling contact, such as bearings. Such bodies can damage each other in several ways, depending on the severity of the contact pressure and the shear or tearing forces in the contact area, which for most trains in Britain is about 15mm in diameter. Damage can be in the form of surface cracks, or the wearing away or plastic flow of the materials themselves.

The RCF was in turn blamed on a wide range of issues, ranging from recent alterations to the structure of the British rail industry, to changes in the materials used on the railway, to the overall condition of the track infrastructure. To help Railtrack gain control of the situation, Arup was appointed jointly with the Transportation Technology Center Inc (TTCI) to identify and investigate all possible causes of the problem.

This was a major task, given the lack of robust information, the contractual arrangements in the industry, and the poor relations between the parties involved in the privatized and fragmented British rail industry. The root cause could be rail metallurgy, maintenance and renewal techniques, working practices, vehicle design/maintenance, wheel condition, some or all of these in combination, or any one of several others.

Arup/TTCI organized an intensive Phase 1 campaign to identify all the potential causal factors, quantify the variables associated with them, and assess the likelihood of each as a major contributor. This was done in November/December 2000, and an interim report was issued before that Christmas. Many measurements, inspections, and analyses were conducted, and several possible causes were rejected. No single 'smoking gun' could be identified.

Phase 2

Starting in January 2001, Phase 2 quantified the relative contribution to the initiation and growth of RCF of the factors identified in Phase 1, with the ultimate goal of designing and implementing a control strategy to minimize and manage its incidence.

The Arup/TTCI team co-ordinated a programme of measurements from track and vehicles across the industry: wheel and rail profiles, track forces, wheel impact loads, and wheel truing machine tolerances. In all, over 4000 wheel profile measurements and 2000 rail profile measurements were taken. Scores of RCF sites were investigated, and the computer modelling analyses of vehicles on specific types and designs of track were numbered in the thousands. The team also initiated a programme of laboratory research to understand the contribution of rail metallurgy and vehicle loadings to the growth rate of the cracks, including both small- and large-scale test regimes. The work performed in 10 months by the Arup/TTCI team (with the co-operation and support of the British railway industry) covered what would normally be a three to five-year major research effort.

Through these studies Arup/TTCI led the development of a control strategy for use by professional engineers and railway group managers responsible for decision-making and directing railway asset maintenance, renewal, and operations. The control strategy recommends the actions that these groups need to take across the wheel-rail interface to discharge their accountabilities and responsibilities for effectively managing RCF.

Phase 3

Phase 2 ended in October 2001, but Arup/TTCI continued to provide wheel-rail consulting services to Railtrack as required. Phase 3 began in January 2002 and continues to the present for Railtrack's successor, Network Rail. Its highlights have included:

- developing a method to include the effects of RCF and remedial rail grinding on Network Rail's long-term maintenance and renewal projections
- initiating RCF monitoring programmes on the Great Western Region and the London, Tilbury, and Southend network run by the train operating company *c2c*
- a major programme to develop remediation methods for poor rail adhesion caused by autumn leaf fall
- dynamic modelling to investigate the tendency for the new *Desiro* trains being introduced on the Southern Region to cause RCF, and monitoring the effects of their introduction
- a preliminary investigation into the feasibility of using acoustic methods to detect defective bearings on high speed trains.

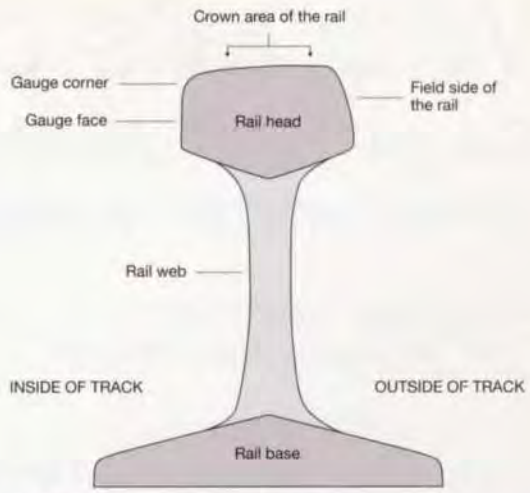
Phase 4

By January 2003 Railtrack had been replaced by Network Rail, partly as a result of the financial crisis that RCF had inflicted on the industry. Network Rail realized that the British railway industry was addressing its wheel-rail interface issues rather haphazardly, and asked Arup/TTCI to assist with industry-wide wheel-rail technology management. This Phase 4 ran formally until March 2004, and some parts continue today.

The first task was to identify and review current and planned work packages throughout the industry and for each to determine the sponsor, supplier, remit, links with other packages, planned deliverables, whether a final report was produced, and the extent to which the deliverables had been achieved. Additionally, each work package was related to the control strategy produced in Phase 2. From this, gaps and overlaps in the programmed work packages were identified and addressed. Further, the programme was to provide encouragement and assistance to turn research effort into tangible results.

Other accomplishments included developing a Southern Region defence plan to mitigate any effects of new vehicle introduction, establishing a 'Golden Mile' section of track where rail best practices are strictly observed, investigating track-friendly bogies, and producing a *Passenger Rail Best Practices Handbook* (still in progress).

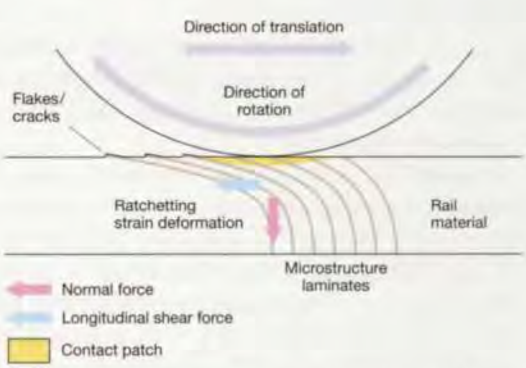
Arup/TTCI was instrumental in designing a new organizational structure to provide the technical backup for the VTI SC (Vehicle Train Interaction Systems Committee), an industry-wide body established initially under the Strategic Rail



2. Typical rail section nomenclature.

3. GCC on a 900m curve high rail.

4. Head checking on a 1300m curve.



5. Contact patch pressure and forces causing surface elastic deformation of the rail microstructure, leading to RCF.

Authority to continue the co-ordination of anti-RCF research. VTI SC replaced the committee WRISA (Wheel Rail Interface System Authority) proposed in Arup/TTCI's report in December 2000.

In early 2003, Network Rail and Arup/TTCI proposed a hypothesis summarizing current understanding of the causes of RCF, and then co-ordinated its presentation to the industry and the establishment of an experimental strategy to test it.

Finally at the instigation of Arup/TTCI and First Group (owner of several train operating companies), an opportunity was taken to input anti-RCF approaches into the design of a new fleet of trains for the trans-Pennine routes. This resulted in significant changes to that train design, incorporating the latest thinking on RCF reduction.

RCF: a natural consequence of bodies in rolling contact

Though the railhead cracks were initially ascribed to GCC (Fig 3), most of it should more appropriately be described as 'head checking' (Fig 4) in that the cracks developed nearer the rail centreline, usually 15-25mm from the gauge face. GCC is found on the gauge corner itself. GCC and head checking are both subsets of the more general phenomenon of RCF.

To illustrate the basic process (Fig 5) the rail is shown as comprising adjacent plates or laminates. Since the pressure and forces are high enough to cause plastic distortion of the laminates near the surface, an accumulation of metal dislocation occurs with each wheel pass until cracks occur at the surface. (RCF inspectors often run their fingers across the railhead and can feel the crack edges.)

At first the cracks are quite short and at a shallow angle, but some may elongate and turn into a steep angle, following a path similar to the laminate boundaries (Fig 5). This tends to occur when the surface length approaches 30mm and makes a rail fracture far more probable.

A useful way to depict the potential for the pressures and forces required to produce RCF is the 'shakedown diagram'[1] developed by Bowers and Johnson of Cambridge University (Fig 6). The actual location of the 'crack initiation' boundary is a function of the metallurgical properties and the friction at the contact patch.

Fig 6 also shows a region of increasing wear that is a function of the force. This implies that when the rate of wear exceeds the rate of crack growth, cracking doesn't propagate before it is worn away by the passage of wheels.

The shakedown diagram shows that:

- RCF can be a natural consequence of rolling contact.
- RCF occurrence depends on the contact patch pressure and forces.
- RCF initiation and growth are influenced by the metallurgical and frictional properties at the contact patch.

Research

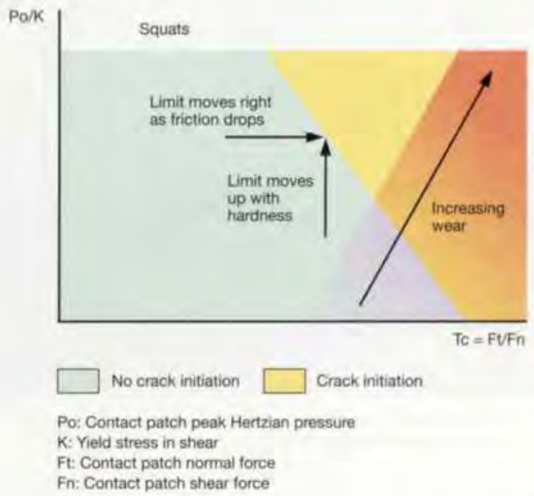
Initially it was thought that RCF in the form of head checking and GCC was caused by quasi steady-state wheel-rail contact forces, but not any longer. The intense investigations from late 2000 through 2003 showed there to be at least three separate modes of RCF initiation and growth on the British system:

- *Mode 0: steady state, generally occurring on tight curves*
- *Mode 1: bi-stable contact, generally occurring on medium curves*
- *Mode 2: convergent motion, generally occurring on shallow curves, straight track, and S&C.*

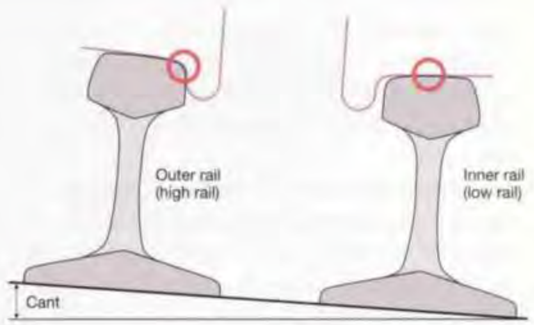
These RCF modes are likely to be similar on other railways. In all cases, the behaviour of the wheel-rail interface clearly can lead to contact pressures and tangential shear stresses that exceed the shakedown limit of the metal at or just below the surface of the railhead.

The following observations were made in the field and laboratory:

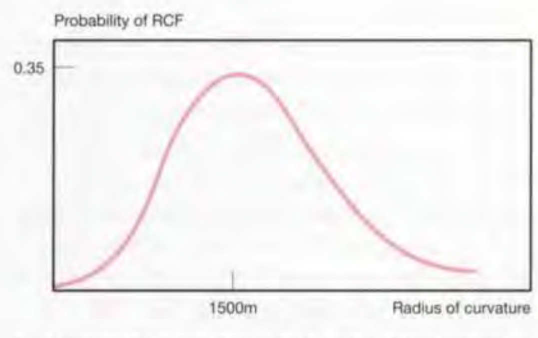
- Almost all RCF in the British system occurs on curves and usually on the high rail (Fig 7). Fig 8 shows an early estimate of the probability of RCF on the British system as a function of curve radius. This shape is largely true of most British



6. A shakedown diagram shows graphically the relationship between contact conditions and the properties of the rail material. Since wear is generally a non-linear function of Tc, cracks eventually give way to wear. (Squats are shallow internal rail defects caused by railhead head surface abnormalities of wear and stress.)



