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1.

Personal Rapid Transit:

implementing the *ULTra* Heathrow system

Location
Heathrow Airport, London

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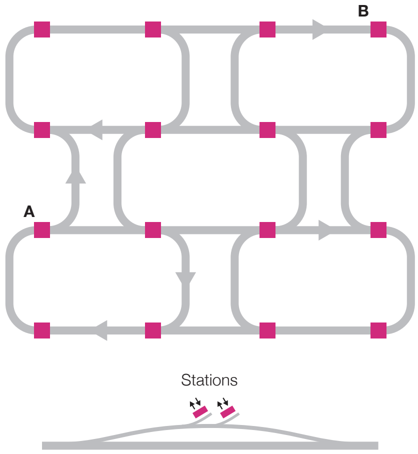
Introduction
Personal Rapid Transit (PRT) is an innovative form of urban public transportation, offering passengers trips with no waiting and no stopping, direct to any point served by its system. Small driverless vehicles run on a dedicated guideway integrated with stations, controls, and the vehicles themselves to meet the overall design and operational requirements.

The PRT guideway network provides access across the area served, with stations in their own side-loops (offline) distributed appropriately for the various origins and destinations of passengers (Fig 2). Individuals or small groups travel separately in vehicles which, once instructed, do not stop until the destination is reached, when they become free for the next demand. Empty vehicles are routed to stations of expected demand, and journey times are predictable between any pair of stations. PRT is public transport, but personal. It does not involve waiting for the service to arrive, or for vehicles to be filled, and busyness does not affect journey times.



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The concept is not new, with the first proposals dating back to the 1950s[1]. Studies were carried out in the UK in the 1970s (*Cabtrack*) and for some 40 years a group travel service using PRT principles has been in successful operation at Morgantown, West Virginia, USA[2]. However, interest has grown over the last 15 years as a result of urban road congestion, the failure of efforts to curb private car use, the need for environmentally friendly transport, and the availability of computing capacity to run reliable control systems.

In response to these demands and opportunities, three European PRT systems now exist. *ULTra* (**U**rban **L**ight **Tra**nsit) — the subject of the present paper — is in operation at Heathrow Airport, UK (Fig 3); *2getthere* (Netherlands) is operating at Masdar, Abu Dhabi[3] (Fig 4); while Vectus (Sweden) has installed a system at an eco-park in Suncheon, South Korea[4] (Fig 5). All three systems use similar-sized vehicles and operating principles.

Implementing the Heathrow system, which links Terminal 5 (T5) and a business car park, was the most demanding of the three in terms of guideway integration within an existing built environment and the critical need for reliable operation to serve passengers catching flights.

This paper focuses on the issues of guideway design, design integration within the airport environment, and the operating system requirements. It concludes with data from passenger experience and from operations and maintenance records. The design of stations, maintenance, control room, and empty car management are not discussed.

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1. Rendering of the Heathrow PRT system, with T5 in the background.

2. Generic layout diagram.

3. *ULTra* Heathrow pod.

4. The *2getthere* system at Masdar, Abu Dhabi.

5. The *Vectus* system at Suncheon, South Korea.

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Table 1: *ULTra* requirements

Requirements[5, 6]	Delivered
Available on demand	Average wait time: ~10 seconds
Goes anywhere	Can go to any point on the network
Non-stop	No stops
Environmentally sustainable	>50% reduction in energy and emissions
Low cost	Less than half the cost of other modes
Safe and secure	Very reliable, fully monitored
Integrates with other modes	Complementary to conventional transport

Table 2: Characteristics of the Heathrow system

Item	Description	Metric
1	One-way track length (including stations)	3900m
2	Vehicles	21
3	Guideway one-way potential capacity	600 vehicles/hour
4	Multi-berth stations	three
5	Maintenance depot and control room	one
6	End-to-end journey time	five minutes
7	One-way length of elevated guideway	2347m
8	Total weight of steel in guideway superstructure	669 tonnes
9	Total weight of concrete (excluding piles/pilecaps)	602 tonnes
10	Discreet piled foundations	76
11	Length at grade or in multi-storey car park	1553m

Initial system requirements, and prototype design

The *ULTra* system design concept originated in 1995 at the University of Bristol, UK. The original objective was to identify an ideal system — better than the car — for urban transport in the 21st century. Requirements analysis showed that the optimum system should offer the features in the first column of Table 1 (anticipating later discussion, the second column shows how these have been met at Heathrow).

Recognising the integrated nature of PRT systems is fundamental to their successful delivery, and analysis suggested that inadequate consideration of this factor was the root cause of the failure of some earlier PRT concepts. Infrastructure issues are a core consideration, with budget reviews showing infrastructure to comprise 50%–60% of the total cost.

Arup was involved from the outset, the firm's Bristol office having been contacted by Advanced Transport Systems Ltd (the original name for *ULTra* Global PRT) to join in designing the infrastructure for such a system. These requirements were considered in depth when, in its initial involvement, Arup designed the structure for a prototype test track. The team undertook stated preference evaluation of a PRT system for Cardiff City Council, and partly as a result of this, the c800m test track, including a three-span bridge, was built at Cardiff in 2001–2002 (Fig 7).

Early guideway designs used parameters developed from road, rail, and footbridge codes, and these generated heavy structures and resulting high costs. The overall loading from a PRT system based on first principles and actual applied loading from vehicles is about 2000N/m^2, compared with the 5000N/m^2 loading required in footbridge design to cover passenger crush loads. Designs which exploit this lower loading for PRT are significantly lighter and lower cost, and those used at Cardiff proved entirely satisfactory. This approach was therefore used in the design for Heathrow.

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6. Pods in service bay at Heathrow.
7. Cardiff test track.
8. The Heathrow PRT layout.

The Heathrow application

The *ULTra* system at Heathrow is based on a four–six person car with a fully laden weight of 13kN, operating at speeds up to 40kph and at six-second headways. The system has capacity for headways to be reduced to three seconds, delivering up to 4800 seats per hour per track. The car is 3.7m long, 1.4m wide and 1.8m high, with a single side door and opposing pairs of seats, separated by space for luggage or wheelchair. The car has four rubber-tyred wheels and on-board batteries powering electric motors for driving, braking and steering.

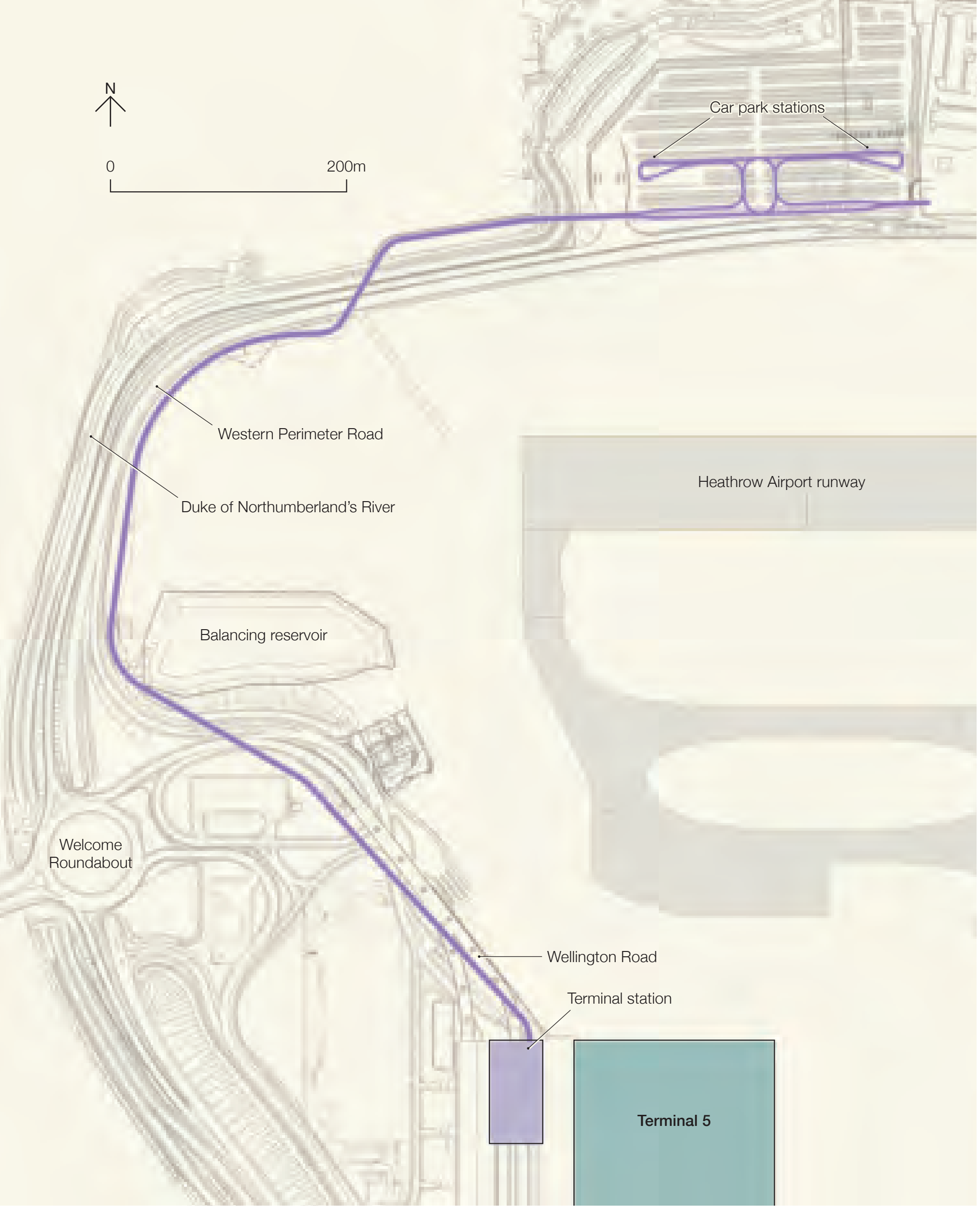
Client brief

The brief from BAA plc (now Heathrow Airport Ltd) was for a system to operate between T5 and a new business car park to the north beyond the perimeter road, around 1km distant. It had to meet strict standards of reliability and availability, and comply with the T5 overall design and construction standards. The instruction to commence design studies for the T5 PRT came in 2006, by which time construction of the terminal and its supporting infrastructure were well advanced towards the March 2008 opening. The PRT works thus could not interrupt any aspect of the T5 construction programme, with which Arup also had a major multidisciplinary design involvement[7–9].

The brief did not specify an alignment or details of station locations; the service envisaged was simply to connect car park and terminal. Although less demanding than a potential urban application serving anywhere to anywhere over a broad area, the Heathrow system includes three separate stations and a complex structure of adjacent merge and diverge points. The fundamental route choice process which would be necessary for a larger system has therefore effectively been tested. Each station is multi-berth, giving further control system decisions as cars are allocated to berth slots.

Route studies established that the guideway could be a mixture of elevated structure and ground running, and that the remote car park end lent itself to a two-station layout (Fig 8).

For the T5 station, space was identified on the second floor of the adjacent multi-storey car park. This had been designed to a floor loading of 2500N/m^2, so the low PRT system loads were fundamental in enabling this choice, though care was required to avoid crowd loads building up in passenger assembly areas on the car park floor.



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Design considerations

The Heathrow system, as built, has the broad characteristics set out in Table 2.

It may also be noted that the guideway traverses two rivers and seven roads and has to avoid obstacle limitation surfaces and in-ground services, while conforming to the T5 architecture — and appear integral to the whole rather than a late addition.

This demonstrates the inherent overall design flexibility of the system.
Design integration between the components of the PRT system and between the system and the whole airport environment was critical, and one of the most challenging aspects of the project for the guideway designers was to take into account and evaluate the wealth of inter-relationships between vehicle performance, site features, construction practicalities, and passenger comfort requirements.

Implementing this system at an operating airport, and largely within the T5 contractor's designated works area, imposed significant restraints in terms of guideway alignment, construction and programme. The *ULTra*/Arup team thus decided to reduce site works by exploiting the basic design's modular nature and maximise off-site fabrication of standard elements. This would also reduce construction impacts in this urban environment.

Finally, the guideway's detailed design had to include features with which the vehicle control system would interface to ensure safe and reliable operations. These include the vehicle-mounted lasers that use the vertical sides of the guideway (the upstand) to confirm vehicle position to the control system. The guideway side upstand also had to be aligned to provide adequate clearance for the vehicles' width sweep on bends.

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9. The running surface is formed from pairs of finely engineered precast concrete planks.

10. The structure in its crowded urban setting.

Design standards

Design code

As this was the world's first application of PRT as a public transport service, no specific design code existed. Experience from the prototype system at the Cardiff test track informed the initial specification of design requirements, and as the guideway design progressed, the decisions taken informed a design code that *ULTra* and Arup developed in parallel with the design itself.

The aim was to capture these decisions and the reasons for them, and thus establish an authoritative basis whereby future checkers and reviewers could avoid taking questions back to first principles to be satisfied that the solutions offered would deliver a safe, reliable and appropriate guideway.

Where relevant, the code refers to existing UK or USA codes or standards, in particular concerning the expected properties of steel, concrete, and corrosion protection, and for foundation and structural design parameters.

Passenger comfort

The issue of a passenger comfort standard was paramount, and parameters developed with the guideway design were based on ASCE APM standards[10] and experiments on the test track. Relationships between speed and alignment radius were established, based on moving vehicle mechanics, a limiting lateral acceleration of 2.5m/sec, and an angular velocity limit of 0.5rad/sec.

This in turn translated into the lengths of transition curves at entry to and exit from circular curves. Standards were specified for surface regularity and steps at adjoining running planks, relating to a jerk standard and the transmission of irregularities through the vehicle suspension system to the passengers. One early design decision was to avoid canting (super-elevating) the running surface, and so minimise complexity and cost. This influenced the speed of travel around turning radii.

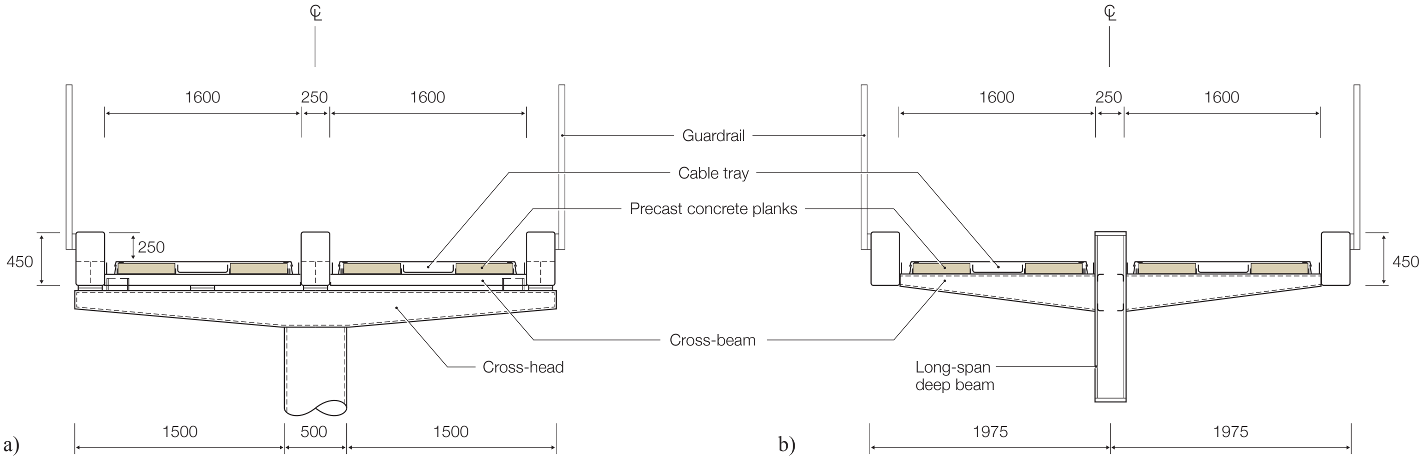
The internal vehicle configuration includes two forward-facing fixed seats and two rear-facing seats. Early trials showed that a direct forward view over and down an incline is discomforting for some passengers, so the forward view needed to be partly obscured. This was provided in the car body design and by limiting gradients to 6.25%.

The running surface — pairs of finely engineered precast concrete planks — gives traction to the vehicles' rubber tyres for steering, acceleration and braking, and is wide enough to accommodate variations in vehicle positioning (Fig 9). Experience at the test track had shown that small surface irregularities transferred to the vehicle and discomforted passengers, so at Heathrow vehicle suspension was introduced to mitigate this. Against this was the need for the lasers to retain their ability to sense the wall, making a firm suspension necessary.

In operation this firmer suspension was found to increase passenger confidence. The design and fabrication specifications also included very tight control of tolerances, and measures to avoid cumulative effects.

Constraints

At Heathrow the overall vertical and horizontal alignments had to be carefully threaded between fixed points, while still respecting ride comfort. Constraints to be worked around included existing and planned structures, particularly roads serving the terminal and its car parks, boundaries between airside and landside (the alignment is largely landside within Heathrow Airport Ltd property), clearances over roads, and the virtual surface (obstacle limitation surface) radiating from the north runway (Fig 10).



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Construction considerations

Background

The basic structural form for the elevated PRT guideway had been developed at the Cardiff test track as a one-way route comprising a pair of side beams with cross-members at regular 2m intervals. Different forms of construction were considered, including fabricated trusses, precast and in situ concrete, and composites.

Steelwork fabrication data indicated that the cost of cutting and welding for a fully prefabricated structure would double the total cost compared with basic steel supply. For its part, concrete lacks flexibility where a variety of radii are used and has high mould set-up costs. On this basis the least costly option was to construct from steel using as little fabrication as possible.

The cross-members support the running surface, cable tray, and drainage channels. The side beams form simply-supported spanning elements, as well as being the upstands to contain errant vehicles and provide navigational direction. The side beams also support the guardrail, and control and safety equipment. As previously noted, pairs of 300mm wide precast concrete planks form the running surface. (Fig 11).

Evaluation from the test track showed this form to be simple and easy to construct; a "standard" 18m span was efficient in its use of materials, and provided the very shallow profile and cross-section, with low visual impact, suitable for constrained urban areas. The 18m length can be transported in one piece and will span over a typical UK urban road at right angles. This basic concept for the elevated structure was applied at Heathrow. The single columns that support it are a constant 500mm in diameter.

Simply-supported beam performance is affected by the wall thickness of the rolled hollow section (RHS) that forms each side beam — a consequence of bringing together load, design life, fatigue, and welding considerations in the overall structural analysis. Adopting simply-supported spans resting on bearings at each end avoids on-site connections for a continuous structure, and is efficient in its use of a foundation and column crosshead to support the ends of adjacent spans.

Foundations

The location of foundations influenced the superstructure alignment due to the need to avoid existing features in particular roads, as well as planned but not-yet-constructed buildings and other infrastructure elements. The PRT system's low loading results in a small footprint to support the structure, generally a pile cap with four continuous flight augured (CFA) piles (Fig 12).
By adjusting the pile cap shape or providing ducts, it proved possible to avoid diverting any buried services — a major benefit of this transport system.

The foundation construction was significantly affected by the T5 building programme, and access to carry out the piling was taken when it became available. As a result the foundations were in place long before the columns and superstructure were added, imposing a "no change" discipline to the alignment design once foundation work had commenced. Airport restrictions required the use of low profile piling rigs in areas of height restriction, but otherwise industry standards applied.

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11. Structural cross-sections:
(a) standard; (b) long-span;
all dimensions in mm.

12. Low loading results in a small footprint to support the structure.

13. Typical columns and spans.

14. PRT between highway structures.

Guideway structure components

The alignment was determined by local constraints, by the aesthetics of the setting and road approach to T5, and by operational and ride comfort requirements. The design had to take in this range of issues in parallel. It was not practical or efficient for any one consideration to take precedence, and so the design was a complex and iterative process involving several parties.

Alignment constraints at certain road crossings led to spans up to 36m long. Most of the guideway is double-track, with edge beams common in dimension to the single-track module, and a central beam of varying depth (Fig 13). At the business car park, as well as access to the two stations, provision has been made for future route extensions towards hotels, offices and rental car depots. This required several low-speed curved elements, including merge and diverge features.

The PRT route comprises the following components of elevated guideway (Table 3):

- From T5 to at-grade section: 571m of double track in 30 spans between 8m–36m
- From at-grade section to business car park: (1) 380m of double track in 21 spans between 14m–30m; (2) 445m of single track in 32 spans between 4m–19m.

From this it can be seen that alignment variants from fitting a route into a constrained site dominate, and repeated use of the "standard" module amounts to only 29% of total elements used.

However the same "design" was used in 76% of the total number of elements. The remaining 24% of elements (29% of one-way track length) were either fabricated from plate due to curvature requirements, or take another form to meet the requirements of the span and shape. The detailed alignment and span designation were selected to avoid the need for both vertical and horizontal curvature in any member.

A PRT system that forms part of an urban regeneration programme, and thus has fewer alignment constraints, should be able to improve on the use of the standard module and therefore realise cost savings. Design reviews based on this experience have indicated ways to significantly increase the number of standard elements in a future design which, compared to Heathrow, is projected to give cost reductions.

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Table 3. Summary of elevated track components

	No of single	Track length (m)	No of double	Track length (m)
Straight 18m standard	3	54	21	378
Straight, same design	13	192	6	88
Other straights	-	-	9	247
Curved as standard	11	129	9	140
Fabricated curve	-	-	5	86
Merge/diverge element	5	70	1	12
Totals	**32**	**445**	**51**	**951**

Procurement of sections

Sections manufactured in rolling mills conform to dimensions established by the industry or through national standards. Since rolling is a mechanical process, tolerances are allowed for overall linear dimensions, section shape, and wall thickness, and these variations must be allowed for when assembling spans, in addition to assembly tolerances on site. In the UK the principal mills produce 15m lengths as standard, so the PRT system's 18m design standard module had to be formed with at least one factory butt weld to achieve the required side beam length.

The long spans were prefabricated off site in manageable lengths, and joined using bolted splice connections prior to being lifted onto the column heads.

Fabrication

Off-site factory fabrication brought the benefits of production in a controlled environment with access to lifting, rolling, and automated welding facilities. It was found that the steel supplied complied reliably with UK codes and standards and little straightening of supplied beams was needed to meet the design requirements.

The combination of fabrication tolerances and rolling tolerances establish the range of likely outcomes for the constructed guideway. This combination of tolerances was a critical issue in establishing a comfortable ride, and was partly countered by specifying the three dimensional location of points for each beam element at each column cross-head, and managing the cumulative effect of construction and component tolerances working together.

Pre-camber was specified to allow for steel self-weight and the impact of the additional weight of the concrete running planks.

Transport and installation

One determinant in selecting the standard module length was the UK road vehicle regulations through which loads up to 18m long can be transported without escort or special timetabling provisions. The same regulations indicate that loads up to 4m wide are permitted without special provisions. The double track is 3.97m wide overall.

On site, the responsibility for dealing with the size and weight was with the contractor, to match the availability of cranes or other lifting equipment with height and access constraints.

The 18m standard module has the weight characteristics set out in Table 4, which shows that the concrete running surface planks form a significant component of the total weight. These may be added after steelwork erection, so contractors have the option to assemble on the ground and lift as one assembly or to order a lighter lift and place the planks once the guideway structure is in place.

At Heathrow it was not possible to use cranes below an already constructed highway ramp, and this particular lifting problem was solved by the use of a transporter (Fig 16) to raise guideway elements into position. A further issue was that of airport operations, which limited the time available for installation to a four-hour period at night. Despite this very limited time window, 1000m of guideway was erected in one week. Once it was in place, all further construction and commissioning was carried out from within the confines of the guideway, avoiding any more interference with ground-level activities.

Commissioning and integration

The basic functionality of the vehicles and the full system was proved at the Cardiff test track, which included fully geometrically representative replicas of the stations at the T5 and business car park ends of the route. At the Cardiff track the central control system was initially installed and tested to the stage of multi-vehicle operations, and then at a convenient point in the programme the system was moved to Heathrow, where it now forms the core of the system's full operational control room. The Cardiff track was also used to undertake endurance trials of a "high time" vehicle, frequently involving 24/7 running.

Table 4. Weight characteristics

18m straight track	Single track (tonnes)	Double track (tonnes)
Steelwork	5.3	8.2
Concrete planks	4.3	9.5
Total	**9.6**	**17.7**


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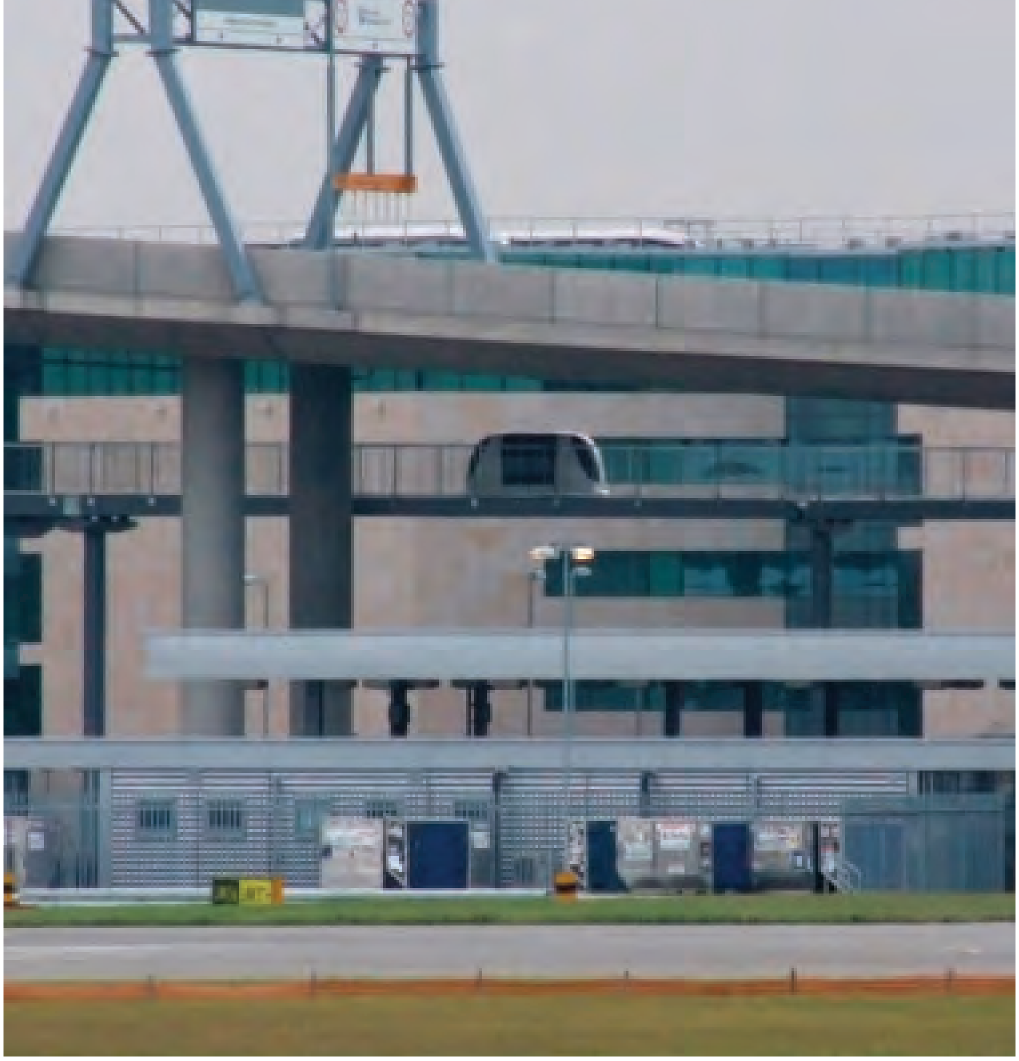
15. PRT exiting its station in the T5 multi-storey car park.

16. Specialist transporter.

17. Mapping vehicle.

18. Comparison of equal capacity transport infrastructure.

19. One of the car park stations.



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(1) System integration: This extensive series of tests of individual system components ensured that each element satisfactorily met its key performance parameters and confirmed the functionality and integrity of the system interfaces.

(2) Mapping: The first requirement was to capture the as-built dimensions of the track for use in the laser control system.
This involved the use of a specialist mapping vehicle (Fig 17). Loaded with the guideway design model, then finely adjusted to account for actual conditions, a data set was established that was used to define the reference track for the operational vehicles.

(3) Single-vehicle testing: This involved fully testing individual vehicles at Heathrow, with a complementary complete check on the functionality of the whole system and key systems interfaces.

(4) Multi-vehicle testing: This checked the full system functionality, particularly including the station control software, and automatic vehicle protection (AVP) system. The initial multi-vehicle trials were carried out at Cardiff, with fuller trials using larger numbers of vehicles done at Heathrow.

(5) Operational readiness: The satisfactory multi-vehicle testing allowed development towards operational readiness to begin.
This involved running increasingly representative trials of the system carrying passengers — either members of the Heathrow Airport Ltd/*ULTra* team acting as passengers, or “real” passengers specially selected for this trial process.

Safety is the major issue for any transport engineering project and particularly so for a system that relies on automatic control.
At Heathrow the initial development was under the responsibility of the UK rail regulator, HMRI (Her Majesty’s Railway Inspectorate). Following development and submission of a complete safety case, *ULTra* received its initial “Letter of no objection” from HMRI in 2003. Each development stage involving the carriage of passengers was subject to a separate safety clearance process under the appropriate regulations.

Practical operating results

Since it opened on 18 April 2011, the Heathrow “pod” system has carried well over 1M passengers, and currently runs 22 hours on weekdays, 20 hours on Saturdays, and 21 hours on Sundays.

Reliability and vehicle availability are monitored. Since opening, the average system availability has exceeded 99%; typical availability figures for other London transport systems in London vary between 94.8%–98.6%. The combined effects of professional operating procedures and a robust testing and development programme has delivered exceptionally high levels of performance for the Heathrow system when compared to other modes of transport.

The average waiting time for a vehicle to date over all passengers using the system is less than 15 seconds, with more than 80% of passengers having no wait at all.
This compares with an average waiting time for the previous bus service of 10-15 minutes. The system has taken 70 000 bus journeys per year off the roads, and is saving 200 tonnes pa of carbon emissions.

Though the scale of the PRT infrastructure is slender indeed compared to that supporting conventional transportation (Fig 18), there is equivalence between the capacity of the highway and the PRT structures.

The business case for PRT systems

Increasing land value

A study for Network Rail by the transportation consultancy Steer Davies Gleave on land values around railway stations has indicated that commercial properties located near them are significantly more valuable. Research undertaken at T5 suggests that, with the PRT system now operating, people perceive equal convenience between the business car park adjacent to the terminal and the remote one accessed by PRT. There is therefore potential for PRT to improve commercial land value when it is built to serve existing airports and railway stations.

Improving efficiency in development

PRT offers masterplanners new opportunities to maximise development potential and the attractiveness of the urban realm, though to date only the development at Masdar in the UAE has integrated PRT planning and masterplanning early in the development. A PRT system linked to remote car parks, either existing or new, reduces the area of on-site highway infrastructure. As a result building spacing is less constrained, allowing more flexibility in locating new construction and more efficient site development. Remote car parking allows surface car parking within transportation hubs to be removed, allowing more commercial and retail development within the area.

Creating a better urban environment

Urban design and sustainable travel will benefit from the reduction in car use that PRT can enable, with designs optimised for pedestrians and cyclists, potentially utilising shared space concepts, and additional opportunities to install public squares, street furniture, planting and public art. Existing buildings can be adapted for use as PRT stations.

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Reducing car traffic also results in noise and air quality benefits, particularly as PRT systems produce little noise and no emissions at point of use. PRT can also be a catalyst for regenerating neighbourhoods, where building form changes as a result of the location of stations and the guideway, and in response to the benefits of the transport service in terms of movement and increased land values.

In 2004 the EU commissioned a study to evaluate the role that innovative transport solutions like demand-responsive transport systems and PRT can have in future cities. Looking at the Swedish city of Huddinge, the aim of the study was to show how a fast-growing urban area such as Kungens Kurva could be supported by a high-tech, up-to-date and innovative PRT system. Similarly, in Cardiff Arup conducted a Stated Preference study, which showed that with PRT providing the last mile connection, there was a propensity to shift to public transport for the whole journey. This was a useful business case finding, but clearly needs more research.

Other benefits

Indirect benefits such as improved urban realm, lower noise and better air quality, can be investigated so as to assess potential benefits resulting from reductions in car vehicle trips. Health benefits and accident savings from the modal shift to public transport enabled by PRT, and mileage savings afforded by remote parking, can be quantified, based for example on the approaches set out in the UK Department for Transport Green Book. PRT is also easily accessible for the disabled, including blind people.

Another indirect benefit is that the batteries used by PRT vehicles can be charged at night when other demands on the electricity system are low, or when the sun is out, or when high winds are blowing. One way or another, PRT is a very good match with renewable energy sources.

Assessment of risks

Given the novel nature of the PRT industry, a robust assessment and pricing of risk is essential.
Risk analysis based on project-specific knowledge will be required to determine the total expected costs. This analysis should be conducted using an industry best-practice approach, combining Monte-Carlo simulation of key risks, risk workshops with the project team, supplier and construction industry engagement, and incorporation of experience from previous projects.

Bath Renaissance PRT design competition


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In 2009 ULTra (then still operating as Advanced Transport Systems Ltd) held an open competition for designs to provide solutions for the integration of PRT into the city centre of Bath in Somerset, south-west England, and a UNESCO World Heritage Site.

Arup took forward the initial concept of a city centre loop as part of a wider future network, including connections to park-and-ride sites and major employment areas on the urban fringe. The concept alignment took account of constraints including the city's historic buildings, the River Avon, the Bristol to Bath Canal, various highways, and the Great Western rail line. The firm's urbanism and landscape team, inspired by the city's Victorian railway bridges, developed a vision using contemporary lightweight mesh technology to produce an effortless flowing structure designed to provide a unique, Bath-specific solution (Figs 21–22).

The Arup entry was awarded first place in the competition, based on the judgment of an independent review panel consisting of local politicians and designers. Though not implemented, it serves as an example of how a PRT guideway can be configured to its environment.

Conclusions

The TV personality James May has tweeted *"I would happily travel the country in a Heathrow pod"*, while unsolicited comments from passengers are overwhelmingly favourable. Typical social media comments include *"The future has arrived!"*, *"Super cool!"*, *"Fun!"*, *"Very impressed"*, *"Greatest mode of transport known to man"*, *"Awesome!"*, *"I love these things"*, *"Amazing"*, *"A transport revelation"*, — comments supported by formal quality of service measure data gathered by Heathrow Airport Ltd. The score of 4.7 for frequency of service is the highest of any element of the Heathrow service, and this in a context where T5 in itself is rated as the best airport in Europe.

The successful operation of the *ULTra* PRT system at Heathrow and the other systems in Abu Dhabi and South Korea has highlighted the opportunities offered by this new form of transportation. PRT requires integration of vehicles, control and structure, with the guideway structure representing the system's dominant cost and therefore of special interest. The light weight of the vehicles allows new approaches to be taken to infrastructure design, with significantly reduced cost, weight, embodied energy, and visual impact.

The small scale of the resulting structure and the modular design provide considerable design flexibility. This was fully exploited at Heathrow, demonstrated by the fact that it was possible to design and install the whole guideway in an existing highly complex airport environment with no need for highway or services diversions. The reduced scale of the infrastructure also allowed modular off-site fabrication, which further reduced cost and enabled rapid installation.

The Heathrow design was captured in a design code that provides a starting-point for further PRT projects. Lessons were also learnt from the Heathrow installation itself, which will enable useful reductions in overall cost in future applications.

Practical operating experience of the complete system has demonstrated excellent reliability and availability, greater than with conventional surface transportation systems, and the exceptionally positive passenger response has been a significant feature. Practical experience provides considerable confidence that PRT systems will become very attractive as a new element in overall transportation provision in cities.

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This article is based on a paper prepared for future publication by the UK Institution of Civil Engineers.

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Project credits

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Image credits

1 ©*Heathrow Airport Ltd*; 2, 12–13, 15-16, 21–22 *Arup*; 3, 6, 9–10, 14, 17–19, 20, 23 ©*ULTra Global Ltd/Heathrow Airport Ltd*; 4 *2getthere*; 5 *Vectus*; 7 *ULTra Global Ltd*; 8, 11 *Arup/Nigel Whale.*

20. Heathrow pod in operation.

21–22. Arup design concept for PRT implemented in Bath city centre.

23. One of the Heathrow stations.

Luton Dunstable Busway

Location
Bedfordshire, UK

Authors
Kim Blackmore Alan Dennis Steve Fancourt Oliver Nicholas Kulvinder Rayat

1.

Background

Arup has been involved with the design of guided busways in the UK for over 20 years. In 1992 it prepared a feasibility study for one in Edinburgh's western corridor[1], and in 1995 undertook another study for a comparable link in Newcastle-upon-Tyne.

In 2000 the firm was commissioned to carry out a further guided busway feasibility study, this time on behalf of GTE for Oxfordshire Ltd, a scheme to provide a fast, reliable and congestion-free route into the centre of Oxford for public transport from surrounding towns and park-and-ride sites.

A year later Arup began to work with Cambridgeshire County Council, and in 2004 the firm developed the *Guided Busway Design Handbook*[2] for Britpave (the British Cementitious Paving Association, an "independent body established to develop and forward concrete solutions for transport infrastructure"[3]).

This handbook continues to be the only guidance on this subject, and has been used for guided busway design across the UK and throughout the world.

1. Bus in operation on the Luton Dunstable Busway.

2. Aspects of the Cambridgeshire guided busway.

2.

Cambridgeshire guided busway
One of the recommendations of the 2001 Cambridge-Huntingdon Multi-Modal Study, which examined transport links between the two towns, was the creation of a guided busway along the route of the disused railway that had once connected them. Arup's involvement began with a commission to assist with the project's business case and to assess its economic viability.

This required some value engineering of the concept so as to meet the clients' vision. The firm carried out a feasibility study and Environmental Impact Assessment — including landscape and ecological mitigation plans and a preliminary qualitative flood risk assessment — and became involved in early public consultations and liaison with stakeholders.

In close collaboration with the Parliamentary Agents, work was done on the technical aspect of the *Transport and Works Act Regulations 1992 (Rules 2000)* in preparation for UK Secretary of State approval. Arup defined the limits of deviation for the scheme and participated fully in a 10-week public inquiry that finished on 4 December, 2004.

The firm was subsequently commissioned to carry out the reference design and continue liaison with stakeholders to ensure that all concerns raised during the consultation were thoroughly addressed and any necessary mitigation measures put in place. This led to further detailed discussions with the Environment Agency, internal drainage boards, Network Rail, Cambridge City Council, parish councils, local authorities and public utilities companies.

Arup also led the procurement of the topographical survey and ground investigation for the entire 26km route, and this was followed by preparation of the technical content and specification of the Contract Documents, as well as the Works Information for the guideway.

The scheme went to tender as a design-and-build project. It was intended that Arup be novated to the successful design-and-build contractor, but at the best-and-final-offer stage, negotiations led to a design joint venture (DJV) being formed with Parsons Brinckerhoff (PB).

PB was tender designer for the contractor BAM Nuttall (formerly Edmund Nuttall Ltd), and had developed the precast concrete guideway proposal. It was agreed that PB continue to develop the tender concepts to ensure a high ride quality guideway.

Arup and PB carried out the detail design of the guideway and associated infrastructure for the entire route. The world's longest kerb-guided busway opened for public use on 7 August, 2011, with passenger numbers far exceeding expectations.

Inception of the Luton Dunstable Busway
While the Cambridgeshire guided busway (CGB) progressed, Luton Borough Council advertised for expressions of interest/PQQ (pre-qualification questionnaire) in its proposed Luton Dunstable Busway (LDB).

BAM Nuttall, Arup and PB decided to keep their design-and-build team together and responded, with the unique selling point that they were the only team to have recently designed, and were building, a precast concrete guided busway along a disused railway line — as part of the LDB was also planned to do. This matched all the aspirations of the LDB promoter and made the team a strong competitor — both aware of the pitfalls and with good ideas on how to improve on the already high quality of the CGB.

The LDB contract was duly awarded to BAM Nuttall in 2010, on the basis that the BAM Nuttall/Arup/PB team best understood the complexities of what was proposed. One fundamental difference between the two busways, however, was that the CGB was a rural route whereas LDB would be an urban development.

The CGB had few access points, which resulted in a linear approach to construction, with 15m long precast concrete ladder beams laid on foundations at 7.5m centres using a bespoke gantry running on the previously placed guideway. This limited the rate of progress on site due to the output of the single gantry. LDB, by contrast, was planned to have numerous access points, and it was decided at the tender stage to keep the precast beams as short as possible and, in particular, not to use bespoke placing equipment that would inhibit progress.

Design overview

Overall, the LDB route extends some 14.5km from Luton Airport to Houghton Regis (Fig 3). Within this dedicated transport corridor is the Arup-designed 10km of busway between the town centres of Luton and Dunstable (Fig 4), comprising 7.4km of guideway and 2.6km of unguided carriageway. The link between these communities improves connectivity as well as travel times, and the scheme is seen as a key catalyst for the urban regeneration of the two town centres. Designed and built for Luton Borough Council (and Central Bedfordshire Council), the new busway relieves traffic congestion by providing a dedicated route for quick and efficient public transport through the urban area along the disused Luton-Dunstable railway corridor. The project also features the added amenity of a cycleway.