7. Wheel contact on a curve with the high rail and low rail.



8. Approximate distribution of RCF on the British system as a function of curve radius.

9. Surface crack angle as a function of contact patch longitudinal and lateral forces.

main line routes, and very similar to distributions in the Netherlands.

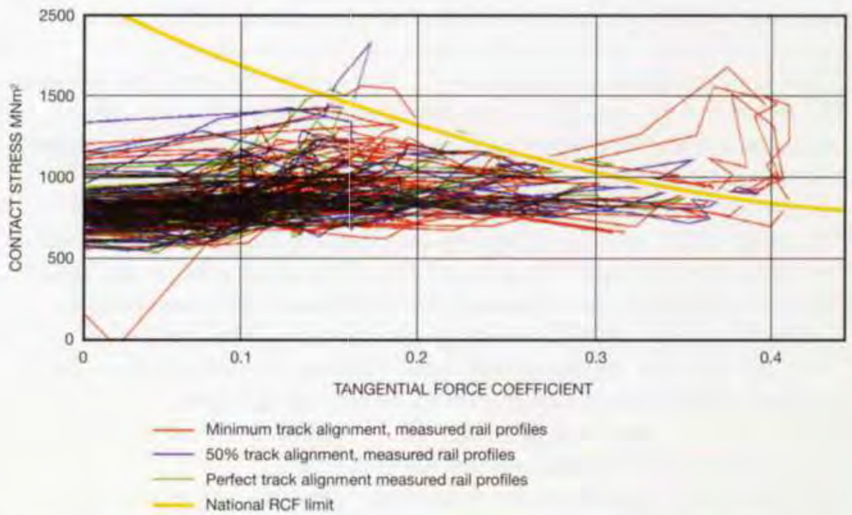
- On the British system, the highest probability of RCF is on c1500m radius curves (Fig 8).
- Most RCF on straight track is associated with S&C. RCF in switches is often found in the same relative position and is thought to be associated with events or 'triggers' that tend to change the rolling radius difference (eg sudden changes in alignment or gauge or the switch/stock rail transition).
- In shallow curves, where wheel/rail contact is on the gauge shoulder of the rail, the RCF is observed as head checks. In tight curves, where wheel/rail contact is near the gauge corner, the RCF appears as GCC.
- Field observations typically show bogies with stiff suspensions contacting near the gauge corner and softer suspensions contacting higher on the railhead.
- Laboratory studies have shown that the angle of the observed surface cracks matches well the ratio of the lateral and longitudinal forces (Fig 9).

The most compelling evidence comes from WRISA-sponsored research[2] that compared very detailed field observations with estimates of contact patch location, pressure, and forces. To date, six RCF sites have been studied in detail and a very high correlation has been found between RCF predicted by shakedown diagrams and observation. These studies were time-consuming and required very detailed RCF maps, both wheel and rail profiles, and specially processed track geometry data. All this information plus a mathematical model of the vehicles traversing each site was combined in a vehicle dynamics simulator. Estimates of contact pressure and forces were then projected into shakedown diagrams (Fig 10). In parallel, a product called the Whole Life Rail Model (WLRM) produced an alternative predictor of RCF using the same outputs from vehicle simulators, but not shakedown theory. The WLRM predictor asserts that not only force is necessary to create cracks but also energy expenditure. The algorithm combines the longitudinal and lateral creep with the corresponding creep forces to predict both RCF and wear potential (Fig 11).

Estimates from both the shakedown limit and WLRM predictor have been consistently good, particularly when inadequacies in the process are accounted for:

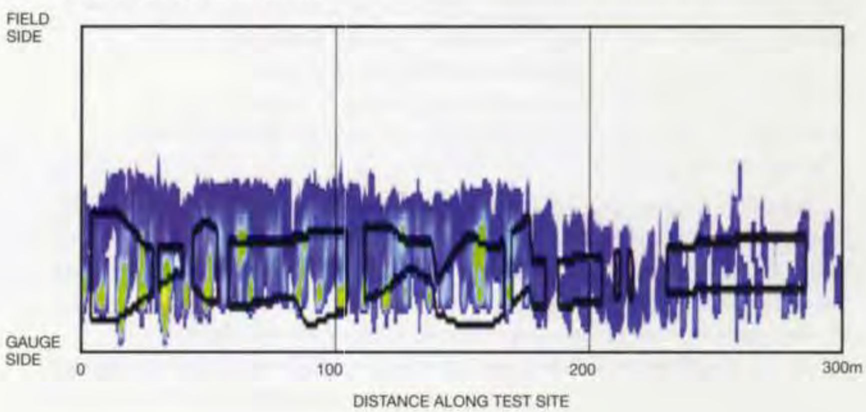
- Only a limited number of wheel profiles are used in the model.
- Past history of track geometry is not well known.
- Vehicle models assume nominal parameters.
- Vehicle models use significant simplifications in modelling the contact patch and its location.
- The friction history of the sites is not well known.

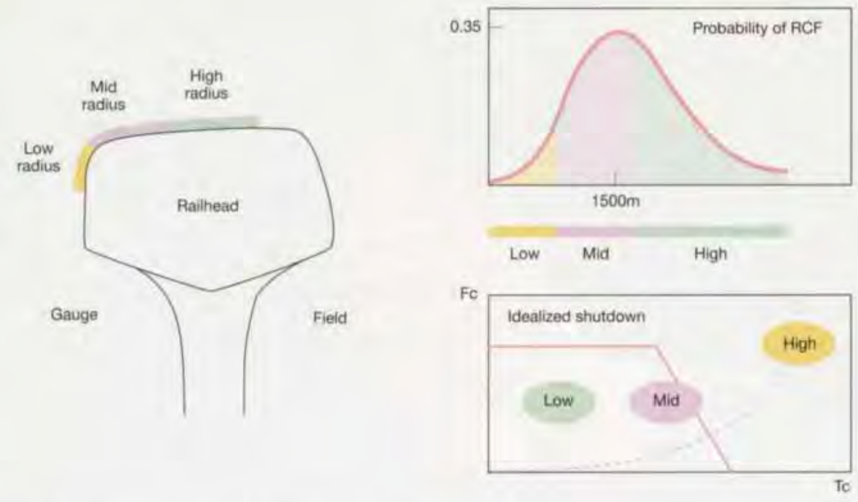
In spite of these inadequacies, the studies to date have provided a credible explanation for the mechanism that produces RCF, reasonable tools to predict it, and valuable insight into the primary vehicle and track factors that produce conditions likely to initiate RCF. The same studies have shown that many combinations of vehicles and track, each well within its own current safety standards, could frequently produce RCF, replicating field observations.



10. Shakedown diagram showing the effect of track alignment on a Class 43 locomotive as it traverses an S&C unit. Points produced by modelling above the 'notional' limit correspond to RCF observed in the field.

11. WLRM RCF index for curve high rail; the black contours are RCF locations on railhead from field observations.





12. General locations of RCF on railhead and curvature of track.

Robert Care is currently Chairman of Arup's Australian Region, and the firm's Project Director for the ongoing Phase 3 and Phase 4 investigatory work with TCCI.

Steve Clark is a Principal Investigator for TTCI, which operates the Transportation Technology Center in Pueblo Co, USA. Their first involvement in RCF research was respectively as Project Director and Arup Manager and TTCI Manager of the Railtrack railhead checking investigation, the first industry-wide comprehensive study conducted in the UK.

Mark Dembosky is a wheel rail systems specialist in the Railway Systems Engineering Group within Network Rail. His first involvement with RCF research in the UK was as an investigator and co-author of the Railtrack rail head checking investigation reports. He remains actively involved in RCF and general wheel/rail interface projects sponsored by VT-SIC.

Andy Doherty is Director of the Railway Systems Engineering Group within Network Rail and is Chairman of VT-SIC, the inter-stakeholder group responsible for RCF research and development in the UK railway system. He has been directly involved in formulating and managing RCF efforts in the UK from the first system-wide studies launched in 2000 to the present work of VT-SIC.

Modes of RCF generation

Of the three modes of RCF initiation and growth, steady state mode (Mode 0) is usually thought of as RCF and best describes GCC and head checking in curves. The wheel-rail contact forces that cause RCF by this mode are generated by vehicle curving behaviour in a specific range of curve radii and operating conditions. This is thought to occur in tighter curves with radii of 1200m and less.

Bi-stable contact mode (Mode 1) describes RCF occurring when the wheel-rail interface operates in a region of instability, where small changes in wheelset lateral shift generate large changes in rolling radius difference. This is thought to occur when the wheel profile wears so that there is conformality* in the flange root area in the wheel, and the wheel-rail contact position occurs there - generally at the gauge corner/gauge shoulder area and under conditions of high conicity**. This is thought to occur in curves with radii of 1200m - 2000m; however, it appears to overlap into curves of tighter and shallower radius.

Convergent motion mode (Mode 2) describes RCF occurring when changes in track lateral position and wheelset lateral shift cause the wheel flange to converge on the rail gauge face, even though flange and gauge face may not necessarily come into contact. This type of behaviour is thought to occur in moderate curves with radii of 2000m and higher, and in straight track. Again, there is assumed to be an overlap of this behaviour into curves of tighter radius where Mode 1 would normally be expected.

These locations of RCF cracks on the railhead fit with the dynamic wheel-rail interface behaviour expected in the three modes (Fig 12). The quasi-steady state behaviour of vehicles in these ranges of curvature with respect to shakedown are shown as well.

In all cases, RCF in the British system is due to excess wheel/rail forces primarily caused by the axle shifting relative to the rail too far to one side or the other. This is true on curved track, straight track, or S&C. In tight curves, the mechanism tends to be steady state, while in S&C and moderate curves and straight track the mechanism is transient. The second part of this paper, to be published in the next edition of *The Arup Journal*, explains how this happens in each mode.

* Close match between the shape of the wheel and the shape of the railhead, so that very small lateral shifts between the wheel and the rail can result in significant shifts of location of the contact patch, from the head to the shoulder of the rail.

** Rail wheels are shaped like a cone to facilitate cornering, although the taper is not uniform. As the wheel tread moves towards the flange the taper flattens out, increasing the 'conicity'.

Acknowledgements

The authors wish to acknowledge the contribution of many people in the British railway industry to the research that underlies this paper.

Credits

Client: Railtrack plc (Phases 1-3); Network Rail Ltd (Phases 3-4) **Lead consultant, project management, economic consultant, transportation engineer, research and development, database management:** Arup - Sophia Andrades, Paul Andrew, Malcolm Appleford, Tim Armitage, Greg Attwood, Carol Bannock, Simon Brown, Susan Brownhill, Simon Cardwell, Robert Care, John Cavill, Richard Cottrell, Jim Dunne, Ulrike Elbers, Mark Grynberg, Neil Ham, James Hargreaves, Deborah Hatch, Chris Hiett, Nick Higton, Carolyn Horan, Robert Jackson, Aimee Joe, Mike Kaye, Robert Linthorst, Fede Marsili, Alastair McConville, John Miles, Nina Milner, Pritej Mistry, Mike Oldham, Adam Pearce, Stephen Robb, Mark Rowe, Sarita Sataiyah, Bhavik Shah, Simon Stocks, Richard Sturt, Tamsin Toefy, Jag Visavadia **Project partner:** Transport Technology Center Inc **Illustrations:** 1 EMPICS Ltd; 2, 6-8, 12 Nigel Whale; 3, 4, 9 Network Rail/Arup/TTCI; 5 Network Rail; 10, 11 Network Rail/ AEA Technology

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(1) JOHNSON, K. Contact mechanics. Cambridge University Press, 1985.