The work included seven new bridges and the refurbishment/reconstruction of three existing and four new high-specification bus stops, and a major bus interchange at Luton railway station. This provides links to Luton town centre, the rail network, and easy access to Luton Airport. Nine junctions were also designed and built to allow the guideway to pass along the route. Two of the junctions are in locations where the disused

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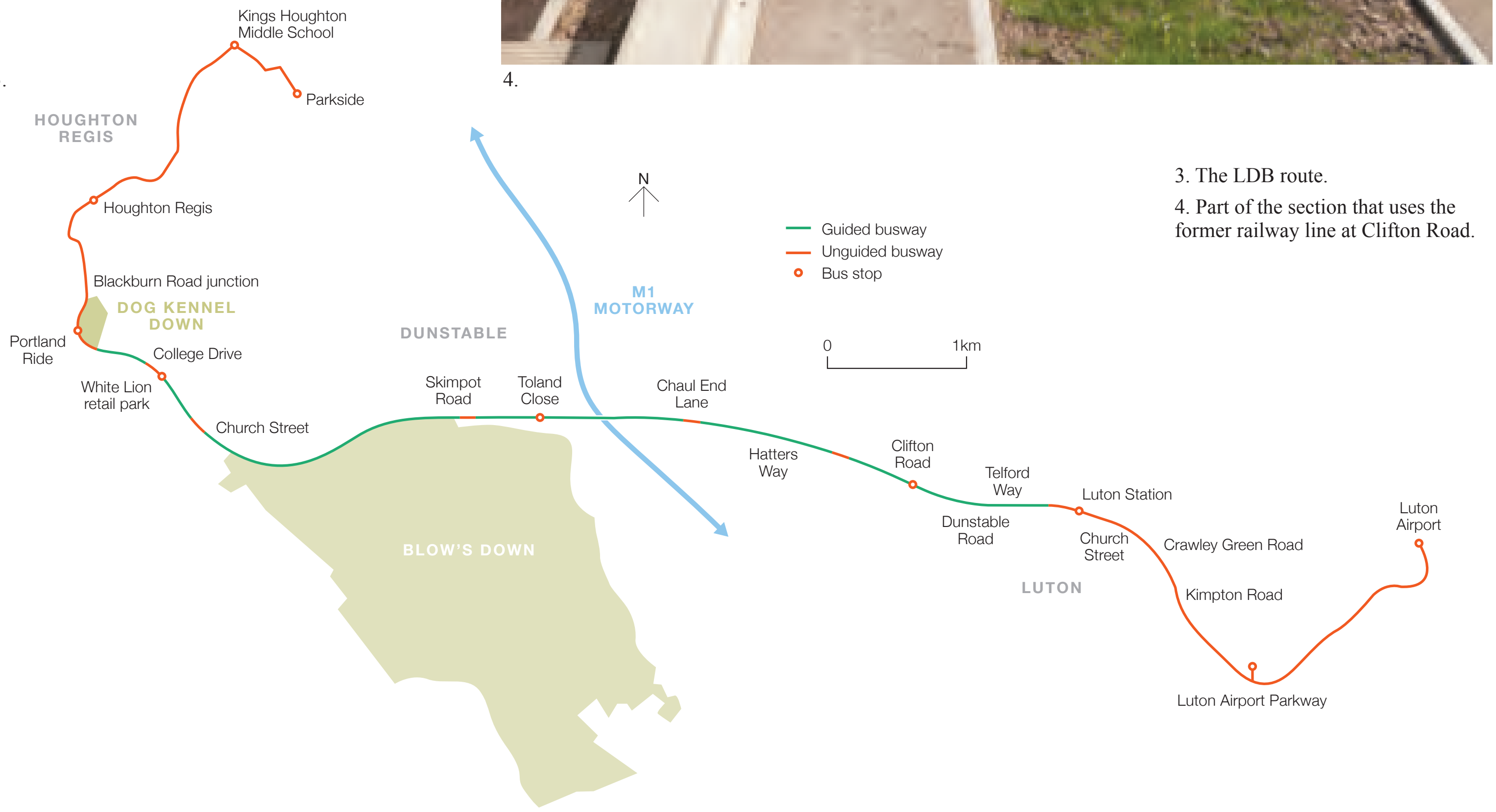
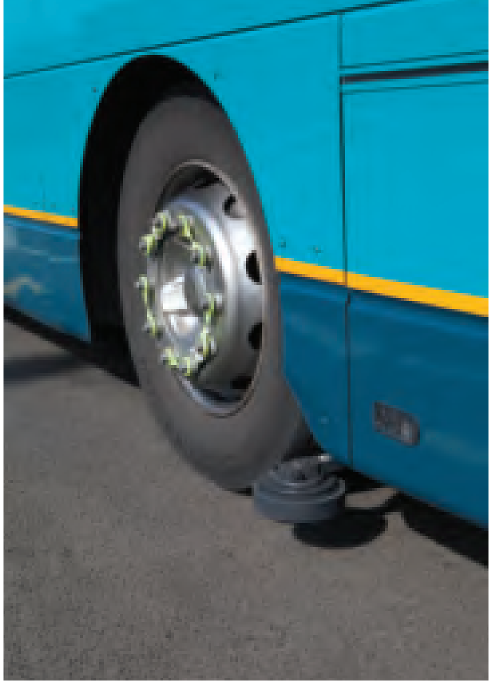


3. The LDB route.

4. Part of the section that uses the former railway line at Clifton Road.



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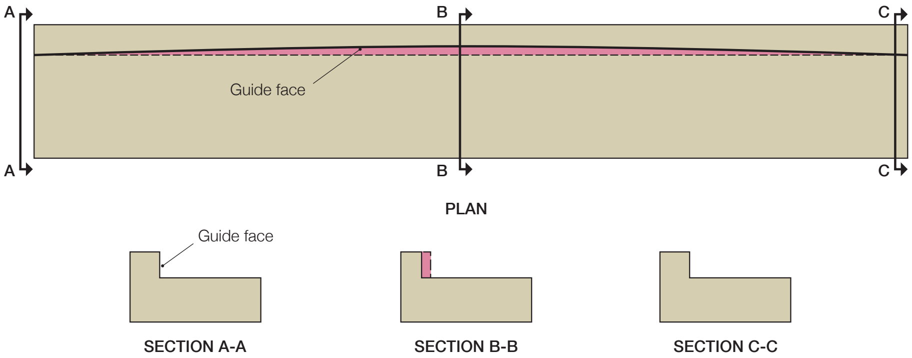

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railway used to pass over existing highways in Luton town centre. Here, the route was cleared to street level by demolishing the bridges and removing embankments. This not only changed the street scene but also freed-up people's mobility.

The design scope of work for the LDB was distributed differently from the CGB, with Arup being responsible for design of the main bus alignment, the junctions, the guideway structure, Luton railway station bus interchange, and all of the project's environmental works.

Guideway design

In the 7.4km guided section, the buses use a 2.6m transverse gauge corridor formed from 6m long precast concrete beams. Standard buses, fitted with two small guide wheels to their front axles (Fig 5), can join and leave the track, and travel on it in both directions smoothly and safely. There is no need for specialised vehicles, and the modified buses can also drive on normal public highways. The alignment design parameters were set out in the contract documents provided by Luton Council, with further guidance from highway design standards in *TD 9/93*[4] and the *Guided Busway Design Handbook*.

The beams and foundation pads were all cast on site in a temporary precast concrete factory, so as to minimise the environmental impact and also keep production of the key components in house using direct labour.

To ensure cost-effective beam production, the number of horizontal alignment radii was limited, and the design was rationalised to four (550m–1880m); as the terrain was suitable, there was no need to consider vertical curvatures of running surface beams.

To create the busway route horizontal curves, the beams were cast with the faces of their upstands slightly concave in the horizontal plane, the depth of the curve corresponding to the radius of curve of that particular section of the route (Fig 6). The outer faces of these beams, however, were still cast straight. To facilitate construction, beams were delivered to the guideway site on standard flatbed trucks and offloaded into position by a *Hiab* loader crane. Keeping the beam weight to no more than 4.5 tonnes ensured easy and safe handling within standard equipment compatibility (Fig 7).

The design speed for the guided section is 85kph, which reduces to 50kph near junctions and pedestrian crossings to allow safe passage through the entry and exit flares. Junctions are signal-controlled and the buses are fitted with transmitters to trigger traffic light priority to the busway as they approach (Fig 8).

Traditional highway transition curves were eliminated, as it would not have been practicable or cost-effective to make the precast concrete beams fit to curves that changed proportionally to their length, ie a clothoid. Special series of beams could have been constructed for individual transition curves, but this would have had a major impact on the cost, programme, and working tolerances.

To compensate for the lack of transition, a series of larger radii curves was placed before and after curves that would in theory require a transition. The larger radii curves assist passenger comfort by smoothing the entry and exit and gradually introducing the lateral force exerted to the vehicle.

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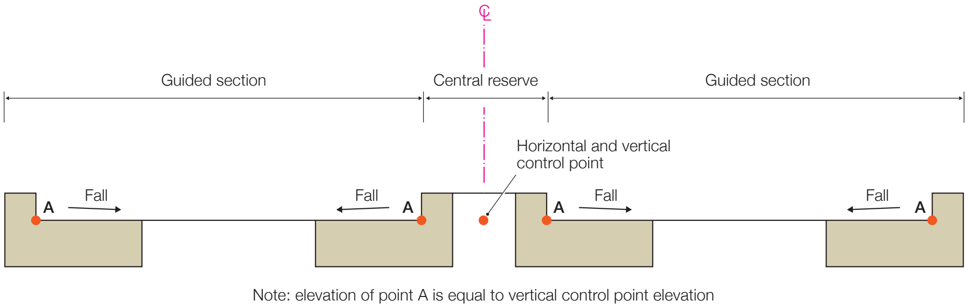
5. Standard buses are fitted with a pair of guide wheels.

6. Plan and sections of typical beam used in curved part of the guideway (dimensions exaggerated for clarity).

7. Beams delivered by standard flatbed trucks.

8. Buses are fitted with triggers to control junction lights.



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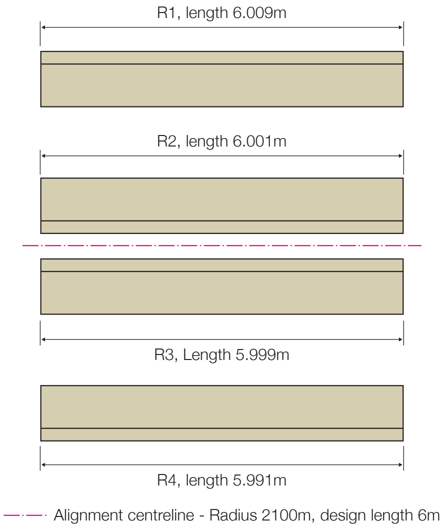

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9. Cross-section of guideway, showing setting-out points.

10. Slightly varying lengths for the four beams making up a 2100m radius.

11. Typical curved section under construction.

12. Completed guided section between Toland Close and Skimpot Junction.

First, the horizontal alignment was designed using a combination of the standard radii selected. As the beams were a uniform 6m long, all elements of the alignment needed to be multiples of 6. They also needed to fit between the land boundaries, and to conform to the requirements of the *Guided Busway Design Handbook*.

The horizontal and vertical control point of the alignment was at the midpoint of the central reserve at the guideway running surface level. However, the setting-out information for the individual beams was provided at the beam edges at the top of the pad foundation level, 0.34m below point A (Fig 9).

Using standard 6m straight beams to create the horizontal curves would have increased the gap width between beams on the outside and decreased the gap on the inside. As this was unacceptable, straights of different lengths (Fig 10) were defined so as to limit the gaps between beams to an acceptable range — maximum 25mm and minimum 2mm. As the beam joints were 6m apart, the actual length of the beams was 5.987m. The initial gap in the joint was 13mm, based on the following tolerance criteria: construction 7mm, thermal 3mm, and settlement 1mm. The available tolerance for the vertical alignment on the gap between two beams was (25-(11+13)) = 1mm.

To achieve the acceptable gap between beams, calculate surface irregularity, and provide setting-out information, Arup developed a process that became known as “segmentation”. With the horizontal and vertical alignment defined, this used a combination of different software (*MX, AutoCAD, Inroads and Excel*) to represent the beams.

The process of spacing beams and checking gaps was repeated until the acceptable gap for each beam was achieved. Once the joints were finalised, the process of creating the drawings and an *Excel* sheet for setting-out information commenced. The segmentation drawing was produced with this and the *Excel* sheet was submitted as setting-out information for the joints and beam centre. These drawings were passed to the contractor and the precast units laid (Fig 11).

The finished result is a smooth running surface on which the buses provide maximum passenger comfort and excellent ride quality (Fig 12).

13. Beams are connected to pad foundations using elastomeric bearings and steel brackets.

14. Pad foundation being lowered onto a layer of wet concrete.

15. Hatter's Way section of route.

16. Bus speed vs elapsed time along sections of the route.

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Value engineering

The beams sit on precast pad foundations via elastomeric bearings, with steel brackets restraining the beams and transferring all horizontal loads to the foundations (Fig 13). In the original design, the pads were at 3m centres. Each is supported on a layer of concrete blinding with a minimum thickness of 75mm (Fig 14).

At the end of the detailed design period, Luton Borough Council found that it would need considerable savings on the capital cost for the project to continue to construction. Arup was asked to review the structural design of the guideway and associated infrastructure, and to identify value engineering options where the guideway cost could be reduced by challenging the employer's requirements, but without compromising the project objectives.

After consultation with the contractor, the team agreed a prioritised list of actions to reduce construction costs. Key amongst these was to use a defined bus loading regime to reduce the design loads from the standard UK highways design loading criteria. This was possible due to the specific and predictable use of the guideway over its design life.

Arup proposed a new loading regime with the client's anticipated weekly total of journeys being used to calculate a total amount of journeys and loads to be used in fatigue calculations. Other vehicles that would use the guideway, eg for construction and maintenance, were also reviewed and included in the new design loads.

Due to the reduced loads, the value-engineered design made possible the removal of the middle pad in all standard areas of guideway, giving a considerable saving in the amount of foundations and bracketry. This saved the client capital cost expenditure and protected the construction programme. Non-typical locations, such as areas of frequent braking, over bridges, and pedestrian crossings, retained the original design due to higher fatigue loads and to protect the overall project programme, as they would need more time to redesign and redraw than the standard beams.

By the time the value engineering was carried out, the contractor had already begun to cast beams and pads for the original design, so these were redeployed in the guideway's non-standard areas.

The increased effective span of the precast beams, from 3m to 6m, required some redesign with the revised loading. Arup added loose reinforcement to the originally detailed prefabricated reinforcement cages to keep crack widths below the maximum limit, and this enabled the contractor to use the cages that had already been procured, fabricated and delivered to the precasting yard. Deflections under static loads were also calculated to be used in the dynamic design of the value engineered design.

The primary concern of the value engineered design was its potential impact on ride quality, which was always the client's main driver. Changing from 3m to 6m spans heightened this risk; the longer span not only increased the maximum deflection of the beams, but also altered the passing frequency of the bus axles over the supports, making resonant excitation of the bus subsystems (tyres, suspension, chassis and seats) a concern due to its influence on ride quality.

Arup analysed the design using the non-linear analysis package *LS-DYNA*, modelling the bus chassis, tyres and suspension as an idealised connected series of masses and springs derived from manufacturer data. The team was able to employ *LS-DYNA* routines typically used for train wheel to track interaction analysis to analyse the vertical accelerations that people sitting on the buses would experience. The results indicated that the effective stiffness of the concrete beams, bearings and foundations had the most effect on the sensitivity of the results.

16.

The analysis showed that the ride quality for single and double-deck buses at the top speed of 85kph was either in the highest band of comfort defined by *ISO 2631-1: 1997*[5] ("not uncomfortable") or marginally into the second highest band ("a little uncomfortable") depending on assumptions. This was deemed acceptable as the buses would only reach the highest speed for 10% of the overall journey distance, and then just for very short periods of constant speed (Fig 16). The analysis demonstrated that the design gave similar levels of comfort to the CGB, for which Arup had also completed on-site vibration testing and non-linear analysis, and which was found acceptable to passengers since it opened in 2011.

By critically reviewing the employer's requirements and the dynamic analysis of the revised scheme, Arup proposed a design that saved approximately £3M of construction costs. Waste was also minimised by enabling the contractor to use all components manufactured before the value engineering exercise concluded.

Site support

The provision of site support from the Arup/PB DJV on the LDB was different from that on the CGB, where there had been a more prominent site team supporting the contractor to ensure design intent was being carried out.

On the LDB there was no permanent site team. In the fee negotiations with BAM Nuttall, a lump sum fee was agreed to cover the detail design and support roles, so the site support was organised on a rota basis in consultation with the contractor's two-weekly and four-weekly look-ahead construction programmes. The contractor was informed when Arup/PB would be on site, and to allow the DJV to compliantly certify that the works were constructed to the design intent, the appropriate site representative had to be on site at least once a week during construction to review their area of responsibility. They also had to attend site for critical construction activities.

The senior DJV site representative was the main contact with BAM Nuttall. He was responsible for managing the site representative team during the technical query process, providing clarification and information on the design and organising experts to be on site when BAM Nuttall required a quick response to any critical issues. As the design manager during the detailed design, the senior site representative brought a wealth of knowledge from the design phase and had already built up key relationships on both the design and contractor sides. This worked effectively when organising responses to key site issues.

Members of site support teams, in particular the senior site representative, must be good communicators in order to foster confidence in and good relationships with the contractor. This enables the contractor to make contact and discuss issues, that might initially seem to be minor, before they turn into project-critical issues.

Having a site team that had already been involved in the scheme design proved very helpful, enabling reinforcement of the joint problem-solving approach fostered previously between BAM Nuttall and the DJV during the design. This was especially important as some of the DJV site team and contractor's site team had not worked on the project during the design phase.

Having a non-full time resident site team did mean that the site representatives had to be flexible with their workload, and attend on days other than their rota days at reasonable and practical notice if a site issue arose that needed immediate attendance to resolve.

Environmental design

With any large transport project, concern for the associated environment and natural habitat resource contributes significantly to the success of the scheme and the lives of the people who use it. To achieve a balance between the need for better transport and consideration of the landscape and wildlife assets required a fully integrated environment/engineering design team.

The abandoned rail corridor was notified as a County Wildlife Site and passes by Blow's Down, a continuation of Dunstable Downs in the Chiltern Hills. Blow's Down is a designated Site of Special Scientific Interest, due to its unique chalk grassland habitat and the species this supports. Dog Kennel Down, also nearby, is a further area of valuable chalk grassland habitat.

This railway was a victim of the 1960s reduction of Britain's network known as the "Beeching cuts", and since then statutorily protected species like slow worms and bats, as well as badgers (whose setts are protected), bird species, flora unique to grass chalkland and associated invertebrate assemblages, had all become part of the wildlife mosaic extending along the route and beyond into the surrounding Dunstable Downs landscape. Mature vegetation and trees (screening the corridor from

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neighbouring houses) had grown to line it, and invasive plant species such as Japanese knotweed had become established. This naturalised rail corridor now formed a primary habitat corridor connecting otherwise discrete areas of chalk grassland.

The challenge facing the Arup team was to ensure that this diverse ecological and landscape resource identified in the Environmental Statement was fully considered in the scheme's design and delivery. BAM Nuttall was responsible for ensuring that the construction works, and their maintenance and monitoring, complied fully with all existing UK and EU legislation concerning environmental protection.

This demanded a carefully co-ordinated approach which protected notable flora and fauna as well as the surrounding landscape features during construction. The approach also had to incorporate appropriate wildlife mitigation and compensation to ensure that there was no net loss, and preferably introduced gains, to biodiversity.

Prior to the design-and-build phase of works, three documents served as the "golden thread" that would guide the approach taken: the Route Biodiversity Action Plan, the Code of Construction Practice, and the Landscape and Design Strategy.

This "golden thread" effectively extended the planning requirement for protecting and mitigating, or otherwise compensating, biodiversity impacts from the construction. It required input from Arup landscape architects and Arup ecologists throughout design development and construction.

To guide how the construction was to be undertaken in respect of the environmental resource and then how the wildlife and landscape would be managed post-construction, two documents were produced, both informed by the Route Biodiversity Action Plan and the Landscape and Design Strategy. BAM Nuttall devised a Construction Environmental Management Plan while Arup produced the supporting Landscape and Ecological Management Plan. To ensure that day-to-day management was in line with the guidance in these over the two years of construction, the contractor appointed an environmental manager from Arup and an environmental clerk of works.

The Landscape and Ecological Management Plan guided the project for both construction and operation, being developed to be relevant for five years beyond completion. It set out the basis for all ecological mitigation needed to compensate for partial loss of land and ecological resources from the railway corridor, and was supported by extensive pre-construction surveys of the route corridor and surrounding habitats.

17. Telford Way.

18. Upgraded railway corridor and cycle route.

19. Around 400 slow worms (*Anguis fragilis*) were relocated.

20. Area of chalk grassland near M1 bridge.

21.

Environmental aims and achievements

The key aims for the five-year post-construction period were to:

- protect existing and retained habitats along the guideway route
- provide ecological mitigation and enhancement measures targeting specific sites, habitats and specific species, especially protected species
- incorporate and record the design proposals for the landscape and ecology mitigation areas created
- ensure that replacement and compensation areas contain appropriate species and habitats to replace lost resources in the long term
- set out management and monitoring tasks and targets.

Local people travelling the busway today now enjoy a green corridor that passes sensitively through the unique chalkland landscape of Dunstable Downs. Environmental successes less obvious to passengers, but nonetheless part of this project's sustainability credentials, include:

- the translocation and safeguarding of around 400 slow worms (Fig 19)
- replanting with native tree and hedgerow species to reinforce and reinstate the Busway as a green corridor, including continuous grass strips along the length of the guideway
- thorough eradication of Japanese knotweed
- enhancement of nearly 4ha of semi-improved chalk grassland at the Hay Meadows, involving translocating several hundred square metres of species-rich grassland turfs known to support common and pyramidal orchids
- enhancement of reptile habitats at the eastern extent of the scheme
- installation of a network of bat boxes to boost local populations
- design of badger-friendly exclusion fencing along the length of the scheme
- wildlife tunnels from side to side beneath the guideway to maintain permeability of the infrastructure to wildlife, including reptiles and small mammals
- a materials management strategy where topsoil was re-used.

Opening

The Luton-Dunstable busway was opened to the public on September 25, 2013, by the UK Transport Secretary, the Rt Hon Norman Baker MP (Fig 21). He noted that the busway would be "beneficial to Luton, environmentally and economically", and went on to state that this new dedicated transport corridor provides a quick and efficient way for passengers to travel between two main town centres, and makes good use of the disused Luton-Dunstable railway corridor. The busway now stands as the second longest in the world and the longest in an urban environment.

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Authors

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Project credits

Project owner: *Luton Borough Council* Client and contractor: *BAM Nuttall Ltd* Joint venture partner and bridge designer: *Parsons Brinckerhoff* Civil and structural engineer, and environmental consultant: *Arup — Rahul Bagchi, Yiannis Baltagiannis, Oliver Barnett, Jess Batchelor, Joseph Bearne, Chris Bellingham, Simon Birkbeck, Kim Blackmore, Andy Boyle, Phil Brand, Grainne Breen, James Brock, Austin Brown, Carol Brownridge, Rory Buckley, Andrew Clarke, Tony Clifton, Ian Davis, Alan Dennis, Ajminder Dhani, Jenny Dunwoody, Michael Evans, Steve Fancourt, Ian Fiddes, John Griffiths, James Hargreaves, Kate Harrington, Rob Harrison, Neil Harwood, Stephen Haynes, Darren Hickmott, Rachel Hotston, Pat Howard, David Hurton, Phil James, Thomas Johnson, Jim Keyte, Areeb Khan, Joe Kingston, Simon Lacey, Yi Jin Lee, Kieran Littley, Angus Low, Neil Mackay, Jamie MacSkimming, Oliver Nicholas, Rachel Oates, Declan O'Shea, Allen Paul, Ellen Pickett, Ben Price, Richard Price, Oliver Pye, Kulvinder Rayat, Henrietta Ridgeon, Jake Sidwell, Andy Turner, Gary Walker, Natalie Walker.*

Image credits

1, 4–5, 8, 12, 15, 17–18, 21–22 *Ian Cooper* 2a-d *James Prestage* 3, 16 *Nigel Whale* 6, 9 *Rahul Bagchi/Nigel Whale* 7 *Oliver Nicholas* 10 *Kim Blackmore/Nigel Whale* 11, 13–14 *Alan Dennis* 19 *Natalie Walker* 20 *Oliver Barnett.*

21. Opening ceremony at the Luton station interchange.

22. White Lion retail park stop.


Luton & Dunstable busway
1955
ARRIVA
KX12 GZS

Wire-free technologies for light rail

Author
David Stuart-Smith

What is "wire-free"?

Electric traction using overhead wires has almost always been used for light rail (LR) systems since horse-drawn and steam trams were abandoned. While some novel solutions were trialled around the turn of the 19th and 20th centuries, the only significant enduring alternative has been cable operation (as famously in San Francisco) and this is not a serious option for new systems.

This paper focuses on new or reinvented technologies that enable electric LR systems to be operated without the need for overhead line electrification (OLE) over some or all of the route. These technologies generally fall into two broad categories: those that use on-board energy storage, and those that can transfer energy to the vehicles (LRVs) without needing OLE.

For the present purposes, LR systems are taken to be those that include some street running, so conventional metro-style third-rail systems are excluded. In addition, technologies that rely on liquid or gaseous fuels as on-board primary energy, supplying either an internal combustion engine or a fuel cell, are not considered here.

Why wire-free?

Aesthetics

During the first half of the 20th century, street tramway systems flourished, with the attendant wires tolerated as a necessary evil in the provision of good public transport. Nowadays the visual clutter of OLE is far less tolerable in locales of high aesthetic value, either historic precincts where the buildings might predate the industrial use of electricity by many years, or modern cityscapes where clean, uncluttered vistas are valued by city planners. While other reasons exist, as set out below, where a wire-free solution has been pursued, aesthetics is almost always the primary reason given.

Existing overhead encumbrances

In planning new or extended LR lines, existing low overhead structures like bridges and viaducts can significantly constrain route choice. Generally a minimum OLE height above the road surface will be mandated for public safety, and several factors contribute to setting it. These will inevitably include consideration of the tallest allowable road vehicle and the clearance from it to the wire. A typical single-deck LRV has a significantly lower roof height than the tallest allowable road vehicle, so adopting a wire-free solution, even for relatively short sections, will allow route options to be considered that would otherwise be excluded.

One alternative has been to compromise on the OLE height at such encumbrances, but in Melbourne, Australia (Fig 1), for example, road vehicle wire strike at low bridges is a significant cause of disruption and delay, with obvious safety implications. In these increasing litigious times a more risk-averse strategy is desirable. Similarly, a wire-free solution can avoid conflicts with routes that are used by open-top tourist buses.

Existing clearance constraints

Clearance constraints like preserved trees, historic shop awnings, narrow streets without space for OLE masts, etc, are issues that can be avoided with wire-free. Some may be side-stepped by pruning trees or altering buildings, but actions like these can detract from the streetscape and cause controversy to the point where a project may be delayed by protracted community consultation. A wire-free solution can be an easier path.

Service relocations for OLE masts

In a mature city, the space beneath road pavements and footpaths is usually crowded with generations of buried infrastructure (possibly including relics of long-since-removed tram systems). A portion of the road reserve will generally be allocated for street lighting columns. Although this will not be for exclusive use, and joint OLE and lighting poles are practical, adding OLE poles will likely require some compromises regarding their positions, and inevitably some service relocations.

A wire-free solution relying on on-board energy storage will usually need little infrastructure beyond the basic track-form, apart from stops. While adopting wire-free purely to avoid service relocations would be unlikely, if it is being considered for other reasons the benefit in avoiding some service relocations might reasonably be factored into the decision-making. Conversely, a wire-free solution relying on energy transfer to the LRVs without OLE could require significantly more in-ground infrastructure, and so more service relocations, than a traditional OLE-based system.

OLE unreliability at junctions

The complex geometry and inherent compromises required for OLE through junctions on street-running LR routes introduces failure modes not seen on plain line OLE, and increased risk of failure.
If wire-free is possible for a system, making its complex junction areas wire-free would seem a particularly useful way to increase

1.

1. Very low overhead line with minimum clearance to the underside of a heavy rail viaduct in Melbourne, Australia.

Technologies for wire-free operation

Introduction

Two broad categories of technologies exist for wire-free operation: those using on-board energy storage, and those that transfer energy to the LRVs without OLE. The latter further divide into those using ground-level electrical contact, and those that transfer the energy inductively without the need for electrical contacts.

On-board storage technologies

Those with potential application for LR include:

- electrochemical: various established and emerging battery chemistries
- electrostatic: double-layer capacitor (“supercapacitor” or “ultracapacitor”)
- flywheel
- compressed air.

As well as facilitating wire-free operation, on-board storage can also improve energy efficiency through effective recovery of regenerative braking energy.

Segmented contact rail

Several of these systems are presently available. All have a top contact third rail (in one case a fourth rail) embedded between the running rails at pavement level. The contact rail is segmented and only those segments fully under the LR vehicle are energised. Switching can be either by active control of line-side switchgear or by a means inherent in the contact rail design.

Contactless (inductive) power transmission

At least one system, now only on a demonstration track, has the energy inductively coupled to the LRVs from coils in the track bed. Such a system can have continuous energy transfer, although the more likely configuration would be to provide charging at stops and high power requirement areas, and rely on on-board energy storage for running between the charging points.

Open vs proprietary architectures

On-board storage systems that use conventional pantographs to recharge from overhead lines when in wired areas are essentially “open architecture”.
In these, vehicles can be mixed and matched from multiple vendors, whereas systems relying on segmented third-rail or inductive coupling are generally proprietary single-vendor solutions. Sometimes the vehicle-mounted element can be provided to fit vehicles from other vendors, but supply of these elements is generally restricted to the fixed-system vendor. The implications of committing to a single-source supplier must be considered when procuring such a system; questions of system obsolescence and vendors’ business continuity through the network’s lifetime must be considered.

Marginal cost factors and scaling factors

Generally, the investment in on-board energy storage directly relates to fleet size. However, while a wire-free section by definition will not require investment in overhead wire, charging points at stations and other locations will still be needed. As noted below, the load factor may have to be dealt with; the parameters of the charging points will be a function of several factors, including traffic density. Conversely, the cost of a segmented third-rail system will largely scale with the track length that includes it. While vehicle-mounted equipment is required, it is not anticipated to form a large portion of the total vehicle cost.

For an inductively-coupled system, significant costs are likely on both sides. Clearly, major investment is required for the fixed infrastructure — scaling with the route length — and the vehicle-mounted part is also likely to be more costly than a simple pantograph or third-rail shoe system. This therefore introduces a fleet-dependent element to the total cost equation.

Interoperability with wired sections

No wire-free technology is inherently incompatible with conventional wired sections; systems based on on-board energy storage can readily use normal pantograph equipment to draw power from a wire or conductor rail to recharge the on-board stores. Controls will be required to ensure that the pantograph is lowered and raised appropriately to avoid entanglement or the unintended operation of automatic lowering devices designed to mitigate dewirements.
The pantographs also need to be suitable for frequent raising and lowering.

Stray current

Modern materials and techniques to insulate rails in street running systems have significantly reduced stray current. For on-board storage and inductive coupling systems, the DC traction system electrolysis risk is further reduced to zero. These systems do not use the running rails for traction return in wire-free areas, and should be able to operate with the rails earthed and insulated from the traction return.

reliability and reduce OLE maintenance. The author is not aware of such strategies being deployed, and the incident risks associated with lowering and raising pantographs (the apparatus on LRV roofs to draw power from the OLE) at the correct points would also have to be factored into any such decision.

Special events

Where part of a proposed LR route might accommodate a regular if infrequent event like an annual parade or a motor sport street circuit, going wire-free might mitigate the complications of such an event.

Safety: fallen conductor risk

Direct current (DC) electric railways often operate with little margin between maximum load current and minimum fault current. This makes detecting a fallen conductor quite challenging, particularly if it doesn’t land on the running rails that provide the traction return. While the catenary systems generally used by heavy rail may continue to support a broken contact wire above ground, a broken trolley wire will always fall to the ground but may not contact the return rails and thus not provide the low-resistance fault needed to initiate fast disconnection of power by the protection equipment.

Broken wire incidents may stem from causes within the rail system, such as spark erosion of the wire at points of poor geometry, or from external triggers like overheight road vehicles and falling tree branches. Adopting a wire-free system can effectively eliminate public safety risk from fallen OLE conductors.

System parameters to consider

On-board energy storage

The amount of energy that must be stored, and so the viability of this approach, will be significantly influenced by the parameters of the particular system. First, large height differences along the alignment will require more energy, as the amount needed to climb an incline is directly proportional to its height. While it will likely be possible to recover some of the energy through regenerative braking in descent, there must still be enough in the store to complete the climb. As LRVs have a relatively low rolling resistance, this can have a very significant impact on energy store size. It should be noted that gradient and speed of ascent are less significant than change in elevation.

Even if the vehicle is not moving, the HVAC (heating, ventilating and air-conditioning) system will still be running, and the energy for it must also come from the on-board store. Accordingly, local climatic conditions and the amount of HVAC required for acceptable passenger comfort must be factored into sizing the energy store, which has to be for the worst design case, not the average. For a system with shared street running, the potential to be held up between charging points by traffic congestion must also be allowed for.

Service frequency considerations

Infrastructure-intensive solutions will be more affordable on sections with high service frequency and thus high asset use. Conversely, if service frequency is low, on-board energy storage is more likely to be economic.

Development of battery technology continues: Siemens[3] offers two new Li-ion types, a "standard" iron-phosphate type battery and a "premium" lithium-titanate type. While these developments are positive, the finite availability of lithium is an emerging concern in this technology. A significant increase in lithium demand (as might be driven by growth in the private electric vehicle market) could result in a sharp price increase.

Electrostatic (capacitor) storage
While some of the earliest electrical experiments involved electrostatic storage (the Leyden jar was invented in the mid-1740s[4]), until fairly recently the volumetric energy density of electrostatic storage made it impractical for traction applications. The development of the double-layer "supercapacitor" or "ultracapacitor" (DLC) around 10 years ago represented a transformational change[5] (Fig 2).

DLCs can now provide around 10% of the energy density (mass and volumetric) of Li-ion batteries (though this is still only about 0.1% of the volumetric energy density of petrol). However, they have two distinct advantages: they can deal with charge and discharge rates (power) 10–100 times that of a comparable electrochemical battery, and endure 100 times as many charge/discharge cycles without degradation. But notably the low internal resistance of these devices results in a very high fault level, so this must be managed carefully to ensure safety.

Hybrid systems
Considering the strengths and weaknesses of both Li-ion batteries and DLCs, the development of a hybrid traction energy store is a logical development. This path has been pursued by Siemens (*Sitras*® hybrid energy storage (HES) system)[6] and CAF (*ACR Freedrive*)[7], bringing together the high power rating and charge-discharge cycle capabilities of DLC with the higher energy density of Li-ion batteries. With recent significant advances in electrochemical and electrostatic energy storage capabilities, it is not unreasonable to anticipate that further improved technologies will emerge.

Flywheels
While there has been some interest in flywheels for on-board energy storage, the only known working LRV examples are those made by Parry People Movers[8] — the Stourbridge Town branch in the UK West Midlands, and others. The energy stored is a function of the square of the angular velocity of the flywheel, and so high energy densities are only achieved with very high angular velocities using high-strength carbon fibre rotors. That said, the Parry People Movers' service has been in operation since 2009, using relatively low-tech 500kg flywheels working at 2500rpm. Alstom also tested a demonstrator on the Rotterdam Network over the Erasmus bridge. While this was successful, further development did not proceed.

On-board energy storage technologies

Battery vs DLC
Historical battery applications
Secondary (rechargeable) batteries have been the default choice for storing electrical energy from the early days. In particular, the lead-acid battery became ubiquitous. More recently, nickel-metal hydride and lithium-ion (Li-ion) batteries have come to the fore in portable devices like power tools and mobile phones. Batteries have a significantly lower energy density (volumetric density and, in particular, mass density) than liquid fuels.

The first trams in Bendigo, Australia, in 1892 were battery-powered (but within three months were replaced by horse-drawn trams)[1]. In New York City some minor lines also used storage batteries. Then, more recently during the 1950s, a longer battery-operated tramway line ran from Milan to Bergamo, Italy[2].

Battery technology
To achieve energy storage, secondary batteries need also to use quite active chemistries. This in turn leads to unwanted reactions, so electrochemical batteries generally have a limited number of charge-discharge cycles before storage capacity has diminished to the point that battery life is considered to be at an end. This technology is also inherently not ideal for high charge or discharge rates — high current flows tend to mean high temperatures, which generally are detrimental to the life of most secondary batteries. This must be considered in hot climates, as effective cooling of the battery may then itself require significant energy.

While the lead-acid cell has been the mainstay of secondary battery technology for many years, more recently the emergence of the Li-ion cell with almost 10 times the energy mass density has been a step change.

Compressed air
While often discussed as a theoretical possibility, and previously implemented using the Mekarski system[9] in a few first-generation French tramways (eg Nantes 1879-1917), no operating examples using this technology are known.

Gradients and HVAC
Gradient and HVAC loads are two specific issues to carefully consider when sizing on-board energy storage. The low inherent energy losses of steel wheel on steel rail mean that a relatively modest input is needed to move a rail vehicle on a level track, even less if the braking energy can largely be recovered. While gradient steepness does not appreciably change the energy needed to negotiate it, the energy required is directly proportional to the height difference. Given that what goes up must come down, this energy can be recovered, but there must be enough in the energy store to carry the vehicle to the top of the incline.

Unlike traction energy which can be recovered during slowing or descending an incline, HVAC load is all one way. It depends on external ambient conditions, the locally accepted conditions for passenger comfort, and the numbers of passengers and door openings. If traffic or other circumstances cause the vehicle to stop, while the traction load will be zero the HVAC load will continue, and such contingencies must be factored into system design.

Managing the "empty tank" contingency
While it is entirely normal for a liquid-fuelled vehicle to arrive at the end of its journey with plenty still in the tank, the cost and density of both batteries and DLCs necessitate only minimal reserve capacity. Accordingly, a real risk exists that the combination of extended delay plus ongoing HVAC load will reduce the store to the point that the next charging station is out of reach.

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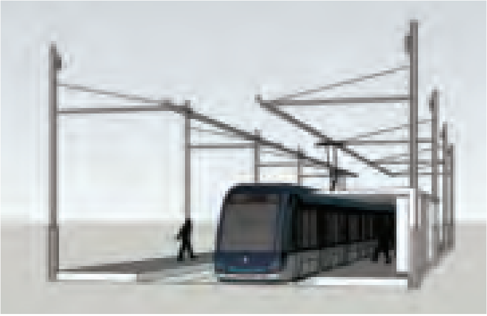

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4.

2. Alstom DLC module.

3. Rigid conductor rails supported from cantilevers.

4. Rigid conductor rails supported from head-spans.

Good planning can readily address this contingency, either with rear assistance from the following vehicle or by using a hi-rail (highway/rail) tow vehicle.

Power supply and load factor

While the on-board power demand of a LRV using on-board storage will be essentially the same as for a conventional vehicle supplied from OLE, the infrastructure situation is quite different. The total energy used might be similar, but if it is delivered in short bursts while the vehicle is at charging points the instantaneous power could be higher by a factor of 10.

This poor load factor and high peak demand may mean that the charging points cannot practically be supplied from the local distribution system. Notwithstanding this, the capacity of elements such as the pantograph may limit the charging current to something similar to the maximum accelerating current. This will mean that the charging load is less onerous, but will also limit the energy that can be transferred while the vehicle is at a passenger stop.

Connecting charging points together via insulated cables in ducts in the track bed can allow the temporal diversity of the loads at the various charging points to be exploited to produce a better load factor at a single supply point. While this approach reduces the number of traction substations, power reticulation cables (typically 750V) between stops are an added cost. If the rails between charging points are to be isolated and earthed to reduce electrolysis risk, then negative cables will also be required along the route.

Another approach would be to include energy storage equipment at charging stations, allowing a relatively modest continuous load on the network to be translated into a high-power, short-time, charging supply to the vehicles.

Life cycle cost factors

Unlike more conventional capacitors, DLCs deteriorate with time and charge/discharge cycles; 10 years is a typical minimum life. Accordingly both batteries and DLCs will require periodic replacement and the vendors will quote expected life cycles for the equipment offered. Both batteries and DLCs are usually supplied as modules and so vehicle down-time for the replacement would be relatively modest.

It would be expected that the charging station equipment (with the possible exception of energy stores) would be essentially the same as conventional substation equipment.

Skids | short OLE for charging points

Where wire-free sections are mixed with conventional OLE sections, the pantographs can provide connections for charging points at stops and other intermediate locations. This will require short lengths of OLE or rigid conductor.

If the stops are accessible to road vehicles, the conductor height must meet the normal minimum OLE height over roadways, and the stop design must include ways to prevent climbing to the tops of passenger shelters and making contact with the conductors. Controls will also be needed to automatically raise and lower the pantographs so that they do not over-extend and the LRV does not miss recharging at the point.

Short lengths of conventional OLE have a slender silhouette but require anchor bays at either end to terminate the wire on a mast. If the stop is immediately adjacent to a road intersection the OLE may need to be carried across the intersection — inevitable if the system design requires the conductor in the stop to extend into the acceleration zone.

Rigid conductor rail has a larger silhouette and might require closer-spaced supports, but anchor spans may not be needed. Also it can carry higher currents with better heat dissipation — both important when high charging currents are involved. Figs 3–4 show two ways that rigid conductor rails may be integrated with a LRV stop.


5.


6.

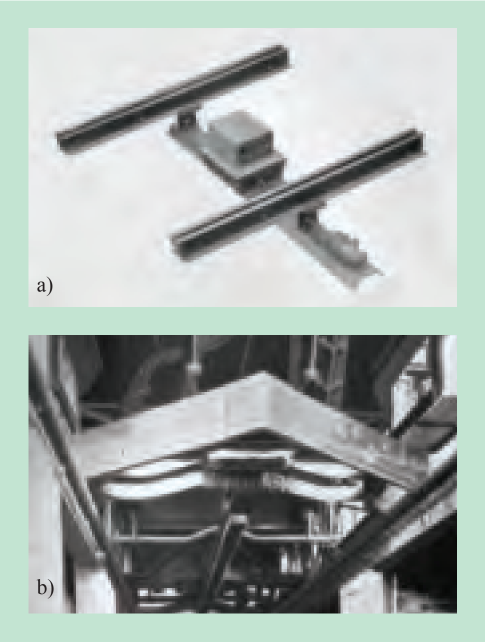

7.

5. Berlin, 1879: The world's first electric railway with an external power source, a 130V DC current supplied by the centre rail.

6. Lichterfelde (Berlin), 1881: 160V DC current supplied by both rails.

7. Tram in Budapest, Hungary, 1889: slotted rail for underground power supply.

8. Tram in Munich, Germany, 1899: (a) current collector (b) relay-activated at-grade point contact.



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Contact-rail technologies

Historical examples

Non-segmented systems

History records several 19th century examples of ground-level power for street tramways. In Berlin, Germany, a Siemens & Halske system was supplied at 130V DC from a centre rail, although from the 1879 photograph (Fig 5) this appears to be more like a fairground miniature railway than a commuter operation[10].

Two years later a full-size Siemens & Halske two-axle tram operated in Lichterfelde (Berlin), this time supplied at 160V DC via both running rails (Fig 6). This system operated primarily on a dedicated right-of-way and at railroad crossings the rails were dead or switched on only briefly before the tramcar approached (though persons and horses frequently received electric shocks). In 1891 the track was equipped with an overhead wire.

Clearly both these early systems represented significant safety hazards for anyone treading on the rails, and conversion to OLE was an obvious development. However, even then some strong drivers to avoid OLE must have existed; in 1889 in Budapest, Hungary, a Siemens & Halske system was built with slotted rail for underground power supply[11] (Fig 7), with the connection being made by means of a "plough". Later systems in London, Manhattan, and Washington DC used similar arrangements although the slot was between the running rails rather than using slotted rail.

Segmented systems

Again in Germany, in 1899 a tram system was built at Munich which used relay-activated at-grade point contacts with a collector "ski" under the vehicle (Fig 8). Similar systems were popular for a while in the early 1900s, as communities objected to the intrusion of OLE, and included the Lorain, Dolter, and GB surface-contact systems — all magnetically operated — and the Robrow surface-contact system, which was mechanical.

In practice, the performance of these technologies was erratic. Studs did not make contact when activated, or remained live after the vehicle had passed over; the systems tended to be replaced with either OLE or continuous contact sub-surface systems.

Modern segmented systems

Actively switched

Alstom's ground-level power supply (APS) system has been deployed in France at Bordeaux (2003, 13.5km, Fig 9), Angers (2011, 1.5km) and Reims (2011, 2km) with further systems under construction in Orléans and Tours. APS[12] features a central third rail in 8m long conducting segments, separated by 3m long insulating joints, and controlled by in-ground supply units at 22m intervals. The conducting segments are only powered when triggered by radio signals from the system-equipped tram when directly overhead.

The system has experienced reliability issues; problems are said to have included waterlogging of the in-ground power boxes when the water does not drain quickly enough after heavy rain, and also with snow and rubbish on the track. APS is deployed in conjunction with on-board energy storage to provide some immunity to local loss of APS supply.

Inherently switched

Much like the early 20th century systems, the Ansaldo STS *TramWave*[13] is switched by direct-acting magnets on the vehicle that lift a flexible strip armature within the contact segment module (Figs 10–11). When the armature drops again, the segment is connected to the return conductor for safety. On the Poggioreale via Stadera line in Naples, Italy, *TramWave* is being trialled on a single track section of about 600m.

Safety

While no reports of electric shock incidents with modern segmented third-rail systems have come to light, the idea of allowing personal contact with an electrical conductor purely via an automated system is almost unprecedented. Generally electrical safety systems require the supply to be isolated, the isolation secure as prescribed, and the conductors — normally energised at a potentially lethal voltage — proved dead before people make contact with them.

Clearly it should be possible to engineer a system with the required level of safety integrity, but there are two challenges:

- conformance with present regulations, codes of practice, etc
- the supply unreliability introduced by systems designed to remove supply as soon as any possible faulty operation is detected.

9.

Reliability

OLE, conventional third-rail, and segmented third-rail all include a sliding electrical contact operating at the vehicle speed. Segmented third-rail systems add further potential causes of unreliability including:

- The third rail is insulated horizontally, so the insulation will become contaminated and wet when it rains.
- Foreign objects on the road surface can damage or become lodged in the pickup shoe.
- Control equipment below the road surface can become wet during rain.
- The necessarily fail-safe fault detection strategy will reduce reliability, as previously noted.

Life cycle cost factors

Life cycle cost is a function of capital cost, and periodic maintenance and replacement. While the collector shoes of segmented third-rail systems may take more damage than a pantograph, the biggest issue for these systems is likely to be the embedded third rail. Damage to the contact surface or insulation could require a section of it to be replaced, necessitating closure of that section of the network. The Bordeaux system now has 10 years in service and it will be interesting to see the timing of any major refurbishment of the contact rail.

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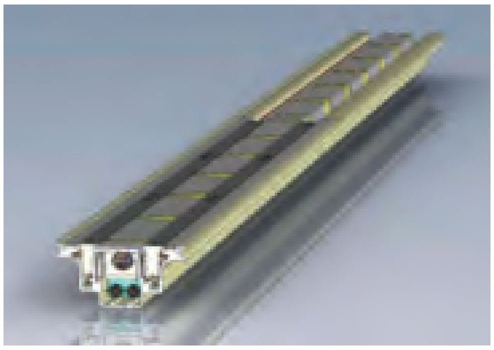


11.

9. Alstom LRV supplied via APS in Bordeaux.

10. *TramWave* contact segments.

11. *TramWave* module.

Inductively coupled systems

Bombardier's *Primove* system[14] uses induction coils between the running rails to transfer energy to the LRV through what is effectively a split transformer (Fig 12). There are no moving parts, sliding contacts, or exposed conductors. The coils are only energised when under an LRV so there is no electric shock risk, and Bombardier claims that the electromagnetic field does not represent a safety hazard. The system would generally be used in concert with on-board energy storage so that the induction coils are deployed only at stops and acceleration areas: Bombardier suggests 10-25% of the route. *Primove* thus can potentially provide a very tidy 100% wire-free solution.

So far there are no commercial deployments of *Primove*, with only a demonstration track at Augsburg, Germany. This system must overcome three challenges:

- It requires much complex and costly fixed infrastructure.
- The component count and line-side location suggest that reliability may be an issue (though a system also using on-board energy storage would have some immunity to service interruptions from a single induction coil group failure).
- *Primove* is a proprietary (closed) architecture — at present both infrastructure and vehicles must come from Bombardier. Such a single-supplier solution may not be acceptable to many government authorities.

Maintenance depot considerations

Earthing and bonding

In traditional LRV systems that use DC OLE, the electrolysis risk is mitigated by insulating the rails from earth. In depots, this would result in a potential difference between the LRV body, the building, and any earthed electric tools used to work on the LRV. One design solution, though costly, is to provide a separate rectifier to supply the depot and to earth the rails in the depot area.

If the LRVs are fitted for on-board energy storage and the depot is configured as wire-free, the depot rails can simply be separated and earthed. This approach has been adopted for the Gold Coast Light Rail depot in Queensland, Australia, which uses Bombardier vehicles fitted with the *Mitrac* energy storage system. While this approach can work for maintenance depots, this is not the case for stabling areas, due to the HVAC load.

In a depot segmented third-rail would have similar electrolysis issues to OLE but would also bring safety concerns. Tow-vehicles may be preferable.

Overhead crane access

One recent depot for an OLE system features swing-away rigid conductor rail to facilitate crane access to roof-mounted equipment; clearly systems without OLE eliminate the issue entirely.

The need for a "stinger"

As with depots for third-rail LRVs where they cannot draw power from their usual source, a pendant cable (or "stinger") will likely be needed to power on-board store-based vehicles in a depot not fitted with OLE. Due to earthing considerations, the stinger will probably need a separate rectifier, but this may be smaller if it is only for slow charging of the stores rather than to supply full acceleration current to move the LRV.

Useful deployment strategies

Wire-free sections in generally wired systems

In all cases considered here, adopting wire-free main line operation has been proposed primarily for aesthetic reasons. Once the decision has been made to go wire-free, the extent of the wire-free areas will be driven by cost/benefit considerations.

Provided adequate charging is available, for on-board energy store-based solutions wire-free areas should be less costly than wire. Conversely, OLE is cheaper than segmented third-rail, which would thus only be more broadly deployed if local OLE constraints require other high cost mitigations. As well as locations with aesthetic drivers for wire-free, it might also be considered for sections through major interactions, with significant tree canopies, with low over-bridges, and for depots.

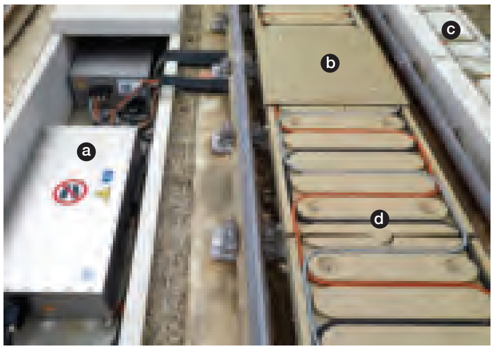
Wired sections in generally wire-free system

With on-board energy store-based solutions, steeply graded areas and those with high-volume shuttle traffic might need to be wired so that the energy stores can be of a reasonable capacity, and to provide adequate recharge opportunity.

Summary and conclusions

Wire-free LR solutions now exist to help preserve or enhance the aesthetics of cityscapes. Except for Bombardier's *Primove*, all the modern versions can trace their lineage to developments around the turn of last century, but they cannot yet be considered mature, and the technologies continue to evolve quickly. There is not yet a clear "winner" between on-board storage and segmented third-rail, although it is clear that battery and DLC technology continues to improve. This, combined with the inherently open architecture of on-board storage based and the reliability issues accompanying segmented third-rail — some driven by safety requirements — will probably give the energy storage-based systems the edge.

Regardless of the specific technology adopted, the availability of wire-free technologies to eliminate one significant area of objection to providing or reinstating LR systems is undoubtedly a good thing — and with some side benefits.



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Wire-free technology proposed for Sydney Light Rail

The Sydney Light Rail project proposes the construction of a new route through the centre of Sydney and on to the inner south-eastern suburbs. It passes along George Street, which is the city's major civic thoroughfare. George Street is lined with many important historic buildings such as the Town Hall, St Andrew's Cathedral, and the Queen Victoria Building, as well as several architecturally significant commercial buildings from the late 19th and early 20th centuries. As part of the project, a portion of George Street will be reserved for pedestrians and light rail, together with restricted access to other vehicles for deliveries. This new public space will include high-quality public realm and a section of wire-free operation.

An on-board energy storage-based wire-free system was selected for the Reference Design prepared by Arup for the client, Transport for New South Wales (TfNSW). This was preferred because:

- The available systems which provide a continuous supply all incorporate substantial amounts of underground equipment. This requires space within the track foundation and can increase construction depth above the minimum required for a structurally sound track slab. George Street has some substantial subterranean structures very close to the surface, including the roof of Town Hall railway station which is only about 450mm below the road surface.
- It is hoped that the Sydney Light Rail network will grow in future, so technology choice should be non-proprietary. An energy-storage solution contained entirely on the vehicle is attractive, as future vehicle choice is then unconstrained.
- Energy storage LRVs make use of the energy storage equipment to maximise energy recovery from braking, even when not in wire-free areas.

Energy storage technologies are a fast-moving area – the main contenders are batteries and super-capacitors. Both have been improving rapidly and both are already deployed in commercial operations.

While the Reference Design has established that appropriate feasible solutions exist, the specification for the procurement of the system will be non-prescriptive, and will be subject to further detailed design by the Public Private Partnership (PPP) appointed to deliver the project.

The intention is to allow suppliers to offer Sydney the proposal which in their experience will be the optimum. As the project is being procured under a PPP structure, there is a strong commercial incentive to deliver a reliable solution with reasonable long-term costs.

13.

12. *Primove* infrastructure:
(a) inverter; (b) cover;
(c) detection loop; (d) cable support.

Author

David Stuart-Smith is a Senior Associate in the Sydney office, and is Arup's Global Traction Power Skills Leader.

Image credits

1 *David Stuart-Smith*; 2, 9 *Alstom;* 3–4 *HASSELL*; 5-8 *Siemens*; 10-11 *Ansaldo STS*; 12 *Bombardier*; 13 © *TfNSW*.

This article, based on a paper presented at the 2013 LTA–UITP Singapore International Transport Congress and Exhibition (SITCE), presents our present understanding of the technologies and outcomes that can reasonably be expected under typical operating conditions. As the technology develops, component lifetimes, energy storage endurance, reliability, and other characteristics are likely to change. Up-to-date information should therefore always be sought before providing advice regarding any specific implementation.

List of sites

Site	Vendor	Technology	Status
Qatar	Siemens	Hybrid energy storage	Commercial operation being developed
Augsburg, Germany	Bombardier	*Primove* inductively coupled	Demonstration
Gold Coast, Australia	Bombardier	*Mitrac* Li-ion battery	Commercial operation under construction (wire-free operation depot only)
Nice, France	Alstom	Ni-MH battery	Commercial operation
Naples, Italy	Ansaldo STS	*TramWave*	Commercial operation, being commissioned
Bordeaux, France	Alstom	APS	Commercial operation
Reims, France	Alstom	APS	Commercial operation
Angers, France	Alstom	APS	Commercial operation
Orleans, France	Alstom	APS	Under construction
Tours, France	Alstom	APS	Under construction
Paris, France	Alstom	DLC	Demonstration
Rotterdam, Netherlands	Alstom	Flywheel	Demonstration
Seville, Spain	CAF	Supercapacitor	Commercial operation
Saragossa, Spain	CAF	Hybrid: supercapacitor	Commercial operation under test and Li-ion battery
Granada, Spain	CAF	Hybrid: supercapacitor	Commercial operation and Li-ion battery
Cuiaba, Brazil	CAF	Supercapacitor	Commercial operation under construction.

1.

first direct arena

Location
Leeds, UK

Authors
Jim Bell Samantha Birchall David Clixby
Ian Drabble Eoghan Given Richard Greer
Neil Hooton Susie Horsefield Lee Kirby
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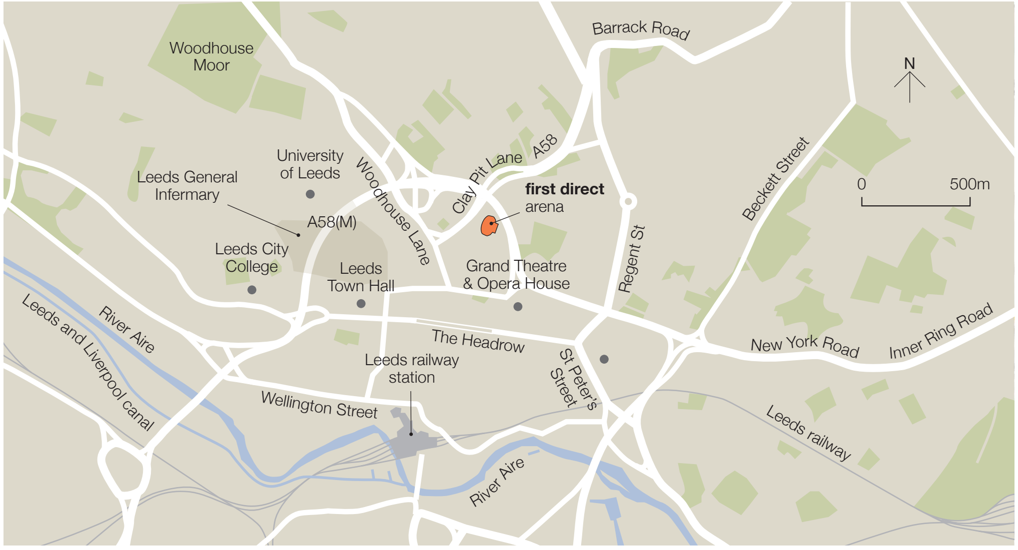
Overview

The £60M **first direct** arena in Leeds is the most sustainable project of its kind in the UK. With its fan-shaped seating bowl terraced into a sloping site, the world-class 13 500-capacity venue optimises sight lines by focusing every seat on centre-stage to bring the public closer to the action (Fig 1). It caters for a wide variety of shows, from concerts to boxing, and comedy to basketball, but whatever the event the arena's inherent flexibility enables unforgettable experiences for audiences.

2.



3.

1. Elton John in performance at the **first direct** arena's official opening night, 4 September, 2013.

2. The arena's close proximity to other buildings in Leeds city centre led to design challenges.

3. Location plan.

The aim for the arena project was to enhance and regenerate Leeds city centre: by creating a vibrant atmosphere and extending the centre's use into the evenings; by acting as a driver for growth and development; by creating around 500 new jobs; and by contributing £25.5M each year to the local economy. However, its proximity to noise-sensitive residential accommodation and position in the heart of the city (Figs 2–3), as well as the challenge of public funding in strict economic times, made delivering the project for Leeds City Council (LCC) a unique technical and commercial challenge.

To the north and east, the site is bounded by the Inner Ring Road (IRR), 5m down in a deep cutting, and the building form was conceived within and around tight physical constraints (Fig 4). Critical issues for the design were:

- The site itself is small for a venue of this scale, and slopes by 6m north to south.
- The adjacent student residential accommodation led to stringent planning restrictions on noise breakout, thus making acoustics the key driver of the engineering design.
- It was to be the most sustainable venue in the UK.

- As a world-class facility, the arena needed state-of-the-art internal acoustics as well as an intimacy to mark it out from other comparable venues.
- Finally, given its prominent location, and with the desire for it to be a visible driver for growth, the brief required the building to form a landmark destination with a striking aesthetic.

The project's delivery during stringent economic times was a commercial success. LCC's funding relied on its pre-let agreement with operator SMG, and this innovative procurement strategy put the operator at the heart of the design process, ensuring that it truly focused on the audience experience. An £8M budget cut, resulting from the demise of the regional development agency (RDA) shortly before construction started, added to the challenge of successful delivery, yet innovative value engineering kept the project on track.

As for its sustainability credentials, the arena has achieved a BREEAM (Building Research Establishment Environmental Assessment Methodology) score of 61%, the highest of any arena in the UK.

Completed in March 2013, and with the first concert performed by Bruce Springsteen at the end of July, the **first direct** arena is being heralded as setting new standards in project creation for city regeneration in terms of procurement, design and delivery — and with Arup at its heart throughout.

Project creation

Introduction

Leeds had long been targeting the development of an arena to strengthen its cultural resources and planned social and economic growth; indeed, the local public and private sectors tried three times in the 1990s but failed. Making the arena finally happen, through the worst economic recession in living memory, took clear vision from LCC, strong management, and innovation at every stage of the project.

Arup, initially focused through its venue consulting offer and then its building engineering practice, is proud to have been central to that innovation throughout the project, which sets not only a new paradigm in arena design and event-goer experience, but also in the planning, finance and delivery strategy for such a venue.

Key site constraints

1 Residential tower blocks
2 Inner Ring Road (IRR)
3 Arena access road
4 Service yard access for articulated lorries
5 Public realm in front of the arena.

4.

5.

4. The arena under construction, showing key site constraints.

5. The daytime appearance of the arena's unique façade.

Feasibility stage

In the early 2000s LCC procured, through open competition, the finance and strategy consulting company PMP Ltd (originally the Peter Mann Partnership) to prepare, firstly, a cultural venue strategy for Leeds and then feasibility studies for an arena and potential conferencing facilities. These studies confirmed that it would be feasible to deliver an arena focused on concerts and family entertainment with a capacity of around 12 500.

Origins of the implementation plan

Following the feasibility studies, in February 2006 LCC placed a notice in the *OJEU* (*Official Journal of the European Union*) seeking a consultant to advise on procuring a consortium to develop the arena and associated facilities.

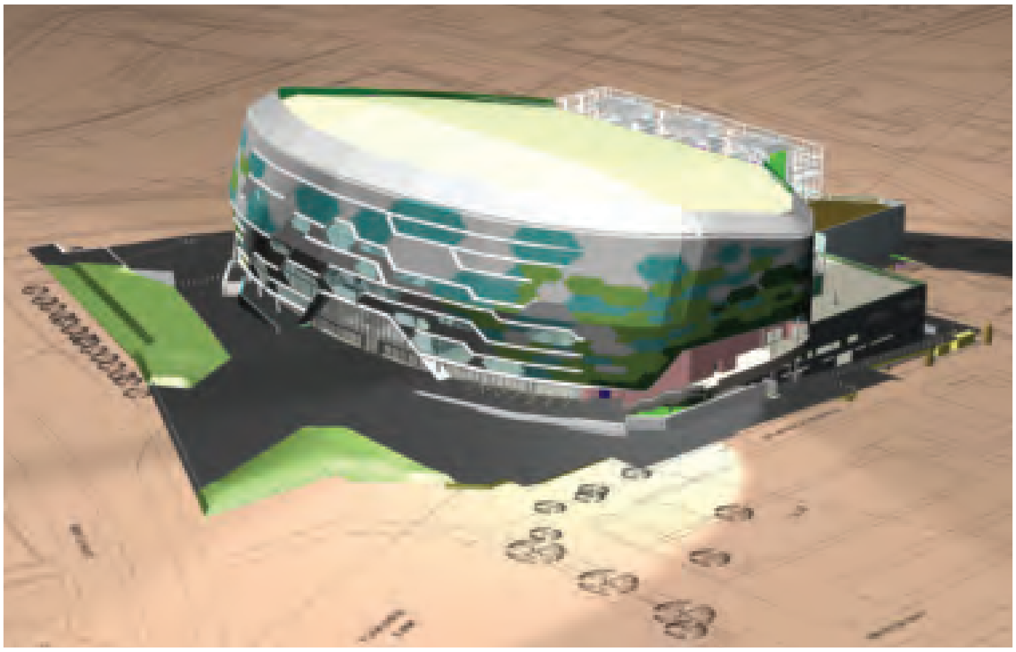
PMP (which in 2009 became "IPW...", ie "in partnership with...") was appointed, with Arup advising specifically on venue consultancy and transport planning, and with Donaldsons (now DTZ) as property adviser. PMP's commission was to prepare an implementation plan and then deliver it on behalf of LCC.

Though the earlier studies had shown an arena to be feasible, it would require "gap funding" from the public sector, with the return on that funding coming from the economic development catalysed by the arena's operation (eg more people visiting Leeds with increased spending on hotels, food and beverage, shopping, etc).

Leeds City Council was, and remained, clear in its objectives:

- for the arena to be delivered in a reasonable timescale
- for it to be developed and operated by the private sector
- to minimise the public sector gap funding (LCC with support from the then RDA).

The IPW/Arup/DTZ team implementation plan recommended that LCC follow an innovative split procurement route, selecting an operator first against a guaranteed rental (maximised by competition) and linking the preferred operator to a private sector developer.



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Implementation plan recommendations and innovations

(1) Prepare an indicative business plan from a private sector operator's perspective, eg the target market and likely event programme (thus enabling the probable income, operational costs and margin to be estimated and hence also the scale of the guaranteed rental that the operator could pay for the benefit of operating the arena).

(2) Establish the minimum practical building cost by:
(a) upfront venue planning,
(b) development of the minimum accommodation schedule, and
(c) an associated draft set of facility requirements (in essence an output specification for the building) focused on operating the venue to maximise income from event-goers, promoters and performers.

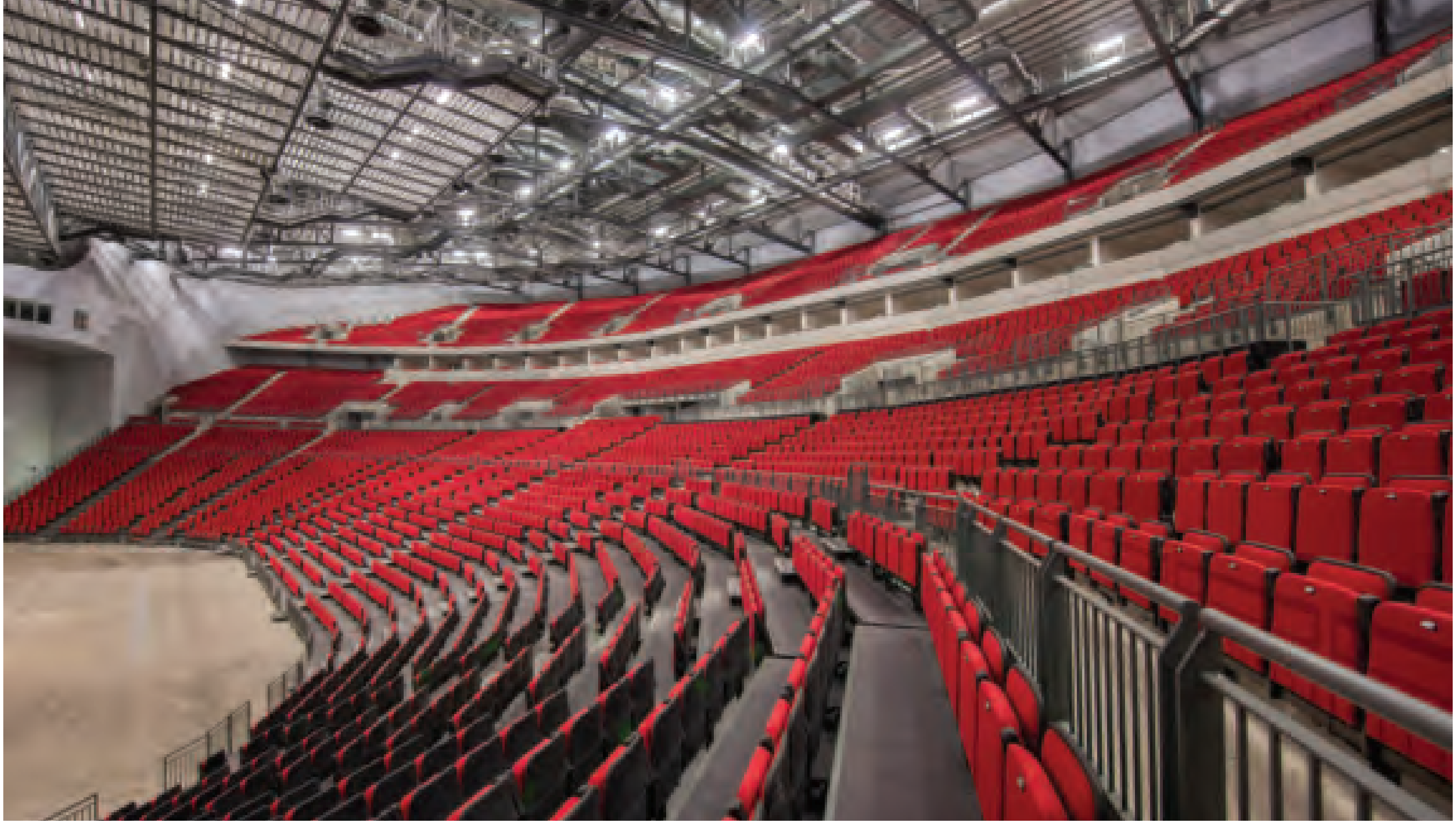
(3) Establish design principles such as design life (to assist securing borrowing against the operator rental) and sustainability/environmental performance (to meet local planning authority requirements).

(4) Establish the availability of feasible sites in and around the city that would support not just the arena's development but also wider "enabling development" around it (eg residential, commercial, or car-parking).

The implementation plan included land around the Elland Road stadium (home of Leeds United football club). Elland Road was not a preferred site, but it was a specifically noted location. Enough land was in LCC's ownership for it to be identified as a site that could be made available to a developer who wanted to deliver the arena and a wider development, but who didn't have a land holding in Leeds available for the tender. (The competition documents were clear that any developer making a proposal based on the Elland Road site would have to include the cost of the land at fair and open market value.)

Key components of the implementation plan

- Market test the business plan and the interest in competing to become the arena's operator (Leeds was seen as a "gap in the market") and/or constructing it as part of a mixed-used development.
- Run an **operator competition** and hence
  (a) maximise operator guaranteed rental,
  (b) enable the operator to finalise the venue facilities requirements,
  (c) minimise arena capital cost, and hence
  (d) maximise the proportion of the project's build cost that could be leveraged off the operator rental.
- Run a **developer competition** to secure a private sector developer who would
  (a) contract with the selected operator as a pre-let tenant,
  (b) deliver the arena, and ideally also
  (c) deliver wider development that could be used to cross-fund the arena.



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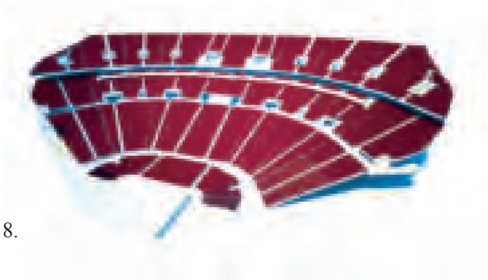

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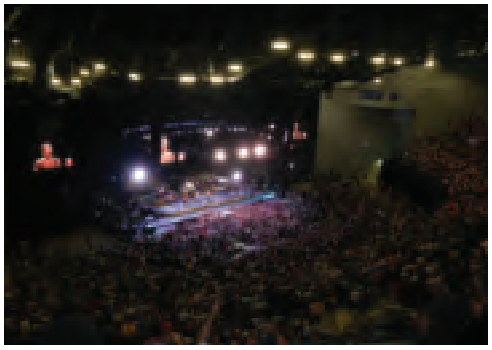


9.

6. Early 3-D model showing the overall massing of the building.

7. The fan shape gives a clear view of the stage from all seats.

8. Architect's graphic.

9. Audience enjoying the Bruce Springsteen concert.

- Secure the minimum public sector gap funding needed to bridge the difference between the arena's cost and the funding otherwise available through borrowing against the operator rental, borrowing against other incomes such as car parking and, for example, cross-funding from enabling development on the selected site. The level of gap funding was demonstrated to be entirely justified by the scale of the arena's economic stimulus, eg spending by people coming into Leeds for events there.

Arup's long experience with performing arts projects highlighted the importance of designing the venue "from the inside out", based on needs in terms of target audience and performers. The Leeds arena implementation plan innovated the way to this next stage, effectively procuring the venue "from the inside out".

Delivering the implementation plan: the operator

Under the contract established, LCC commissioned IPW Ltd (then PMP Ltd) supported by Arup and DTZ to deliver the approved implementation plan. Arup was technical advisor throughout this phase.

This team developed the procurement documentation which LCC issued as two competitive tenders under *OJEU* procedures, with the developer process intentionally planned to lag a few months behind that for the operator. This was to ensure that the selected operator could be introduced to the shortlisted developers, to test and ensure that the operator could be contracted with the developer selected.

Both competitions were launched in June 2007. Interest in the operator competition was very high, and competition between major global venue operators continued through short-listing to the final stage of the process.

In May 2008, SMG Europe was announced as the preferred bidder and was temporarily contracted to LCC to guarantee fulfilling the terms of its successful bid until SMG could be contracted on the same or better terms to the selected developer.

In addition to its guaranteed rental, SMG's successful bid was differentiated by a range of innovations. These included the requirement for a fan-shaped auditorium to provide the best possible experience for event-goers with all seats facing to a clear view of the stage (Figs 7–9), a high level of front-of-house food and beverage offering both for events and at other times, and clear facility requirements to deliver these innovative components at a fundable cost.

For SMG, this project was an opportunity to meet its long-held objective to set a new paradigm in new-build arenas.

10.

10. Night-time façade lighting.

11. Oblique view of public realm in front of the arena.

Delivering the implementation plan: the developer

Interest in the developer competition was not as strong as for the operator competition, but nonetheless two tenders were taken into competitive dialogue. The first proposed a mixed-use development including the arena, using the prospective developer's own land holding of a gateway site on the city centre's south-western edge. The second proposal was also mixed-use, but this time using the land available at Elland Road.

In late autumn 2007 the developer competition and the scale of the gap funding sought was challenged by the "credit crunch". This began to adversely affect developers' ability to borrow private sector money at reasonable interest rates and terms, and diminish the value of other development proposed by the bidders in addition to the arena, hence the scale of any contribution to the build cost that could be taken from the margin on such enabling development.

To improve the developer competition the consultant team recommended options to LCC. The first, introduced in spring 2008, was the offer for competitors to use "prudential borrowing", whereby the developers would guarantee to pay future private sector income from the arena operation to LCC, which would then use this guarantee to raise capital through the UK government Public Works Loans Board, and fund the arena construction with this capital.

In 2008 the interest rates for prudential borrowing were much better than for private borrowing, so the scale of the capitalisation possible from the prospective operator rental could be maximised and the capital gap funding from the public sector reduced.

The second recommendation, which wasn't accepted by LCC until May 2008, was to run a public sector comparator (PSC); this essentially tests whether better value for money can be achieved by a local authority delivering a project itself.

One consequence of the credit crunch, which by spring 2008 was starting to be considered a recession, was that development proposals began to fail for several city centre sites, including some wholly or partly in LCC's ownership. One of them, Claypit Lane at the very northern edge of the city centre, was occupied partly by a LCC surface car park and partly by a derelict building owned by Leeds Metropolitan University.

11.

This site became available in April 2008, and Arup confirmed that its two areas taken together could accommodate both the arena itself and the enabling development, and that there were no technical "arena show-stoppers" associated with the site.

In May 2008, LCC instructed the consultant team to prepare a PSC based on SMG'S facility requirements, for the Claypit Lane site; subsequently LCC asked the team also to prepare a comparable PSC for the Elland Road site. The shortlisted developers, in the second stage of competitive dialogue, were told about the PSCs as a way to increase competitive tension and hence stimulate, it was hoped, more proposals from them.

The PSCs were prepared that summer, and for them Arup developed the masterplans as well as all the technical and cost estimates needed for the on-site and off-site works. This included transport planning, evaluating the work and costs involved in preparing or modifying adjacent car parks to handle the arena parking, and enabling the project to capture the parking income to help fund the arena construction costs.

The developer competition was moved to a simplified, intended to be interim, stage to focus on value for money. This led to a "best offer" submission by the final tenderers in early autumn 2008, which was compared in terms of value for money with the PSC. The consultant team's detailed evaluation recommended that the PSC at Claypit Lane provided the best value for money and, after scrutiny, LCC's Project Board accepted this recommendation.

In November 2008, papers were presented to the LCC Executive Board which voted to firstly cancel the developer competition — an action clearly allowed for in its original documentation — and secondly to progress arena delivery at the Claypit Lane site with LCC taking the developer role.

Arena design development, 2008–09

In December 2008, LCC directly appointed Arup to provide technical advice and a "check and challenge" role while LCC procured the design development primarily through the Strategic Design Alliance (SDA), a private sector partnership with its in-house designers. The first steps involved establishing inception and delivery plans.

LCC led on developing the inception plan, which set project objectives, management team, and governance structures.
The objectives were confirmed as:

Level 1

- control out-turn cost
- meet SMG's requirements
- ensure a deliverable project (get planning permission, licence to operate, etc).

Level 2

- maintain project momentum
- minimise risk
- ensure quality of external design regarding "place-making" a landmark destination.

Arup led on preparing the delivery plan, including the following key components:

(1) *establish a "best in breed" delivery team*

(2) *split the project into three parts:* on-site (arena), on-site (other development), and off-site (car parks, public realm, highways)

(3) *planning approach:* the recommendation, which LCC accepted, was for this to progress in two stages — outline planning followed by detailed planning. This was unusual at the time for council projects but was considered to best fit the needs of the arena development (see panel)

(4) *procurement approach:* the full range of options were considered, ranging from "turnkey" solutions based on a high-level output specification, through design-and-build options, to traditional construction contracts based on LCC retaining complete design responsibility. Given LCC's objectives for the project, the best option for controlling costs and risks, with the benefits of two-stage planning, was recommended to be design-and-build, with procurement occurring at the end of scheme design

(5) *budgeting for the delivery and design team costs*.

It was accepted that establishing a full delivery would require separately procured specialists. Firstly, a cost consultant was needed, who could also provide project management support. Competitive tenders were sought under OJEU regulations, and this contract was awarded to Davis Langdon (now AECOM).

Secondly, an architect for the arena's internal planning was appointed. A mini-competition was run between the architects who had advised those tendering for the previously cancelled developer competition, and the contract, to act as a subcontractor to the SDA, was awarded to the US-based practice Populous (formerly HOK Sport).

Arup provided the technical input to both these procurement processes.

Separately, the council sought competitive tenders under the OJEU for a planning agent, and for this the contract was awarded to Arup.

Arena design development, 2009–10

Through 2009, Arup provided on-going technical advice, planning agent duties (including a full environmental impact assessment) and "check and challenge" for the SDA's developing arena design.

A key part of the latter role was in venue planning skills to ensure that, working with SMG, the SDA's design was consistent with the operator's facilities requirements. At this time Arup also gave technical support to preparing and finalising the agreement for lease between SMG and LCC.

During summer 2009, as the scale of work on the arena delivery grew, the council appointed Davis Langdon, under its existing contract, to take on full day-to-day project management duties. As part of this role it was confirmed that the arena construction would be procured by competitive tender under OJEU rules as a design-and-build contract, with the tenderers appointing their own detailed design teams. Davis Langdon prepared and ran the procurement for the main construction contract.

The UK contractor BAM Construction Ltd asked Arup to join its team tendering for the construction contract. The firm sought advice from LCC, who agreed that Arup could support the BAM tender provided that it involved an entirely separate team from that giving on-going technical advice to LCC, and that strict confidentiality management processes were put in place and operated. As a result of this LCC then launched another procurement process, again under OJEU rules, this time for a technical advisor to cover the period after the construction contract was awarded.

Through the end of winter 2009 and into spring 2010, the following milestones were achieved:

- Arup, as LCC's agent, secured outline planning permission for the arena. The main issues associated with the application were (1) the mechanisms for securing detailed planning permission for the external appearance; (2) noise control (not only from the arena itself but also vehicles accessing and egressing the service yard at night); and (3) the taxi and coach drop-off and pick-up facilities.
- The principles for the arena's external design were established through a mini design competition.
- Arup and IPW as advisors supported LCC's successful, but highly scrutinised, application for funding support to the then RDA and in turn the RDA's application for approval to central government to make the funding.
- The scheme design was accepted, with some conditions, as compliant with the project objectives.
- The design-and-build contract for the arena was awarded to BAM Construction.
- LCC appointed a new technical advisor.

Summary

Working with LCC, Arup had thus produced a business case to demonstrate that the Council could self-fund this important project by securing a pre-let with an operator, and helped to procure SMG on a 25-year deal.

This innovative strategy put the operator at the heart of the process, ensuring that the arena design was truly focused on the audience experience. Based on this, the Council's SDA produced a scheme design for tender, while Arup acted as technical advisor and delivered full planning services.

In 2010 BAM won the construction contract, with full engineering support from Arup, and Populous as architect.

12.

Procurement review: workshops and conclusions

The workshops that Arup ran with LCC departments, major project teams, and external advisors demonstrated unanimously the critical need to integrate planning and licensing into the arena design development from the outset, both to ensure design quality and to de-risk the programme. This was consistent with LCC Planning Services' "planning performance agreement charter"[1]. The procurement review's strong recommendation was to seek initially outline planning permission to confirm:

- access requirements (and hence costs)
- arena orientation, massing (as driven by SMG and site requirements), and location on site (with sufficient flexibility to permit future design detailing as part of the detailed planning)
- other development on the site (and hence income and value generation)
- stakeholder requirements for external design, materials and finishes (as a "design code" that would be enforced by planning condition).

This approach, combined with the parallel development of a concept-level design for the arena, had several key advantages:
(1) "close down" principal off-site risks;
(2) confirm off-site costs;
(3) establish with more confidence the monies available to meet planning requirements; and
(4) develop stakeholder understanding of the project requirements and project understanding of the planning requirements.

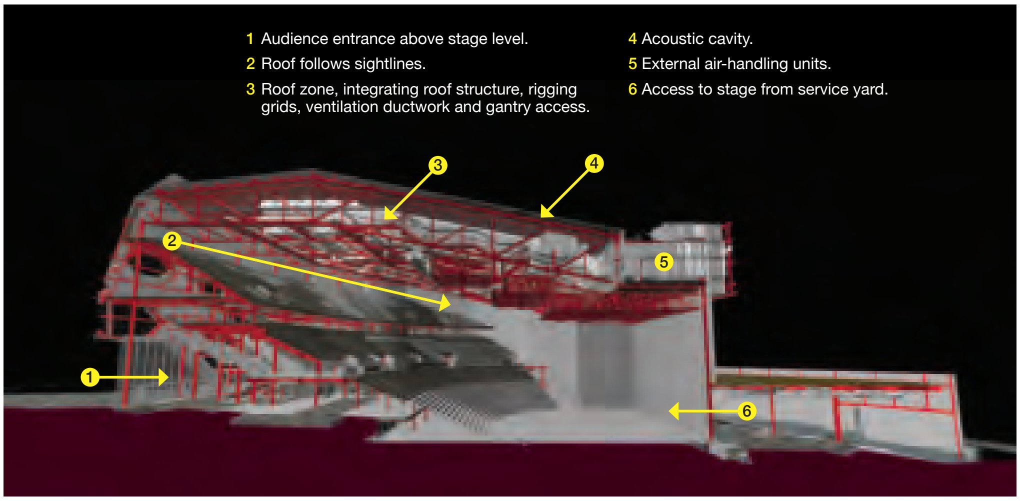
During previous discussions, LCC Planning Services had suggested that to ensure transparency it would be useful to appoint an external planning agent to promote and submit the planning applications.

This would reduce the risk of external challenges to such a high-profile project, where LCC was both developer and planning authority.

Another facet of this approach was that it separated the architectural and design development of the arena's internal elements from the external, the initial emphasis on the former leading to a "form follows function" approach to the building's overall design.

The external design principles were also strengthened by the fan-shaped auditorium that resulted in a strong "front door" to the building, quite different from traditional arena designs (Fig 12).

13.



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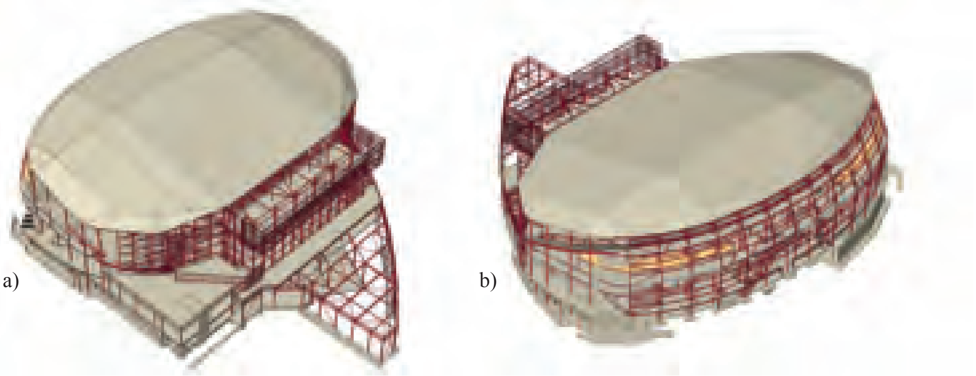


15.

13. Site plan.

14. Building cross-section.

15. Structure viewed from:
a) the south-east, showing the roof-top plant deck and the tight service yard;
(b) the north-west, showing the tracery steelwork, and how the structure is built into the terraced site.

The structural design

Overall concept

To provide an arena on this tight, sloping site required the UK's first fan-shaped bowl, overlooking a stage set into the slope. This innovation allowed the desired capacity to be achieved — impossible with a conventional in-the-round configuration — and thereby unlocked the commercial potential of this central location to host a large venue, cementing LCC's belief in a city-centre location for the arena as a catalyst for growth and development.

The arena then "grew" around the auditorium: concourses to the north-west, service yard to the south-east, performers' entry from the south-west, and the access road to the east creating a building resembling a scallop shell in plan (Fig 13).

All areas were kept to a functional minimum, and the building was metaphorically "shrink-wrapped" by the roof and the façade to minimise its volume. This strategy, however, created many challenges for the structural design.

Initially, the access road was placed well clear of the IRR to avoid overloading the large retaining structures. But this resulted in the upper levels of the bowl significantly overhanging the road, creating dynamic issues with the structure and uplift on the foundations, and making the turning access into the service yard excessively tight for large articulated vehicles.

Greater efficiency could be achieved by moving the road closer to the IRR. Detailed structural investigation and back-analysis of the IRR structure enabled the access road to move adjacent to the wall, with a limited strengthening of just its top 2m.