(2) DEMBOSKY, M, *and* BAKER, P. Great Western Zone RCF pilot study modelling report. WRISA, 2003.

1. Main circulation stairs between the centre and south pod.

Pfizer pharmaceutical sciences building, Sandwich, Kent, UK

Steve Berry Clive Cooke Jennifer DiMambro
Tony Greenfield Andrew Jones Nick Olson
Peter Thompson Gordon Wills Peter Samain

Together with the visitors' centre and other millennium projects, Pfizer's new research laboratory Building B530 now forms part of the western gateway to the company's European R&D headquarters campus.

Introduction

Pfizer Ltd is the largest pharmaceutical company operating in the UK, and its campus near the ancient Cinque Port of Sandwich, Kent, is the European headquarters for research and development. Building B530, was designed by architects CUH2A and Arup. This is the first pharmaceutical sciences building to be built by Pfizer based on, and designed around, the concept of integrated research teamwork:

- chemical research, responsible for developing drug substances for candidate treatments (CRD)
- pharmaceutical research, responsible for developing the delivery product, eg tablets, capsules, etc (PhRD)
- analytical research, responsible for checking the purity of substances (ARD).

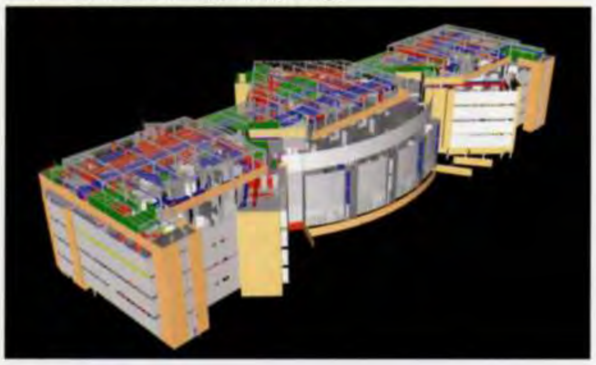
The facility totals approximately 35 000m^2 of laboratories, write-up areas, and support spaces, to accommodate more than 550 research scientists over two phases of fit-out.

Arup's role

For this building, Arup was multidisciplinary engineering designer for civil, structural, MEP, fire, communications, and acoustics. The service included a full construction support team, drawn from the original design team, who worked closely with Pfizer project management, contractors, cost management, and architectural teams to ensure that the original design thinking was continued through the construction, commissioning, and handover stages.

2. Site development plan of the Pfizer campus. Building B530 is at the top, connected to the main part of the campus by the connector link bridge.

3. 3-D model of complete building.



Architectural form and configuration

The Sandwich campus buildings have been designed and built for the 21st century, being 'leaner' and more flexible than comparable earlier developments. Arup's work there has parallels with other R&D facility design work being undertaken in California and elsewhere.

Spatial planning is vitally important to research facilities, and must fully respond to the needs of the science user groups However, these complex, highly serviced buildings are often heavily influenced by engineering solutions. Examples include the need for deep interstitial spaces between floors for servicing and access, large riser spaces, environmentally compliant fume dispersal, high degrees of fire separation for some areas, and very low vibration transmission in others.

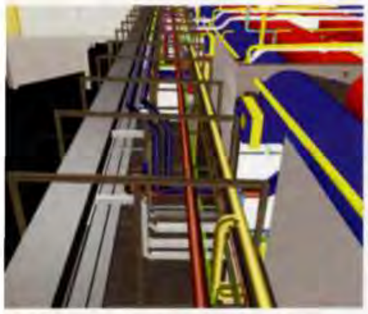
A principal driver in CUH2A's design for the internal layout was to promote communication between scientists in the different research departments. Development work often continues informally 'at the water cooler', where scientists chat about latest results and effects. Thus the four principal floors of Building 530 are connected by two open spiral staircases, in part to promote this interaction.

There are five lifts and seven further staircases, access to the top-level plantroom being via the emergency staircases or one of the lifts. Since the building is located on a flood plain, the ground floor is 2.5m above ground level, with an uninhabited undercroft below. One in 200-year flood prediction calculations were carried out for the building's design life, allowing for predicted changes in sea level.

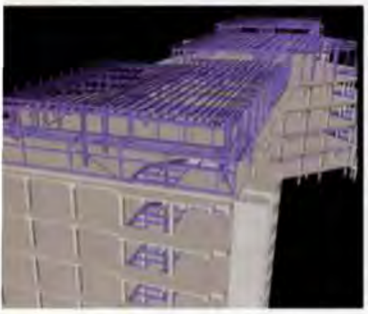
There are three main blocks ('pods'), serviced from plantroom areas above all three, and linked together along the east side of Ramsgate Road on the eastern side of the Pfizer Sandwich site. Each pod accommodates laboratory and write-up areas, where research staff document their experimental work. The main entrance is via the central pod, which also houses administration areas, with a perimeter corridor providing a strong communication conduit for both people and services.

The north pod differs slightly from the south pod in that 'wet' mechanical plantroom space is also located at ground floor level for water tanks, pumps, and chiller plant. Vertical service risers, generally at the ends of the laboratory areas, give structural stability against lateral loading, primarily wind.

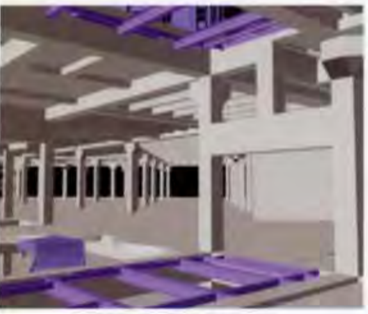
4. West elevation.



5. Science access services distribution zone.



6. Structural framing at roof level.



7. Steel plate girders support the 'armpits' and structural framing to laboratory levels.

8. Laboratory air extractors.

Apart from the main building, the B530 project also includes external work such as cooling towers, underground service trenches, external hardstanding, the perimeter access road, a bridge over the campus steam main, mains services connections, security fencing, and soft landscaping.

Structural engineering

The structure's primary functions, apart from realizing the architects' aspirations, are to provide a column-free laboratory space and support a demanding services distribution, whilst preventing vibrations from interfering with the use of sensitive laboratory equipment.

Some statistics indicate the building's scale:

- total floor area: 37 300m^2
- building footprint: 7610m^2
- 240 precast concrete columns of approximately 3m^3 each
- 1061 precast concrete double-T units manufactured in lengths up to 8m, with an average volume of 2m^3.

The soil characteristics (alluvial clays overlying the solid Thanet Beds) determined that the foundations be piled, with continuous flight augers chosen to minimize noise and vibration pollution. The main building and adjacent plant areas are supported by 1200 piles of three different diameters, around 20m long. Their pile caps are raised out of the ground in the uninhabited undercroft to minimize excavation and save cost.

The structural frame is of both precast and in situ concrete. Some 70% of the floor area comprises precast, prestressed double-T or precast concrete hollow core units with a nominal 100mm thick in situ topping. In the laboratory areas 600mm deep double-Ts were used to reduce deflections (and thus vibration), whilst 400mm deep units were used for the plantroom floor. The floor units span between precast boot beams, which in turn are supported on precast concrete columns. The floor acts as a plate, distributing lateral loads to in situ concrete shear walls.

The perimeter comprises reinforced edge beams, cantilevered between 1.525m and 1.945m and restrained by floor units supported on an inner boot. The beam- and column-free perimeter forms a deep service zone around the building (Fig 5).

Precast concrete was chosen for:

- *Constructability:* site access was restricted due to heavy peak traffic flows. Precast concrete could be delivered at off-peak times, reducing congestion.

9. Services support system from precast 'T'.

- *Vibration resistance:* equivalent steel sections would have had to be substantially deeper to achieve the same stiffness. There were planning restrictions on the overall building height and hence on the floor-to-floor heights.
- *Fire resistance:* steel would have needed an applied fire protection.
- *Speed of construction:* precast can be installed faster than in situ concrete.
- *Repeatability:* the design has much repetition, lending itself to the reuse of precast concrete moulds. However, since precast concrete costs depend largely on the reuse of moulds, and because the nodes and cores contain many elements that would require unique moulds, they were cast in situ.

The plantroom is steel-framed, seated onto the precast/in situ floor plate (Fig 6). Although the plantroom grid does not match that of the floor plate below, column locations match those of the precast columns as far as possible to minimize the need for transfer beams. However, the precast floor for the areas on either side of the central pod at the rear of the building is supported on steel plate girders (Fig 7).

Services are suspended from the concrete floor slab using cast-in channels on the bottom of the double-Ts (Fig 9). This reduced the amount of on-site drilling, with clear benefits to the installation programme and health and safety. In the plantroom the main services route was via a pipe gantry suspended from the main portal frames. Smaller services were suspended from roof purlins.

The site cranes could handle precast cladding panels of up to 12 tonnes, ie panel areas >27m^2. The programme required the structural frame to be manufactured before the precast cladding subcontractor was appointed and so the cladding had to be restrained by post-drilled anchor bolts. A precast frame already manufactured and erected on site with no cast-in provision for cladding fixings could have meant major problems, but close working by all parties identified reinforcement-free zones across the whole project and an optimum number of fixing types was chosen. This had cost benefits in detailing, manufacturing, and installing the fixings on site. Most fixing angles were installed before panels arrived on site and, by designing angles with slots and oversize holes to give sufficient tolerance, site fixing became very efficient.

Electrical design

A key part of the electrical strategy was to establish optimum distribution arrangements, including numbers and location of substations, while ensuring a resilient supply to critical items of laboratory equipment and mechanical plant.

Initially, time was spent establishing the building's maximum demand; the load centres; the internal low voltage (LV) distribution; and zoning arrangements to maximize the efficiency of the main electrical plant and minimize cable lengths.

The electrical loads were split into different categories and areas in the building, which resulted in a maximum ultimate demand figure of 6.25MVA. To accommodate this, one substation (substation A) was located on the ground floor and a second in the roof level plantroom (substation B), each equipped with two 2.5MVA transformers. Under normal conditions each substation supplies approximately 2.5MVA across the transformers, with the loss of one resulting in the other supplying the entire load. To allow for future growth and the potential 6.25MVA maximum load, the transformers are designed for a 30% overload using forced cooling. To achieve a balance of loads, substation A supplies the mechanical loads on the ground floor and all electrical equipment from the undercroft to the third floor, while substation B supplies the mechanical and electrical loads within the roof level plantroom.

The incoming power supply is an extension of the existing 11kV distribution network for the site, with dual 11kV feeders following diverse routes into the building.

The LV system vertical distribution uses the service risers, where all the sub-distribution and final distribution boards are located. The main LV and sub-distribution boards are split into essential and non-essential supplies, and integrated via a power management system. Critical laboratory equipment is supported by a 400kVA UPS unit in a controlled environment within the roof level plant space. The power supply system is monitored via the dedicated power management system interfaced to the building management system (BMS).