Internally, the challenge to create an intimate auditorium with world-class acoustics and energy performance required a minimum-volume space, without interruption to sightlines, while accommodating extensive rigging structures some 20m above the event floor, integrated with the ventilation system, gantries and lighting. The solution was a folded roof, falling towards the stage to reflect the profile of the site and the sightlines, and creating above the stage a recessed plant well, 54m x 15m, to conceal six large air-handling units behind an acoustic wall (Fig 14).

It was tempting to have a radial roof grid to mimic the scallop shell, bringing the roof trusses together to a point above the stage. However, this would have placed excessive load on a single element — the proscenium arch (PA) truss, spanning 54m clear across the stage — and the non-parallel trusses also presented a buildability challenge. Instead, 13 trusses up to 72m in length span north-south at 9m centres, limiting the load on the PA truss to a third of the total, better spreading the load across the foundations and greatly simplifying the two-layer roof construction. This also dramatically simplified the integration of services, rigging and gantries within the roof structure.

Stability for the roof is separate from that for the concourses to the north, enabling the cranked trusses to spread under load without impacting the overall structural efficiency. The concourses themselves are steel-framed, stabilised with concrete stair cores and shear walls.

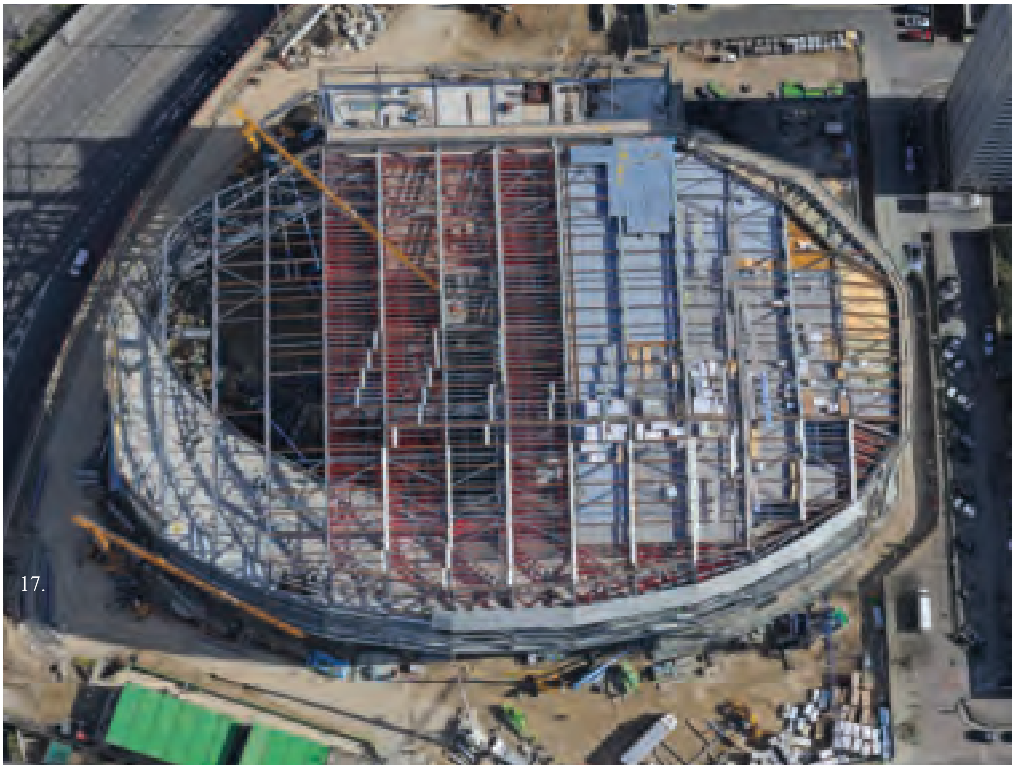
16.

Structure of acoustic insulation

The greatest design challenge, however, resulted from the planning conditions limiting noise breakout to 10dB below background levels. This dictated the structural form of the roof and façade. Solutions making use of simple technologies for affordability were combined with extensive BIM (building information management) co-ordination to solve the complex geometry arising from the "shrink-wrap" façade surround. A "box-in-box" solution needs two layers with significant mass separated by an air gap so as not to transmit vibration, particularly at low frequencies. Given the adjacent residences, the performance requirements were unusually demanding.

The roof solution was a major innovation, responding to the cost and performance issues of the cassette-based systems more commonly used to mitigate such acoustic concerns. In these, a lower cassette layer rests on top of the roof trusses, and a further layer is supported from a secondary truss system 1m above. In this arena, however, without increasing the overall roof depth, the roof trusses were pushed up into the air gap, and an in situ concrete layer was poured on a metal deck, supported on purlins isolated on acoustic bearings. A second, built-up layer of insulation and plasterboard created the inner layer; the counter-intuitive approach of adding mass and building in situ saved £1M, with no increase in truss weights owing to their greater depth (Figs 17–18).

The façade required a similar concept (Fig 19). For the main entrance behind and beneath the terracing, the front façade itself and the precast bowl (with joints carefully sealed) provided the mass; the concourse the air gap. The side and rear walls, however, required two heavy layers resiliently separated. The building overhang dictated that they could not continue to the ground, and the detail developed uses precast panels as an outer layer, supported on the primary frame, with an inner layer of plasterboard lining on a secondary frame resiliently supported from the primary structure.



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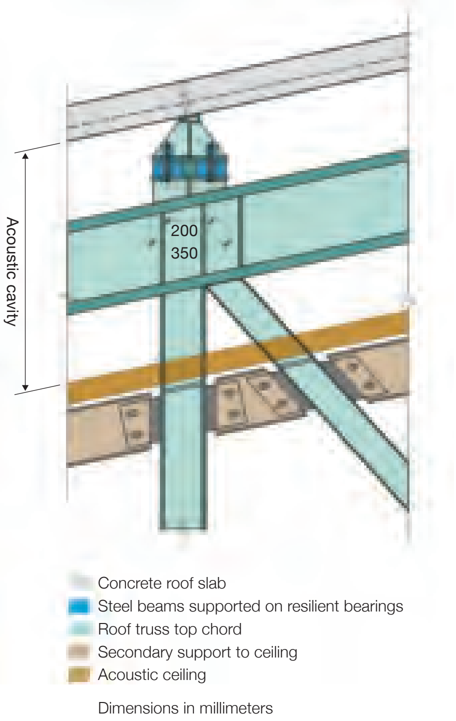

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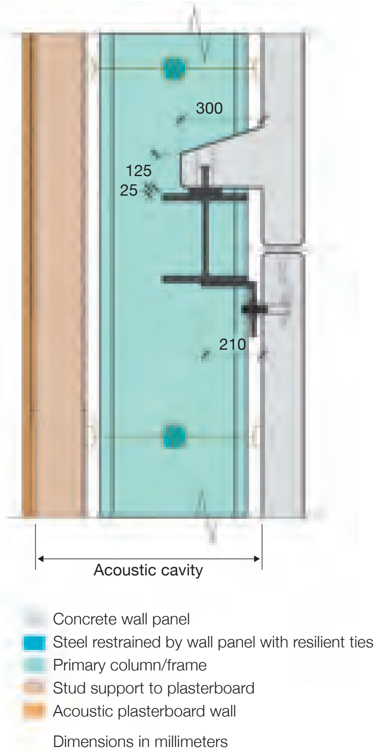


19.

16. Daytime view of the façade from the west.

17. Roof construction, showing "layers" of acoustic insulation.

18. Section through roof.

19. Section through façade.

MEP design

Capacity and resilience are essential requirements across all the primary services, as failure in any of them — electrical supply, ventilation, heating/cooling, or water — would result in event cancellation.
This key consideration informed their strategy and design.

Through the day, the arena ticks over with a low background demand on the services, but in the period leading up to doors opening and final audience exit, the full capacity of all HVAC, public health and electrical systems will have been tested in an arduous four-hour workout. The increase in demand is rapid and extreme, with the electrical load rising from a nominal daytime maximum of 100kVA up to 3.2MVA during an event.

Capacity and resilience

Enjoying its city centre location with robust local infrastructure, the site is served by single-feed HV (high voltage), gas, and water supplies. Here, the electrical HV connects to a private ring main incorporating two building-integrated HV substations, each housing two 2MVA transformers providing 100% spare capacity. One 330kVA generator supports life safety systems, while the rear service yard incorporates connection to a 500kVA outside broadcast generator that is brought in for live televised events.

Heating is from a combination of modular gas-fired boilers (2850kW) and two air source heat pumps (250kW) with dedicated 80/60°C and 50/45°C heating circuits respectively. Although hydraulically separated, the systems are arranged to offer additional reliance by sharing heat through a plate heat exchanger interface.

Chilled water resilience is spread across three 950kW *Turbocor* chillers, selected for their inherent low-noise performance and good seasonal efficiency. With limited external roof space, two of them are tucked away in an external stage left plant area, shielding the adjacent residential tower from direct line of sight and airborne noise.

The remaining chiller is on the main south plantroom roof, and as it overlooked by the adjacent tower, it is fully enclosed in a bespoke acoustic housing. A generously-sized buffer vessel with 7.5% chiller turn-down provides flexibility to meet daytime office loads, rising to peak summer daytime conference gains, via a common chilled water system.

Step changes in occupancy patterns, from pre-event drinks to mid-show interval, place heavy demands on the domestic water supply, which is supported with 46 000 litres potable water storage split over two tanks. Demand profiling demonstrated the robustness of water availability through various event scenarios, from a daytime conference to a sell-out concert. With a comprehensive suite of "stars" and band dressing rooms, the hot water demand from simultaneous shower use was the main influence on domestic hot water sizing, with two 540kW direct gas-fired water heaters close-coupled to 1000 litre buffer vessels.

Bowl and concourse

These are the locations where most of the public enjoy their overall event experience. The bowl and the concourse are inextricably linked through their ventilation strategy, given that occupation of the concourse is transient. There are ample toilet facilities here, plus 12 food and beverage concession areas. These generate large extract ventilation flow rates, equating to a nominal two air changes per hour.

By positively pressurising the bowl (out-of-balance supply and extract), acoustically treated spill chambers on either side of each vomitory transfer air through into the triple-height concourse to balance out the extract. As there was no other means of providing concourse ventilation and cooling, the team undertook studies of the impact on the internal environment during normal evening events and midsummer conferences.

The multi-function bowl has a ventilation and distribution strategy designed around four modes of operation, covering a range of event types and stage arrangements.
Six air-handling units (with full cooling, heating, thermal wheel and mixing box) (Fig 20), each providing a nominal 23m^3/sec, are uniformly spaced over the stage roof to allow the alignment of associated 1.8m diameter supply and extract ducts through the proscenium arch truss and into the bowl services zone. Once in the bowl, fingers of supply air ductwork radiate out, weaving between the main roof truss sections to serve 118 active core diffusers and twist nozzles (Fig 21). Different combinations of in-line motorised dampers enable the ventilation system to respond to pre-set event scenarios.

With air throws from 6m–20m, CFD simulations carried out during the design proved the need to carefully select and position diffusers to deliver uniform comfort for high-occupancy and low-occupancy event scenarios (Fig 23).

At high level, a large over-stage rigging grid connects to two full-width arching services gantries that give maintenance access to lighting and ductwork service hatches, *VESDA®* fire panels, and local switchboards for use with event lighting.

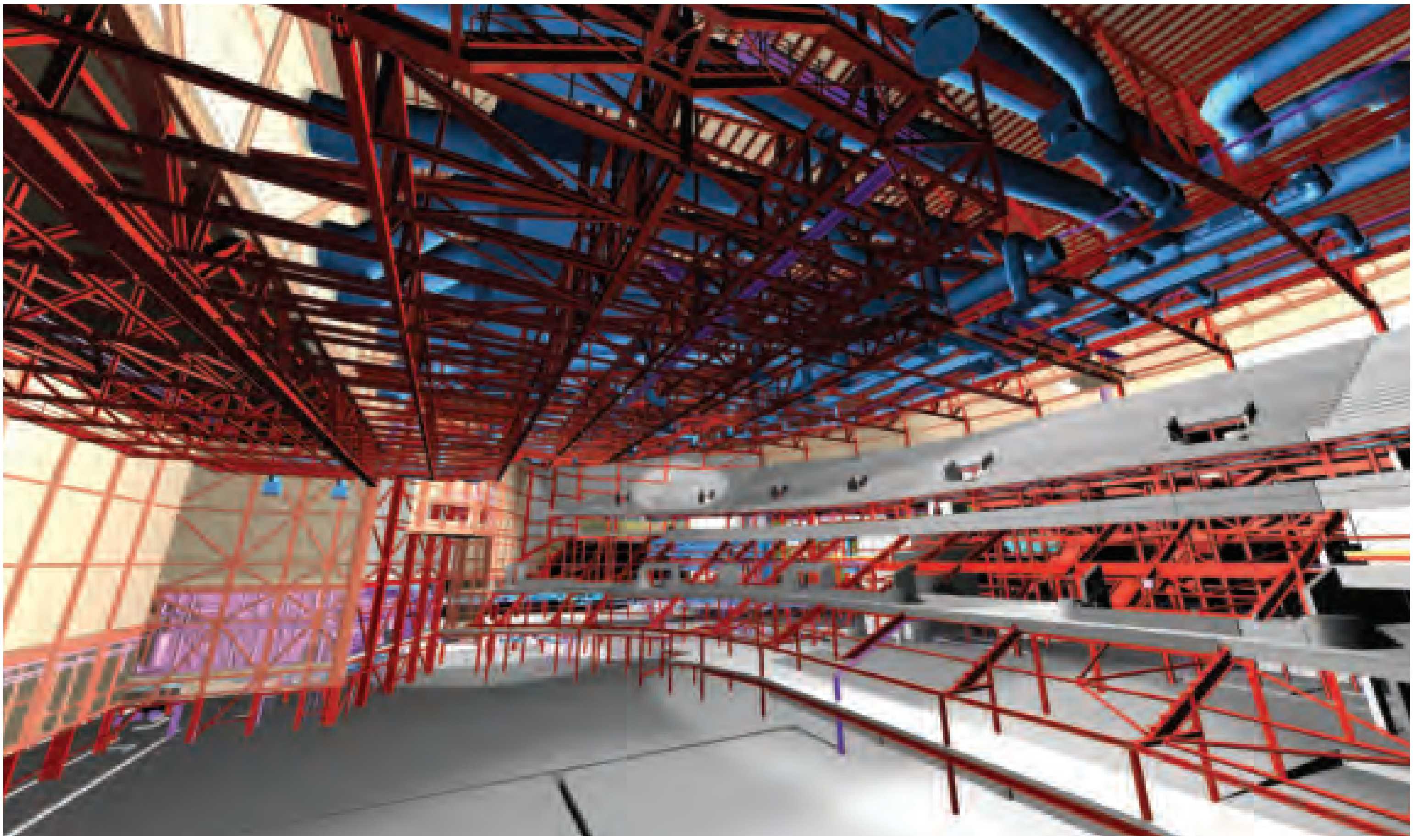
So as not to distract from the overall in-show ambience, no permanent lighting is used to illuminate the tiered access routes.
Instead, photoluminescent edge strips are provided at each riser tread, charged via the pre-show house lighting. Should additional charging be required, some UV (ultraviolet) lights are located on the high-level gantries.

Hospitality

The front-of-house space includes a couple of themed restaurant bar areas for on-site dining and hospitality, each with dedicated kitchens and full comfort-cooled VAV (variable air volume) and perimeter fan coil systems. At level 3, 24 hospitality boxes open to the main bowl offering a commanding view of the stage area.
Each room has its own void-mounted fan coil unit and fresh air system, allowing use for daytime meetings or other events and thus avoiding the need to activate the primary bowl systems.

20.

21.



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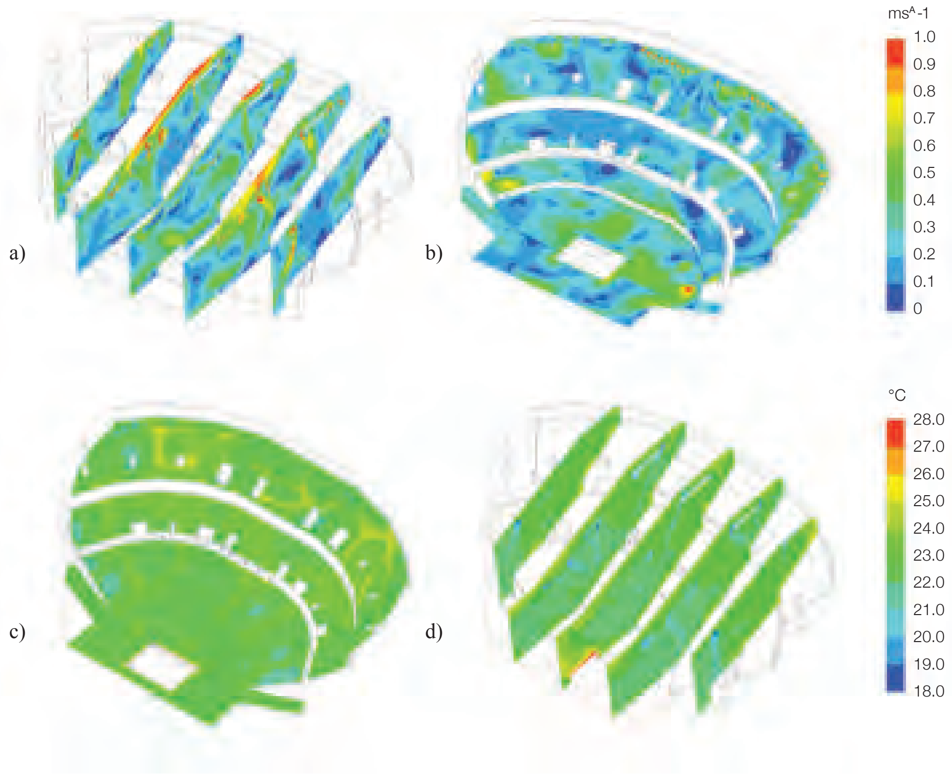


23.

20. Testing an air-handling unit.

21. The performer's-eye view reveals the careful co-ordination of structure, ductwork and gantries.

22. BIM with the supply chain: the Arup models brought together with Creagh's precast, Fisher's steelwork and Rotary's MEP installation models.

23. CFD profiles for:
(a–b) air movement/velocity;
(c–d) temperature profile.

Construction

Delivering the detail and construction the develops from a concept is a collaborative effort. Procured through a two-stage design-and-build tender, BAM and its supply chain worked closely with the design team to realise the project. Key to successful completion was true collaboration between all parties, supported by advanced BIM throughout, with a focus on simple construction using standardised components where possible, and maximising repetition.

As the agreed design was finalised through the tender period, Arup's structural 4-D BIM model was used for construction sequencing. The model enabled visual illustration of residual risks, and focused the construction team on the detail of critical aspects such as placing the 180 tonne, 54m PA truss. The 75-hour continuous operation involved two 500 tonne cranes lifting and holding it in position whilst the restraints to the stage box were installed for stability (Fig 24).

This lift enabled the roof trusses to be installed — an operation that was on the critical path, given the time required to install the double-layer construction of the roof itself. All the noise barriers had to be constructed to extremely high standards, as any weak points would jeopardise the building's entire acoustic performance.

Early engagement with the supply chain, and the use of BIM to bring together and co-ordinate information in 3-D between all parties, were key to the project's smooth running (Fig 25). Picking up Arup's detailed model, which was shared freely with all parties and used by steel fabricator Fisher as the basis of its final model, BAM Construction led this process through fortnightly online BIM sessions. The precast bowl and acoustic cladding was modelled in 3-D by the concrete contractor, Creagh, and the three structural models — Arup's, Fisher's and Creagh's — were co-ordinated together and with the other installations.

BAM has measured the benefits of BIM on the arena as saving at least 1000 design co-ordination issues and £350 000–£500 000 in site change costs against what would typically be expected on a project like this.

24.

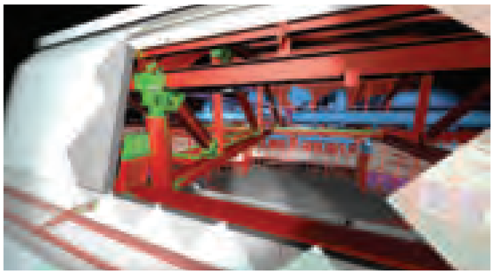
Achieving high quality installations to meet the noise transmission standards, while enabling rapid construction, required simplicity in components.

This is particularly apparent in the design of the seating bowl. Acoustic requirements dictated that it should be concrete, rather than a lightweight system. Working from the architect's parabolic seating and vomitory layout (Fig 26), a suite of elements capable of meeting the required structural performance in terms of strength and dynamics were defined, focusing on providing maximum repetition and allowing realistic construction tolerances.

A simple yet effective seal to provide fire, acoustic and water resistance was developed for joints between components.

The dynamic design meets *Event Scenario 4*, the Institution of Structural Engineers' designation in structural design for dynamic loading that relates to high-energy situations with synchronised/co-ordinated dancing.

Similarly, despite the irregular geometry of the external acoustic walls, simple rectangular panels were used, with careful attention to detailing of the joints to ensure tolerance of structural movements while meeting the acoustic performance.



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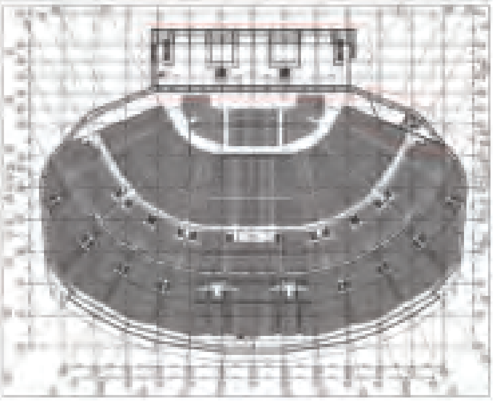


26.

24. Placing the proscenium arch truss, November 2012.

25. BIM cutaway showing interaction of roof structure and service ducts.

26. Architect's seating layout.

The front façade geometry was particularly complex, and the design of the steel frame supporting these elements was completed entirely in 3-D through shared models (Fig 27), including with the façade subcontractor, Lakesmere. Integrated drainage and colour-change lighting is concealed within the façade to achieve a dramatic effect that can be altered to reflect the nature of the events on show (Fig 28).

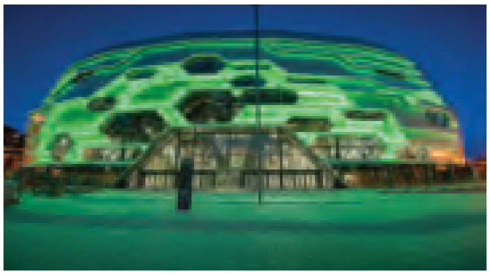
27.

Delivering to budget was a constant focus, and became a particular challenge when external factors influenced the project. One such instance was a significant raw material price increase for steelwork, announced shortly after BAM entered into contract. Arup successfully delivered the 3900 tonne steel frame design to an accelerated programme to beat the price hike with just eight weeks' notice, saving an estimated £150 000. Further value engineering generated an additional £350 000 to keep the project on track.

Acoustic design strategy

As already discussed, the arena's proximity to high rise, naturally ventilated, residential units necessitated some of the highest sound attenuation levels of any similar arena worldwide, to comply with strict environmental noise criteria. This made a high-performance yet cost-effective facade and roof system vital (which the inherited Stage D design did not provide), and as part of BAM's winning strategy Arup radically redefined the building envelope to ensure this happened.

The acoustics team took the issue back to basics, defining the internal baseline noise levels by benchmarking against rock concerts at various European venues. This baseline was then used to generate a detailed 3-D acoustic model of the arena interior and façade attenuation and map the sound pressure levels at the adjacent residential receptors (Fig 29). This approach allowed the attenuation performance of the façade and roof to be optimised, which also included value engineering of these elements in an acoustic testing laboratory.



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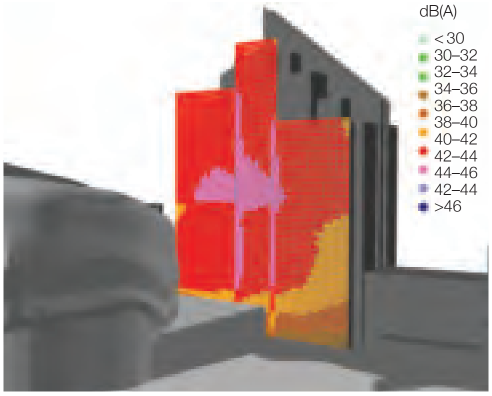


29.

27. The complex geometry of the façade structure.

28. One of the many colour-change façade lighting effects.

29. Sound mapping in the locality around the arena.

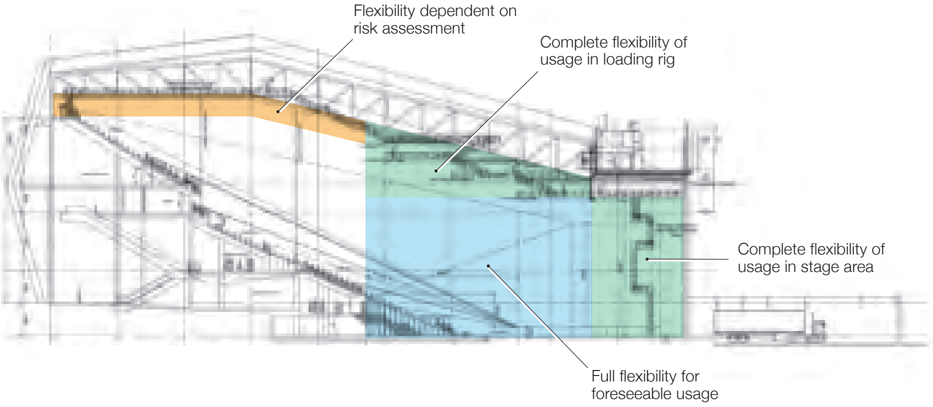
Achieving the cost-effective roof build-up previously described on page 43, was key, and the Arup team provided the series of costed-out acoustic and structural options for differing double skin roof constructions to meet the criteria. The study recommended introducing the mixed concrete and composite roof system, replacing the proposed costly acoustic cassettes and saving over £1m.

Innovations introduced by Arup minimised the technical approval risk and ensured the scheme's commercial viability, which was seriously jeopardised by the tough economic conditions.

As for the internal acoustics of the bowl, the brief required quality sound for events, with clear speech and music, even sound level coverage, and freedom from echoes. All of these aspects were achieved through the detailed 3-D acoustic modelling, design development with the architect, and acoustic laboratory testing.

The controlled level of reverberance was achieved through the use of an acoustically absorptive roof liner and acoustic treatment around the stage area and around the side and rear walls, all within the constrained materials budget.

Upholstered seats were installed to enhance the user experience and also to provide a suitable level of reverberance, irrespective of the level of occupancy.



30.

Fire strategy

Achieving an efficient and working fire strategy required Arup to work closely with all stakeholders. This initially involved redeveloping the original Employer's Requirements fire strategy, which was seen to be based on an unsustainable management regime. Arup set out to take into account the operational requirements of the arena operator and provide a manageable solution when the building went live.

The fire team worked to ensure that approval in principle was granted early in the design to control approval risks. Changes during construction were closely managed, and the fire strategy developed further as the design evolved on site. The full process focused on attaining a suitable level of safety and sufficiently flexible operation, while limiting cost and impact on sustainability credentials for the operator and client.

Concourse

In the original strategy, reliance had been placed on the prevention of fire in the concourse. In the real-life operation of a modern arena, this is considered restrictive and reduces potential revenue streams such as merchandising. Working with SMG, Arup identified flexibilities that could be enabled, and a zoned evacuation plan based on a manageable use was developed.

30. Internal flexibility enabling risk assessment-based approach to fire protection.

31. Simulation of emergency egress into the local surroundings: at one, six, nine and 11 minutes.

32–35. The ever-changing coloured façade.

Basement

The unseen workings of a live building can represent a heightened risk to the entering fire and rescue service. Basement storage space is one example where ventilation may be limited and high fire loads exist.
To address this, the team developed an innovative natural ventilation approach. A louvred plenum for initial pre-ventilation, prior to site arrival of fire and rescue personnel, is provided, together with traditional break-out panels, to increase the amount of ventilation if needed.

The initial qualitative review was backed up by a quantitative assessment of the likely conditions, indicating that the approach achieves a reduced likelihood for flashover and backdraught conditions, versus the traditional "break-out panel only" approach.

Roof

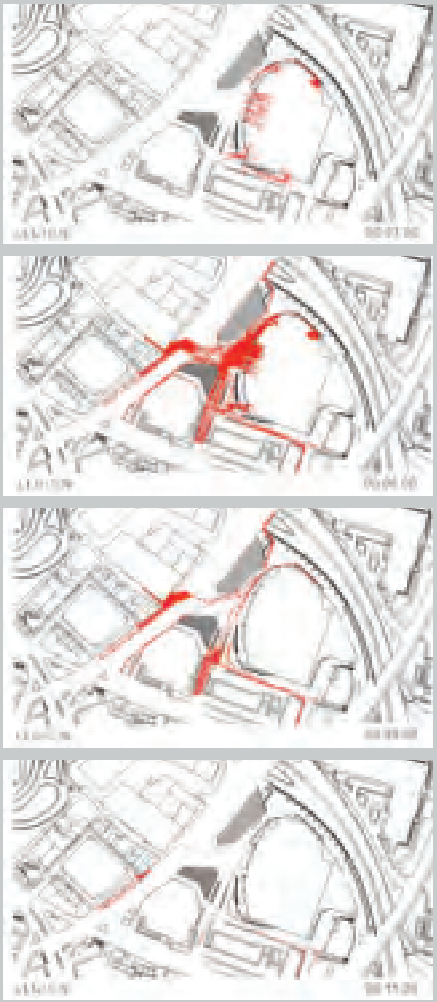
Contemporary fire safety guidance does not require structures only supporting the roof of the "more common type" of building to be protected. At face value the new roof in Leeds would therefore not require protection, but the **first direct** arena is anything but common. The roof provides support to the external walls, and in turn the walls support each floor.

Previously unidentified and un-costed roof-level fire protection was therefore required, and represented a budget deficit to the overall project. Arup set about agreeing the required level of protection for the trusses. Of key importance for stage productions, a risk assessment-based approach for the on-going use of the various areas close to the roof enabled optimisation of the structural fire protection to be identified and implemented: costs mitigated, operator satisfied (Fig 30).

Public realm

Ordinarily a fire evacuation assessment assumes that once occupants reach a place of safety outside the building, they can be considered to have made their escape.
At the arena, however, this needed to extend beyond the building perimeter to ensure that the 13 500 capacity audience could be accommodated by the proposed landscape design and restricted areas of the local public realm. All occupants had to flow from the building, without the excessive queuing that could potentially expose them to a fire within (Fig 31).

Extending the fire and smoke spread and evacuation analysis for the premises, Arup undertook evacuation modelling to review and assess the external conditions, including traffic control and management implications, on the evacuating occupants. This successfully demonstrated adequate means of evacuation from "seat to street", as well as addressing wider planning and fire and rescue service concerns for the premises.



31.

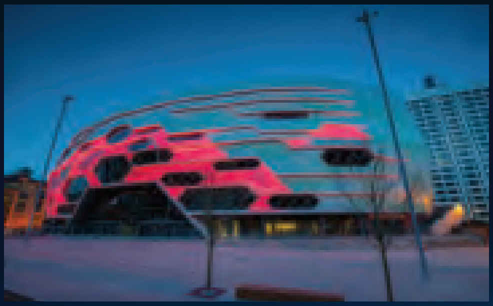
Lighting and façade

The arena's fan shape creates a highly prominent façade that looks west out over the city. As the first interface between venue and visitor, it was vital that this primary façade communicated the aspirations of the arena and formed a strong part of the overall event experience. Arup's lighting team in the Sheffield office developed an external lighting design concept, including the feature lighting of the primary façade.

The concept was essentially to complement the architectural design with a dynamic and eye-catching frontage. The design presents a kaleidoscope of materials, colours and textures, a combination of solid acrylic panels, perforated mesh sections and coloured glazed elements, stitched together with protruding tracery lines snaking across, and acting to break down the vast façade. Arup proposed a layered lighting approach to enhance the varied façade elements, and provide a flexible treatment that could be tailored to the arena's operating mode.

Tall lighting masts frame the primary entrance, illuminating the public realm and providing focused illumination of the solid coloured acrylic hexagonal panels of the façade. Functional lighting from within the arena emanates out through the coloured glass, giving views of activity within. Arup proposed a back-lit solution to the mesh panels to emphasise the texture and give depth to the façade, with light from within reflecting the energy of the stage bursting outwards to the city. The undulating illuminated tracery lines tie all these varied elements together and create continuity across the building.

Throughout the development of the façade lighting concept, adaptability was a key theme. The fully dynamic colour-changing façade treatment would visually represent the arena being tailored to the event taking place. RGB LED lighting was proposed for the backlit mesh and tracery lines to transform the façade to complement and promote the on-going event. This bold and vibrant façade treatment creates a vast and ever-changing colour billboard that transforms the building and makes each visit unique and dazzling (Figs 32–35).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Civil engineering

An initial enabling works package was needed to remove of an area of Japanese knotweed from directly behind the IRR wall, and divert an existing sewer outside the building footprint. Drainage connections on the site had to be split into three for surface water and two foul sewers to match the limited discharge at existing connection points. A separate attenuated system was provided for the adopted highway drainage to one of the connections, and a further system of sustainable drainage was provided beneath the public realm in front of the main entrance.

To connect to one of the existing sewers, the main attenuation system, taking well over half of the main roof, was constructed above ground within a raised loading dock inside the internal service yard. The yard is limited to a small triangular area, so an extensive analysis of turning manoeuvres was undertaken to design the loading bays at just the correct angle to enable all possible forward and reversing manoeuvres.

As previously noted, the arena access road was pushed tight against the existing retaining wall above a dual carriageway, providing turning access to the service yard and minimising the overhang of the seating bowl over the road. To assess the impact of the arena on the IRR retaining wall, the team made a detailed investigation and analysis of the existing structure, enabling strengthening works to be limited to just its top 2m.
The access road was designed to adoptable standards that included vehicle restraint systems to prevent errant vehicles falling onto the IRR over 5m below.

The foundation design was driven by CDM (construction design and management) and by buildability. The founding stratum was too shallow for cost-effective piling, but too deep to work in the excavations for spread footings. Mass concrete infill was therefore used to bring excavations from rockhead to the working level, and the reinforced cages for the pads were then placed safely above (Fig 36).

Utility and building services penetrations were concentrated adjacent to the access road. The installation sequence was critical and so each one was modelled and co-ordinated in the BIM workflows.

Sustainability

To achieve the record BREEAM score for this kind of arena in the UK, the materials selection resorted to recycled products and sustainable materials. BREEAM credits were obtained for the precast structural slabs, in addition to the use of recycled cement replacement products and recycled glass sand for paving and external works. Cut-and-fill was carefully balanced to dramatically reduce the export and import of material, and sustainable drainage systems were applied to the new public plaza to the front of the arena. Rainwater is also harvested and used for toilet flushing.

BREEAM is the world's most widely used environmental assessment method for buildings. It sets the standard for best practice in sustainable design and has become the de facto measure used to describe environmental performance.
The interim BREEAM score for the **first direct** arena was 60.99% ("Very Good").

Beside its other roles, Arup was BREEAM assessor for this landmark project. The scale and building end-use meant that several complex BREEAM requirements formed part of the assessment, including acoustic, thermal and lighting issues. Integrating these on such a major project with a very tight programme was highly challenging, and was only achieved with proactive support from the whole design team.

Conclusion

Delivering the **first direct** arena overcame technical and commercial challenges, gave the client a highly sustainable, world-class venue, and provided a huge catalyst for growth and employment in the city of Leeds. The end result is an iconic building that met the requirements of the operator, and to a demanding programme in a difficult economic environment.

Complex constraints and requirements were used to develop a unique response, with innovative solutions at all stages of the project, from the positioning of the arena on the site to the creative use of concrete for acoustic containment on the roof.
Using state-of-the-art modelling and collaboration between all designers and members of the supply chain, an integrated solution was delivered that minimised problems and waste during construction.

Chris Coulson, executive officer at Leeds City Council Asset Management department, commented: *"Arup's multidisciplinary team and their ability to combine innovative engineering solutions have contributed significantly to the success of this exciting world-class venue. These services have been delivered consistently to a high standard and to the City Council's satisfaction.
The Council would be pleased to recommend Arup to other clients on similar projects."*

The arena has also received accolades from some of its first superstar performers.
After his appearance in July 2013, Bruce Springsteen remarked: *"This is a great building, and a great place to play."*[2]
Two months later Rod Stewart commented: *"It's good to be here in your new arena in Leeds... the acoustics here are better than those at Caesar's Palace in Las Vegas."*[3]

36.

36. Excavation and foundation construction in progress.

37. Bruce Springsteen in performance, with the house lights on so he could see the audience.

37.

References

(1) www.leeds.gov.uk/docs/Planning%20 Performance%20Agreements%20Protocol.pdf

(2) http://tinyurl.com/kanbjuv

(3) http://yorkshiretimes.co.uk/article/Rod-Stewart-At-Leeds-Arena

Awards

Institution of Structural Engineers Structural Awards: Winner

Institution of Structural Engineers Yorkshire Structural Excellence Awards: Winner

Yorkshire Property Industry Awards, Development of the Year & Design Excellence Awards: winner

YorHub Constructing Excellence Awards, BIM project of the year: Winner

YorHub Constructing Excellence Awards, Project of the year: Winner

Institution of Civil Engineers Award – First Direct Arena (shortlisted)

Authors

Jim Bell is a Director and leader of the Sheffield office, and was Project Director for the detailed design of the **first direct** arena.

Samantha Birchall is business development co-ordinator in the Sheffield office, and for the arena.

David Clixby is an Associate Director in the Sheffield office, and led the MEP team for the arena.

Ian Drabble is an Associate Director in the Sheffield office, and led the civil engineering design of the arena.

Eoghan Given is a senior engineer in the Leeds office, and led the fire engineering design of the arena.

Richard Greer is a Director in the Leeds office, and led the planning advice team and the venue consulting input for the arena.

Neil Hooton is an Associate in the Leeds office, and the multidisciplinary Project Manager for the arena.

Susie Horsefield is a senior engineer in the Sheffield office, and was a member of the structural engineering design team and BREEAM assessor for the arena.

Lee Kirby is a senior consultant in the Leeds office, and led the acoustic design for the arena.

Helen Marsh is a designer in the Sheffield office, and was a member of the lighting design team for the arena.

Ben Watkins is an Associate in the Sheffield office, and led the structural engineering design for the arena.

Project credits

Promoter: *City of Leeds* Clients: *City of Leeds; PMP Ltd (now IPW Ltd); BAM Construction Ltd; Yorkshire Forward (due diligence review); SMG Europe Ltd (fitout)* JV consortium partner: *Donaldsons* Planning agent, technical adviser, civil and SMEP engineer, acoustics, fire, lighting and BREEAM assessment services consultant: *Arup — Iain Adcock, Gareth Ainley, Stuart Allinson, Pete Allison, Ben Aston, Mohd Bahardin, Susanna Bathe, Jim Bell, Andrew Bradshaw, Ryan Brate, Adam Brown, Jonathan Burton, Neal Butterworth, Rachel Capstick, Lee Carl, Andrew Carter, Judith Chan, Josh Childs, David Clixby, Robert Collett, Anna Coppel, Ben Cox, Richard Crabtree, Paul Davies, Derek Devereaux, Andrew Dickinson, Ian Drabble, Cathy Edy, Keith Emmett, Mike Fletcher, Nigel Foster, Chris Gibbs, Chris Gauntlett, Eoghan Given, Alastair Gordon, David Green, Richard Greer, Llew Hancock, Jim Harbord, Nicole Harrison, Steven Hazlehurst, Andy Heath, Adrian Hides, Peter Holt, Neil Hooton, Susie Horsefield, Ray Houghton, Will House, Justin Howell, Richard Hunt, Paul Irwin, Robert Issott, Richard Jackson, Phil Jagger, Matt Johnson, Laurence Kearsey, Rory Kenneally, Lee Kirby, Ian Knowles, Mike Kong, Angus Law, John Linnell, Dan Lister, Matt Lovell, Laura Marchant, Stu Marley, Helen Marsh, William Martin, Sandra Murray, Robert Nash, Darren Parker, Chris Parsons, Owen Phillips, Gavin Poyntz, Alan Rowe, Judith Ruttle, Gary Smith, Hannah Smith, Jim Smith, Neale Smith, Adam Smout, Martin Stanley, Ryan Taylor, Pete Thompson, Nick Troth, Dave Twiss, Dave Wade, Ben Watkins, Paul Wheatley, Gary White, Laura Wilson* Architect: *Populous* Project manager: *Davis Langdon LLP* Steelwork subcontractor: *Fisher Engineering Ltd* Concrete subcontractor: *Creagh Concrete Ltd* Façade subcontractor: *Lakesmere.*

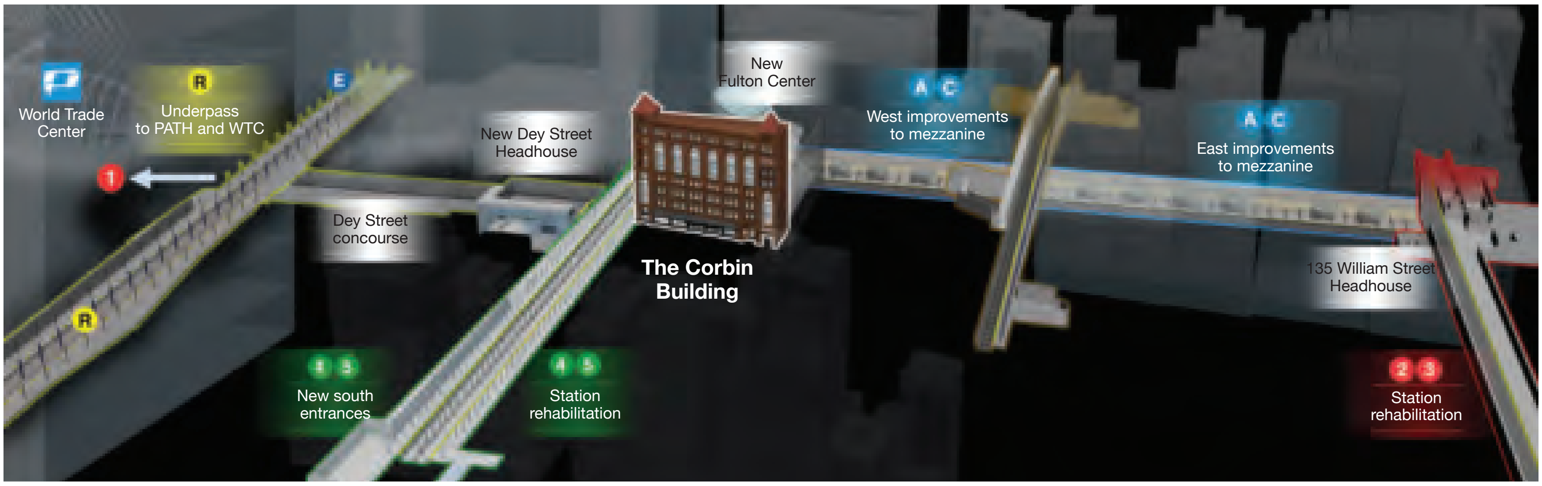
Image credits

1–2, 5, 7, 11, 16, 21, 28, 32–35 *Giles Rocholl Photography*; 3, 13 *Nigel Whale*; 4, 17 *BAM Construction Ltd*; 6, 8, 10, 12, 14–15, 20, 22–25, 27, 29, 31, 36–37 *Arup*; 9, 26 *Populous*; 18–19, 30 *Arup/Nigel Whale.*

The Corbin Building, Fulton Center:

rediscovering and renewing an architectural gem

1.



2.

Location
New York City, USA

Authors
Ian Buckley Craig Covil Ricardo Pittella

Introduction

The Fulton Center transit hub in Lower Manhattan is one of the most ambitious capital projects undertaken by the Metropolitan Transportation Authority (MTA) since its inception in 1968. The goal of the $1.4bn scheme is to connect and rationalise access to 10 separate New York City subway services that converge in and around Broadway and Fulton Street, and to enhance the experience of the 300 000 passengers who daily move through the facility (Figs 1–2).

Central to the project is the redevelopment of approximately one third of a city block adjacent to Broadway to create a new multi-level mixed-use station and retail destination, which opens in 2014, at the intersection of the IRT Lexington Avenue line (4 5) and IND Eighth Avenue line (A C). The Corbin Building encloses the southern boundary of the new facility and forms a highly visible main entrance at street level, as well as providing retail and commercial space above grade and building services and utility space within its two levels of existing basement.

In 2003 MTA Capital Construction appointed Arup as prime consultant for the Fulton Center redevelopment in a wide range of multidisciplinary architectural and engineering design services (including the analysis and design of the cable net that supports the huge art installation around the interior of the central oculus, described previously in *The Arup Journal*[1]).

One of the biggest challenges would be to rehabilitate and integrate the Corbin Building within the development.

History

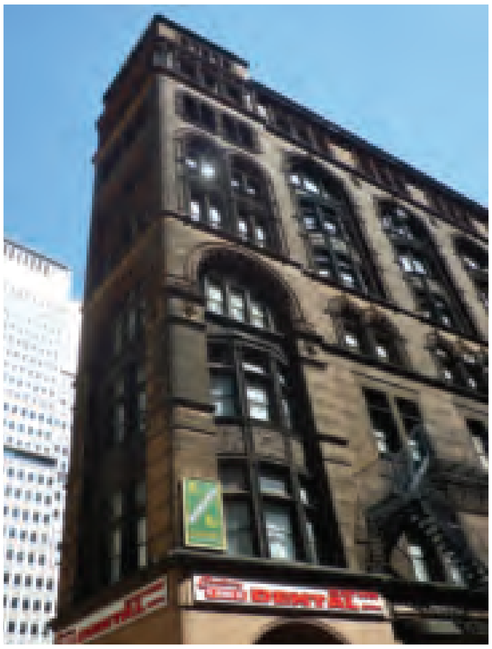
Described by contemporaries as the "father of the skyscraper", the prominent NYC architect Francis Hatch Kimball (1845–1919)[2] designed the building in the highly decorative Romanesque Revival style, and at the time of construction in 1888–89 it was Manhattan's tallest (Fig 3). After training in England, Kimball pioneered the use of ornamental terracotta and metalwork, both structurally and decoratively, in realising his often extravagant designs.

Austin Corbin (1827–96) commissioned the building to serve as offices, bank, and prominent symbol of his own success, located as it was on Broadway squarely downtown in the heart of the developing financial district. Corbin, a famous "robber baron" and President of the Long Island Rail Road, had consolidated his competition in the 1870s, and his desire to display his resulting wealth ostentatiously was a perfect match for Kimball's creative ambition. The history and significance of his architectural gem, however, were all but forgotten under the accumulation of more than a century's dirt and neglect (Fig 4); ironically, it was to be saved more by chance than by intent.

This proto-skyscraper also pushed the boundaries of engineering design. The Great Chicago Fire of 1871 had destroyed over three square miles ($8km^2$) of that city, and examination of the NYC Building Code from this period reveals that preventing the spread of fire was the design consideration foremost in the minds of contemporary architects. Kimball thus turned to the Guastavino Fireproof Construction Company to help solve the technical challenges of constructing a high-rise building rapidly in light fireproof materials while also using the benefits of iron framing to provide flexible internal spaces for his client.

The Guastavino Company was owned by a father/son team. The Spanish-born builder and architect Rafael Guastavino (1842–1908) — a contemporary of Gaudí — had arrived in the US in 1881. He immediately realised the potential of combining the strength and flexibility of traditional Catalan vaulted arch construction with the contemporary emerging iron-frame technology. He created the "Guastavino timbrel vault"[3], a tile arch system that he patented in the US in 1885. This used multiple layers of thin terracotta tiles, laid at angles with mortar in between, to produce


3.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1. The refurbished Corbin Building forms part of The Fulton Center, still under construction on the left (2013).

2. The Fulton Center is the focal point of 11 NYC subway services.

3. The Corbin Building, c1910.

4. The Corbin Building in the early 2000s, prior to redevelopment.

6.

5.

5. Boston Public Library under construction: Guastavino standing on a partially constructed arch.

6. Load testing of timbrel arches for NYC Department of Buildings.

7. Photogrammetry as a base for producing the HABS documentation, showing the original "pepperpot" roof on the right.

> "This is not the kind of building you see every day. For an engineer, this is the highlight for us... for our whole career."
>
> - Uday Durg, Program Executive, MTACC.

7.

slender masonry arches with an inherent flexural capacity that significantly increased their loadbearing ability.

Guastavino and his son Rafael III were later to become famous for works at the Boston Public Library (1891, Fig 5), and New York's City Hall station (1900), Grand Central Station Oyster Bar (1913) and Ellis Island Main Hall (1917). In 1888, however, this technology was radically new to a sceptical New York City Buildings Department, and Guastavino had to conduct full-scale load testing of his unprecedentedly thin timbrel arch system before he obtained approval for its use (Fig 6).

Following Austin Corbin's sudden death in a horse carriage accident, his building lost much of its central importance and began its slow decline. Early in the new century (c1905), when New York City's subway system was being constructed, a portion of the basement was acquired and converted to staircase access direct from the street to the northbound platform of the IRT Lexington Avenue Line, which runs directly adjacent to the building's west façade on Broadway. In the 1920s a further portion of the street level and basement was purchased by the subway, which allowed the access stairs to be moved inside and the dangerously congested sidewalks reinstated.

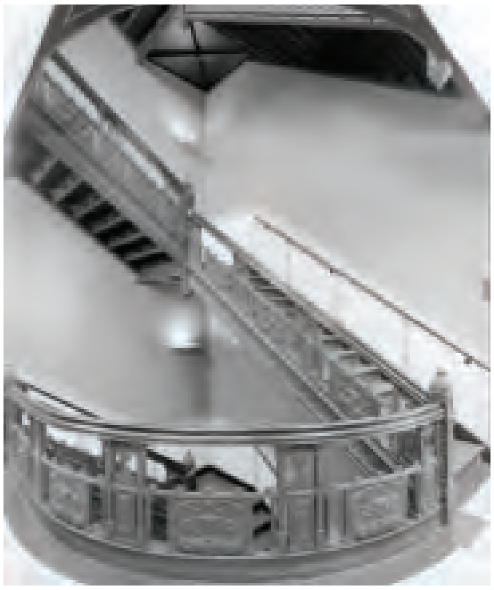
As the century wore on the building lost its distinctive "pepperpot" tiled roofs and was split into individual stores and small-scale offices. In the 1970s the ubiquitous New York City iron egress staircase and ladders were hung from the south façade, and through-window air-conditioners were installed.

HABS documentation and rediscovery

To make way for the new Fulton Center pavilion, the Corbin Building was initially scheduled for demolition along with others occupying the west end of the block between John Street and Fulton Street, and Arup sub-contracted the historic preservation specialists Page Ayres Cowley Architects (PACA) to research and document the building before it was demolished. Due to its age, drawings had to be produced for the Historic American Buildings Survey (HABS), a national repository documenting the history of construction in the US, so PACA supplemented its document research with photogrammetry of the building façade to produce highly detailed drawings of the architectural elements (Fig 7).

PACA's investigations revealed what years of neglect had masked: here was a highly ornamented architectural gem of historic significance. One outstanding feature was the extravagantly decorative staircase, formed using slate cantilever steps with ornamental balustrading in brass and copper-plated cast iron, a mass of intricate relief and detail (Figs 8, 11). Also resonating with the proposed redevelopment were the building's connection to the history of mass transit through the original owner, builder, and later conversion; the HABS survey identified that it had one of the earliest Otis passenger elevators.

As a result, late in 2003 the Corbin Building was added to the National Register of Historic Places, and momentum grew through both public and government opinion that it should be saved. The Fulton Center design would be revised, and this was formalised in a MoU (Memorandum of Understanding) between the MTA, the State Historic Preservation Office (SHPO), and the Federal Transit Authority, which provided overall funding for the project to save and incorporate the Corbin Building into the new Fulton Center.


8.


9.

10.


11.

8. Elaborately decorated staircase.

9. Uday Durg, MTACC Program Executive, examining decorative detail on Corbin.

10. The Corbin Building "signature".

11. Detail of brass and copper-plated cast iron balustrade.

The original structure

With a hybrid structure of loadbearing masonry and an ironwork gravity frame, Corbin is wedge-shaped on plan, 40ft (12.2m) wide at the east end but only 20ft (6.1m) wide at the west elevation overlooking Broadway. Its overall length is 152ft (46.3m), and it has two basement levels, double-height retail space at street level, and seven full levels of office space above. The building ends were once crowned with "fairytale towers" but lost their peaked roofs in the early 20th century.

The façade is predominantly self-supporting masonry. Cast iron columns were used internally and are also embedded within the perimeter masonry walls as support for the internal floors and roof. Wrought iron beams frame between the columns and perimeter walls and support the Guastavino tile arch floors. The large projecting bay windows in the south and west façades were formed as self-supporting decorative cast iron structures. For all lateral stability the building relies on the masonry elements acting as shear walls.

While the exterior was found to be more or less intact (albeit suffering from its long neglect), the building interiors had been extensively redecorated and remodelled. But the grand ornate staircase still connected levels 2 through 8, and some elements of the original Otis elevator remained.

12. Recreated "pepperpots" crown the restored building.

13. Interior detailing around the elevator doors, including reinstated marble wainscot.

Plans for adaptive re-use

Although a limited restoration of the façade would have met the obligations the MoU imposed on the MTA, the client and design team agreed on a more ambitious plan, benefiting both the new and the existing buildings, to integrate Corbin and the Fulton Center pavilion into a single coherent design that allowed each part to support and rely on the other. Key design decisions were to:

- ***use part of Corbin's street level space as the main south entrance to the Fulton Center***, so that the public would access the building through the central arches on the existing façade below a new steelwork canopy into an escalator lobby, and pass through a large new opening in the north wall to the Fulton Center beyond.

- ***install a new deep escalator***, running from the Corbin south entrance lobby through its existing basement and sub-basement levels to connect with a new concourse under the IRT Lexington line on Broadway. This concourse (effectively a below-ground promenade) would access the PATH station over a block away and allow passengers to cross the existing subway line without having to return to street level.

- ***locate egress stairs for both Corbin and Fulton Center in a unified space between them***, an "interstitial building" that would require new penetrations in the north wall of the former at every level above ground, but enable removal of the typical intrusive and ugly NYC external iron escape stairs from the façade. This would also allow the historic ornamental stair in Corbin — not compliant with modern codes due to the height of the existing decorative handrails — to be kept unaltered.

- ***share MEP systems between Corbin and Fulton Center***, with basement and sub-basement spaces in Corbin for incoming electrical vaults, a PRV station for the steam heating system, an escalator motor, and control room. Multiple services would pass through, including generator fuel piping and storm and sanitary drainage, and there would be a shared fire command centre at street level between the two buildings.

12.

- ***strengthen Corbin's lateral system*** by a connection to the new Fulton Center steel frame. As this could only be efficiently achieved at the pavilion's lower levels, due to floor diaphragms becoming discontinuous above level 3, this would also necessitate lateral stiffening to Corbin above the roof connection level.

- ***replace the existing parapet structure*** with a reinforced masonry backing wall tied to the roof. As the parapet is Corbin's most vulnerable element in a seismic event, and had undergone significant weathering due to its exposed location, it was decided to rebuild the wall, improving its ability to cantilever (rather than just rely on its own mass).

- ***reconstruct the fairytale pointed roofs*** to the two towers that bookend the roof level. Code and safety concerns required a "modern construction" framed with pyramidal steel members and ring beams to minimise vertical load and outward thrusts on the existing masonry.

13.

- ***expose the underside of the terracotta tile arch ceilings*** previously hidden behind modern suspended ceilings, so that users could experience the spaces as originally intended. This would necessitate burying all electrical power, lighting, and IT conduits within the building slabs.

- ***retain the existing elevator shafts***, and renovate/upgrade the elevator and cabs to a period design with minimal impact to the existing. Parts of the original Otis elevator cage were found during construction and incorporated in the lobby design.

- ***relocate and consolidate historic features***, including the marble wainscot throughout to level 7; replicate the historic floorplate/ internal corridor; repair in situ the historic wood partition office on level 7; display the decorative terracotta from the parapet and the existing cast iron boiler doors in the escalator wellway; display the historic Otis elevator cage in the entrance lobby.

Arup submitted all details for the work to the SHPO for its review and sign-off, as the building had previously been designated as Landmarked.

Survey and investigation

Through most of the design process, Corbin remained occupied by its various tenants. Even access to spaces owned by part of the client body, New York City Transit (NYCT), was far from straightforward, as the subway system typically operates 24/7 and most of the areas owned by NYCT were egress corridors or staircases that couldn't be closed without significant advance warning. Only the basement and sub-basement could be freely accessed with little nuisance or disruption to tenants — which was fortunate as these spaces, which had remained without finishes or decoration, provided much useful information on the original construction.

Fortunately some of the original structural drawings had survived since 1898 (copies obtained from the NYC Department of Buildings), and these showed rudimentary framing plans and beam loading data, together with some details of cast iron column sizes.

Some discrete field surveying and testing were also allowed — essential for preparing the design documentation — and the design team used these windows of opportunity for a series of focused studies. These started with visual inspections and then focused on specific areas of interest, or later, as the design progressed, on areas that showed an important need for information. Nevertheless, as with all existing-building projects, there were information gaps that could only be closed out once construction began, requiring the design to react and evolve rapidly in response to any unforeseen conditions. The following summarises the investigation work:

- structural visual survey inside and outside
- architectural spaces survey determining size and configuration of internal walls (many were later partitions masking the original structure)
- levels survey within the historic stair core, agreed to be the location taken as the datum for the building
- 3-D topographical surveying, including a limited survey of façade alignment
- photogrammetric survey of the façade for HABS documentation
- structural and architectural survey of the external façade by hoist (requiring a 24-hour closure of the street in front of the building)
- structural probes:
  - *through partitions to determine walls behind*
  - *at beam and column locations*
  - *at critical connections/interfaces (eg column brackets)*
  - *to take samples for materials testing*
  - *through the Guastavino floor vaults and cinder fill above*
  - *to help determine critical masonry wall thicknesses*
  - *to establish sizes and thickness of beams to match against published historical data and information in the NYC Department of Buildings drawings.*
- materials testing:
  - *existing masonry and mortar (compression)*
  - *suspected cast iron columns (tensile, chemical and weldability)*
  - *suspected wrought iron beams (tensile, chemical and weldability).*

The measured size and strength of the wrought iron beams gave the designers an immediate problem: based on historic values of design strength for the period, the floor beams could not carry the design floor loads. Testing showed the wrought iron to have a tensile yield strength close to 30ksi (207Mpa), but contemporary design would have limited the typical flexural design capacity to 12ksi (83Mpa) (working loads) due to variability in quality of manufacture. This lower value was not enough to justify even the existing floor condition and loading under current design codes.

Pursuing a solution, the team managed to access an area of floor slab in the basement for an in situ load test of the existing floor system, fully monitored by strain gauges. This was enough to demonstrate its capacity, given typical office live loadings plus a 50% factor of safety consistent with current codes and standards. However, this also placed a design constraint that existing office loadings should be maintained, as well as requiring that existing floor construction weights should be mimicked in the new design to avoid reduction in allowable live loads.


14.

Working with historic materials

One of the largest challenges in the restoration was to effectively clean and repair the wide palette of materials Kimball had used in the decorative façade to express his client's taste for opulence (Table 1). The restoration required all these elements to be cleaned, or replaced/repaired/repainted as appropriate. Each presented specific challenges to the team, whether through the selection of appropriate lime putty mortar to match existing; replication of the terracotta bricks for spot replacements; sourcing new stone to match existing; cleaning the stone and terracotta; or patching the stone with Jahn repair mortars.

The project was funded with money from the American Recovery and Reinvestment Act 2009, so this introduced additional challenges to comply with the Act's "Buy America" clause. This imposed a general requirement that any public building or works project funded by the stimulus package must use only iron, steel and other manufactured goods produced in the US. As the contract documentation was mostly prepared before this Act came into existence, it presented the team with a huge challenge to achieve compliance, effectively requiring redesign of many key components while the works were under way.

Inside the building the team faced similar issues, sourcing three kinds of wood for the window framing repairs, and matching marble for the decorative wainscot panelling and floor tiles and slate for repairs to the historic stair core.

Table 1.

Material	Location
Terracotta brickwork	Typical south and west façades above level 2
Decorative terracotta pieces	Parapet, water table and window surrounds of south and west façades
Red sandstone	Banding of south and west façades below level 2 including street-level archways
Brown sandstone	Banding of south and west façades below level 2
Decorative cast iron armatures	Large self-supporting windows spanning multiple levels of south and west façades above level 2
Wood windows	Operable sash windows typical for all locations other than within the cast iron armatures
Common brickwork	North façade: replaced with facing brickwork where visible in the final design.

14. Restored room interior.

15. Detail of restored cast iron façade element.

15.

Cast iron façade repairs

The original design called for wholesale removal of cast iron elements in the façade, so that individual pieces could be documented, cleaned down to bare metal, and repainted. Damaged pieces were to be replicated. This approach was based on the assumption that the cast iron was erected bottom-up after the main masonry façade, as was common in many similar buildings of this period.

Work commenced with the careful removal of the decorative cast iron leaf-shaped tracery elements that stood proud of the window framing (Fig 15). Unfortunately, as removal of the internal wood window framing began, it was discovered that the original cast iron armatures were built into and behind the decorative terracotta window surrounds. It would be impossible to remove these elements without wholesale damage to the terracotta, and extending the project schedule by several months. Fortunately the back side of the cast iron windows was found to be generally in excellent condition.

Faced with this, the team recommended a change of approach. While the multiple small decorative elements fixed onto the face of the windows would still be removed and either cleaned off-site or replicated if too damaged, the cast iron windows and frames would be left in place and repaired there.

This gave the team new challenges: to clean and repaint the cast iron in situ, repair non-structural cracking in infill panels and window sills, and the in situ structural repairs to load-bearing armatures.

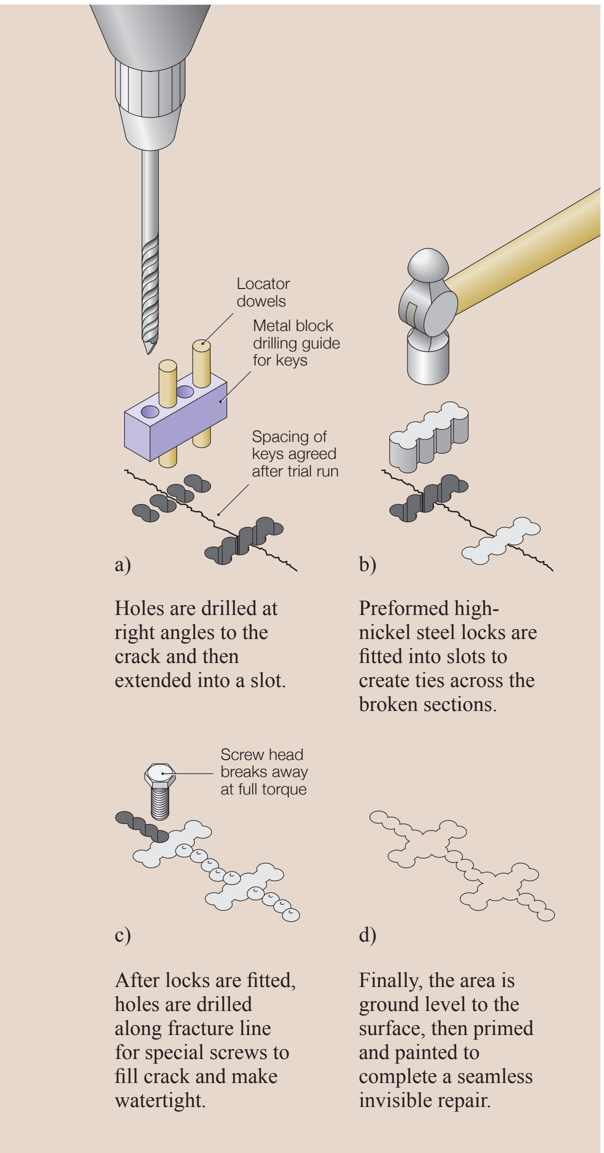
Solutions had to be rapidly developed while engaging the contractor to perform necessary field testing and mock-ups to ensure that both designer and client were happy with the final solutions.

Cleaning and repainting cast iron in situ

The team conducted shop and field testing of several cleaning options, including *Vacu-Blast* and needle-guns, to determine which would be most effective. Traditional blasting was considered but dismissed, due to the likely excessive cost of site containment and blast media collection. Although *Vacu-Blast* performed well in the shop, it did not translate effectively to the field due to the quantity of decoration on the existing metalwork forming a high relief and preventing a good seal between equipment and working face.

Fortunately the needle-gun (a drill-like device with multiple metal needles driven percussively by pneumatic action) proved effective in cleaning but still avoiding damage to the base metal decoration.

Meanwhile, PACA examined the paint on the existing ironwork and came to a startling conclusion: it had not always been black as originally thought, but rather a bright red color (somewhat ironically named “shy cherry”). This was further backed up when PACA found a contemporary citation to Corbin as “the red building”.



a)

Holes are drilled at right angles to the crack and then extended into a slot.

b)

Preformed high-nickel steel locks are fitted into slots to create ties across the broken sections.

c)

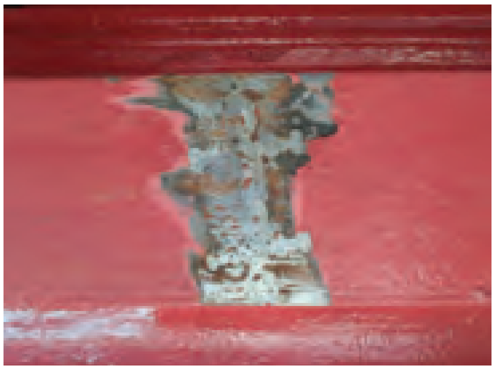
After locks are fitted, holes are drilled along fracture line for special screws to fill crack and make watertight.

d)

Finally, the area is ground level to the surface, then primed and painted to complete a seamless invisible repair.

16.

17.



18.

19.

Repair of non-structural cracking in infill panels and window sills

Cast iron cannot be easily welded, and material tests on the cast iron at Corbin confirmed high levels of carbon in the base metal that would precipitate cracking if welding was attempted. An alternative approach was needed, and research revealed "cold stitching", a common means of repair to cast iron engine blocks that could potentially be applied here.

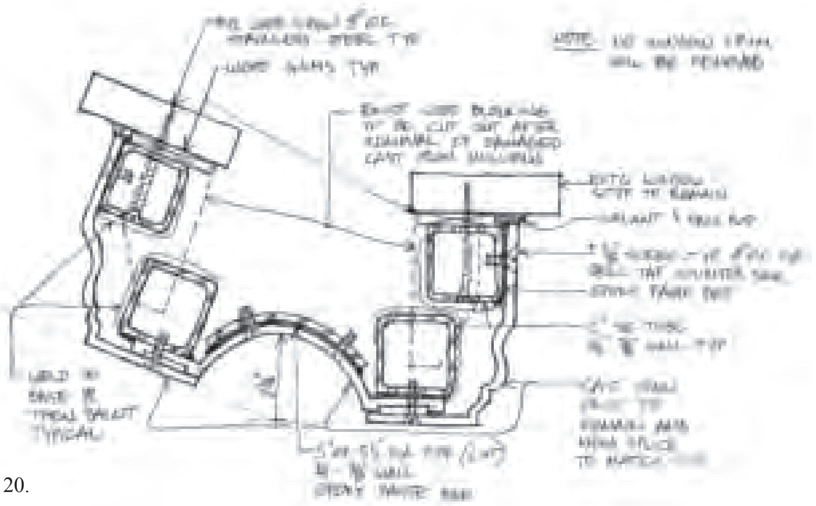
Cold stitching consists of carefully drilling a series of interconnecting holes through templates that allow shear keys to be installed, providing tensile resistance across the crack. The crack line is then drilled out with contiguous threaded holes which accept inserts of slightly larger diameter so as to achieve a compression fit. The system is then polished down to be flush with the surrounding metal (Figs 16–18).

The infill metal is a high nickel steel alloy with the same coefficient of expansion as cast iron, to avoid any stress cracking of the repairs when subjected to the norms of temperature cycles.

The method, although effective, is somewhat empirical, so the design team worked with the sub-contractor on a series of field tests to establish maximum allowable spacings and edge distances between the shear keys. Ultimately this solution proved very successful for the areas of plain cast iron, which could be polished down afterwards to form a smooth finish without any signs of the intervention. The system is difficult to apply to decorative areas, so it was fortunate that these were almost entirely intact, and thus left as found.

In situ structural repairs to loadbearing armatures

The structural repairs to the vertical mullions (Fig 20) were probably the most technically challenging impact of the decision to repair the cast iron façade in place. The existing armature comprised a hollow section built up from flat and U-shaped cast iron pieces with staggered joints.



20.

16. Stages of cold stitching process.

17. Drilling holes for crack repair.

18. Completed repair to crack.

19. Damaged cast iron window before repair.

20. Detail of armature repair.

21.

21. Armature repair: first stage was local removal of corroded elements.

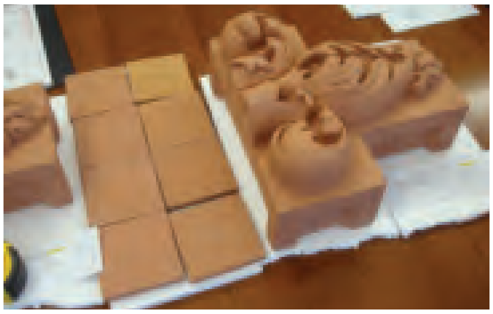
22. Colour matching tests of the terracotta: clay body and firing times were varied to achieve near-perfect results.

23. Recreating the detailed design using originals as a guide.

24. Finished pieces ready to be fired.

25. Close examination was needed to ensure the fireskin was left intact.

26. Cleaning tests on the terracotta.



22.

23.

24.

As these vertical elements were very long, it was impractical to remove them without wholesale deconstruction of the façade, but typical corrosion patterns were only evident at the base of the armatures coincident with window sills (in many cases due to drains from 1970s air-conditioning units).

Arup worked with the specialist sub-contractor to develop an internal "splint" detail — a series of stainless steel struts that could be inserted after the lower corroded part of the cast iron mullion was cut away (Fig 21). The repair could then be reclad with new cast iron pieces formed to the original profile. The internal splints were bolted to the armature above and below using flat head bolts in countersunk holes and the join between old and new repaired by cold stitching.

Terracotta replication and repair

Individually mapping each piece of terracotta in the façade for cleaning, repair or replacement was an exhaustive task undertaken by PACA with the specialist façade repair sub-contractor. Out of the total of over 5000, around 500 were beyond repair and needed to be replaced (including over 225 in the high-level parapet zone) (Fig 22).

Replicating terracotta is a complex process, and selection of the specialist supplier (Boston Valley Terra Cotta) was probably the most important decision in getting the right result on site. Replication starts with matching the clay body to give a close colour match after firing. Similar clay can give a range of colour depending on the heat of firing, so a series of firing tests had to be carried out by the supplier. Even then the natural variability of temperature in any kiln means that within a single firing some colour variation is to be expected.

Clay shrinks about 10% in firing, and the implications were significant. Instead of being formed from original pieces from the building, new moulds exactly 10% larger than the proposed finished article had to be made. This is no mean feat of artistic skill, as the sculptor creates the clay master working by eye from an original piece (Fig 23). Even when the moulds were formed, the inability to press out any kind of re-entrant detail required that the individual pieces be hand-finished and stippled/marked to match the originals prior to placing and firing in the kiln (Fig 24). Given the level of artisan skill needed, the typical price was around $500/piece, uninstalled.

25.

26.

The pieces not replicated needed to be cleaned. During design it had been envisioned that a dry system called "sponge jet" — bombarding the façade with thousands of micro-sponges that are then collected and recycled — would be an acceptably mild approach, but preliminary testing with this revealed the existing terracotta to have a very fragile fireskin, susceptible to mechanical damage.

The team looked for alternatives. Trials using the wet *Prosoco* alkali-based cleaning agent were carried out (Fig 26), with different dwell times and various degrees of agitation, until an acceptable result was achieved. This had some advantages in that a similar system had been specified for nearby areas of stone cleaning, so the contractor could readily adapt his means and methods of protection to extend this approach.

27.

The final results were generally very good, although micro-analysis of the terracotta surface showed that, despite the design team and contractor's best efforts, significant areas of the fragile fireskin were lost. In fact it was highly probable that beneath the grime this had always been the case.

To extend the life of the newly cleaned terracotta, a specialist *KEIM* coating was used. Being a stone-based product, this was relatively inert, and had the benefit of consolidating the terracotta surface as replacement for the fireskin, giving a more uniform surface appearance without acting as a cheaper sealant would, trapping salts and moisture within the terracotta and causing potential long-term damage.

As the different cleaning and coating systems were considered a significant change to the original details submitted to SHPO, the design team had to detail everything in a technical memo and seek SHPO approval, which was duly granted.

27–28. Details of restored terracotta façade with wood windows.

28.

Engineering analysis and implementation

Modelling masonry

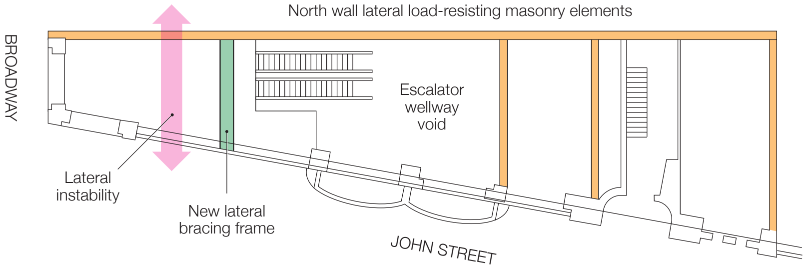
Engineering investigation proved what was already expected: Corbin's iron frame was designed as a gravity-only structure — fairly typical for the time — and it clearly relied on the various masonry elements of the façade for lateral stability. The plan (Fig 29) shows the main stiffnesses of the lateral system to be along the length of the extreme north perimeter wall and in and around the main building core at the wider east end.

Though lateral east–west loads would clearly introduce some torsional irregularity, equally clearly there was enough solid masonry (over 152ft (46.3m) length) to resist any overturning. However, consideration of lateral north–south loads gave immediate cause for concern: there was no significant solid element anywhere close to the Broadway end of the structure, as the only wall present, the façade, was highly punctured by window penetrations. The desire to form multiple new penetrations in the north wall (Fig 30), the single strongest element of the building, would also change the load paths within the walls and potentially overstress parts of the historic unreinforced masonry.

To assess both the existing condition and the proposed alterations, Arup built two 3-D *ETABS* structural models, one for the existing and one for the proposed structure (Figs 31–32). These were accurately detailed from topographical survey data, including the north wall's curvature by over 1ft (300mm) in the middle (presumably introduced at the time of construction as a response to poorly surveyed lot lines).

This allowed the current stress regime in the unreinforced masonry to be reviewed and then compared to stresses after the proposed removals. It was hoped to keep the change of stress within elements to less than +10% when considering lateral loads and less than +5% when considering gravity-only loads, as this would avoid triggering seismic upgrade. (The building upgrade was designed in accordance with the NY State Existing Building Code 2002, which allowed for these modest increases of stress for an existing building as a pragmatic approach to managing old building stock).

But the news wasn't good. The results indicated Corbin already to be performing badly under north–south lateral loading, and the proposed changes would make it worse.



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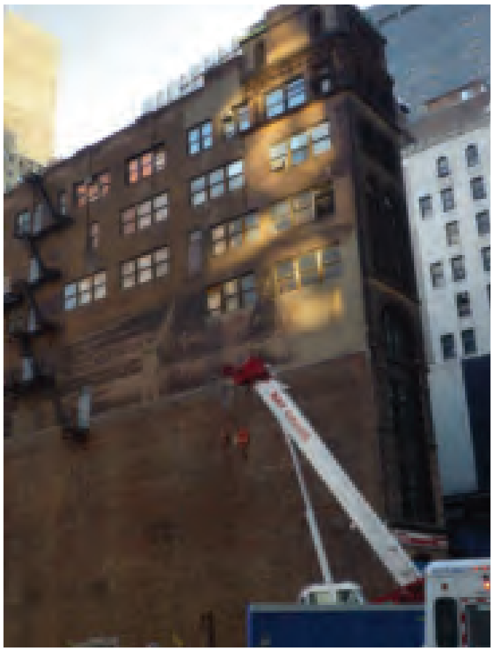

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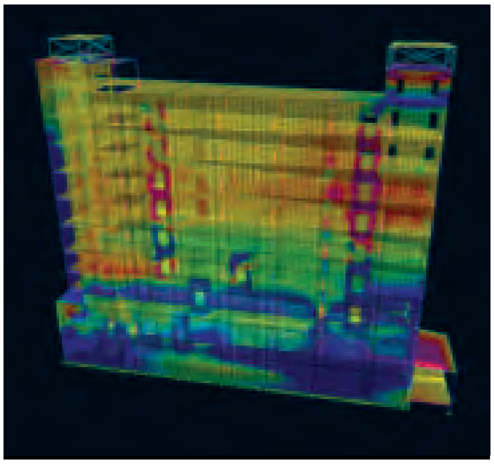

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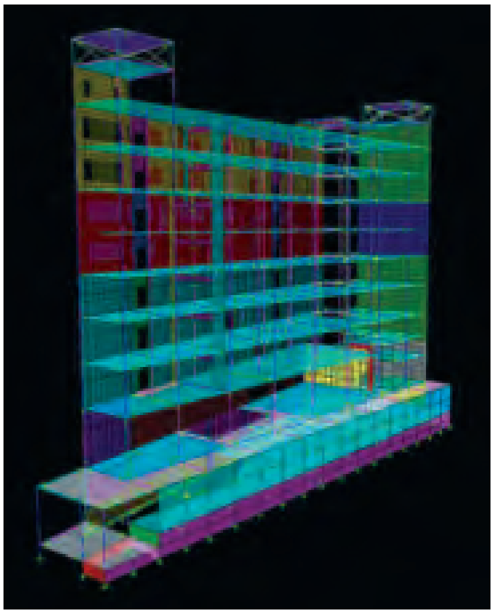


32.

As the internal floor plan is relatively small (around 2500ft^2 (232m^2) per floor) and the wedge-shaped geometry further restricts placement of walls (and the existing façade is both original and decorative on both faces), it was considered extremely inefficient and counter-productive to try and reinforce the building within its own footprint. The team therefore decided that tying it to the Fulton Center to resist north–south loading would be more efficient, and allow most of the new lateral load structure to be outside Corbin's floorplate where there was significantly less pressure on the real estate.

It was still necessary to review the increases and concentrations of stress introduced by the many new penetrations of the north wall. Analysis showed these could be controlled within acceptable limits without intervention above level 2. However, between level 2 and street level, the thresholds previously defined were exceeded.

29. Plan view showing narrowness and plan irregularity, which dictated the need for lateral bracing.

30. The north wall at the beginning of the project.

31–32. 3-D *ETABS* structural model used to establish levels of stress in masonry.

33.

34.

35.

33. Drilling of north wall to accept epoxy-anchored reinforcement prior to shotcreting lower portion of wall.

34. New in-plane reinforcement in the north wall.

35. North wall with completed strengthening works up to level 2 and new egress connections (two per floor).

The solution was borrowed from a flexible approach used to seismically upgrade masonry buildings on the US west coast. The walls between level 2 and street level were encased in a shotcrete layer 4in (100mm) thick on each face. This layer was heavily reinforced in-plane to provide some ductility, and anchored to the existing masonry wall by resin-dowelling several thousand L-shaped reinforcing bars at a 2ft x 2ft (610mm x 610mm) grid across the surface (Figs 33-35). The 3-D *ETABS* model was used to review and then rationalise and reduce the overall amount of reinforced surface to meet the code overstress criteria.

Lateral stability frame

Linking Corbin with the Fulton Center pavilion at lower levels allowed much of the lateral shear forces to be transferred to the new structure, which could be designed to resist them adequately without the constraints on floor space in Corbin itself.

However, this only partially solved the problem. As the structures could only be effectively tied at levels 2 and 3 because the Fulton Center had much reduced stiffness due to its own geometrical constraints above this level, a means was needed to convey the lateral loads from roof level (9) to the Corbin street level back to the ties. At street level and below, introducing the escalator wellway void also compromised the effective diaphragm action of the floorplate, and it was necessary to replace this action by a series of lateral framing systems described below ("Escalator wellway").

The solution adopted for the above-grade transfer of lateral loads was a concrete moment frame, which:

(1) would allow east–west passage of both people and MEP services through the frame

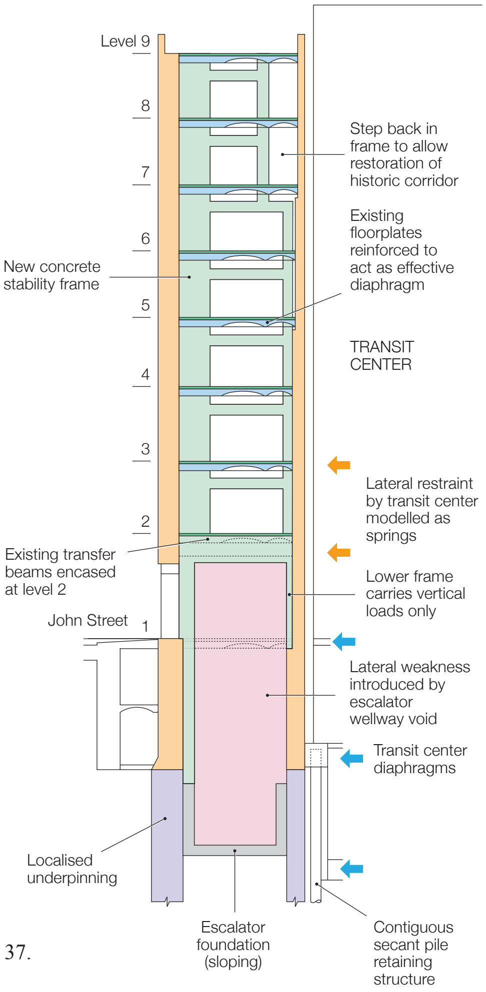
(2) was a flexible form of construction that could be field-adjusted to suit existing conditions and potential variability of wall alignment much better than steel

(3) could be easily formed into moment frames without expensive connections

(4) could interface easily with concrete floor diaphragms without difficult or expensive connections

(5) could wrap around existing structural members, allowing them to be retained in situ; this reduced the need for temporary supports to account for existing member removals, and risk of structural movement if existing members were removed.

36.



37.

38.

The frame was located on plan as close to the west end as possible, while still allowing for a horizontal connection to the Fulton Center pavilion. The concrete frame was added into the 3-D *ETABS* model and the connection to the Fulton Center was modelled as a series of springs.

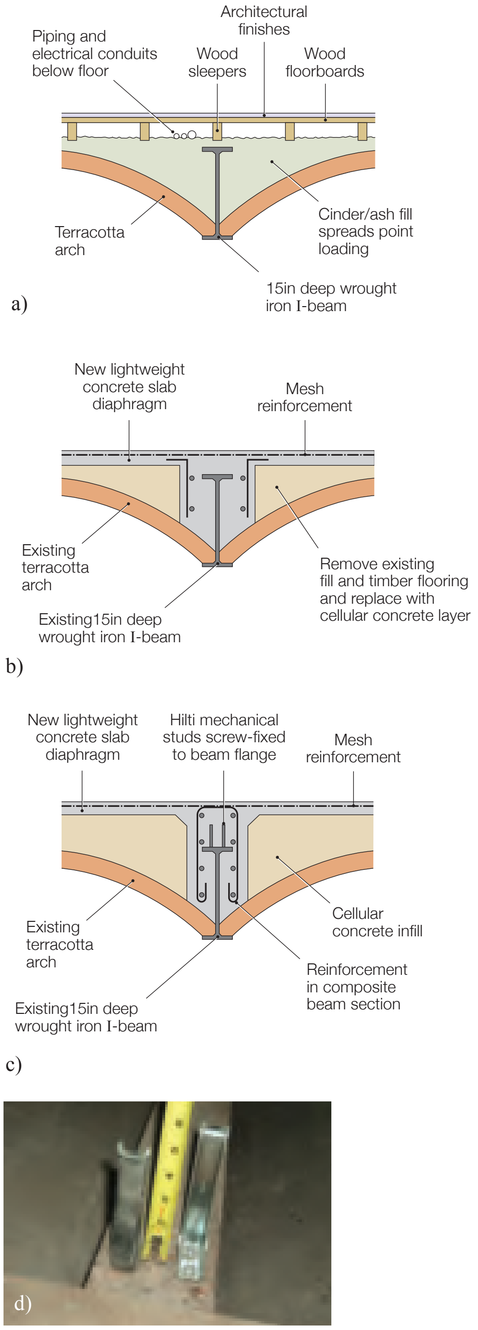
The Fulton Center superstructure had been modelled separately in *GSA*, so it was necessary to iterate lateral loads and corresponding spring stiffnesses between the two models, adjusting framing and geometry in each until the results converged satisfactorily, limiting deflections in Corbin to an acceptable level and at the same time minimising additional steel tonnage in the Fulton Center.