10. Lighting control in the laboratries is fully automated via the open architecture BMS.

11. Write-up and administration areas.

The lighting is an important element of the interior design, with the brief requiring full functionality and a pleasant working environment in all areas. The design team used 3-D lighting software programs extensively to demonstrate that the required lighting levels were achieved; these also provided a visual simulation of the illuminated space. Of particular concern to Pfizer were the lighting criteria for the laboratory spaces and workbenches, which required specific lighting tolerances; the design solution combined direct and indirect lighting over the benches and write up areas. Lighting control is fully automated via the BMS.

The building has a fully addressable fire detection system, integrated with a public address voice alarm system. Due to the amount of services in the ceiling voids and their depth, a VESDA™ system serves these areas.

The hazardous areas include the hydrogenation suite and bottle stores, and these are rated zone 1, where a volatile atmosphere is likely to occur during normal operation, and zone 2, where a gas build-up is unlikely to occur during normal operation but if it does, it will only exist for a short time. Calculations confirmed the extent of these areas, minimizing risk to the electrical and mechanical services.

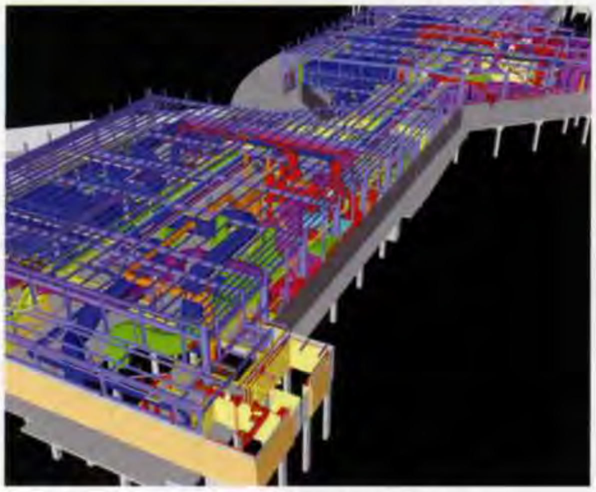
Mechanical systems

The mechanical design is split into two distinct areas, the laboratories and administration. Design for the latter was led by conventional comfort criteria, but process demands drove the design for the laboratories. Within each pod, groups of labs are located on the outer edges, zoned from 1-8, bounding central write-up areas. The central zone also contains the main administration area. Each laboratory zone is served by dedicated ventilation plant, as are the write-up and administration areas.

Write-up and administration areas

The write-up areas are entirely internal open-plan spaces, comfort-cooled using active chilled beams, some of which have integral light fittings. Ventilation is supply only, maintaining the write-up areas at a positive pressure relative to ambient, and with the adjacent labs kept at negative pressure. This results in a continuous, positive flow of air from the write-up areas to the labs, thus containing odours and potentially harmful fumes.

The administration area, in the central part of the building behind the sweeping fully glazed façade, is a mix of open plan and cellular offices requiring careful specification and co-ordination of the chilled beams. Trench heating and four-pipe fan coil units along the curve of the façade offset the high external gains and losses. The administration area has dedicated supply and extract, maintaining ambient pressure.



12. Rooftop plantrooms and major ductwork routes.

Laboratories

These are grouped into zones based on the type of work being carried out, and their location. As well as the main groups (CRD, ARD, and PhRD), there is a zone of biological laboratories. A science corridor runs between them and the façade, providing a clean corridor for circulation between the labs, many of which open to the corridor (which also acts as a thermal buffer zone).

In all zones the HVAC design is driven by the requirements for fume cupboard and biological containment cabinets. System capacity is based on a 60% diversity. The piped services include a high density of medical gases, among them nitrogen, argon, helium, methane, ammonia, and hydrogen, together with purified water, chilled water and low temperature hot water (LTHW), compressed air, steam, and condensate return. Separate domestic water services and drainage for the laboratory areas prevent potential cross-contamination of non-laboratory systems.

The zones are stacked vertically through the building, each served by dedicated central ventilation plant, comprising a variable volume supply air-handling unit (AHU) and variable speed fume extract fans. The main fume extract fans serve the general fume cupboards, with further extract systems for hazardous areas (solvent stores, hydrogenation), powder cabinets and microbiological safety cabinets (MBSCs). The supply air temperature and humidity are controlled centrally at the unit, with LTHW reheat batteries at each floor level for an element of local control. The supply air is distributed through a pressurized plenum with perforated ceiling tiles - typically open across the entire lab zone with supply to each lab driven by the pressure differential acting across the ceiling.

Fume cupboards

Some 570 variable volume fume cupboards, powder cabinets, and MBSCs are provided across both fit-out phases, allowing the client to optimize energy usage by varying the airflow according to laboratory use. A minimum air change rate must be maintained in each lab to ensure containment of processes within the cupboards and cabinets – for B530 the minimum air change rate is generally 12 changes per hour with higher risk areas operating at up to 20.

Extract from the cupboards and cabinets in each zone is via a manifolded system, with duty/standby fans serving each zone. System capacity is based on a 60% diversity. This approach minimized plant requirements and kept riser sizes to a minimum. Local lab and floor variations prevented oversizing of the extract systems.

Configurations of cupboards and cabinets in use range from 0.8m to 3.3m wide, including powder cabinets (with integral safe-change HEPA filters), walk-in fume cupboards, robotic enclosures, fume cupboards suitable for hazardous environments, and MBSCs. Arup developed the specification for the fume cupboards in conjunction with client user groups.

Fume dispersal analysis

The quantity of fume extract stacks on the roof of B530, plus the client's desire for a clean roofline, led to high-velocity stub stacks being adopted to reduce visual impact. These are 500mm high and produce a constant efflux velocity of 30m/sec to achieve good dispersal and prevent re-entrainment in the wake of the stack or local air intakes, etc.

Traditionally, fume extract stacks are 3m high or 25% of the building height (whichever is greater), with a constant efflux velocity of around 15m/sec. To proceed with the stub stack approach Arup had to prove that they would perform as well as or better than traditional stacks, and that the resulting dilution of fumes would meet Pfizer's rigorous environmental control requirements. Wind tunnel tests of the building and surrounding site were therefore undertaken by

13. Connector link bridge and western elevation.

Oxford University Wind Research Department, using for accuracy a scale model of the building and entire surrounding site. The tests were carried out in a low-velocity wind tunnel with the model on a turntable, rotated to simulate different wind directions.

Smoke tracing showed the dispersal patterns under different wind conditions for the conventional and stub stacks. Also, a mixture of 'zero air' with 50ppm (by volume) of propane was released from the top of a stack at a given velocity and stack speed/wind speed ratio, and concentration measurements were taken at different points on the site, eg air intakes and areas of congregation. This indicated the level of dilution being achieved from the point of discharge to the point of interest. These dilution ratios were then applied to the 'real' chemicals to be used in the labs, and using information on maximum spillage sizes, evaporation rates, and rate of dilution in the extract system, the predicted concentrations at specified locations were calculated. The acceptable level was based on the Pfizer site standard of STEL/40 (ie 1/40th short-term exposure limit as specified in EH40/2000[1]).

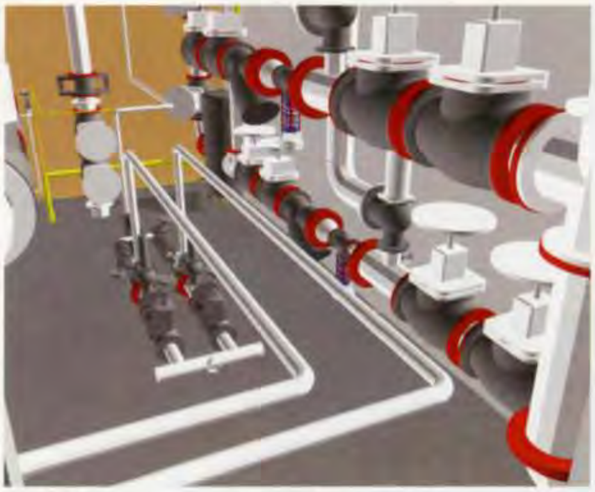
Chilled water

Having an existing combined heat and power system on the site meant that using absorption chillers for chilled water generation was an obvious consideration. Following detailed analysis of the cooling load profile and the characteristics of absorption chillers, the team decided to install two 2.5MW absorption chillers. They are not, however, ideally suited to operate under low load and rapid load fluctuation conditions, so Arup recommended the parallel installation of an 800kW vapour compression chiller to accommodate minimum base load and rapid changes in cooling requirements.

Purified water

The building needed purified water, as defined by United States Pharmacopeia[2], to serve general lab outlets and fume cupboard taps. Initially the building was to house its own purified water generation plant, fed with raw water. However, the decision was subsequently taken to build a remote sitewide generation plant, complete with storage to feed several buildings, one of them B530, whose plant was reduced to a polishing and distribution loop. This equipment includes UV sterilizers to control bacteria and total organic carbon (TOC), a heat exchanger to maintain water temperature, and a mixed bed de-ionization unit.

Careful consideration was given to the pipework materials and jointing techniques. Unpigmented natural polypropylene with crevice-free, fusion-welded joints was ultimately considered the best choice to give the required water quality at the lowest installed cost. Two distribution loops were provided for the building (with a further two intended for future requirements), each with its own dedicated polishing equipment.



14. Steam pressure reduction valve piping trains.

Steam system stress analysis

The building is served by a branch from the trenched sitewide steam main, which runs directly beneath. Steam is supplied to the absorption chillers, the low pressure hot water system (via heat exchangers), and the AHU frost coils and humidifiers. The main pipework distribution, including a section of the existing sitewide main, was modelled in 3-D and analyzed for stress and thermal expansion, using AutoPipe software, to determine appropriate locations for anchors, guides, supports, and expansion loops.

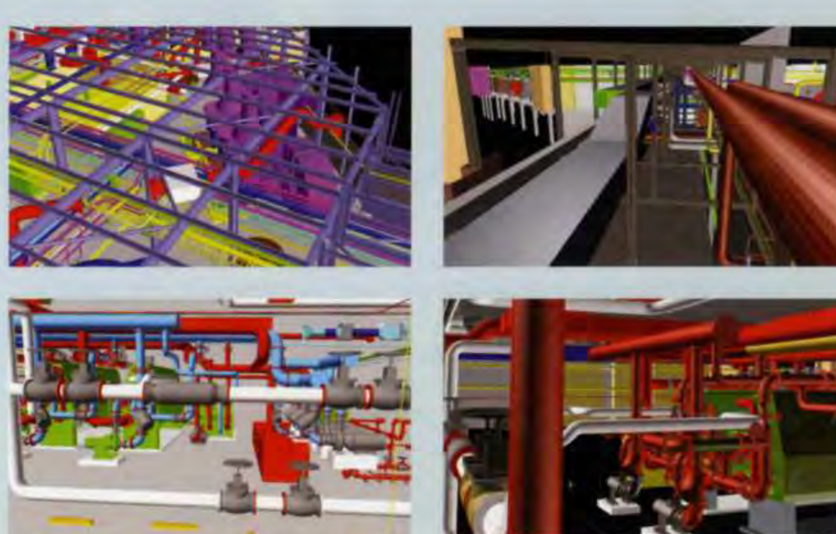
Where possible, thermal expansion was accommodated using the pipework's natural flexibility, expansion bellows being used only where absolutely necessary. The analysis was complicated by the fact that adjacent steam loops would not necessarily be active at the same time, and also by the need to connect into an existing steam main that was active and thus in its expanded state at the time of connection. When the steam system was enlivened for the first time, key points were marked with expected expansion movement, and carefully monitored as the system was brought up to temperature. Satisfyingly, modelled predictions were reflected by live site performance!

Fire

The project's hydrogenation suite presented a potential risk. Available guidance indicated that this should be mitigated by flammable gas detection and automatic fire detection to provide an early warning. Should an incident be unavoidable by manual intervention, a system for relief (blow-off panels) was also proposed. To assess the risk, Arup worked with Pfizer to identify the maximum credible hydrogen gas release into the space, based on the size of reactor vessels and the operating pressures that may be involved.

The increase in pressure/air volume that may occur is related to the maximum amount of heat energy that would be liberated if all the gas released is consumed by a fire. Calculations confirmed the maximum thermal energy that could be generated if the released gas were to ignite, and the maximum pressure rise was also calculated. This, assuming the room was sealed, was found to be less than the set pressure for the relief vents, indicating that they would not open and so provide no benefit.

The facility could thus be built without relief vents but remain safe in both normal and extreme operation. Deleting the vents gave a significant saving both in capital investment and ongoing operational and maintenance costs.



15. Further examples of the CAD modelling used in the design of Building B350.

3-D CAD modelling

During the submission process the team decided, due to the complexity of the services and the need to co-ordinate them effectively, to produce 3-D CAD models for the more complex 'typical' lab areas and plantrooms. However it was soon realized there were too few similarities between the labs and so the whole project was modelled in 3-D.

To ensure full co-ordination it was important that all disciplines be modelled in 3-D, and this raised a challenge. The architect was not modelling in 3-D and had no prospect of doing so. To address this, Arup wrote a complex conversion program that converted their 2-D CAD files to 3-D CAD models. This worked very well and was run on all new incoming files prior to being used as backgrounds.

The building services were modelled in 3-D using AutoCAD. Arup initially decided to model the structures for co-ordination purposes only using standard 3-D AutoCAD and prepare the 2-D drawings in parallel, but after numerous changes and redraws, the team adopted a parametric AutoCAD application that allowed 3-D modelling and automatic generation of the drawings from the model. This saved significant time and ensured that changes could be implemented much quicker. 3-D modelling gave the team enhanced visualization of how the services and structure co-ordinate, and enabled design reviews by walking through in real time to highlight problem areas before construction started.

Software statistics

AutoCAD (CAD software); **BSLink** (Building services modelling application from COINS); **3D+** (Structural parametric modelling application from CSC); **Navisworks** (3-D walkthrough, visualization, clash checking software from Lightworks Designs); 7Gb of CAD files (25 000 CAD files); 1400 drawings produced from the model(s).

16.

Controls and instrumentation design

This is based on open systems technology. The network has dual redundancy, using Cisco switches and Adept routers, as Pfizer require alarming and trending as part of their business support to users in the labs. The Cisco switches are connected via fibre optic cables to the Adept routers, and by installing two routers before every subnet, dual messaging to each node is removed. The building BMS will be integrated by the client into the existing sitewide intranet-based system.

Where feasible the open system technology requirement was extended to packaged plant.

To provide distributed intelligence, variable speed drives (VSDs) - installed throughout - included a standard interface, which meant that it was only necessary to install a network cable to the controller, device, and drive. Using VSDs and locally mounted control removed the need for costly motor control centres and saved space in the plantrooms.

Lighting control system

B530 is also provided with a lighting control system that is compatible with the open controls system technology used on the project. The lighting control system facilitates occupancy time setting in unoccupied areas. When a user enters, an occupancy sensor detects their presence and activates the lighting, which remains on until the occupancy period has expired.

Within the cellular office area, occupancy sensors use an interface device that communicates with the infrared (I/R) temperature sensor in the office. This I/R device controls temperature and is also used to activate the lighting. Using battery I/R sensors meant that it was not necessary to install wall conduits, and allows easy relocation of the sensors to facilitate future layout changes.

Conclusion

Design development took 12 months and the building was successfully completed on budget and within the 30-month construction and commissioning period.

Credits

Client: Pfizer **Architect:** CUH2A **Multidisciplinary engineer:** Arup - Edward Adamczyk, Andrew Arrowsmith, Kathy Beadle, Steven Berry, Andrew Brooks, Peter Bryans, Lyudmila Burke, Patrick Campbell, Paul Charlesworth, Bob Clapham, Cormac Cleary, Daniel Clifford, Stephen Connery, Derek Cook, Clive Cooke, Martin Coulstock, Charlotte Dangerfield, Paul Davenport, Christopher Deacon, Jennifer Dimambro, Kirstin Donaldson, Troy Dyall, Richard Edwards, John Elissa, David Flanagan, Leanne Fowler, Ben Francis, Neil Francis, Paul Frondella, Mark Garrett, Ben Glover, Tony Greenfield, Philippa Hall, John Hammond, Richard Henderson, Trevor Hodgson, John Hunt, Brian Jakins, Simon Johnson, Andrew Jones, Mike Kopinski, Sam Long, Paul Longhurst, Fred Loterijman, Mark Marlowe, Simon Mather, Mark Mitchell, Peter O'Jumu, Nick Olson, Steve Pennington, Peter Platt-Higgins, Simon Rainsbury, Nihal Rajapakse, Jane Roberts, Keith Robins, Zoe Rushby, Peter Samain, Nicola Sanderson, John Sansbury, Mohammed Shehata, Paul Stacey, Sasi Suresh, Charlotte Swart, Peter Thompson, Mark Togher, Robert Toon, Michael Underhay, Jomel Uy, Owen Webber, Gordon Wills, Chris Wood, Steven Wood, Rebecca Wright, Alexey Zavgorodniy **Main contractor:** Fluor Daniel **Precast concrete subcontractor:** Tarmac Precast Concrete Illustrations: 1 Creative Services, Pfizer; 2 CUH2A Architects, UK; 3, 5-7, 9, 12, 14, 15 Arup; 4, 8, 10, 11, 13, 16 Miranda Parry/Image Creation

References

(1) HEALTH AND SAFETY EXECUTIVE. *Guidance note EH40/00*. Occupational exposure limits. HSE, 2000.

(2) UNITED STATES PHARMACOPEIA. *USP#24/NF19*. USP, 2000.

1. The new terminal building complete, on its island location.

'Centrair': Central Japan International Airport passenger terminal building

Shigeru Hikone Isao Kanayama
Jin Sasaki Hitoshi Yonamine

2. Satellite photograph of the artificial island in Ise Bay; the southernmost areas of Nagoya City are visible at the top of the image.

Introduction

In February of this year, the Central Japan International Airport (CJIA), started operations after six years' design and construction. It has been built on an entirely new 580ha artificial island in the Ise Bay about 35km south of Nagoya City, a major industrial area with a population of some 10M. This airport is Japan's third major international hub, after Narita and Kansai, and was developed through a public-private partnership involving central and local governments as well as over 200 companies. The consortium, known as Central Japan International Airport Company Ltd, was appointed by the national government in July 1998 to be the constructing and operating body for the airport.

The airport island was created by land reclamation in relatively shallow waters and contains the airfield, terminal, and landside facilities. It is connected to the mainland (1.1km to the west) through new rail/road bridges and a ferry terminal, and is 70ha larger than the Kansai Airport[1] island. Reclamation began in August 2000 and finished in February 2003; building construction started in January 2002 and was completed in September 2004, on schedule.

The nearly 500m-deep passenger terminal building comprises a main arrivals/departures hall and a central pier, with 'wings' on either side extending 1030m north-south. Running parallel, the airfield comprises a 3500m runway and taxiways to accommodate the Airbus A380.

The terminal is designed to handle about 7M domestic and 5M international passengers annually. With a total floor area of 219 224m², it has a maximum height of 30.5m and four floor levels, and cost approximately US$750M from a total project budget of US$7bn. Future plans include an option to extend the runway to 4000m and to build an identical parallel runway nearby, in which case the airport island would be enlarged to 900ha.

Arup has been involved in this project since the schematic design contract for the terminal building was won by the Nikken/Azusa/HOK/Arup joint venture in 1999. Nikken Sekkei Ltd led the architectural design in collaboration with Azusa Sekkei Co Ltd and Hellmuth Obata Kassabaum (HOK) Inc. Arup was appointed as lead structural, seismic, and structural fire engineer, as well as for site supervision, in collaboration with Nikken Sekkei. Arup also provided key input to the value engineering, façade schematic design, geotechnical engineering, and advised on sustainability systems.

4. Indoor garden in the central pier.

Building configuration

The terminal's steel and glass architecture is designed to express both its aviation theme and Japanese character. The design concept was guided by Universal Design[2] principles, aiming for equal ease of use for everyone, regardless of age or any level of disability. The building has four floor levels. The flow planning separated the Arrivals and Departures onto the second and third levels respectively, reducing the need for passengers to move between floors. There are direct access paths from the train, parking lots, and ferry piers, in keeping with the easy way finding concept.

Whichever way they arrive, the public pass through the 'multi-access plaza' in front of the terminal building and transfer via upward and downward bridge links to the Departures and Arrivals levels respectively. Passengers arriving by car can also enter the building from the 'welcome garden' at ground level, and move up to Departures or Arrivals by elevator or escalator. The south side of the Departures floor is for international and the north side for domestic flights, and no passengers need walk more than 300m to get to their flight. There are 13 bridge-served gates for international flights and nine bridge-served gates for domestic flights.

The fourth floor at the west side of the building contains a zone of restaurants, shops, and other commercial activities, accessing an observation roof deck on the central pier where there are large indoor gardens for passengers to relax, and for events hosted by local people. Effective use is made of natural energy, with large spaces like the check-in lobby being sunlit, and solar power supplying electricity to planes.

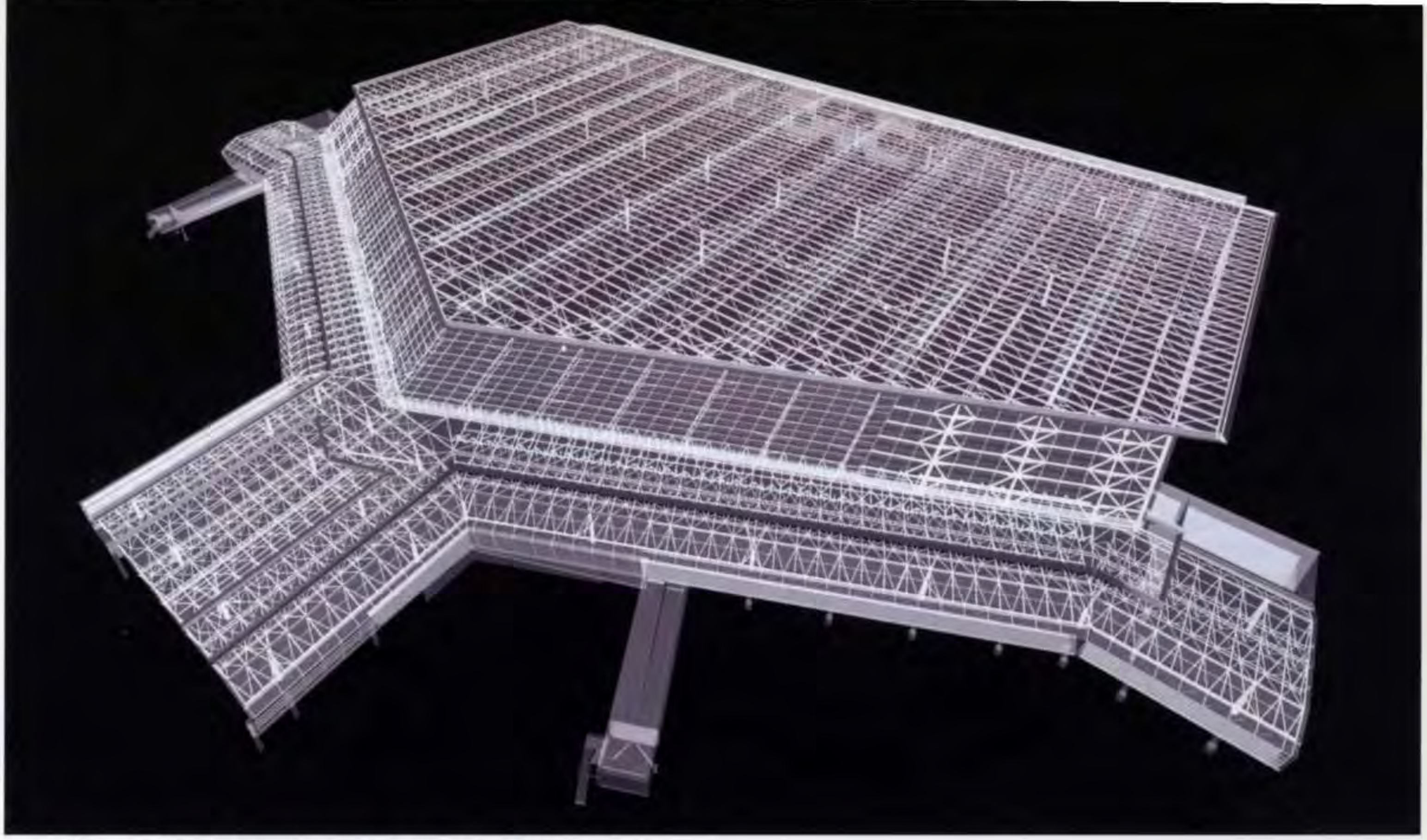
5. Departure area in one of the 'wings'.