One other advantage of the concrete lateral frame was its own dead weight, which helped resist overturning forces and hence the force transmitted to the pavilion. However the frame also required support from a suitable foundation. This had to be carefully co-ordinated into the design, as below the stability frame a new void had been introduced for the deep escalator wellway, with one side of the frame actually sitting on the wellway retaining wall.

At level 7 a step back in the frame was needed, as the architecture called for reinstating the historic floorplan which had a corridor running parallel to the north wall. As this is almost the top of the frame it was easily accommodated (Figs 36–37).

As part of the lateral system upgrade it was also necessary to strengthen the floor diaphragms at each level, which typically comprised wood flooring on timber battens on cinder fill over the terracotta Guastavino arches. As previously noted, upgrading the floor diaphragms had to be achieved without any substantial increase in floor weight if allowable live loadings were to be maintained.

A system in which most of the fill was replaced with lighter cellular concrete (a low-strength stiff material filled with micro-bubbles) allowed key elements at the wrought iron beam surrounds, together with the final wearing surface, to be replaced with heavier lightweight concrete, which also had the strength needed to act as a diaphragm (Figs 38–39). Cellular concrete is relatively uncommon in the US, but had been used successfully in the past on UK heritage projects by members of the Arup team.



39.

36. New concrete lateral frame.

37. Lateral frame solution to reinforce weak end of building.

38. Forming the new concrete frame at level 2: secondary beams were left in place while large girder was encased; original floor construction can be seen in the background.

39. Strengthening floor diaphragms:
a) original Guastavino floor;
b) typical structural upgrade;
c) composite beam upgrade;
d) Hilti *X-HVB* shear connector.

Escalator wellway

The structural modifications for the new deep escalators (Fig 40) were probably the most challenging aspect of the Corbin renovation. The escalators have an overall rise of about 40ft (12.2m), and terminate in a pit nearly 20ft (6.1m) below the existing foundation level. The excavations were almost entirely within Manhattan's notorious "Bull's Liver" soil, a vibration-sensitive stratified silt and fine sand that is prone to consolidation, causing settlement under construction vibrations, and rapidly loses strength when disturbed or wetted.

Firstly, the whole of the west end below this level had to be underpinned. To counteract potential issues with the liquefiable soils, the entire perimeter of the underpinning zone had to be stabilised by a system of contiguous jet grouting, which itself caused some minor soil settlement that was reflected in the superstructure. Corbin was instrumented and regularly monitored by a series of real-time strain gauges in combination with a conventional system of readings from static targets strategically positioned on the structure[4].

Movements were reviewed daily throughout the underpinning to ensure that the building did not develop any unacceptable tilt or masonry overstress. The team was able to observe daily expansion, contraction, and "tilting" of the building caused by cyclical weather patterns, which were far greater than would have been imagined (up to 0.2in (5mm) vertically and 0.5in (13mm) horizontally). As an additional safeguard visual structural surveys continued in parallel with the monitoring.

40.

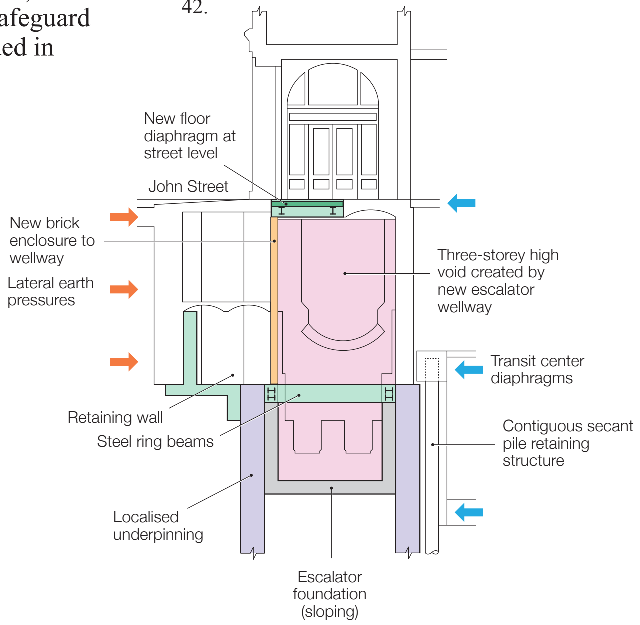
41.

40. The top of the new escalators.

41. Underpinning in progress.

42. Creating the deep escalator.

42.

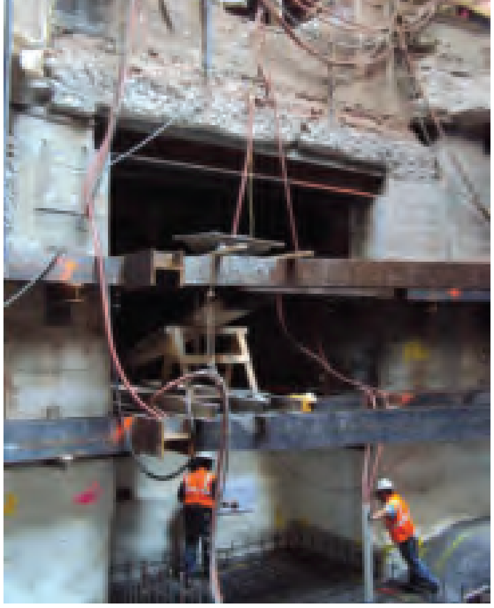


Once the grouting was in place, a series of traditional underpinning excavations in maximum 3ft (900mm) wide sections were hand-dug (Fig 41), and the full perimeter of external wall and internal spread footings for the west half of Corbin were underpinned with mass concrete to a level below that of the proposed escalator footings. These works alone took almost a year, and as before, monitoring supervised by Arup helped ensure that they were carried out without approaching an unsafe condition in the field.

The next step required excavation of the soils between the underpinned footings within Corbin's footprint, and construction of a profiled concrete wellway slab up through the building at a steep angle of around 30°. This required removal of three levels of internal floor diaphragm: at the street, basement, and sub-basement levels. All these floors carried substantial lateral loading from soil pressure on the south (John Street) masonry wall.

Historically these forces had been balanced by equal and opposite forces from the basements of buildings to the north, but these were removed during construction of the Fulton Center foundations. This created a much deeper three-storey "bathtub", with contiguous piled retaining walls that only aligned floor levels with Corbin at street and sub-basement levels. It was thus necessary to design a system within Corbin to transfer the lateral loads from the south retaining wall into the new Fulton Center floor diaphragms and consolidate three levels of loading into two levels of support (Fig 42).

The street level support was relatively straightforward, as here the two buildings matched and it was only necessary to create a new steel and concrete floor to span the width of the new opening in the floor and to act as a horizontal beam (Figs 43-44).



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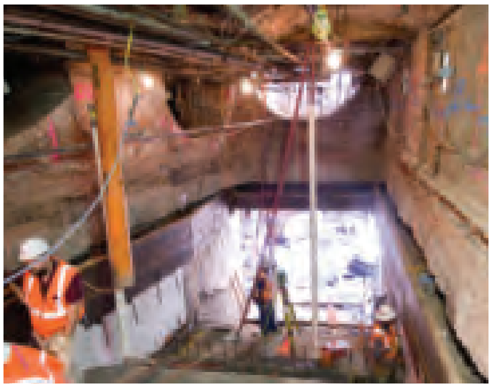


44.

43. Construction of new escalator foundations with temporary ring beam steelwork in place.

44. Creating the escalator wellway through and below the original foundations.

45. Down the deep escalator, with salvaged terracotta on the left and the original inverted arch foundation exposed to view.

45.

For the basement and sub-basement levels a massive ring beam was needed within the escalator wellway to match as closely as possible the Fulton Center diaphragm level. This ring steel was located slightly below the existing foundation level in Corbin. To get the loads from the south basement wall into this ring beam a new concrete retaining wall was formed within the Corbin sub-basement as a collector element (Fig 43). The design for the wall was a delicate balance, as resistance to overturning and soil bearing below the wall base needed to be controlled, but the wall geometry was tightly constrained by the existing heavy masonry superstructure and available space at the building's very narrow end.

Inevitably, unforeseen conditions arose during construction. It transpired that the existing masonry sub-basement wall had a series of projecting piers, presumably incorporated as stiffeners, which greatly reduced available width for the new concrete retaining wall behind. The geometrical changes were sufficient to make the original design unworkable, as the lever arm for the new wall would now be too small. The solution was to underpin the existing basement retaining wall with concrete needle beams projecting from the base of the new retaining structure so as to mobilise the existing wall's weight and effectively counteract the negative effects of the shorter base.

A benefit of the escalator wellway beyond its basic function was that the new shaft would allow the public to see a vertical section through the building. The masonry walls and columns are supported off a series of inverted masonry arches designed to spread the superstructure loads back into the soils more evenly (Fig 44); these are relatively uncommon, and wonderfully aesthetic at the same time. Instead of hiding the structure, the architectural design incorporated the inverted arch foundations as the central theme of the space and mirrored the existing arches in the new masonry liner wall that needed to be formed to the south side.

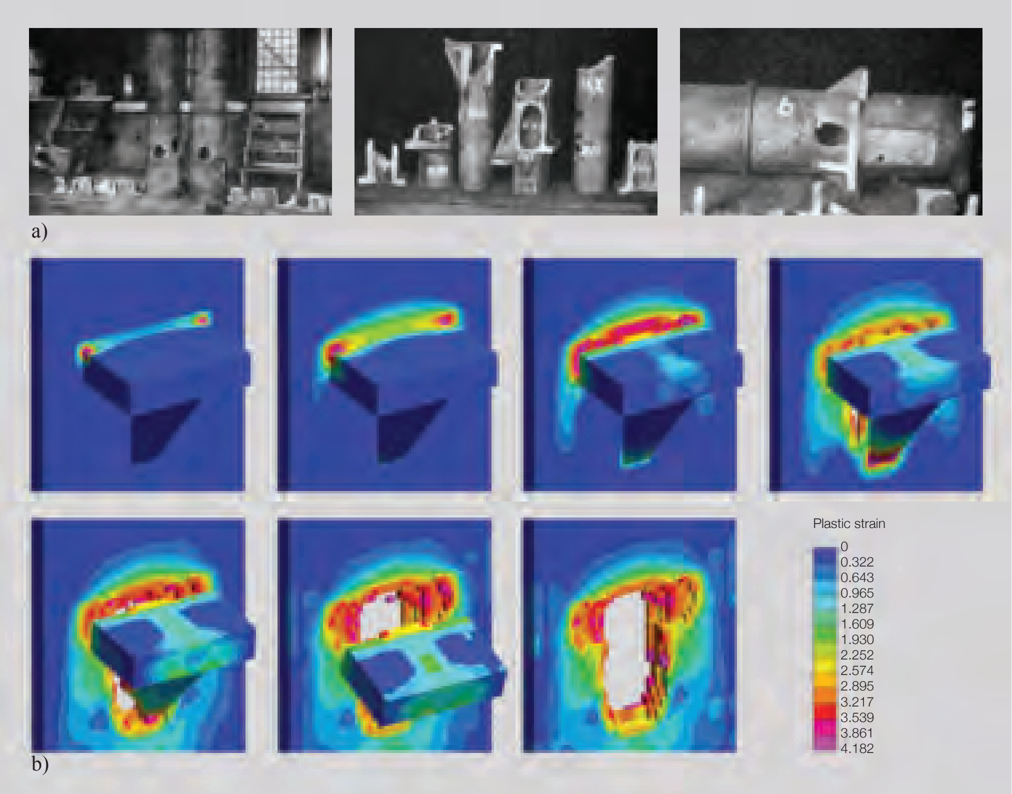
The wellway is also a great place for the public display of salvaged terracotta from the roof and the old cast iron boiler doors, and these elements were incorporated into the new liner wall to the south side (Fig 45).

Guastavino floor strengthening

As discussed above, the typical floor upgrade used a combination of cellular concrete fill and lightweight concrete slab to control overall floor weight, but part way through construction the client decided to change the proposed use of levels 2 and 3 from offices to retail, with consequences for floor loading. This decision was driven partly by the location at corresponding levels of retail space in the Fulton Center pavilion; this would enable connectivity through both buildings for a larger retailer, thus adding value to the project.

Individual strengthening of the wrought iron beams with continuous steel plates at mid-span or similar would have been costly, visually intrusive, and inefficient, as the weights of the remedial plates would have impacted overall floor loads. A solution of minimal weight but increased strength was needed, and the weldability test results showed that it was also highly desirable to avoid welding to the wrought iron, as the necessary preheat would have proved costly.

The team developed a solution with a proprietary Hilti product, originally aimed at the new-build/metal deck market. By using Hilti shear connectors screw-fixed to the existing beam flanges by self-drilling screws, the team proved a 30% increase in overall beam capacity without changing any other floor diaphragm details; the design was verified using Arup's in-house *Compos* software. This was a flexible system that could easily be installed by the contractor without any site-welding. Hilti also made field tests to verify that the anchor capacities reached published values.



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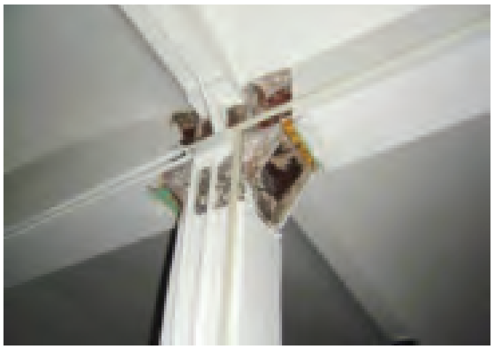


47.

48.

46. Modern analysis compared with historical evidence:
(a) Images of column testing carried out in 1890 by NYC Department of Buildings engineers;
(b) Arup *LS-Dyna* analysis of corbel failure.

47. Column head before restoration.

48. Restored cast iron central columns and corbels in typical interior space.

Cast iron corbels

Upgrading the existing floor capacity from 75lb/ft^2 (365kg/m^2) to 125lb/ft^2 (610kg/m^2) at levels 2 and 3 required the increased forces to be successfully transferred back to the vertical load-bearing structure. The existing columns were square hollow cast iron, with uniform wall thicknesses. Arup's field investigation had established that the floor beams were typically supported off cast iron corbels (or brackets), cast integrally with these columns; they took two distinct forms, either single T-section corbels in the column face for secondary beams, or double TT-section corbels aligning with the column perimeter walls for the primary beams.

While researching contemporary design methodologies for cast iron and wrought iron sections, Arup had referenced the typical 1890s "Engineer's Pocketbooks" — a prime source of information on safe design, in the absence of any nationally-published design codes or guidance. One such contemporary guide referred to testing of similar cast iron corbels by the NYC Department of Buildings that had yielded surprisingly low results, potentially invalidating the perceived wisdom of the time (Fig 46a).

Given the critical nature of the connection, this clearly required further investigation and prompted Arup's structural team to work with its advanced technology group (ATG) to try to replicate the unexpected failure modes and gain further insight into the problem (Fig 46b).

The results, to be published in a forthcoming paper[5], demonstrate how the engineers of 1890 had limited understanding of the behaviour of shear versus flexure, not to mention more complex biaxial and triaxial states of stress, and how this may have led to the under-design of similar connections in thousands of buildings throughout the US.

The direct result for Corbin was to adopt a reinforced concrete shear head detail cast within the slabs, transferring a proportion of the loading between the relatively weak single T and the much stronger double TT brackets. This also avoided any awkward upgrade of the bracket detail, which would be made doubly difficult by the lack of weldability of the section, and particularly undesirable as the brackets were to be left exposed for aesthetic reasons.

49.

50.

51.

49–50. Conduits for main electrical feeders through the north wall at sub-basement level.

51. Restoration of the Corbin Building main entrance lobby required careful co-ordination of the new lighting design with exposed cast iron ceiling.

Building services co-ordination
Although much of the Corbin restoration and upgrade focused on structural and architectural elements, integrating modern MEP and IT systems within an irregular constricted structure that was difficult to modify and lacked normal headroom in many areas presented its own set of unique challenges.

Space within both the Fulton Center and Corbin was constrained by an architectural vision for the pavilion that required a large slice of the volume to be dedicated to bringing daylight and a sense of openness to a traditionally subterranean space. This had the impact of pushing all the back-of-house spaces to the interstitial building and perimeter of the Fulton Center, and put pressure on the design to use every available corner of the Corbin Building next door.

The MEP programme in the final Corbin building design included:

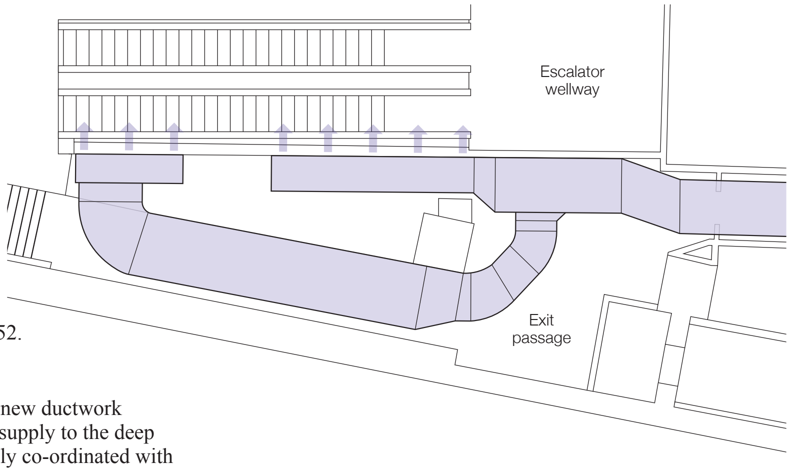
- vaults for electrical service disconnect switching (supplied by Con Edison) hung from the new sidewalk structure
- concrete-encased electrical duct banks that drop from basement to sub-basement, then pass through the masonry north wall (Figs 49–50), taking the 13.2kV electrical feeders to transformer vaults on the sixth floor of the Fulton Center
- a new steam service and PRV station (also supplied by Con Edison) for distribution to both Corbin and Fulton Center
- electrical distribution room containing transformers and building electrical panels
- a fully addressable fire alarm system with its panel located in the historic lobby
- the fire command centre, at street level, for both Corbin and the Fulton Center
- local IT and electrical closets on each floor
- mechanical plantrooms with individual air-handling units on each floor
- mechanical plantroom for street-level commercial spaces, located in the east penthouse tower
- combined storm and sanitary drainage for the whole site passing through the Corbin basement
- diesel fuel line supply from sidewalk level, through Corbin, to backup generators on the level 7 roof of the Fulton Center
- all incoming IT infrastructure from street level to the Fulton Center
- the escalator control room, in a sunken area of the sub-basement to gain additional headroom for the control panels
- the escalator motor room at basement level, directly above the sub-basement control room and below the escalator trusses, with a direct drive to the escalators themselves (the large uplift forces generated had to be tied down to new foundations)
- rehabilitated electrical control and motor room for the historic Otis elevators (Fig 51).

Above street level, most of the space was reserved for either commercial or transit use and was of high value, so most of the MEP space was pushed below ground if possible.

Even though some two-thirds of the existing basement and sub-basement spaces were allocated to MEP systems, in reality this was only 2000ft^2 (185m^2) in total, and further divided up by a split-level basement, below-sidewalk vaults, low headroom areas throughout the sub-basement, and the integration of the new escalator wellway into the plan. What was left was a series of tightly constricted rooms divided by large piers of unreinforced load-bearing masonry that could not be removed, and headrooms that varied between 8ft–10ft (2.5m–3m) at best. Fitting a lot of services within such a small space required considerable detailed co-ordination between all disciplines.

Additionally, as the new escalator wellway connected Corbin with a large underground network of tunnels, Arup's CFD model for smoke control in the connected areas required that, as well as extracting smoke directly from the bottom of the Corbin escalator within the adjacent Dey Street concourses, large volumes of make-up air had to be provided at the top of the wellway in the event of an underground fire.

This required that a fan at the top of the Fulton Center supply more than 15 000ft^3/min (425m^3/min) through a tortuous route that entered Corbin at basement level through the existing north wall and then split around existing and new structural columns to feed into the escalator wellway from the side (Fig 52). The makeup grills were selected to look antique in finish to match the historic brick walls.



52.

52. Plan view of new ductwork for make-up air supply to the deep escalator, carefully co-ordinated with tight headroom and plan constraints.

53–54. Inside and out, the restored Corbin Building now bears witness to both the craftsmanship of the original and the care and skill of the restoration.

53.

Within the commercial spaces to be restored to their original open-vaulted appearance, the Arup/PACA design typically incorporated the electrical lighting, power and IT conduits within the replacement topping to the Guastavino vaults, or in the dry-lining of the north wall, keeping it out of sight. Lighting is controlled by occupancy sensors to comply with energy conservation codes. In the entrance lobby, the lighting is carefully concealed within the existing decorative ceiling.

Air-conditioning systems were streamlined and minimised, and designed to thread between the existing cast-iron framing and the new concrete lateral stability structure. Heating is provided by low-profile perimeter fin-tubes at each floor, replacing traditional large radiators.

Conclusion

The Corbin restoration has been a striking success, and exemplifies how Arup can bring diverse knowledge, skills, and analysis techniques, with a willingness to be bold and experimental, to a historic renovation. Many engineers perceive existing building and renovation projects to be either limiting or constraining by nature, and while there are certainly a diverse range of existing criteria that need to be fully understood and accounted for in designs, this project shows that they can be a catalyst for creative thinking and innovative design approach rather than an excuse for limited vision.

Also, designers should anticipate the need to continue this responsive dialogue with the building throughout construction, in which they will be greatly helped by the selection of the right contractor and specialist sub-contractors.

Arup's role as lead consultant helped significantly in fostering a creative collaboration between client, approving authorities, engineer and the several architectural firms that assisted with the overall development. The depth of knowledge from Arup's structural skills networks, with early and consistent input from the firm's ATG on the behaviour of materials and the resulting local delivery of international skills and approaches, formed a great benefit for the client.

As for the New York City public, they will be able to enjoy the Corbin Building from late 2014 when the Fulton Center as a whole is completed and opened.


54.

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(4) APPLEBY, J, *et al.* Fulton Street transit center — foundation design and construction in a dense urban environment. Presented at the 2011 Pan-Am CGS Geotechnical Conference, Toronto, October 2011.

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Awards

- American Institute of Architects (AIA) New York State Design Awards: Adaptive Reuse/Historic Preservation: Award of Merit 2013
- American Council of Engineering Companies of New York (ACEC NY): Diamond Award for Engineering Rehabilitation 2014
- American Council of Engineering Companies (ACEC): National Recognition Award 2014
- New York Historic Districts Council Design Awards: Honorable Mention 2014
- AIA New York State, Excelsior Award 2014
- Structural Engineers Association of New York (SEAoNY) Excellence in Engineering Awards 2014: Engineer's Choice Award
- New York State Society of Professional Engineers (NYSSPE) Central New York Chapter 2014 Project of the Year Award (for the complete Fulton Center).

In addition, the Corbin Building restoration was the main contributing factor in MTA being given a special Stewardship Award in the 2013 New York Landmarks Conservancy Lucy G Moses Preservation Awards, for the "management and care of its many historic properties".

Authors

Ian Buckley is an Associate in the New York office, and was Project Manager and structural design team leader throughout construction for the Corbin restoration.

Craig Covil is a Principal in the New York office, and was Project Director for the Fulton Center and the Corbin restoration.

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Project credits

Client: *MTA Capital Construction* Lead consultant and multidisciplinary engineering design: *Arup — Joseph Appleby, Leo Argiris, Liam Basilio, John Batchelor, Gillian Blake, Mark Brand, Ian Buckley, Alison Caldwell, Bob Cather, Foram Chaliawala, Ann Chamley, Ho-Yan Cheung, Anthony Cortez, Fiona Cousins, Craig Covil, Casey Curbow, Carmen Danescu, Star Davis, Michael Deutscher, Nicola Dobbs, Jonathan Drescher, Alex Engelman, Adam Friedberg, Bethel Gebre, Tom Grimard, Gregory Hodkinson, David Jacoby, Igor Kitagorsky, Tanya Kokorina, Marina Kremer, Steve Lasser, Deborah Lazarus, Adrian Lee, Hillary Lobo, Andrew Marchesin, Cecy Martinez, Cliff McMillan, Kristina Moores, Mark Nelson, Patty Nordhausen, Elizabeth Perez, Clare Phillips, Ricardo Pittella, Samantha Plourde, Lana Potapova, Marie Reedy, Tom Rice, Robb Risani, Justin Rodriguez, Arkady Rubinstein, Yet Sang, David Sivin, Nick Watkins, Chelsea Zdawczyk* Architect: *PACA (Page Ayres Cowley Architects)* General contractor: *Judlau Contracting* Specialist sub-contractors: *Brisk Waterproofing, Western Facades Group, Boston Valley Terra Cotta* Foundations contractor: *Skanska Construction.*

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1, 11–15, 27–28, 40, 48, 54 *MTA/Patrick Cashin*; 2 *Anthony Cortez*; 3, 6, 46b *New York City Library*; Back cover, 4, 17, 19, 22–24, 26, 30, 36, 38, 45, 47, 49–51, 53 *Ian Buckley*; 5 *Boston Public Library*; 7 *Peter Aaslestad/Frazier Associates*; 8 *Geoffrey Gross*; 9–10, 25 *PACA/Carlos Carrera*; 16, 29, 37, 39a–c, 42, 52 *Nigel Whale*; 18, 21 *Brisk/James Norberg*; 20 *Brisk/Mike Radigan*; 31–32, *Yet Sang and Ho-Yan Cheung*; 33–34 *Lana Potopova*; 35, 43 *Joe Appleby*; 39d *Yet Sang*; 41, 44 *Skanska Construction*; 46a *Mark Nelson.*

The CIC ZCB:

designing a zero carbon building for a hot and humid climate

1.

Location
Hong Kong

Authors
Vincent Cheng Tony Lam Trevor Ng
Raymond Yau

Introduction

Buildings account for a large proportion of energy use — over 40% in the case of the US[1] and over 60% for Hong Kong[2] — so an emerging imperative is to reduce their carbon emissions to zero. Zero net energy (ZNE) and zero carbon (ZC) buildings are becoming a global design trend, with the goal of creating climate-neutral communities. In the UK, legislation calls for zero carbon emissions in all new housing by 2016, and the European Parliament recently targeted all new construction to be ZNE by 2019. In 2007, California energy regulators set a goal for every new home to be built to ZNE standards from 2020. Various initiatives and policies are in place to accelerate this trend. Pilot ZNE/ZC projects, initially built in Europe through government initiatives, are now widespread.

In Asia, many challenges lie ahead in getting to ZNE/ZC for buildings, but blindly copying European or North American models can lead to higher consumption rates than conventional design. Ignorance of local contexts in terms of climatic conditions and building performance, and of appropriate technologies for analysing and constructing ZNE/ZC buildings, have hampered the standardisation of low carbon practice in Asia[3]. More effort is needed from government and industry to tackle the technical issues and to grow experience.

Responding to the quest for low carbon technologies applicable to Hong Kong, in 2011 the Construction Industry Council (CIC) commissioned the design and construction of ZCB, a showcase zero carbon building for industry to demonstrate these technologies in practice (Fig 1). It was designed as mixed-use, so as to engage a wide mix of specialists and users in the common goal of creating a better, safer and more sustainable environment to the industry. The building features more than 80 sustainable installations (Table 1).

This article looks at how the most appropriate building and systems design strategy was achieved, and the thinking behind the building's core system, its combined cooling, heating and power (CCHP). Lessons learned are also discussed.

The ZCB design approach

Climate-responsive designs

Climate is the most important factor shaping low/ZCB design. Hong Kong has very distinct seasons: the summer months are hot and humid, while winter is cool and dry (Fig 2). People escape from the hot summer into mechanically conditioned buildings, and the typical cooling season is about 2000 degree-hours in Hong Kong, very different from London's 200 degree-hours or even San Francisco's 1300 degree-hours. Such a cooling demand is a huge challenge to adopting the kind of passive architectural designs common in Europe and North America. However, it has been shown[4] that human response to the sub-tropical climate can be significantly improved by blocking direct solar heat (thus reducing temperatures) and encouraging breeze (increasing skin evaporation). This extends the year-round natural ventilation period — a key climate-responsive design strategy on this project.

In the mid-seasons there is good potential for buildings to be naturally ventilated; massing them to allow free passage of air can significantly reduce HVAC (heating, ventilating and air-conditioning) usage. The CIC ZCB was thus planned with cross-ventilation and microclimate enhancement in mind. It is set in a large open space with the prevailing south-easterly wind flowing across Hong Kong's first purposely-created area of urban native woodland, including 220 trees of over 40 species and a diversity of shrubs, effectively reducing ambient temperature through evapotranspiration (evaporation + plant transpiration).

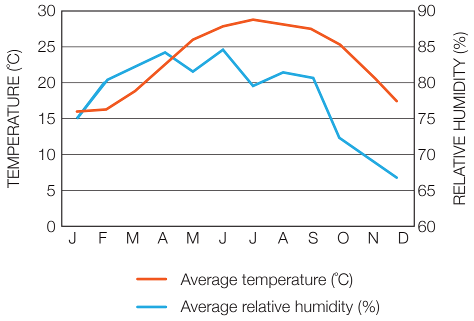
Table 1. Types of accommodation within the CIC ZCB.

Accommodation		Net floor area (m²)
Entrance lobby and reception	Orientation/break-out/information	100
Temporary exhibition area	Temporary exhibition zone with changing showcases from local industry/stakeholders	150
Permanent exhibition area	Permanent exhibition zone on low/zero carbon design and technologies	490
Multi-purpose room	Audiovisual presentation for organized visits, public lectures, CIC seminars, and conferences	260
Eco-office 1	Live showcase and active eco-office for CIC itself	230
Eco-office 2	Live showcase and active eco-office	120
Eco-home + display gallery	Demonstration of low/zero carbon home design, features and involvement in low-carbon living	150
Souvenir shop	Souvenirs/eco-products retail	10
Eco-café	Ancillary catering facilities, with an eco-theme of sustainable food	10
Total net floor area		**1520**

1. The completed CIC zero carbon building.

2. Hong Kong's challenging range of climatic conditions for achieving comfortable human occupancy.

3. Life-cycle approach for the CIC ZCB.



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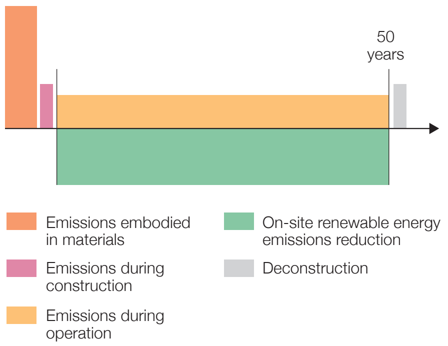

3.

The building shape also enhances cross-ventilation. As wind flows over its sloped roof and leaves the sharp-trailing edge, a low-pressure region is created downwind that sucks pre-cooled air from the urban woodland into the building.

Life-cycle considerations

There is no standard global definition for a ZCB. The generally accepted practice is to estimate the components of the building's carbon emissions and offset them with renewable energy, using the stand-alone or grid-connect approach[5]. The CIC ZCB adopts the life-cycle concept (Fig 3), whereby carbon emission-producing processes associated with the building's life-cycle are identified: materials manufacture, construction process, 50 years' operation, and finally decommissioning. To achieve carbon neutrality, a building's own renewable facilities are designed to produce enough energy to meet annual consumption demands, giving net ZC with all life-cycle emissions "offset" by on-site renewables after 50 years' service life. The CIC ZCB is connected to the local grid, so energy can be exported from the on-site renewables, setting the grid power consumed on an annual basis.

The equation for calculating carbon neutrality annually is as follows:

Carbon neutrality =

- emissions reduction from excess electricity produced from renewables "displacing" grid consumption +
- emissions associated with electricity supplied to the site +
- emissions associated with biodiesel supplied to the site.

Carbon neutrality and “energy cascade”

The site has two major renewable systems: photovoltaic (PV) panels and a small-scale biodiesel CCHP plant. The area of PV panels — limited by the total roof area — was optimised for cost-effectiveness, but solar only provides 66% of required renewable energy for carbon offset. It cannot be relied upon as a constant energy source to satisfy the building demand, so the biodiesel generator plays a crucial role. The decision to use biodiesel was helped by the existence of plenty of waste cooking oil in Hong Kong as feedstock. The emission factor from this is very low, as it not only displaces fossil fuel combustion, but also avoids the generation of methane gas at landfills.

Detailed analyses of how and when energy would be used in the building led to an energy matching strategy aligned with the consumption pattern, and based on the first and second laws of thermodynamics. Energy is not destroyed, it just becomes lower-grade when used, so usages are aligned so that the lower-grade output from one piece of equipment is used as the input of another in an “energy cascade” (Fig 5).

The electricity generated serves the building and landscaped area, with any surplus fed to the grid. Waste heat from the generator is recovered to drive an absorption chiller and desiccant dehumidification system. The energy generated and fed to the grid are continuously monitored by intelligent metering and transmitted to the building management system (BMS).

Energy simulations

The design team conducted whole-building energy simulations early on to predict the ZCB’s energy consumption, and used the results to size the building energy systems as well as the renewable systems needed for neutralisation. This process was also important in evaluating the effectiveness of different design strategies to reduce cooling and electrical loads and energy demand, helping the team to make its decision using standard cost-benefit analysis.

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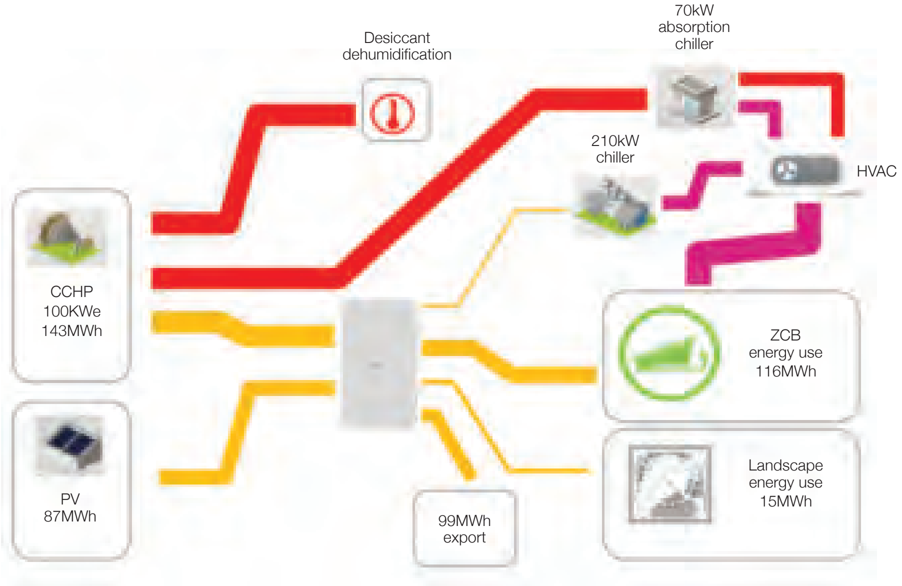


5.

4. Main lobby, showing ceiling fans.

5. Schematic of PV and CCHP systems operation.

The simulations were done with the Integrated Environmental Solutions' tool *IES V6.4*[6] using two major inputs, hourly weather databases and the ZCB architectural and building system designs. The TMY (typical meteorological year) method, developed by the US Sandia National Laboratories and the most widely used for determining typical weather years[7], was adopted in the study. A TMY comprises 12 typical meteorological months (TMMs) selected from various calendar months over a 25-year period (1979–2003) measured weather database[8]. An 8760-hour TMY weather file was used to represent the characteristics of the prevailing Hong Kong climate.

Base building

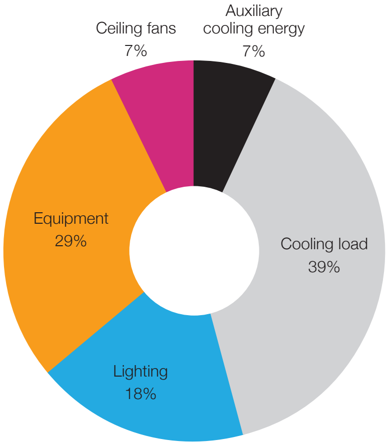
New buildings in Hong Kong are becoming more efficient, partially due to the mandatory 2012 building energy code (BEC)[9], which provides best practice design guidelines for all new developments there. In addition, BEC regulates the design of overall thermal transmittance values (OTTV)[10] of the building fabric and the minimum requirements for major building services systems, eg air-conditioning (AC), electrical, lighting, escalators, etc.

BEC thus supplies the baseline and design targets for practitioners. To achieve its objective of ultra-low energy use, the ZCB was designed to substantially surpass such baseline performance.

The typical energy use intensity (EUI) range for office buildings is 250–350kWh/m^2 [11], while the base building design per BEC is around 157kWh/m^2 (Fig 6). In other words, adopting BEC requirements can effectively reduce energy use in a building.

Energy performance of ZCB

Table 2 summarises the design values of the ZCB's key parameters, and the energy model was performed with these values as the design case. The predicted EUI of the ZCB was 86kWh/m^2, 45% lower than the BEC-compliant baseline building. Due to its mix of uses (office, conference and exhibition) and intensive application, the CIC ZCB is relatively more energy-intensive than other ZCBs in cities with similar climates, as in Singapore, where the EUI of one ZCB is only 46kWh/m^2 [12]. The building type and operation schedule may cause the large difference in annual energy use.



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Effectiveness of design strategies

The energy simulations predicted the effectiveness of passive and active energy saving strategies in Hong Kong (Fig 7), the design considerations and performance of which can be summarised as follows:

Façade thermal performance

The envelope loads must be minimised to reduce heat build-up. The ZCB's peak cooling load was calculated as approaching 163W/m^2, with the general average being around 80W/m^2. Table 3 shows the cooling load breakdown of this building if it were constructed to BEC standards. Note that fabric loads comprise the major portion, as the building has a high envelope-to-floor area ratio.

Table 2. Key design assumptions for system design and energy simulation.

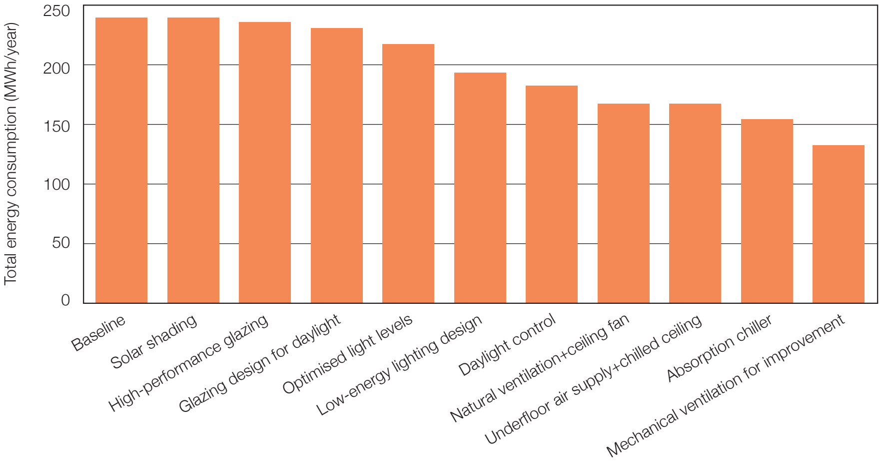
Thermal characteristics	Design
Window-to-wall ratio (NE/SE/SW/NW façade)	10%/80%/0%/6%
Shading coefficient	0.33, Double Low-E window panes
Visual light transmission	0.54
Internal design conditions	**Design condition**
Space condition (in general)	25.5±1°C DB; 55±10% RH
Lighting load (in general)	6W/m^2
Equipment load (multi-purpose room/exhibition/office)	5 W/m^2/10W/m^2/20W/m^2
People load (multi-purpose room/exhibition/office)	95W/person/130W/person/130W/person

Table 3. Estimated cooling load and breakdown for the CIC ZCB.

Components	Cooling load
Fabric load	64.4kW
Equipment load	18.4kW
Lighting load	6.0kW
People load	20.2kW
Fresh air load	53.4kW
Total peak cooling load	**162.4kW**

6. Results of energy simulation on the energy use of various building systems.

7. Summary of energy simulation results for different design strategies.



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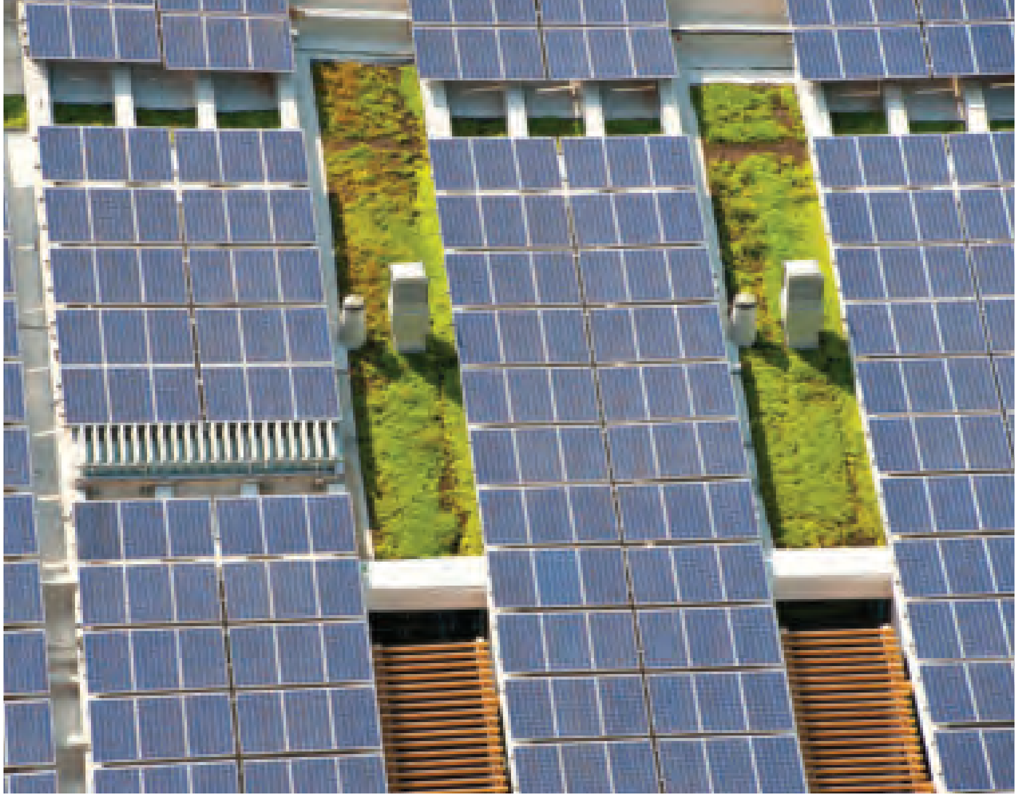


10.