3. Fourth floor shopping zone.

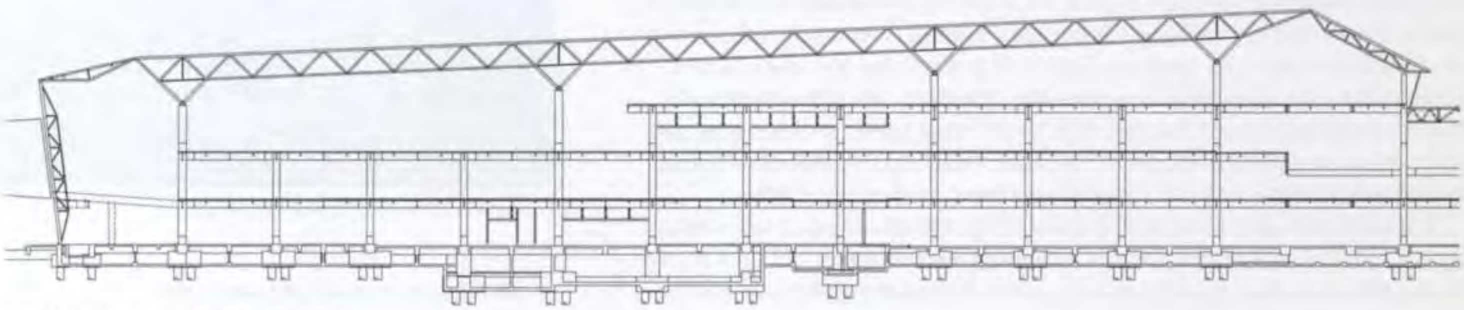
The superstructure and steel roof

The superstructure was designed as an unbraced steel frame to enable flexibility in the architectural planning, avoiding the need to find suitable locations for bracing, and to improve its seismic performance. A 12m x 12m grid was selected for the steel moment frame up to the Departures floor level, as the optimum solution to co-ordinate with the floor functions for baggage handling, MEP services, check-in desks, and the shopping zone beneath of the roof.

The steel roof structure covers more than 80 000m² of the entire building, providing a continuous large space for the check-in lobby of the main Arrivals/Departures area, the Departures lounges of both wings, and the central pier with its indoor gardens. The design of the roof structure is key to the architectural design as well as the structural engineering, facilitating both the 'form follows function' design principle and the desire for a Japanese character.



6. CAD image of the roof superstructure of the main Arrivals/Departures building.



7. Longitudinal frame section (east/west).

With simplicity of assembly and cost-effectiveness in mind, the team carefully considered a modular design approach with standardized structural sections, taking into account the fact that construction would be on the airport island. Arup's previous project experience of steel roof truss systems for airport terminal buildings included Hong Kong International Airport[3], Kansai Airport[1], and Stansted Airport[4], and these inspired a new truss system for the building to meet the design requirements.

The roof structure was designed as a space truss using steel tubular sections and expressed architecturally by visibly exposing the truss elements. The truss has a triangular-shaped section, comprising two rows of repeated V-struts, supporting a flat roof and creating a saw-toothed ceiling shape which recalls the Japanese art of paper folding, origami.

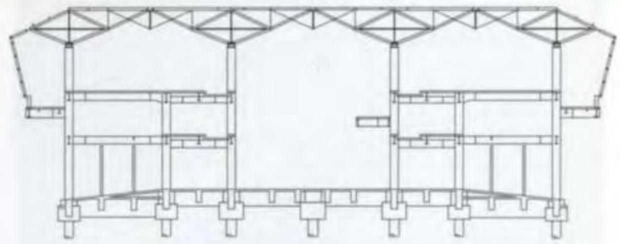
The steel truss was fabricated from uniformly-sized chord elements and lattice elements, the thicknesses of which vary. For consistency and standardization, this space truss system is used for the entire building, with the module size only varying when this was necessary to fulfil the architectural design concept and to improve cost-effectiveness. The roof incorporates a double-glazed skylight, whilst the inside space created by the steel roof truss will be able to retain smoke during evacuation in the event of a fire. To achieve efficient shop fabrication, site assembly, and site erection, two sizes of truss module were used respectively for the main Arrivals/Departures building and for the two wings and the central pier.

In the main Arrivals/Departures building the roof truss spans 24m, 36m, and 48m in the longitudinal (east-west) direction and every 24m in the transverse (north-south) direction. The roof module size was set typically at 24m x 12m to span transversely between roof columns at 24m centres. The 2.7m high steel roof trusses are supported by raking steel columns with a circular hollow section. The tops of each set of four raking columns are tied together by horizontal cables, whilst their bottom ends meet at the tip of a main steel column. The raking columns reduce the effective span of the roof trusses and decrease both their deflections and their steel tonnages.

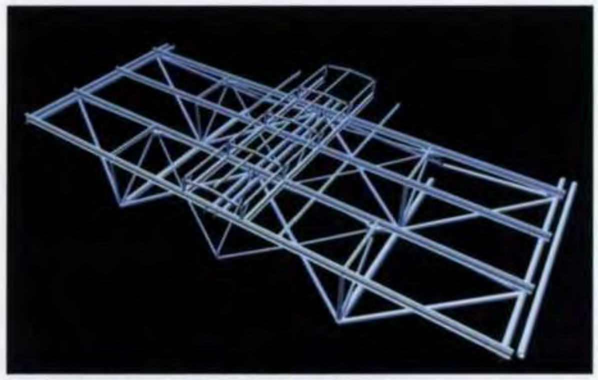
The horizontal tie cables at the building corners were prestressed by 500kN so as to remain taut under large typhoon loads, and the team conducted a 3-D linear finite element analysis of the entire roof structure to prove its stability under a typhoon or seismic event as well as serviceability loading. V-struts effectively spread roof loads both longitudinally and transversely, reducing deflections by 20% in comparison to a truss system without V-struts.

In the two wings and the central pier, the roof module size is typically 7.5m x 12m. Here, the steel trusses are 1.6m high and span 12m to 24m, supported by steel raking columns. As in the roof of the main arrivals/departures building, the tops of each raking column are mutually connected by horizontal high-strength steel rods, and their bottoms linked to the tops of main steel columns. Each top truss node is tied vertically to the main steel column directly beneath to resist wind uplift. Elegant cast steel details were developed and used for the exposed main column head and the truss connections, with both the raking column and the horizontal cable/rod having threaded anchor-ends. This was not only because of the high stresses but also the complex geometrical constraints and architectural concentration on these details. In the architectural concept the steel truss connections and main column heads became key features of the entire building.

The steel structure supporting the cladding on the east side - at the 'welcome garden' for the main Arrivals/Departures building - spans about 20m from ground floor to roof. The vertical trusses were developed as bow-backed lattice frames fabricated from rectangular and circular hollow sections, and are typically at 12m centres, with latticed struts supporting sub-mullions on both sides.

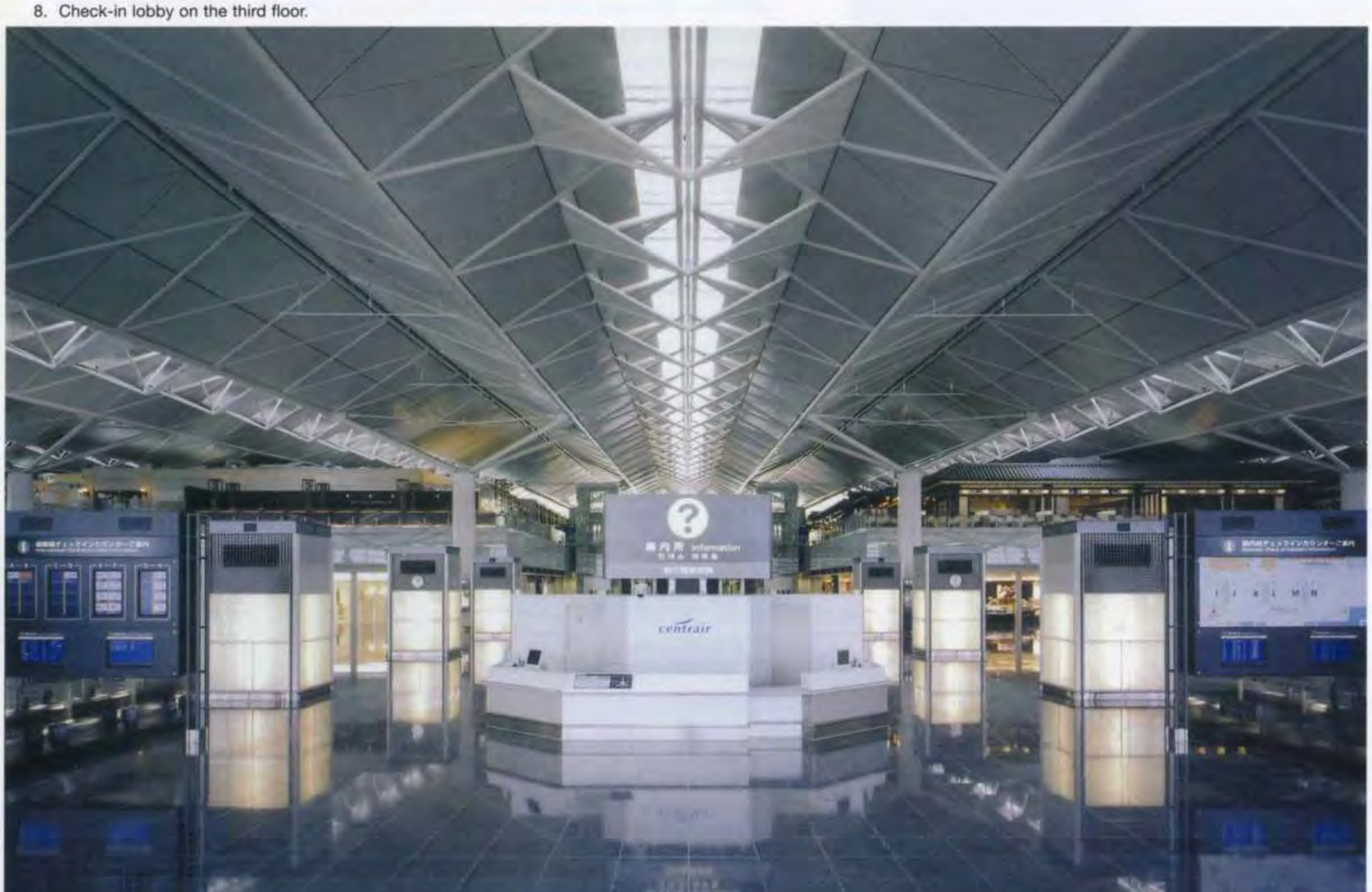


9. Cross-section through the central pier.



10. Roof truss module of the main building.

8. Check-in lobby on the third floor.



Horizontal rectangular-section transoms span 6m between the sub-mullions, supporting a central sub-mullion, and in turn the sub-mullion/transom assemblies support 2m x 1m glass panels. In-plane lateral stability to the wall is provided by 50mm diameter rod cross-bracing on both sides of the vertical truss mullions. To accommodate a large out-of-plane displacement of up to 200mm from horizontal movement of the roof under a large seismic event, the mullions and diagonal skylight beams are pin-connected; roof movement results in rotation of the joints rather than high bending stresses in the elements.

Soil and foundation design

The 580ha island was reclaimed by building concrete revetments on the seabed at an average depth of 6m and then constructing the island upward with hundreds of millions of tons of rock and sandstone landfill. The island's ground level was set at 5m above the surface of the sea. The total landfill was approximately 5200M m^3 - less than one-third the quantity used at Kansai, because the seabed here is particularly shallow and stable.

The top landfill lies within 11m depth from ground level (GL). From GL-11 down to GL-30 there is alluvial sand with a standard penetration test N-value of 10 and clay/silt with an N-value of 5; beneath these is a stiff diluvial sand and silt layer with an N-value of 60.

As the optimum solution for both construction efficiency and the limited time schedule, and taking account of the various landfill soil properties and seismic performance, Arup decided on steel driven piles to support the main Arrivals/Departures building and steel-cased precast concrete driven piles for the wings and central pier. So far there have been no reports of differential settlement. The steel piles are typically 0.9-1.0m in diameter and the steel-cased precast concrete piles 0.8-0.9m diameter. Both have good ductile resistance to seismic loads.

The piles' end-bearing capacity was tested using the *Statnamic*™ load test, an accurate and cost-effective method of determining pile capacity. Loading is achieved by launching a reaction mass from the pile top; solid fuel propellant is ignited inside the piston connected to the pile head, generating high-pressure gases and accelerating the reaction mass. An equal and opposite reaction pushes the pile into soil. The reaction mass equals only about 5% of the weight needed for a static load test, loading is axial, and the relatively slow application and release of compressive forces eliminates tensile stresses, compressing the pile and soil as a single unit. As a result, static load-displacement behaviour can be obtained.

Concern was expressed during the detailed design about the durability of a concrete basement structure below sea level. The team's approach was to use epoxy-coated reinforcement bars and ground granulated blastfurnace slag in the concrete, which was mixed on a site batching plant.

11a.

11b.

11c.

11. Progressive construction of the artificial island: top, in 2000; middle, in 2002; bottom; in 2004.

12. Aerial view of the airport on 17 December 2004, showing the main runway to the east (bottom).

13. The first roof truss modules in position.

14. Roof truss module ready to be raised.

Fabrication and erection

The roof truss individual elements were cut to the required length, prepared for jointing, and sub-assembled at steel fabricators in Japan and Bangkok prior to shipping to the island. To ensure accurate shop fabrication, a trial erection of a whole space truss module was conducted at the fabrication yard. Once on the island, individual roof elements were welded together to form 24m x 12m or 15m x 12m truss modules on a series of accurately formed jigs at the on-site fabrication facility. This was a large shed mounted on rails, which enabled it to be moved directly over a truss block. After assembly, the truss modules were painted and then transported from the site fabrication facility.

The truss modules for the Arrivals/Departures building's west side, both wings and the central pier were lifted from the airside construction yard and placed directly in the position on the supporting structure, using a 400 tonne capacity crane. However, the centre of the main arrivals/departures building was too remote for a crane to reach, so an ingenious self-moving erection staging system comprising oil tension jacks and rails was used to erect the entire trussed roof, based on the following operation sequence:

1. A 24m x 12m truss module was lifted on the central axis, placed on the staging at the east end of the building, and moved forward by 12m.
2. Second and third modules were lifted and placed on the staging behind the first, temporarily connected together, and moved forward 12m at a time.
3. Longitudinal trusses were formed in the east and north directions with raking columns and ties, the module being connected together by site welding.
4. The process was then repeated transversely until the entire roof erection was complete.

This site erection was controlled well, and achieved high tolerances so that the exposed steel truss elements became, as intended, a part of the building's refined architectural finish.

The façade system schematic design

Arup Façade Engineering conducted various investigations to provide preliminary information for the detailed design of the building's façade system. These included studies on the support structure for the façade, on glass and aluminium-framed curtain walls, on lighting glare for the interior, on the use of energy studies for cost savings, on roof shading to the west side, and preliminary cost studies on procurement from overseas manufacturers.

The structural fire engineering challenge

In the design a one-hour fire-rated paint coating was specified to the 16 000m^2 of exposed steel roof truss covering the departures floor and central pier, because of the fire safety for visitors on the observation deck. However, the Building Standard Law of Japan was modified during the detailed design of the building so that a performance-based design approach to the structural fire response became acceptable instead of conventional fire protection methods. Nonetheless, there was no specific technical precedent in Japan to assess the structural fire performance of a steel truss system over such a large space.

15. Façade support structure at the 'welcome garden'.

16. Entrance approach: the 'welcome garden' is immediately behind the façade.

Arup therefore proposed and conducted the following study approach:

- develop a scenario for a fire event on the Departures floor and indoor garden of the central pier, due to their proximity to the roof truss system
- conduct a combustion test on real chairs to validate the design fires chosen
- calculate the resulting temperature distribution from the design fire and resulting smoke production
- calculate the resulting temperature distribution through the steel truss elements affected during the design fire events
- conduct a thermal tensile test of the steel materials used in the building, including cast and high-strength steel, as used in the truss
- carry out a thermal structural analysis of the entire steel roof truss
- confirm the steel elements' capacity and the stability of the roof structure under the fire event.

The combustion test, conducted at the Takenaka Research and Development Institute, showed that the fire resistance inherent in the steel elements was sufficient to maintain their stability without the need for additional fire-resistant paint coatings. Arup made a formal presentation to the building technology centre of the General Building Research Corporation of Japan and, after discussion, the performance-based fire strategy was accepted - with clear benefits for the robustness of the design and cost efficiency of the building. The resulting cost saving of approximately US$2M was part of the value engineering during construction.

Conclusion

The CJIA was the largest public works project at the beginning of the 21st century in Japan. Throughout the design and construction, the client, the design team, and the contractors worked together to create a world-class airport terminal building with an aesthetic and functional harmony. It was a challenge to Arup in Japan, but its successful completion as the firm's second airport project in the country after Kansai demonstrated the firm's capability.

Since the CJIA opened to the public the number of passengers and visitors has increased significantly beyond the initial predictions, swollen by visitors to Expo 2005 Aichi in Seto City, Nagakute Town, and Toyota City. The airport has now been dubbed 'Centrair', as a symbol of the central Japan area.

17. Combustion test on fire resistance of steel elements.

Credits

Client: Central Japan International Airport Co Ltd **Design team:** Nikken Azusa HOK Arup JV **Structural, seismic, and structural fire engineer:** Arup - Graham Carter, Jonathan Drescher, Shigeru Hikone, Greg Hodkinson, Walter Job, Isao Kanayama, Keiko Katsumoto, Tatsuo Kiuchi, Yuji Kusawake, Eiko Nakahara, Ashok Raiji, Jin Sasaki, Masamichi Sasatani, Haico Schepers, Ikuhide Shibata, Yusuke Shirai, Hitoshi Yonamine Main contractors: JV led by Taisei Corporation, JV led by Takenaka Corporation **Illustrations:** 1 © Arup/Central Japan International Airport Co Ltd; 3, 5, 8, 16 ©Arup/SS Nagoya; 4, 15 ©Arup/Isao Kanayama; 6 ©Arup/Taisei JV & Takenaka JV

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(3) FOSTER, A, *et al*. Hong Kong Airport terminal building. *The Arup Journal*, *34*(1), pp4-11, 1/1999.

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Issue 2/2005 erratum

In *The Arup Journal* 2/2005, p44, the article 'Miami Airport QTA: risk-informed performance-based fire protection' opened with the sentence '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.' This should have read '... ranking third by international passenger numbers...'.

Sea of glass

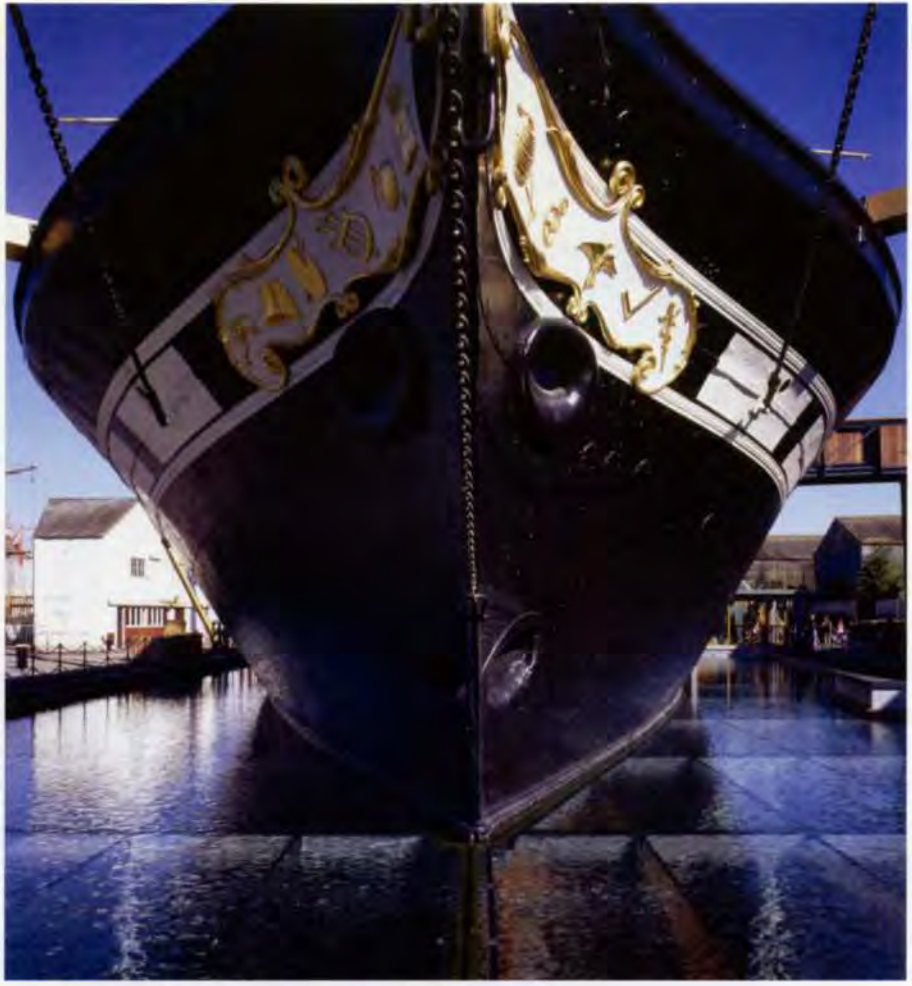
'Refloating' Brunel's *ss Great Britain*

Chris Jofeh Alf Perry

History

Among his many other achievements, Isambard Kingdom Brunel (1806-1859) designed three great steamships. The first, the 1340-tonne *ss Great Western*, was launched in 1837. Bigger than any other vessel in Europe, she served successively as a trans-Atlantic passenger carrier and Crimean War troopship before being broken up in 1856-57. By that time her second and ultimate successor, the double-hulled *ss Great Eastern*, weighing 15 times as much and around 210m in length, was under construction. Her stressful construction and agonizingly protracted launch, not to mention several fatal accidents, are commonly regarded as hastening if not causing Brunel's premature death, but the *Great Eastern* had a 30-year career as ocean liner, transatlantic cable-layer, and floating fairground and hoarding, before being sold for scrap in 1888.