8. The CIC ZCB's profile is tilted toward the north.

9. Illumination from skylight.

10. Skylight from above, surrounded by PV panels.

11. Interior close-up of skylight.

12. Light pipes feed daylight to inner areas.

Reduced window-to-wall ratio (WWR)
Solar heat gain through windows is approximately 10 times that through opaque façades, so minimising the extent of glazing is dramatically effective. Accordingly, there is no glazing on the south-west façade, and the building's ramped cross-section naturally reduces WWR on the south compared to the north. The overall WWR of the CIC ZCB is 0.4, a value optimised to meet the daylight requirement.

Envelope absorptivity and façade insulation
Minimising the flow of heat through the opaque walls is also important. Two steps reduce this impact:

(1) Lowering façade absorptivity reflects more heat away from the building, reducing the surface temperature (absorptivity below 0.3).

(2) Adding insulation to walls stops the flow of heat through them, giving U-values below 0.6W/m^{2}K for the walls and under 0.2W/m^{2}K for the roof.

White walls or glazed finishes can give an absorptivity of below 0.3. PV panels sitting above the roof have high absorptivity, but the ventilated air gap beneath them will reduce heat flow to the building. To achieve 0.6W/m^{2}K, the building was designed to incorporate 40mm–50mm of high quality polyurethane board or 80mm–90mm of glass fibre insulation. To achieve 0.2W/m^{2}K, 120mm–150mm of high quality polyurethane board or 180mm–200mm of glass fibre insulation would be needed.

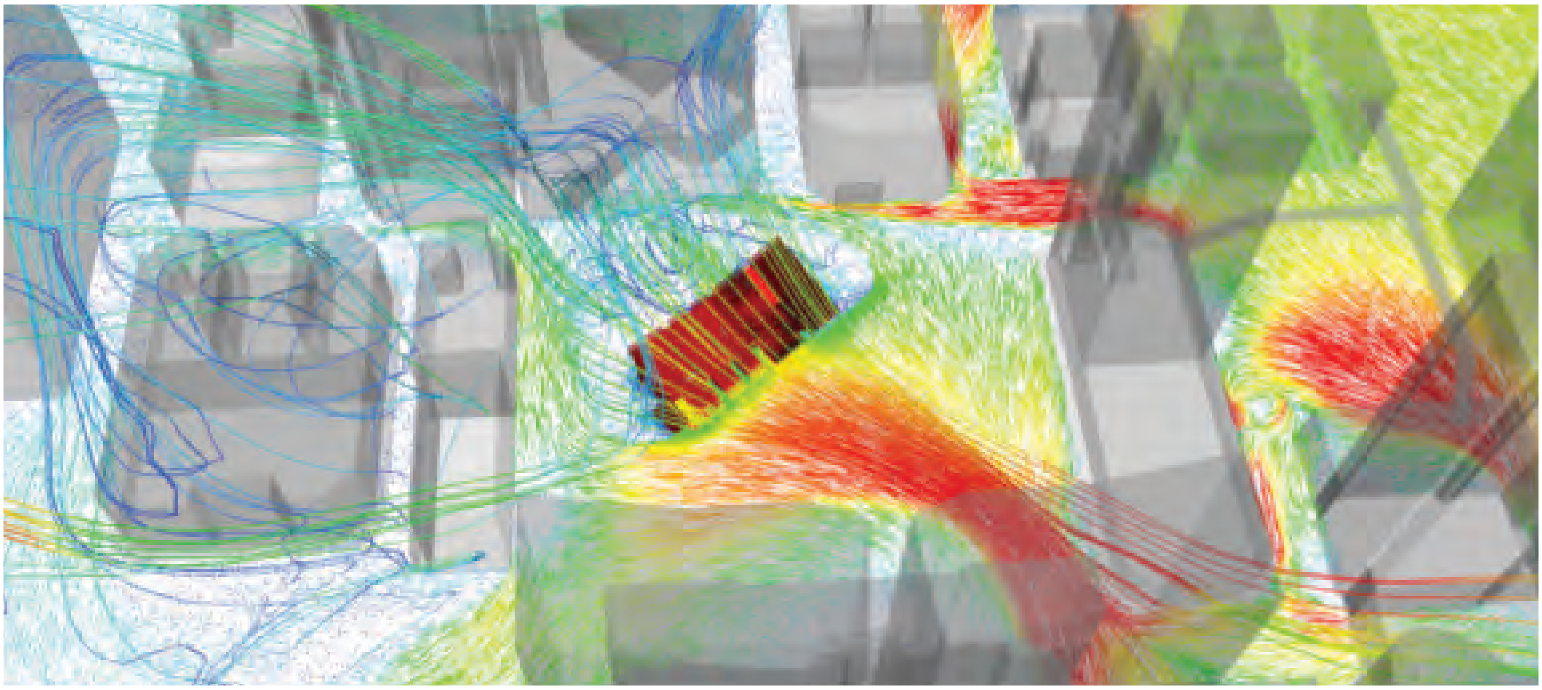
11.

12.

Daylighting
Tilting the ZCB's profile to the north provided maximum daylight while still reducing solar penetration (Fig 8). Effectively this was northlight design, and gave the daylighting needed for most of the spaces. To increase the amount of natural light reaching the middle of the floorplate, the building incorporates an active skylight (Figs 9–11) illuminating the upper and lower exhibition areas, and two light pipes above the lower exhibition space.

The active skylight comprises a standard skylight with moveable fins above, which are rotated manually from below to adjust the amount of daylight passing through the skylight, thus allowing occupants to enjoy control over the building around them. The light pipes are reflective light transmitting tubes to guide additional natural daylight into inner areas (Fig 12).

Envelope airtightness
This is particularly important for low-energy design in the Hong Kong climate, because dehumidifying high humidity infiltration has a disproportional impact on the size of mechanical plant and its energy use. Good airtightness also reduces condensation. Infiltration occurs primarily at window and door joins, so these features were detailed to reduce it to below 5 litre/sec/m^2 of door area and under 2 litre/sec/m^2 of window area.



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Optimising microclimate and natural ventilation

As previously noted, enhanced natural ventilation reduces the CIC ZCB energy loads, as air moves through naturally for 30%–40% of the year (helped by ceiling fans). The building is oriented to receive the site's prevailing south-easterly wind, so as to optimise natural air flow availability (Fig 13). A thermal dynamic study showed that in natural ventilation operation, cool fresh air is brought in through orifices, warmed by the internal loads, and exhausted.

The internal temperature to be maintained is 25.5°C, and for this level of internal gain natural ventilation can function below external temperatures of 20°C, taking into account increased air movement due to ceiling fans. This delivers a minimum of six air changes/hour under typical conditions.

Radiant cooling

The radiant cooling systems rely primarily on radiation heat transfer. Typically, chilled water is circulated through ceiling panels or beams to maintain comfort by collecting and removing heat from the space. Also, radiant systems are more energy-efficient than air-based systems, requiring less parasitic (pump and fan) energy to deliver cooling, and higher operating temperatures mean that a chiller can operate more efficiently if it is not required to serve other, cooler, areas.

Because the floors are radiantly cooled, the air temperature can be higher to achieve the same level of comfort, and higher air temperatures also result in lower heat losses to the outdoors. And radiant cooling systems are silent, enhancing occupant comfort.

A limiting factor for the panel temperature and the cooling capacity is the dew-point temperature in the space. Standards recommend a limit of 60% or 70% relative humidity, which at an air temperature of 26˚C corresponds to a dew point between 17˚C–20˚C, ie lower than the floor temperature (typically 21˚C).

The CIC ZCB radiant system is sized to deliver 50W/m^2, accounting for 30%–50% of the total heat load. Energy savings occur through the reduction in fan-power (by 30%–50%), though are slightly offset by an increase in pump power — additional energy for the chilled water circuit.

Given the risk of condensation, the radiant panels are located away from the perimeter, with appropriate control methods outlined below. The panels are provided with higher water temperature compared to conventional fan coils, leading to higher coefficient of performance (COP) at the chillers.
The cooling energy savings are around 6%–12%, with the corresponding overall energy reduction approximately 1%–3%.

13. Building massing and orientation optimising natural ventilation.

14. Wind catcher.

15. CCHP biodiesel generator.

16. Absorption chiller.

14.

Underfloor air supply
The underfloor systems mainly use the same equipment — chillers, pumps, and air-handling units — as conventional AC systems. The main difference is the way the air is distributed. To avoid drafts, the temperature of the supply air is higher in an underfloor system (15˚C–20˚C compared to 10˚C–15˚C with conventional AC).

While jet-throw systems are considered semi-stratified, fully stratified displacement systems have a higher return air temperature, even though the exhaust inlets are at similar height, at ceiling level. The final temperature difference between inlet and exhaust depends on the detailed air-flow, but as a reasonable starting point, the effect of increased stratification is assumed to be exactly offset by the effect of increased supply temperature, ie the temperature difference is 10°C for both systems and so both will have similar volume flow rate.

Energy savings arise in two key areas:

(1) The plenum underfloor design and low-velocity outlets minimise pressure drop and hence fan power (15% reduction).

(2) The higher supply air temperature allows more free cooling, increasing from 200 hours/year to 600 hours/year.

The overall energy reduction from the underfloor systems is 0.5%–3%.

On-site renewable energy generation

After applying the passive and active design measures described above, energy consumption was greatly reduced: to 116MWh/year in the building and 15MWh/year in the surrounding landscape. To achieve net ZC, these energy demands were met through renewable means. An additional 99MWh/year is exported to the grid to offset the embodied energy in major building materials and, if possible, the embodied energy in other building components, water use, and the energy used by the building's occupants in various transportation modes. This also gives the opportunity for carbon trading of any such energy output in the future.

The CIC ZCB site is surrounded by buildings, with one high-rise office tower to the south completely overshadowing it during winter solstice. The expected power output of the PV system, which includes both monocrystalline and polycrystalline panels, is approximately 85kWh/m^2. Even complete coverage of the building footprint (which would amount to a total 1015m^2 of PV panels) would produce only 87MWh/year of electricity, insufficient for the building's needs.

As already noted, a biodiesel CCHP system was therefore chosen as a suitable additional renewable system[13]. The thermal energy produced can drive an absorption chiller, providing cooling that reduces the chillers' electrical energy use by 85%. Table 4 summarises the energy and carbon balance using the biodiesel CCHP and PV systems.

Combined cooling, heating and power system

The core element of the central system is the generator powered by biodiesel for carbon offset (Fig 15). But commissioning a generator and absorption chiller (Fig 16) is complicated, requiring calibration of the condensing water temperature to provide the cooling design capacity and the supply temperature of the chilled water for the AC systems.

System selection

Four system options were investigated:
(1) electricity generated by PV, cooling by electric chiller; (2) electricity generated by CCHP, cooling by electric chiller;
(3) electricity generated by CCHP and PV, cooling by absorption chiller; and
(4) electricity generated by CCHP and PV, cooling by absorption chiller and electric chiller.

Table 4. Life-cycle calculation of energy and carbon balance in 50 years.

Energy use	Energy	Carbon
Embodied energy from construction materials	14MWh	-
Energy use from construction process	4MWh	-
Energy use of ZCB	116MWh/year	-
Energy use of the landscape area and others	15MWh/year	-
Generation		
Output from biodiesel tri-generation system	143MWh/year (100kWe)	-
Output of PV panels	87MWh/year (1015m^2)	-
Offset		
Surplus energy export	99 MWh/year	-
Carbon emission reduction by on-site renewable energy (over 50 years)	-	7100 tonnes

15.

16.

The key considerations in evaluating them were:

- system sized to instantaneous cooling demand
- smaller central plant size
- PV panels contained within building footprint and covered walkway
- electric chiller increases resilience
- excess electricity exported during peak hours (high value)
- potential for waste heat for desiccant dehumidification
- optimised running cost.

Option (3), which provides the opportunity for energy cascade, was concluded to be the most energy-efficient. In it, the central cooling plant is an absorption chiller operating with a water-cooled electric chiller; the absorption chiller "absorbs" waste heat from the biodiesel generator and produces chilled water with minimal electricity demand. The absorption chiller deals with the cooling load provided by underfloor AC and ceiling air supply, while the electric chiller handles the remaining cooling load, as well as serving as back-up chiller to ensure system reliability.

Design capacity

The CCHP system uses biodiesel to generate both electrical and thermal energy to run the chiller system and meet the building cooling and electrical loads. The size of the system is 100kWe and operates when a cooling demand is present.

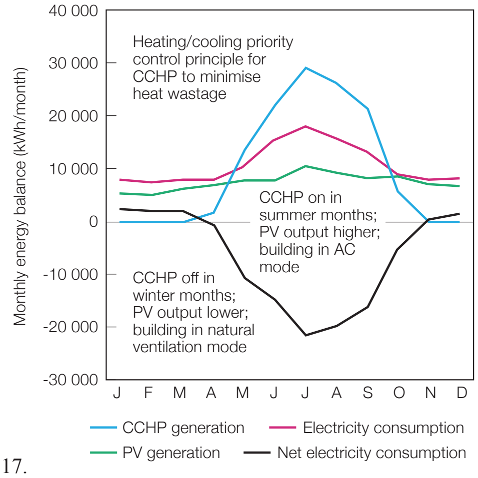
This design marked a new approach to chilled water production in a building, with a concept of "energy grading" applied to match renewable energies to the remaining energy demands. "Energy grading" ranks the full range of possible renewable sources against end-use energy needs, to generate a checklist of building design priorities. The key issue is to match the lowest possible grade of source against the grade of the end-demand.

Energy grading highlights interesting issues, like the inherent inefficiency of many conventional systems that consume high-grade energy and deliver only low-grade energy to building users. It shows that the high energy penalties of chilled water production can be supplied by waste heat rather than conventional grid electricity; an annual energy balance can be achieved between consumption and renewable generation (Fig 17).

Applying the general carbon conversion factor of 0.7kgCO^2-e/kWh in Hong Kong[14] shows the carbon trade-off for the whole year (Fig 18); it can be seen that carbon emissions in the cool season (November–March) can be fully offset in summer (June–September).

Commissioning

The CCHP was installed and commissioned to test the system performance. The results showed (Fig 19) that at the design power generation (100kWe), the absorption chiller can deliver a cooling capacity of 70kW. The COP is at 1.1 with overall thermal efficiency of 80%. The chilled water temperature can achieve the design conditions, ie supply temperature of 9˚C and return temperature of 12˚C. More testing results are expected in the future after a longer period of occupancy of the building.



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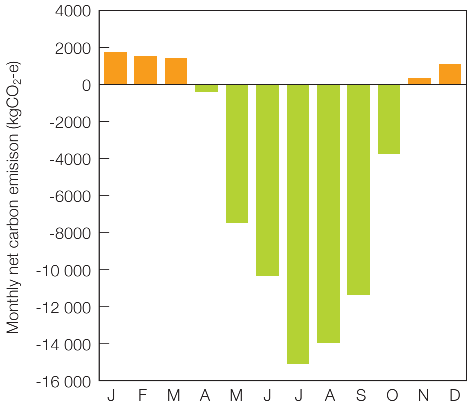

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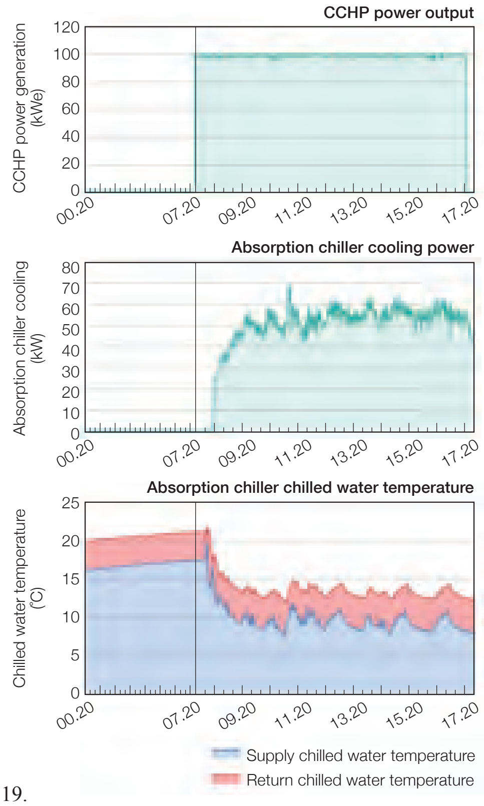

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Conclusion

Construction of the CIC ZCB was completed in June 2012, and it officially opened in January 2013. The design had to consider the particular local context of Hong Kong's hot and humid sub-tropical climate, leading to a new kind of life-cycle concept and the incorporation of a whole series of sustainable, passive architectural, and energy-efficient active systems in the design and construction. These include the high-performance façade with low OTTV, effective airtightness, and optimised window design that allow natural ventilation and daylighting. Energy-efficient AC systems use desiccant dehumidification, and underfloor supply and radiant cooling also contribute to achieving ultra-low EUI values.

Over 45% energy saving is achieved compared to the local standard, and the energy cascade concept was introduced to maximise the thermal efficiency of the biodiesel CCHP system. Overall this is 80%, a significant performance that helps to lower the building's carbon footprint. The total life-cycle carbon emission is offset by on-site renewable energy generated by PV and biodiesel CCHP systems.

Commissioning the building tested the performance of the CCHP system; generator output power, absorption chiller cooling capacity, and supply and return chilled water temperatures were all logged and investigated. Several rounds of condensing water temperature calibrations showed that the system delivers the design cooling capacity and chilled water temperatures. Further comprehensive analysis is anticipated when more testing data are available.

Since the CIC ZCB opened, a campaign of regular guided tours for both professionals and the public has enabled visitors to experience the ZC built environment. This has raised the level of discussion about and awareness of climate change, ZC technologies, and behavioural change, etc.

The building was awarded the Grand Award in the Hong Kong Green Building Awards 2012.

17. Annual energy balance of energy consumption and renewable generation.

18. Annual carbon trade-off of the CIC ZCB.

19. Output of biodiesel CCHP.

20.

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Project credits

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Client/architect: *Ronald Lu & Partners (Hong Kong)*
Building physics, MEP, civil, geotechnical, environmental, structural and traffic engineer: *Arup — Chris Chan, Eddie Chan, Ray Chan, Winifred Chan, Vincent Cheng, Sam Chow, Gigi Kam, Samuel Ku, Kin-Kei Kwan, Mole Kwok, Desmond Lam, Sandy Lam, Tony Lam, Barry Lau, Papko Lau, Gary Leung, Mike Leung, Tao Li, Alvin Lo, Patrick Lui, Trevor Ng, Mark Richardson, Edward Siu, Candy So, Erica Tang, Raymond Wong, Raymond Yau.*

The John W Olver Transit Center

Location
Greenfield, Massachusetts, USA

Authors
Julian Astbury Matt Franks Geoff Gunn
Michael Hovanec Leroy Le-Lacheur Charles Rose

1.

Introduction
Located in the heart of Greenfield in north-west Massachusetts, the new John W Olver Transit Center (OTC) is an intermodal depot for all of the area's fixed-route bus lines and private inter-city, taxi and paratransit (community transport) services.

It also houses the offices of the Franklin Regional Transit Authority (FRTA) — the public transportation provider for this part of Massachusetts and client for the OTC — and the Franklin Regional Council of Governments, the successor organisation to the Franklin County government.

The two-storey, 24 000ft^2 (2230m^2) OTC, named after the long-serving Massachusetts congressman John W Olver, is the first zero-net energy (ZNE) building of its type in the United States. Embedded in its design are numerous strategies for energy conservation and generation.

One example is the textured brick cladding on the western side: a respectful nod to Greenfield's past, but with "green" as its main purpose — a high-tech strategy for managing the building's exposure to afternoon sun. In parts, the brick dissolves and the façade becomes a kind of screen, the resulting patterns controlling the amount of heat entering the interior in summer and winter (Figs 1–2).

The OTC is part of an ongoing effort by the Commonwealth of Massachusetts to foster projects that use renewable energy systems, and it is one of a handful of ZNE buildings in the state.

Working closely with Charles Rose Architects (CRA), Arup provided a range of services including mechanical, electrical, plumbing and lighting design, and sustainability advice.

Project goals

The project goals, developed early on by the design team and the client, were identified as to: (1) achieve a ZNE building, (2) use energy-efficient, user-friendly systems, (3) be sustainable in operation, and (4) optimise capital and running costs. These design principles were developed from a review of the legislative compliance requirements, from commitments by the client and project team members, and the identified additional project options.

What is zero-net?

To design the building and meet the project goals, the team needed a clear understanding of what a ZNE building is. Wikipedia[1] has an extensive series of definitions, while the National Renewal Energy Laboratory in 2006[2] formulated as follows: *"In concept, a net ZEB is a building with greatly reduced energy needs through efficiency gains such that the balance of the energy needs can be supplied by renewable technologies."*

The Massachusetts Executive Office of Energy and Environmental Affairs' Zero Net Energy Buildings Task Force, July 2008[3], concluded that: *"a zero net energy building is one that is optimally efficient and, over the course of a year, generates energy onsite, using clean renewable resources, in a quantity equal to or greater than the total amount of energy consumed onsite."*

The definitions are similar in intent but with subtle differences; given the OTC's location, the design team opted for the Massachusetts Task Force terms of reference and conclusions.

Performance targets

Energy use

The goal was to reduce the energy consumption compared to a typical code compliant office building by 50%. A good quality code compliant building would have had an Energy Use Intensity (EUI) of around 60kBtu/ft^2; the goal here was an EUI of ~30kBtu/ft^2.

Design conditions

The design conditions are 5.9˚F (-14.5˚C) for winter, and 82.5˚F (28˚C) dry bulb/ 69.8˚F (21˚C) wet bulb for summer. According to ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers), these temperatures are only exceeded 1% of the time during each calendar year and thus are the conditions to which system capacities are matched (Table 1).

2.

Table 1. Indoor design conditions.

Space	Temperature		Lights	Equipment	Ventilation rate
	Summer	*Winter*			
Administration	78˚F (25.5˚C)	70˚F (21.1˚C)	0.75W/ft^2 (8.1W/m^2)	1W/ft^2 (10.7W/m^2)	5ft^3(0.14m^3)/min/person and 0.06ft^3/min/ft^2 (0.018m^3/min/m^2)
Bathrooms (1st/2nd floor)	80/78˚F (26.6/25.5˚C)	68/70˚F (20/21.1˚C)	0.75W/ft^2 (8.1W/m^2)	NA	70ft^3(2.48m^3)/min/fixture
Cafe	80˚F (26.6˚C)	68˚F (20˚C)	0.75W/ft^2 (8.1W/m^2)	NA	15 air changes/hour
Conference	78˚F (25.5˚C)	70˚F (21.1˚C)	0.75W/ft^2 (8.1W/m^2)	NA	5ft^3(0.14m^3)/min/person and 0.06ft^3/min/ft^2 (0.036m^3/min/m^2)
Mechanical	80˚F (26.6˚C)	60˚F (15.5˚C)	0.5W/ft^2 (5.4W.m^2)	Per equipment	0.12ft^3/min/ft^2 (0.036m^3/min/m^2)
Storage	80˚F (26.6˚C)	60˚F (15.5˚C)	0.5W/ft^2 (5.4W/m^2)	NA	0.12ft^3/min/ft^2 (0.018m^3/min/m^2)
Waiting area	80˚F (26.6˚C)	68˚F (20˚C)	0.75W/ft^2 (8.1W/m^2)	8.6W/ft^2 (92.6W/m^2)	7.5 ft^3(0.21m^3)/min/person and 0.06ft^3/min/ft^2 (0.018m^3/min/m^2)

Water consumption

To reduce water consumption, low flow water fixtures are used throughout the OTC. The flow rate targets shown in Table 2 were set for the use of low flow fixtures.

Materials and waste

The team selected materials that had a high recycled content and low embodied energy wherever possible.

Table 2. Flow rate targets.

Fixture type	Target flow rate
Water closets	1.28gal (4.85 litre)/flush
Lavatory faucets	0.5gal (1.89 litre)/minute
Showers	2.5gal (9.46 litre)/minute or less
Kitchen faucet	2.5gal (9.46 litre)/minute or less

1. The largely glazed north façade.

2. The west façade, showing the textured brick cladding that acts as a sunscreen.

Energy model

To deliver the ZNE building, the team's approach was to design for ultra-low energy consumption. With this achieved, the energy that would still be used within the building could be offset by renewable energy notionally provided through a photovoltaic (PV) array and a biomass boiler (Fig 3).

The design strategy (Figs 4–5) was to estimate annual energy usage by energy modelling, the inputs to which were based on the building design and included assumptions of anticipated occupancy and owner-provided equipment information, so that the results gave an estimate of annual building energy consumption. Energy modelling identified heating and air-conditioning as major users; looking for ways to reduce energy use and therefore the size of the PV array, Arup worked with the client to establish higher acceptable space temperature set points during the summer, so as to reduce air-conditioning use.

For heating, the team opted to go with the biomass boiler concept rather than natural gas. Under the ZNE and renewable energy portfolio standards for Massachusetts[3], biofuels derived from waste products — including forestry and lumber milling and processing residues — are considered to be eligible renewable resources. So to eliminate natural gas energy from the ZNE equation, the OTC design included a biomass boiler fuelled by wood pellets made from lumber milling waste sourced locally.

Energy modelling software is generally used for system sizing and comparison purposes, and rarely predicts accurately the actual building energy demand and consumption, so the team needed to calibrate the model and make sure all the building system components were included.

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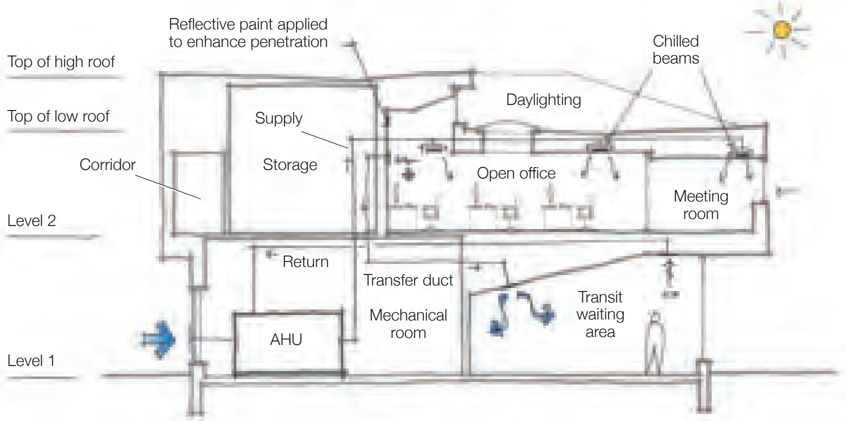

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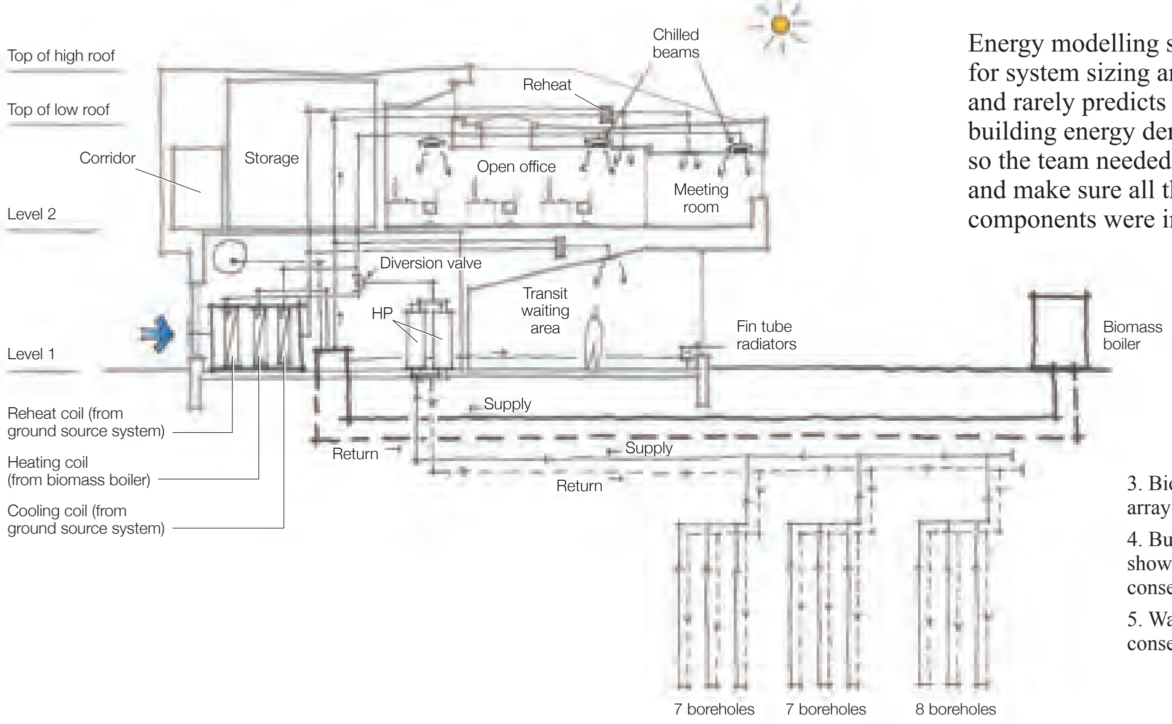

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3. Biomass boiler (left) and PV array (right).

4. Building cross-section showing air-side conservation strategies.

5. Water-side conservation elements.

The server room was determined as being energy-intensive, so Arup's IT specialists worked with the client to select equipment that balanced the OTC's technological and energy conservation requirements.

The site

When designing a ZNE building one of the first design decisions to make is its orientation, which can impact heating, lighting and cooling costs. For example, maximising southern exposure takes optimal advantage of the sun for daylight and passive solar heating. Cooling costs will be lowered by minimising western exposures, where it is most difficult to provide shade from the sun.

The OTC site is close to the centre of downtown Greenfield on the corner of Bank Row and Olive Street, and the building orientation was fixed by the size of the site and the requirements for the bus driveway (Fig 6). This resulted in a long north–south axis and a short east–west axis. Arup worked with CRA to relocate elements such as storage, plantrooms and bathrooms to the west side of the building, which insulated the offices on the east from solar gain. For this façade Arup and the architect developed a perforated copper screen that reduces glare in the office space (Fig 7).

Reduced loads

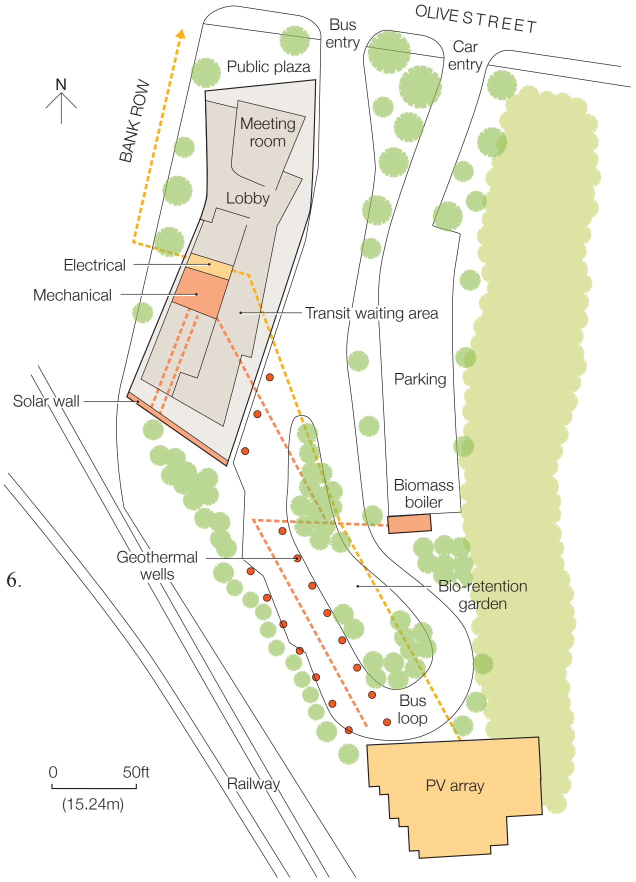
Envelope

In the initial design, Arup worked closely with the architect to improve the envelope performance beyond code minimum requirements (Table 3). By reducing the amount of heat gains and losses through the building envelope, the team was able to reduce the overall mechanical plant required.

Lighting

Lighting is a key component in the design of low-energy buildings, and there are two primary ways that it can influence energy use in a space:

- reduction in installed lighting loads, which have a corresponding reduction in the mechanical cooling loads
- use of daylight and/or lighting controls to reduce the amount of time the lighting is activated.



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7.

Table 3. Comparison between building code requirements and modelled results.	
IECC 2009 (code)	**Modelled**
Wall R-value = R13+R7.5ci/U-value = 0.064	Wall R-value = 32/U-value = 0.031
Roof R-value = 20/U-value = 0.048	Roof R-value = 41/U-value = 0.024
Fenestration: U/SHGC (solar heat gain coefficient) = 0.55/0.4	Fenestration U/SHGC = 0.4/0.3

6. Site plan.

7. Perforated screens reduce glare in the office spaces.

8.

The OTC's lighting systems were designed to minimise the energy used for artificial lighting by extensive use of energy-efficient LED sources (Fig 8). Lower overall light levels were used in open and private offices so as to reduce the installed lighting power, but where required by individual needs, local user-controlled task lighting is provided. The careful application of new lighting technologies and aggressive lighting power densities resulted in a 44% reduction of installed lighting power compared with a code compliant building.

The design approach of providing a relatively low level of ambient light in the office spaces, with supplemental task lighting at workstations if required, allows a lower level of installed power by focusing higher light levels only on spaces where it is needed and locating those sources closer to the surface. The reduced level of ambient light illuminates the space evenly and allows for circulation and orientation. Once again, Arup worked with CRA to review fixture selections and ensure that energy-efficient lamp types and luminaire designs were used — while at the same time being sensitive to the architectural design of the ceiling.

Passive strategies

Daylighting

While reducing the installed lighting power helps to contribute to a building's efficiency, a more direct way to reduce the impact of electric lighting on energy use is simply not to use it. If electric lighting is not used, however, sufficient glare-free daylight must permeate all spaces that are occupied for significant periods of time.

The daylighting strategy for the OTC ground floor was fairly straightforward. Since the space primarily consists of a waiting area with transient users, the light level targets were lower than in the offices. The glazed eastern façade provides most of the light for this waiting area, while the larger plan of the building's second floor creates an overhang above it, reducing direct sunlight penetration and glare, helping lighting levels and visual comfort, and reducing thermal loads on the façade glazing (Fig 10).

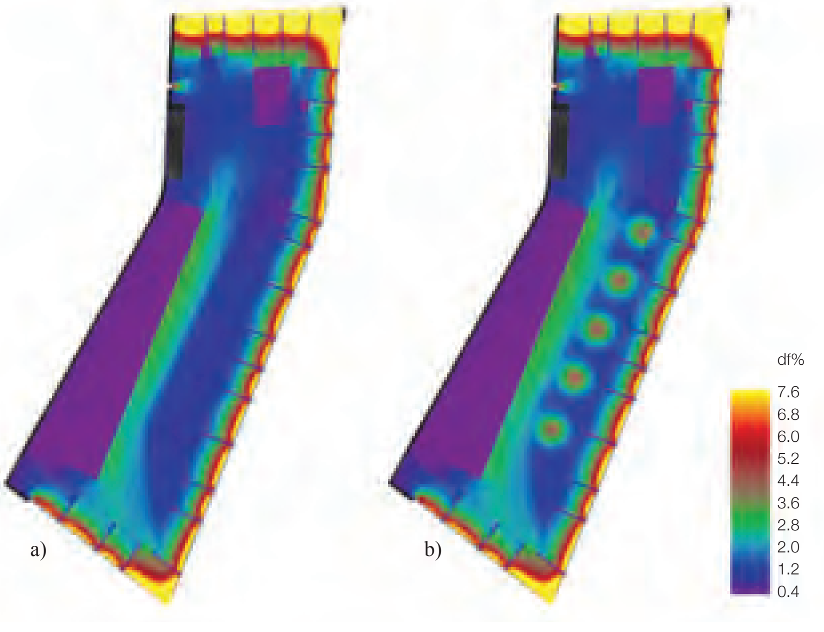
The second floor comprises office space on the north, east, and south sides, and programme requirements dictated that private offices occupy the areas near the façades. A clerestory was included to introduce daylight into the open office space in the centre of the floorplan.

To assess the quantity of daylight throughout the second floor, an initial "daylight factor" study (Fig 9a) was completed. This is a measure of the amount of daylight at a point inside compared to an unobstructed point outside; office daylight factor targets are typically in the 2%–5% range.

The initial study indicated that daylight levels in the perimeter offices were sufficient without being excessive. The clerestory also provided even lighting at an appropriate level, but only illuminated part of the interior floor area. So, to increase daylight levels in the interior and reduce electric lighting use, skylights were added, supplementing the light levels so that the entire space is illuminated (Figs 9b, 11).

To further understand the daylight performance here and provide accurate input to the energy modelling, an hourly annual illuminance simulation was performed. This analysis determined the "daylight autonomy" for each workstation in the office space — the percentage of operating hours during a typical year when illuminance levels from daylight can be expected to exceed the light level design criteria, allowing electric lighting to be turned off. Daylight autonomy is expressed as a percentage.

The project team defined 75% daylight autonomy as an appropriate target, ie for 75% of all operating hours there would be enough daylight for electric lighting not to be required. After the addition of the skylights on the second floor it was calculated that 89% of the workstations on the second floor met this criterion, and 100% achieved a daylight autonomy of >50%.



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8. Lobby with LED lighting minimising energy use.

9. (a) Initial second floor daylight factor study; (b) revised second floor daylight factor study incorporating skylights.

10. South and east façades showing second floor overhang shading the first floor.

10.

Glare control

While one aspect of daylighting design is to achieve appropriate minimum light levels, it is also important to ensure that measures are taken to reduce daylight glare.
Glare from direct sunlight or high sky brightness can not only be distracting, but also increase energy use by encouraging users to close shades or blinds, which in turn requires electric lighting to compensate for the reduced daylight.

Each façade had different conditions, so a different approach was taken on the north façade compared to the east and south.
The north façade is glazed, without additional shading, due to the minimal level of direct sunlight striking it.

The east and south façades, on the other hand, have glazing protected by custom-designed copper screens with roughly 50% openness (Fig 10). These reduce the daylight entering the spaces but maintain enough for internal illumination, and protect against glare by reducing the average sky brightness seen through the screen. They also reduce thermal loads.

There is also automated shading on the west and south façades; this is controlled based on the time of day and exterior daylight conditions, with an override capability for local users.

Active strategies

Chilled beams

Compared to traditional all-air systems, active chilled beams (ACBs) typically save money on operating costs. These systems combine water-based "sensible cooling" at the room level with "latent cooling" via the air-handling unit (AHU) system. As a result less conditioned air needs to be moved through the building.

ACBs include a sensible cooling coil and high-velocity nozzles. As conditioned air is supplied through the beam, the nozzles create a pressure differential that induces or "pulls" room air into the beam. As it flows through the beam the room air passes through the sensible cooling coil and mixes with primary supply air.

The central system is designed to circulate only the amount of air needed for ventilation and dehumidification, with the ACBs providing the remaining sensible cooling through the induced room air and sensible cooling coil. Fan energy is one of the largest building energy uses, and ACB systems require less energy since they move less air throughout the building.

Ground source heat pumps

Primary cooling and auxiliary heating are provided through ground source heat pumps, which use the earth as a heat sink in summer and as a heat source in winter for chilled and hot water. The heat pumps are coupled with a geothermal well field and ground loop.

The OTC has 22 closed loop geothermal wells, each over 400ft (122m) deep.
Arup worked closely with the geotechnical sub-consultants to co-ordinate building loads and service connections between the indoor heat pumps and the geothermal well field. Geothermal heat pump systems typically use less energy than conventional HVAC systems, are less obtrusive, and reduce water consumption by not requiring a cooling tower.

Transpired solar collector (solar wall)

Almost all the south-facing opaque façade forms (Fig 10) a transpired solar collector, used to preheat ventilation air in the winter. As the collector absorbs solar radiation, perforations in it allow fans to draw ventilation air into the cavity between it and the façade itself. This preheated ventilation air is then ducted to the central AHU for further conditioning and distribution.

As well as the winter energy savings, the added cladding to the south façade reduces the summer cooling demand by shading direct sunlight. In the summer months the transpired collector is bypassed so as not to overheat the incoming air.

Advanced lighting controls

To help meet the project energy goals, a comprehensive building lighting control system connects to occupancy and photo sensors that automatically shut off the fixtures when the space is empty, and provide continuous dimming when sufficient daylight is detected. This ensures that all spaces are adequately lit when occupied, and do not waste energy when unoccupied. In addition, the system zoning, control, and set points can be easily reprogrammed from a tablet or smartphone to cater to changing user requirements and allow for ongoing performance optimisation. All regularly unoccupied spaces, such as plantrooms and storage closets, have occupancy sensors to ensure lighting in these areas is not left on when not in use.

Variable frequency drives

Building fans and pumps operate with variable frequency drives, allowing turn-down during off peak use.

Energy recovery

The central AHU includes multiple energy recovery technologies. An enthalpy wheel transfers energy between the supply and exhaust air streams, recovering sensible and latent energy which would otherwise be wasted in the exhaust air, while a refrigerant-based wrap-around heat pipe heat recovery exchanger is included at the chilled water cooling coil.

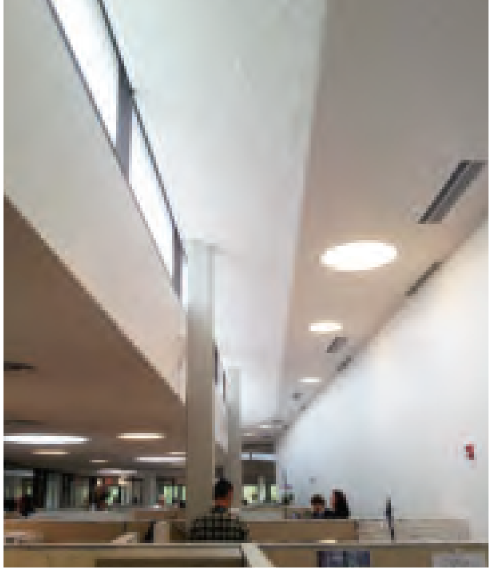
For the active chilled beam system, critical humidity control is provided by overcooling the air to condense out the excess moisture, requiring reheat. Heat pipes wrapped around the cooling coil pre-cool the supply air before it hits the coil, allowing it to condense out moisture more effectively. The heat pipe then re-heats the air on the rear of the cooling coil to eliminate the need for reheat.