Between the two came *ss Great Britain* (initially named the *Mammoth*). Launched in 1843, she was both the longest (98m) and largest (3066 tonnes displacement) ship in the world: with her wrought iron hull and 4.9m steam-driven propeller, a one-vessel revolution in shipbuilding. Accommodating over 250 passengers, *ss Great Britain* is often dubbed the 'first great ocean liner'. From 1845 to 1886 she served as a North Atlantic passenger liner, a Crimean war and Indian Mutiny troopship, and made over 30 round trips between England and Australia (carrying the first English cricket team to visit Australia), plus two Liverpool/San Francisco round trips. She ended her active career as a storage hulk in Sparrow Cove in the Falkland Islands, where she was eventually scuttled in 1937. In 1967 the late Reverend Ewan Corlett[1] wrote to *The Times* pointing out the historic value of Brunel's great iron ship and appealing that 'the authorities should at least document, photograph and fully record this wreck and place her on display as one of the very few really historic ships in existence'. This led to her return to the Great Western Dock in Bristol on 19 July 1970, the same date as her launch in 1843.



1. The bow of the *ss Great Britain*, 'floating' in her dry dock.

Conservation

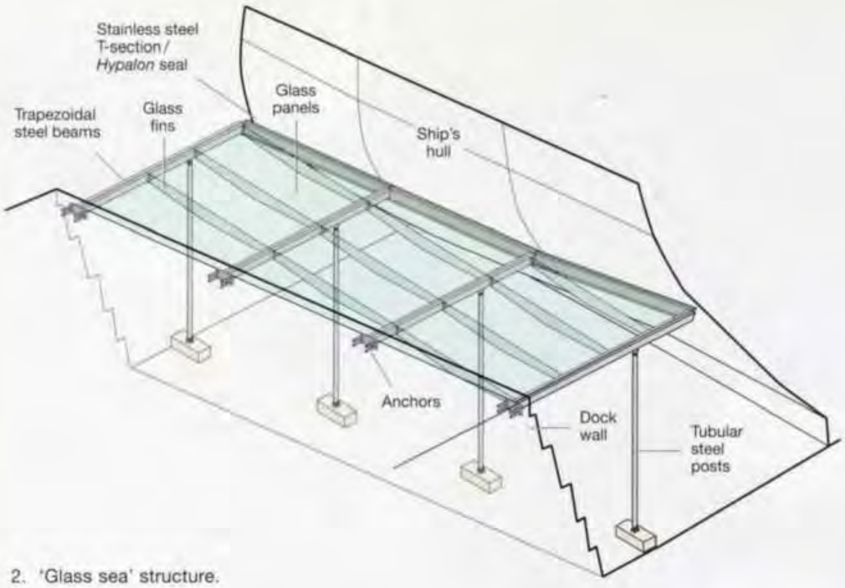
ss Great Britain's new life had begun, but it took 35 years to complete the painstaking conservation and restoration. Brunel's great ship had suffered serious damage since she was scuttled and abandoned, and conservation work focused on all original, pre-1970 material as this original fabric provides the most tangible and important link with her past.

Iron corrosion, particularly of the lower hull, was as at an advanced stage, so a 'glass sea' at the ship's waterline was constructed to form the roof of a giant airtight chamber around it. Beneath the glass plate special dehumidification equipment creates a dry environment to stop further corrosion, almost as if the ship were placed in a vast display case. The glass sea is covered by a thin layer of water flowing from bow to stern, so the ship appears to be floating. Visitors can descend beneath into the dry dock, to see the ship's great curved flanks and her mighty propeller.

Arup's role

Together with architect Alec French Partnership, WSP Group as services engineers, and Capita Symonds quantity surveyors, Arup was appointed by the ss Great Britain Trust to design the glass sea, as well as to lead the repair and restoration of the dry dock.

Though only 50mm deep, the water supported by the glass plate extends over 1000m^2 and weighs in total around 50 tonnes, so a robust structure was needed to support it (Fig 1). Arup's design for the glass comprises about 170 individual laminated heat-strengthened plates 21mm thick, mostly measuring just under 4.35m by 1.5m and weighing up to 350kg. Impact testing of prototype panels was undertaken to validate the design and thus ensure both the safety of visitors beneath and the integrity of the glass plate to protect the dehumidified space beneath from flooding. Two potential impacts were tested: a 1.5kg hammer dropped from 15m up in the ship's rigging and the 6m fall of a 100kg person from the ship's deck. Neither was allowed to cause significant leakage.



2. 'Glass sea' structure.

3. Low level dehumidified air supply and high level extract ductwork at the bow.

The panels are supported on a framework of 250mm deep trapezoidal steel beams, between the edge of the dock and the hull, and tapered glass beams 1.5m apart, spanning 4.35m between the steel beams. The latter are bolted by *Cintec* grouted anchors to the dock wall and supported by tubular steel posts that spring from the dock floor and walls (Fig 2).

It was crucial that the connection between the iron hull and the glass waterline plate be watertight, but visually unacceptable to use a rigid dam and a flashing. Nor could it be a rigid seal because of thermal movements in the hull (it was reputed to 'banana' by 300mm, but the Arup team struggled to predict even 100mm - the figure adopted for the movements the joint was designed to accommodate). The plate edge is sealed to the hull by a membrane of *Hypalon*, a flexible waterproof sheet widely used for sealing reservoirs (Fig 4). Initially it was to be attached mechanically at non-historical rivet locations, but as these were not consistently at the right level the team turned to adhesives. An adhesive has several advantages, including flexibility, watertightness, dimensional tolerance, easy connection between unlike materials, and not causing damage to exposed iron or corrosion protection, but it also has drawbacks in terms of fire performance, long-term experience in use, variable properties between suppliers, and lack of experience in use compared with other methods. Also, the conservation contractor had already blasted the hull and painted it with three layers of corrosion protection, which the client understandably did not want removed.

The underlying imperative was to do nothing that would cause irrevocable damage to the hull or its corrosion protection. Rather than fix the *Hypalon* directly to the ironwork, the top (decorative) coat only of the corrosion protection was removed by gentle abrasion and a stainless steel T-section glued to it. Parts of the hull had corroded to very thin or non-existent. This would concentrate the forces to be carried onto areas of adhesive and paint that were backed by more substantial sections of the hull. Calculations showed that in these regions, factors of safety would be reduced but the design strength of the adhesive and paint would still comfortably exceed the maximum predicted stresses. Extensive laboratory and in situ testing was carried out to establish the right adhesive and the strength of the paint. Ultrasonic surveying showed where the hull could and could not carry load from the *Hypalon*.

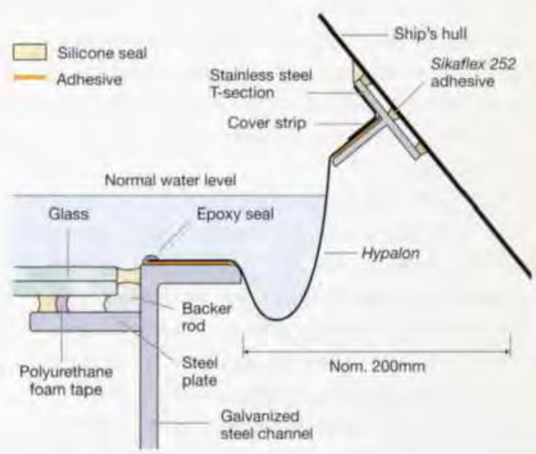
Conclusion

Crucial to the adoption of this solution was the client's acceptance that it was not without risk. Work duly began in January 2005 to install the plate, and in July the *ss Great Britain* was 'relaunched' amid celebrations to mark the anniversaries both of the ship's original launch in 1843 and her return to the dock in 1970.

The dock

The *ss Great Britain* is housed in the dry dock that was itself built to construct the ship. Little is known about the dock's origins; some evidence suggests that a pit used for extracting brick clay was enlarged or remodelled. The original inverted barrel vault shape still exists at the bow and stern, but the central portion was extensively enlarged to accommodate the later construction of bigger ships.

Investigations and analysis showed that the dock walls and floor exist, and have existed for around 170 years, with a theoretical factor of safety of around one. Slow, continuous pumping from the base of the dock kept the water table lowered to coincide with the dock floor, and great care was taken to ensure that nothing was done that would alter the water table. The stonework has been extensively repointed, but deliberately not cleaned. The foundations for the glass plate are very low bearing pressure concrete pads. A new concrete plug outside the dock provides for permanent water exclusion with the original iron caisson left on display, but now redundant.



4. Waterline plate seal.

Credits

Client: ss Great Britain Trust **Architect:** Alec French Partnership **Civil and structural engineer:** Arup – Nicholas Bailes, Simon Birkbeck, Matthew Blackburn, Stuart Clarke, Tony Clifton, Frances Condon, Mike Cronly, Graham Dodd, Martyn Duffin, Graham Gedge, Dave Hughes, Chris Jofeh, David Lancaster, James Nicholls, Fabio Parenti, Clare Perkins, Alf Perry, Brian Simpson, Edwin Stokes, Keisuke Tanikawa **Services engineer:** WSP Group plc **Project manager, planning supervisor, and quantity surveyor:** Capita Symonds **Specialist conservation contractor:** Eura Conservation Ltd **Main contractor:** Bluestone plc **Concept design:** Matthew Tanner (ss Great Britain Trust)/Robert Turner (Eura Conservation) **Concept development:** Julian Harrap Architects/Jane Wernick Associates **Illustrations:** 1, 3, 5 Lance McNulty Photography; 2, 4 Nigel Whale

5.
The *ss Great Britain*, dressed overall, at the Great Western Dockyard in Bristol. Visible on the ship's port side are the bridge which takes visitors to her upper deck and the entrance pavilion that houses stairs and a lift to the base of the dry dock. In the background in Bristol Harbour is a replica of John Cabot's 1497 caravel or navicula, the *Matthew*.

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Front cover: roof superstructure of the main Arrivals/Departures building, Central Japan International Airport: Arup

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