Self-generation from renewables

Photovoltaic array

With building loads reduced as much as possible through the designs and systems described above, on-site renewable energy generation offsets the remaining building energy consumption. PV energy modelling using local weather conditions was performed to estimate the annual energy output and determine the optimal array size to meet the ZNE goals.

The resulting 98kW ground-mounted PV array is sized to offset 100% of the estimated building electrical energy usage.



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The array is installed on a single stadium-style rack, minimising its overall footprint on the already tight site (Fig 12).

A total of 416 polycrystalline 235W panels are divided into two approximately 50kW sub-arrays, each linked to a dedicated 50kW PV inverter which connects to the main distribution system at the building switchboard. The PV array is separately metered and reported to the building dashboard so that the array's output can be monitored, displayed, and trended.

An agreement with the neighbouring railway right-of-way was required to allow the project to remove overgrowth shading the PV array. Post-occupancy measurement has confirmed that the array's actual energy output meets the estimated production.

Biomass

A relatively low-carbon renewable fuel source is biomass, of which there are three main types: woody biomass (energy crops and wood), biofuel (from processed vegetable oil), and biogas (animal waste). The term biomass is used to describe biofuels that are solid and require little or no processing prior to being burned. These are considered to be carbon neutral, as the amount of CO_2 released when they are burned equals the amount absorbed during their lifetime.

The building's HVAC system uses one 750MBH biomass boiler in lieu of traditional fossil fuel-fired boilers. An important consideration of this type of system is the availability, delivery, and storage of the fuel source. Locally sourced woodchips and pellets are available in the Greenfield area and a reliable supply chain is in place.

Water

The domestic water usage was first reduced by using low-flow fixtures at flushometers for the WCs and urinals, and also for the faucets at lavatories. The team analysed the domestic hot water needs, and first considered its generation from solar thermal panels and geothermal heat pumps, both of which require constant electrical pump loads.

However, compared with other building loads the total daily domestic hot water loads were found to be very low, and after further investigation it was determined that serving them from the biomass boiler in winter and from electric immersion heaters in summer would be more effective than trying to incorporate either of the other two seemingly more green and sustainable alternatives. This approach also keeps the systems simpler, with fewer pumps and water loops making maintenance easier.

As the building has no basement, there was no need for sanitary or sump pumps, which kept reduce plumbing power loads.

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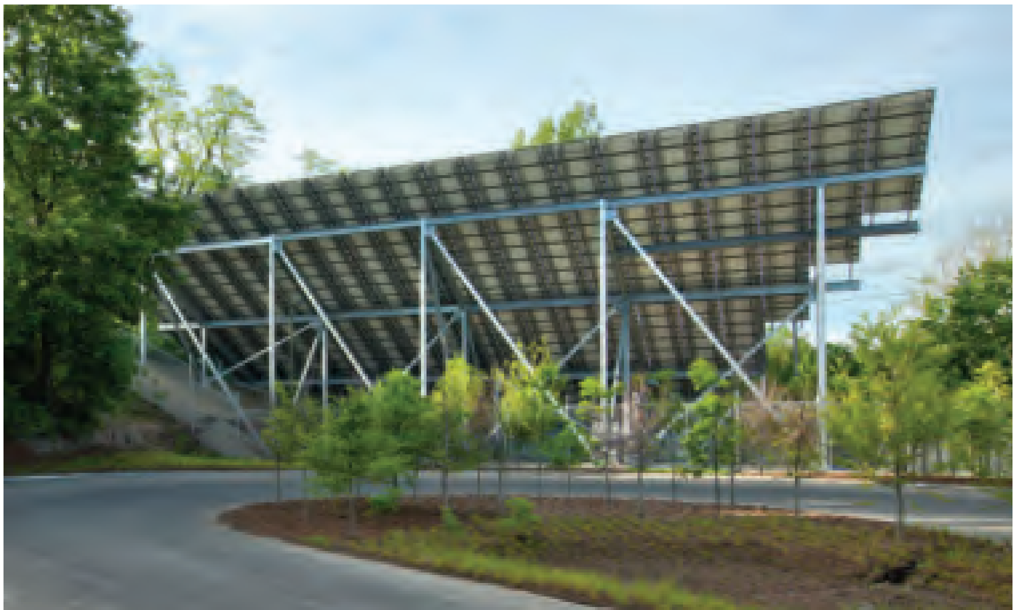


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Conclusion

The John W Olver Transit Center opened on May 4, 2012, in a dedication ceremony with Massachusetts Governor Deval Patrick, Lieutenant Governor Timothy Murray, and other state officials present. At the time of ground-breaking in April 2009, the construction budget was $12.8M, but the building came in $2.4M under budget, with all its numerous sustainable and ZNE features intact and operating.

"*Zero-net energy design has revolutionised the way we work,*" said architect Charles Rose: "*We are creating buildings that are highly integrated. In other words, the only way to get to net-zero is by integrating mechanical and electrical engineering into the conceptual design phase. It's a fundamentally different way of designing a building. Our mechanical engineers are serious collaborators now. That's very important.*"

Arup is currently conducting a post-occupancy energy survey of the building to confirm that the design goals have been met. This is planned to be completed in 2014, to confirm that the team achieved the goal of designing a high performance building with energy consumption reduced by 50% compared to a typical code-compliant office building.


14.

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(3) MASSACHUSETTS EXECUTIVE OFFICE OF ENERGY AND ENVIRONMENTAL AFFAIRS. Getting to zero: final report of the Massachusetts Zero Net Energy Buildings Task Force, March 11 2009. http://www.mass.gov/eea/docs/eea/press/publications/zneb-taskforce-report.pdf

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Leroy Le-Lacheur is an Associate in the Boston office and led the plumbing and fire protection design..

Charles Rose is Principal of Charles Rose Architects, Somerville, MA, which designed the OTC.

Project credits

Client: *Franklin Regional Transit Authority*
Architect: *Charles Rose Architects Inc*
Building services engineer and sustainability consultant: *Arup — Julian Astbury, Fiona Cousins, Matt Franks, Geoff Gunn, Michael Hovanec, Beth Iacono, Carey Jones, Kevin Kresser, Leroy Le-Lacheur, Nora McCawley, Anna Murray, Sasha Velic, Mark Walsh-Cooke, Craig Webster* Civil engineer: *McMahon Associates* Geotechnical engineer: *McPhail Associates* Structural engineer: *Richmond So Engineers* Cost consultant: *Faithful & Gold*
Code consultant: *RW Sullivan*.

Image credits

1, 7–8, 11, 14 *Charles Rose Architects*;
2–3, 10, 12–13 *Peter Vanderwarker Photography*;
4–5 *Rebecca Hatchadorian*; 6 *Nigel Whale*; 9 *Arup*.

11. Daylight enters the second floor office space through overhead skylights.

12. The PV array.

13. Eastern elevation with second floor perforated screens.

14. Transit waiting area.

1.

A30:

Autoroute 30 Montréal Southern By-pass

Location
Montréal, Québec, Canada

Authors
Douglas Balmer Matt Carter Tim Hackett
Alan Phear Nick Sartain Derya Thompson

Introduction and outline history

This article presents the summary details and Arup's involvement on the 42km long A30: Autoroute 30 Southern By-pass PPP (public-private partnership) project. The firm's role commenced in 2007 with the Request for Qualification process and was concluded when the A30 opened on time on December 15, 2012. This major highway project had an exhaustive history of development, as with most major projects, and this is summarised in this article.

A new highway to bypass and connect the municipalities along the southern shore of the St Lawrence River in Québec was originally mooted in the 1960s, and in 1968 work began on this new 161km transport artery, the A30.

Several sections were constructed, including a short length completed in the early 1980s to the south of Salaberry-de-Valleyfield on the Île de Salaberry, which did not connect into the highway network until the whole project was finished in December 2012.

Growing road congestion in and around Montréal led to pressure for the route to be completed. Following public hearings in 1997, a recommendation from the Québec *Bureau d'audiences publiques sur l'environnement* (BAPE) in 1998, and an authorisation from the *Commission de protection du territoire agricole du Québec* (CPTAQ), the project obtained the necessary *certificat d'autorisation de réalisation* in May 1999 from the Québec *Conseil des ministres* (provincial cabinet).

Throughout the preliminary stages, studies were undertaken that both helped to define the project requirements and enabled most of the land inside the proposed right of way to be acquired in advance of the start of procurement. In due course the decision was taken to procure the eastern portion of the project through a series of traditional design-bid-build contracts, while the governments of Canada and Quebéc agreed to procure the western portion through a PPP contract — the western portion forms the A30 Southern extension.

In 2006 the Ministry of Transport of Québec, or *Transports Québec* (MTQ) announced that the A30 would be completed as a southern bypass to Montréal. The Request for Qualifications was released in late 2006, and in February 2007 three consortia were shortlisted to design, build, operate and finance the CA$1bn project: Infras-Québec A-30, SNC-Lavalin, and Nouvelle Autoroute 30 — a consortium of Spanish contractors including Dragados and Acciona, with Arup as lead designer. The Request for Proposals (RFP) process started in June 2007, and in June 2008 the government selected as its preferred bidder Nouvelle Autoroute 30.

The concession to finance, build, maintain and operate this section of the A30 for 35 years was awarded to the consortium on 25 September, 2008, and the detailed design commenced thereafter. The construction itself was carried out on a design-build basis by the Nouvelle Autoroute 30 Construction Joint Venture (CJV). This PPP procurement method is estimated to have saved the Québec government an estimated CA$750M compared to the traditional procedure.

Overview and Arup's role

The A30 Montréal project comprises 42km of highway, plus 30 bridges — two of them major crossings of the St Lawrence River and the Beauharnois Canal — and a tunnel.

This was one of Arup's longest and most complex highway projects, and a truly global design effort with input from offices in the USA, Canada, UK, Europe and East Asia; in 2009 the team size peaked at over 200 engineers, technicians and support staff. An Arup design co-ordination team, co-located in Montréal with the A30 construction joint venture (CJV) client, managed and delivered the firm's global design input.

1. Looking north-east at the Northern Interchange in Section 1 (previous page).

2. Plan of Autoroute 30 Montréal Southern By-pass, highlighting the five Sections.

3. Western approach piers of the Beauharnois Canal bridge (Section 4).

The project was divided into five discrete Sections (Fig 2):

Section 1: from Vaudreuil-Dorion to north of the St Lawrence River (including Northern Interchange)

Section 2: St Lawrence River bridge

Section 3: A30 and A530 on the Île de Salaberry (including Southern Interchange)

Section 4: Beauharnois Canal bridge, and finally

Section 5: from Beauharnois Canal to Châteauguay.

The design was substantially complete in 2010, though changes were needed later to optimise it, as the construction methods were further developed by CJV. Arup's scope included structural, geotechnical, highways, pavement, environmental, bridge, and drainage engineering design, with the Montréal project management team liaising with external sub-consultants for pavement design, lighting, communications, utilities, signalling, signage, landscaping, road marking, ship impact assessments, seismicity, wind, river hydraulics, snow and ice analyses and studies, bridge architecture and specifications.

Designing the major bridges across the St Lawrence River and the Beauharnois Canal were significant challenges. This was fast-tracked and, to meet the rapid schedule, the bridge foundations were begun before completion of the superstructure design. This approach required careful planning and control to ensure that the superstructure scheme design, particularly the articulation, was sufficiently well-developed for the foundations to carry final design loadings.

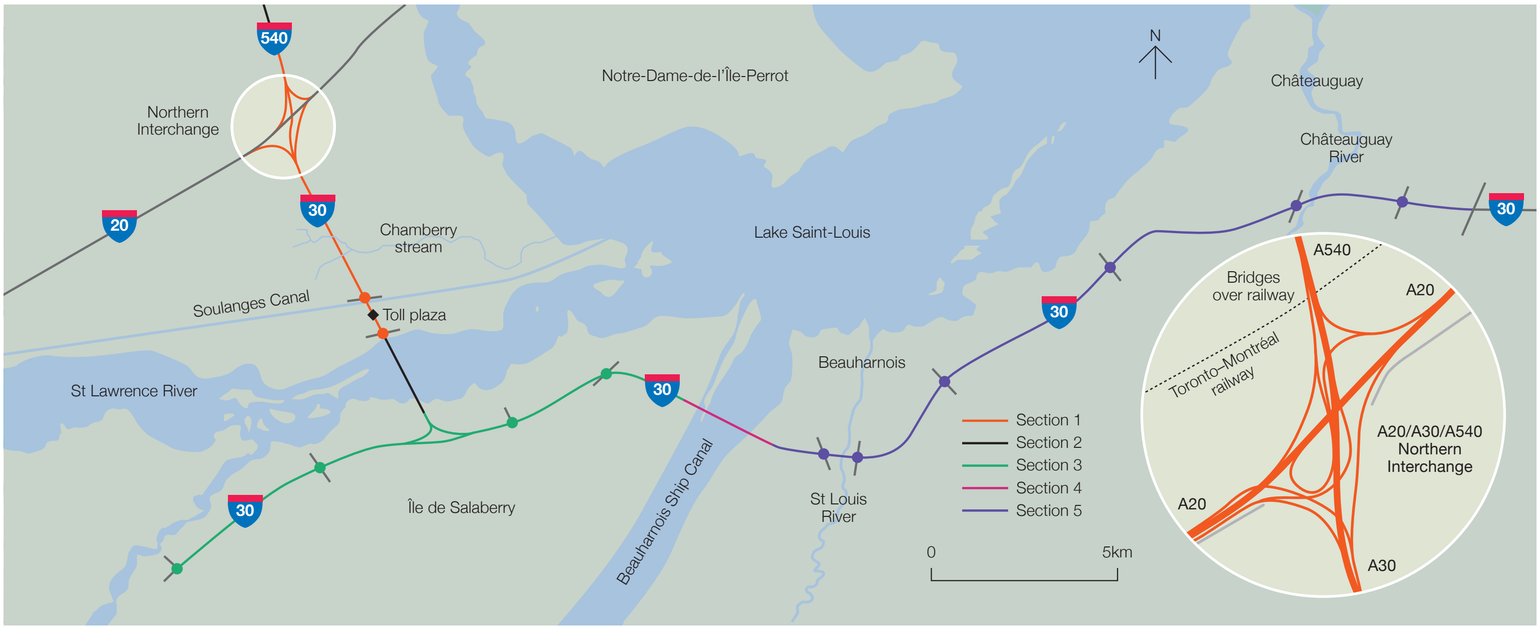
Arup undertook an independent check of these works, with analysis and structural verification carried out by an independent team not involved in the original design. Additionally, MTQ appointed an independent engineer to review and audit the design and construction. Construction of the two major bridges began in May 2009 and they were completed on time and opened to traffic in December 2012.

The ground engineering for the A30 project was also particularly challenging, primarily because the route crosses a deep deposit of soft, sensitive and compressible Champlain Clay. The largest geotechnical risks were associated with building on this clay the high embankments needed for link roads at interchanges and for approach ramps to the bridges throughout the autoroute. The highest embankments (up to 11m) were at the Northern Interchange, where the A30 joins the existing A20 and A540 autoroutes; here the Champlain Clay is up to 20m thick. Designing and building these embankments required careful co-ordination between the design and construction team's preferred methods and schedule, and was successfully completed on time.

Arup also provided Construction Phase Services (CPS); this essentially comprised an audit role to check that CJV had discharged its construction phase obligations, including detailed site supervision in accord with the Arup design.

Data management

Intrinsic to Arup's total engineering ethos is the seamless delivery of holistic designs. With A30 design work going on in locations around the globe, it was important to ensure that interfaces between the various teams were managed and co-ordinated. In addition to coherent design co-ordination by the discipline leaders, regular interdisciplinary design reviews ensured that each discipline took account of the needs of others as well as its own speciality. In their simplest form these reviews involved engineers from different disciplines critiquing sets of drawings to ensure that any issues were clarified. At other times reviews were by teleconference, with the drawings shared on-screen between all offices concerned.



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Given the design team's geographical spread, regular data management protocols would have been inefficient and risky, with large volumes of data and drawings being exchanged between servers in each office, duplicating storage, and bringing the danger of working from out-of-date information. To overcome these potential problems, Arup adopted two key systems.

The main data management tool used was Bentley Systems' *Projectwise*, which enabled all the data to be stored in one location, accessible to all the design teams. Sensitive information was handled by setting up user permissions that could control read/write privileges allocated to users or, if necessary, deny access. Approved users checked out documents or drawings to work on, and check them back in once any edits were made. Other users could open the same document but in a read-only format without making changes to the master version. This reduced the complications of individuals updating different versions of the same document, and the changes having to be consolidated at a later date. Arup also enabled its subconsultants to have access to *Projectwise*, which helped the team to share and control data.

Email now being the default means of communicating data and information on projects, the second key application used by Arup on the A30 was *Mail Manager*, an add-on to Microsoft *Outlook* developed by Oasys, Arup's internal software development team. This simplified filing and searching for emails — with over 180 000 generated on the project, the ability to store and recover any one within a few seconds was a real asset.

Project correspondence also included letters to and from the client, CJV. All these documents were also stored on *Projectwise*.

Both systems were made possible by the quality of the data network connections that Arup has in place between all its offices, a factor that was planned into the project infrastructure and links from the outset.

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4. The Northern Interchange in use in October 2012, prior to the official opening.

5. The toll plaza, between the south end of the Soulanges Canal tunnel and the north end of the St Lawrence Bridge.

6. The St Lawrence Bridge, December 2012.

The St Lawrence River bridge

Design constraints

Several constraints influenced the design of the St Lawrence River bridge (now named the Serge Marcil Bridge after the prominent Québec educator, administrator and politician who was tragically killed in the 2010 Haiti earthquake). They included, first, the low-level profile: this would require short piers which, given the minimum practical dimensions needed for robustness, would be relatively stiff.

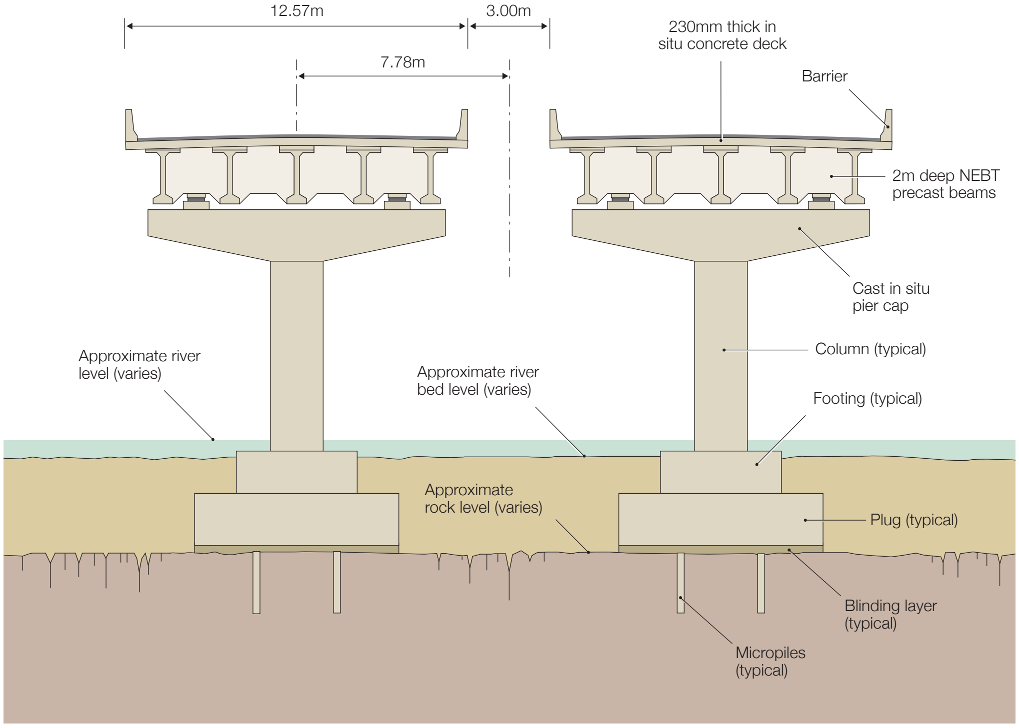
Secondly, the rock in the riverbed, along the bridge alignment, is at shallow depth with little soil overburden, while seismic ground accelerations are substantial and the forces from ice in the river during winter are very large. Permanent disturbance to the riverbed, however, had to be minimised, due to environmental restraints.

Last but not least, the CJV client sought a fast track design to start building temporary works in the first construction season. As the river level was controlled by hydroelectric dams both upstream and downstream of the A30 alignment, the design of the bunds and cofferdams required close co-ordination with the construction team and early completion of the bathymetry and hydraulic studies and preliminary substructure design.

General arrangement

This reach of the St Lawrence River is not navigable, so the bridge could be designed as a low-level crossing. It extends between Les Cèdres on the north shore and St Timothée on the south shore, approximately 1km downstream (east) of the Les Cèdres hydroelectric generating station and 4.5km upstream (west) of the Pointe-du-Buisson barrage. The river is almost 1.5km wide here, requiring a total length of bridge structure of 1.862km (Fig 7).

Twin separate concrete structures carry two-lane carriageways (Fig 8), each superstructure comprising five New England bulb-tee (NEBT) 2.00m deep, precast, prestressed concrete beams supporting a 230mm thick concrete deck. The beams are continuous except at the abutments, which eliminates intermediate expansion joints, removing a maintenance "black spot". The deck spans transversely, comprising permanent precast concrete panels working compositely with the in situ deck.



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7. Early conceptual graphic.

8. Typical cross-section.

9. Columns and footings at low water level.

Each of the 42 spans is 45m long, with expansion joints at each abutment and at intermediate piers to divide the total into six interior units of five spans each, and two exterior units of six spans each. Separate piers, all of them reinforced concrete hammerheads, support each carriageway, with solid circular columns 2.0m in diameter at Piers 2 through 34, and 2.5m in diameter at Piers 35 through 42. The larger-diameter columns are required to resist higher wind loads due to the presence of noise barriers on those spans.

Superstructure seismic isolation

The low profile grade, combined with conventional bearings on short piers, would have resulted in a bridge with an undesirably short fundamental vibration period, placing the structure in the region of the design response spectra where accelerations would be highest. Ductile design of the substructure columns would have been difficult, if not impossible, and the foundation demands correspondingly high.

The solution to this challenge (as discussed below) was to seismically isolate the superstructure from the substructure with friction pendulum (FP) bearings. There are two per pier at continuous piers, and two on each side of the expansion joints (four total per expansion pier). Concrete shear keys between the end diaphragms of adjacent spans at the expansion joints restrain relative transverse movement between the spans, while two uni-directional single-pendulum FP bearings (longitudinal) are provided at each abutment.

The FP bearings use a triple pendulum mechanism which combines three different radii of spherical sliding mechanisms to control seismic forces. As the substructure imparts load, the superstructure, as restrained by the FP bearings, is guided to firstly rise, dissipating energy, and then fall, with correspondingly lesser horizontal movement; this limit the displacements and reduces the accelerations, and the system re-centres after the seismic motion stops. The bridge's effective period is lengthened, the effective damping is increased, and permanent offset of the superstructure avoided.

These beneficial effects were accurately captured by the non-linear *LS-DYNA* seismic modelling of the interaction between the sub- and superstructures during various seismic events. A large reduction in the seismic demands was achieved, to the point that ice forces control for all the piers in the river. Relative to the total cost of the bridge, the cost of the FP bearings was small and well-justified in terms of corresponding savings made to other bridge elements.

10.

Another benefit of FP bearings was realised during construction. As the elevation of sound rock varies along the length of the bridge, founding elevations varied from those predicted from the limited pre-RFP site investigation. Isolating the superstructure on FP bearings makes the seismic demands on the columns and foundations relatively insensitive to the length of the columns, so that column length variation could accommodate the final founding elevations by fairly simple linear checks of the increased moments from ice and wind forces, and avoid updated seismic analysis.

Lengthening the columns was more economical than increasing the depth of the tremie plugs, achieving cost-effective and rapid design modifications to accommodate the field conditions.

11.

10. The completed deck.

11. Placing the deck structure.

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12. Conceptual graphic, showing on the left the navigation span over the St Lawrence Seaway.

13. 3.5% carriageway gradient, and 38.5m clearance over the Seaway.

14. Constructing the western approach deck.

The Beauharnois Canal and St Lawrence Seaway bridge

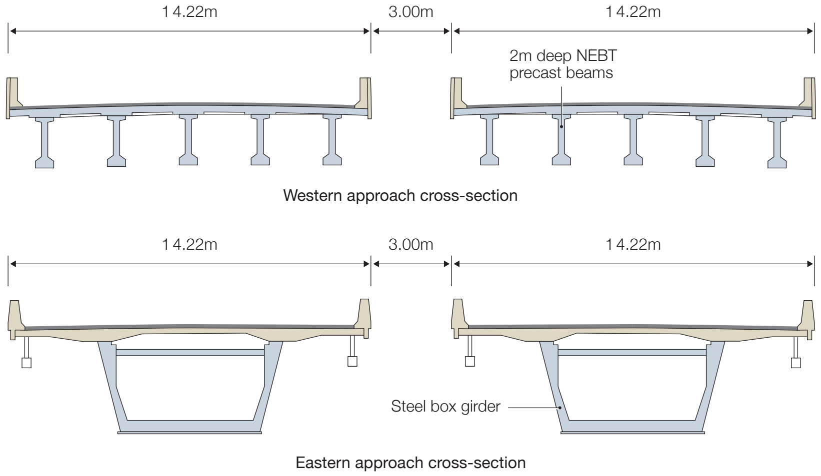
General arrangement

The 24.5km Beauharnois Canal connects Lake Saint-Francis and Lake Saint-Louis in Québec, bypassing a series of rapids on the St Lawrence River. The canal was originally opened in 1843, but in its present form was built between 1929–1932 as part of a hydroelectric barrage development to take advantage of the 24m drop in elevation between the two lakes. To allow ocean-going vessels to travel from the Atlantic to the Great Lakes, a pair of locks bypasses the barrage to the west, forming part of the St Lawrence Seaway.

At the bridge location, the A30 crosses the St Lawrence Seaway and Beauharnois Canal on a structure 2.5km long in total, this length being dictated by the need to provide 38.5m of clearance above the Seaway plus the maximum preferred gradient of 3.5% in the approaches (Figs 12–13).

The bridge utilises two structural types. The first comprises precast NEBT beams (similar to those on the St Lawrence bridge), precast deck units and in situ topped deck for the western approach (over land), with 24 spans of typically 45m (Figs 14–15). The total length of the western approach is 1095m, subdivided into three articulation sections by intermediate expansion joints.

The second is a continuous steel-concrete composite box girder superstructure over the canal itself and the eastern approach; there are 17 spans with a typical length of 82m, plus the 150m navigation span, giving a total length of 1457m (Figs 15–16).



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Key constraints

The major construction constraint that led to the final scheme was a third-party agreement between MTQ and the St Lawrence Seaway Management Corporation. This completely forbids construction activities above the Seaway except during the winter months when the Seaway is impassable and closed due to ice. Faced with this constraint the design team had to find an appropriate construction method for building the 150m main span quickly and in freezing weather. The solution lay in launching a steel box girder (Fig 18, overleaf).

A second constraint was that the bridge river flow obstruction footprint within the Beauharnois Canal had to be minimised, both to limit the loss of fish habitat area and to reduce any head-loss in the river flow from the bridge's presence that might impact the efficiency of the downstream hydroelectric barrage. This was achieved by designing the long 82m spans with the pilecaps above water level (Fig 17).

17.

15. Differing cross-sections of the western and eastern approaches.

16. Constructing the eastern approach deck.

17. The completed eastern approach, showing pilecaps above water level.

18. Launching the steel box girder navigation span (overleaf).

19.

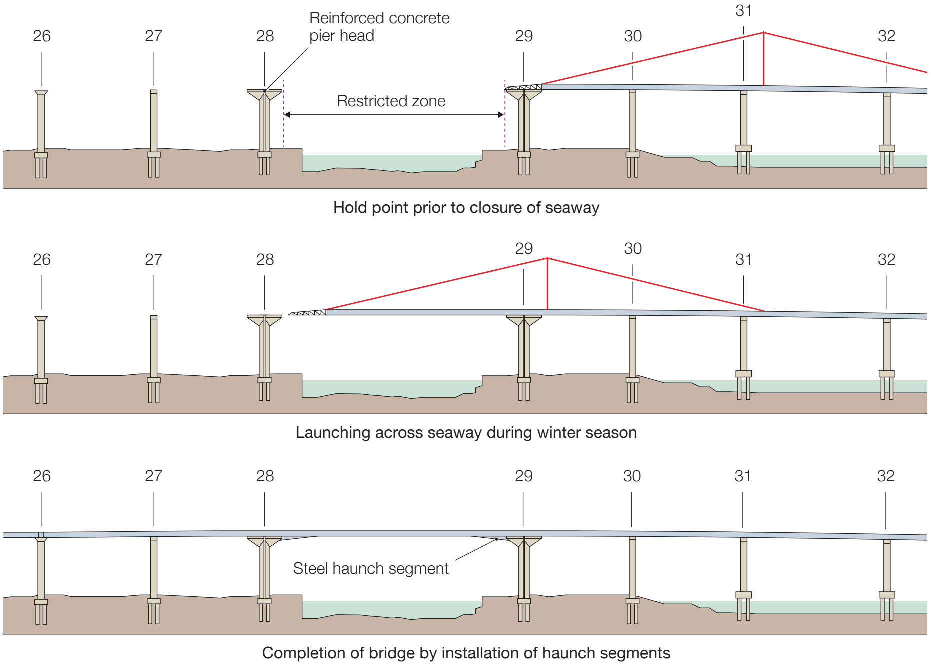
Launching sequence

The steel box girder was launched incrementally over the Beauharnois Canal using the east abutment as a reaction point, with a 22m long launching nose used to cross the typical 82m spans. This was paused when the main navigation span was reached, allowing a stay cable system to be erected to provide additional capacity for launching across the navigation span.

At the same time, precast semi-slabs were placed in the part of the girder that would be above the Seaway, so as to provide a safe working platform. These slabs were not placed at the launching abutment so as to avoid the temporary launching bearing loads having to be designed to support the additional weight.

When the Seaway was closed for the 2011–12 winter season, the box girder was launched across the main span and into its final position.

The temporary forces during the launching dominated the design of the steel section and to reduce these forces, the maximum launch cantilever was reduced to 130m by supporting the bridge at two points on a concrete hammerhead at the top of each main pier. Hydraulically-linked jacks ensured that the reaction load was evenly distributed between the two lines of support.



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19. Eastern approach under construction.

20. Construction sequence of navigation span.

During the bridge launch, snow loading on the deck was a dominant design factor, as over the course of a winter the weight of snow could potentially exceed the deck's self-weight. Close co-ordination between the contractor and the designer was needed to ensure that appropriate measures were in place to clear snow from the deck and confirm that the residual snow loading in the design was consistent with these measures.

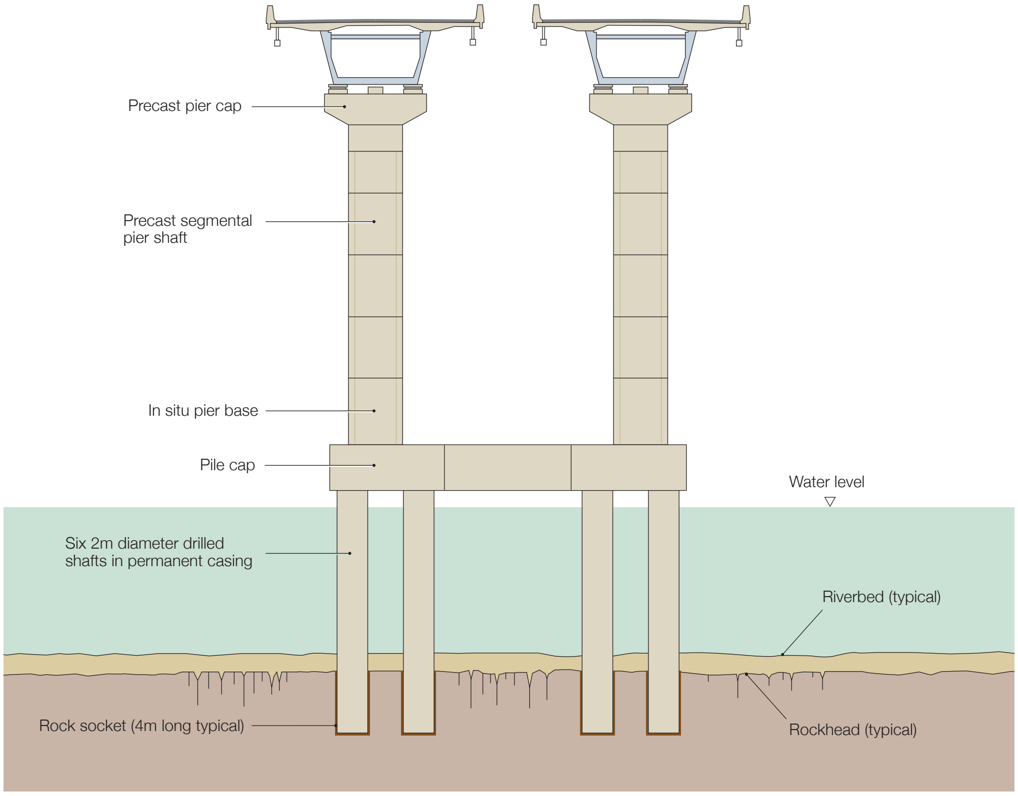
When the launch was complete, the deck was made monolithic at both piers and an additional haunch segment was erected to increase the girder's structural depth at its supports (Fig 20). This strengthening was needed to resist in-service loading.

Precast piers

The piers on both approaches are 3.6m diameter circular hollow sections with a 400mm thick wall (Fig 21). Their construction was originally envisaged as being traditional in situ, but a precast segmental alternative was developed to improve productivity, quality and safety by maximising off-site construction. Though precast segmental piers have been used on other projects, care was still needed to ensure that seismic performance and durability would not be compromised.

The seismic performance was ensured by using in situ construction for the plastic hinge zone at the base of the pier. The tendon prestress that holds the segments together is anchored on internal blisters above this zone. The segment joints themselves were designed as capacity-protected elements to ensure that ductile yielding in the in situ base takes place before the joints reach their ultimate capacity.

Durability is catered for by specifying zero tension at the segment joints under serviceability loading, as well as by using an acrylic resin mortar instead of adopting dry joints. More traditional epoxy glue was not used because of its poor performance in cold weather.



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Seismic design of the major bridges

Performance criteria

The seismic design guidance of the Canadian Highway Bridge Design Code (CHBDC) *CAN/CSA-S6-06*[1] is based on a single-level procedure in which forces and displacements are derived from analysis of a 475-year return period event.

Recognising that it is often uneconomical to design a bridge to resist large earthquakes elastically, the CHBDC makes allowance for redundancy and ductility in a bridge structure by dividing the elastic seismic forces by response modification factors (R-factors) that reflect the ultimate capacity of ductile substructure elements in various configurations. This use of R-factors is common in seismic bridge design.

The CHBDC is also performance-based, in that different levels of performance in a seismic event are contemplated based on the bridge's "importance" category, again a common element of seismic design codes. The A30 major river crossings are classified as "lifeline bridges" that must be open immediately to all traffic after the design (475-year return period) earthquake, and to emergency traffic after a large earthquake, eg a 1000-year return period event.

A similar concept is considered in the American Association of State Highway and Transportation Officials (AASHTO) LRFD (load and resistance factor design) specifications[2], except that these combine the ductility and importance factors, so that the latter is not explicitly given.

The use of importance and ductility factors allows performance under larger earthquakes to be inferred from a single-level design earthquake. However, the CHBDC notes that for "lifeline bridges" a separate evaluation under a larger earthquake may be more appropriate than using the code method to infer performance under the larger event. An explicit evaluation of the performance of the two A30 major bridges under a larger earthquake was chosen.

21. The eastern approach piers and river foundations.

22. Construction progress at April 2012.

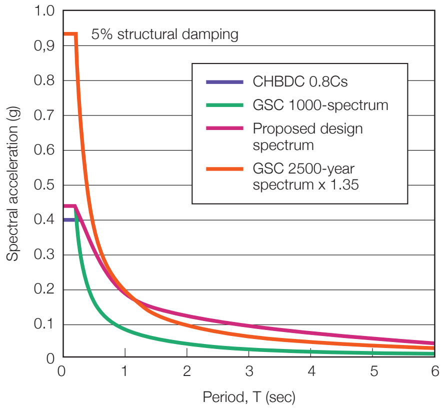
23. The navigation span complete.

Design response spectra

The Geological Survey of Canada (GSC) has developed site-specific uniform hazard spectral accelerations, representing site conditions of rock and firm ground for all of Canada for return periods of 500, 1000 and 2500 years. Based on the GSC data, a site-specific bedrock response spectrum for a 1000-year return period was generated for the A30 major bridge locations.

These spectral accelerations are significantly lower than the 475-year CHBDC spectrum at medium-to-long periods, but higher than the codified spectrum at short periods. Since CHBDC does not allow the ordinates of a site-specific spectrum to be less than 80% of the codified values, a hybrid design response spectrum was developed by enveloping the GSC spectrum with 0.8 times the CHBDC spectrum (Fig 24).

The design of the major bridges was based on elastic performance under the larger earthquake, which was initially taken to be this hybrid spectrum. After discussions with the Independent Engineer, it was agreed that the bridge designs would also be checked under the demands of the GSC site-specific 2500-year return period spectrum, scaled up by a factor of 1.35, and thus giving a greater level of safety than derived from international practice. For periods greater than 1.0 sec, the ordinates of this extreme design spectrum are still lower than the hybrid spectrum, but significantly higher for shorter periods (Fig 24).



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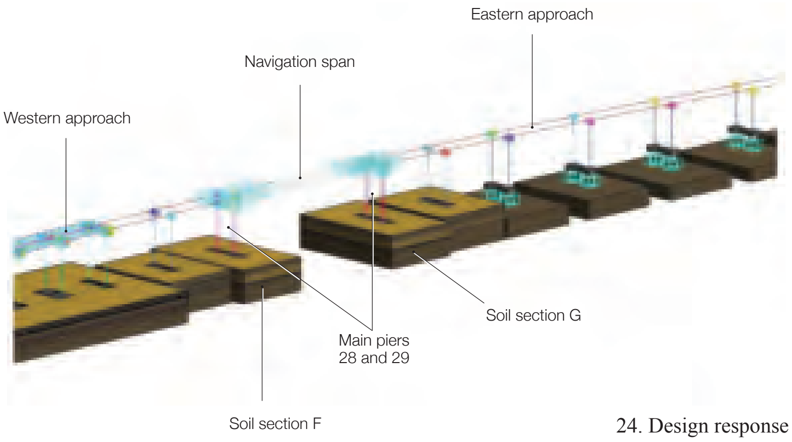

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24. Design response spectra.

25. Central portion of the Beauharnois Canal bridge time history analysis model, showing the typical extent of the soil sections.

Analysis method

Both bridges had elements not readily amenable to analysis by traditional multi-modal response spectrum techniques. As previously described, the St Lawrence River bridge incorporates seismic isolation of the superstructure by FP bearings, a relatively inexpensive and effective way to reduce the seismic demands on the bridge's short stiff piers, but requiring in-depth analysis to model the bearings' non-linear hysteretic behaviour.

The Beauharnois Canal bridge is an irregular structure with various span lengths and column heights, and significantly different soil conditions along different segments of the structure. These soil conditions in particular warranted special analysis, since amplification of the bedrock spectrum through the soil varies along the length of the bridge.

To cope with these irregularities and non-linear elements, time history analyses were carried out using *LS-DYNA*. The bridges were modelled in their entirety and soil elements explicitly modelled. This allowed the input ground motion to be consistently applied at bedrock level and for site response to be analysed directly, as opposed to estimated from the CHBDC site coefficients. Non-linear soil column models were developed and analysed in isolation with the results compared against Arup's in-house site response analysis software *SIREN*, so as to optimise the finite element soil mesh density and validate the behaviour.

The soil was then incorporated in the global analysis model, extending sufficiently far for the motion at the artificial side boundaries to be considered identical to those of the free field. The interaction between soil and pile elements was then modelled by nonlinear springs (Fig 25). For closely spaced piers, where the free field boundaries would overlap, the foundations were included within one larger soil section.

Five sets of design time histories were developed for each of the design response spectra (hybrid and 1.35 x 2500 years). The *RSPMatch2005* program takes an actual recorded ground motion as input and modifies its acceleration history so that the corresponding response spectrum matches a target design spectrum. Since *RSPMatch2005* makes modifications in the time domain (as opposed to some earlier programs that used approaches based on white noise), it preserves the non-stationarity of the original seed record and does not add unrealistic energy content to the entire duration of the history.

RSPMatch2005 can closely match a target spectrum across a wide range of periods, but is most effective when the original seed record response spectrum has a reasonably close match to the target spectrum before spectral matching. This ensures that the program can successfully converge, and that the modifications to the record are as small as possible. Seed spectra were obtained from UC Berkeley's PEER NGA database[3] which contains over 3000 records, predominantly from the western USA, but also some international records.

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26. Looking southwards along the A30 at the Northern Interchange.

27. Rolling sub-base, July 2010.

Ground engineering

Overview

The ground engineering for the A30 project included embankments on soft ground, two deep cuttings, the foundations for the two major bridges as well as the many other smaller bridges, and a cut-and-cover tunnel under an old but "working" ship canal[4]. Also, the design solutions needed to be constructed by the CJV using a self-certification procurement approach.

As with other aspects of the project, Arup drew on its expertise in soft ground engineering, heavy foundations, seismic engineering and highway earthworks to meet the short design schedule and project complexities. In addition, outside experts with particular experience of constructing in the local Champlain Clay were identified and brought into the team. Several experienced Arup geotechnical engineers were brought into the Montréal project office to work alongside the CJV team during the construction phase. The detailed geotechnical design was carried out by Arup teams in the UK and USA, as well as by Aecom in its Montréal office acting as a design sub-consultant to Arup, and co-ordinated by the Montréal Arup team.

Geology and ground conditions

The area through which the A30 passes is relatively flat and predominantly rural. The ground conditions under the route generally comprise deep Champlain Clay deposits, overlying granular glacial till which in turn overlies bedrock.

The Champlain Clay is marine clay and comprises a stiffer weathered surface crust of brown clay, typically about 3m thick, over unweathered softer, compressible and sensitive grey clay. Bedrock is typically strong or very strong quartzitic sandstone with beds of dolomitic sandstone.

Several construction challenges were inherent in the soils encountered on the site. They included the Champlain Clay being "sensitive" soft clay, fairly typical of eastern Canadian and Scandinavian glacial soft clays. When disturbed, either naturally (river erosion or earthquakes) or by human activities like construction or excavation, the soft sensitive clay has the potential to lose much of its strength, resulting in a danger of retrogressive landslides.

In addition, the very cold winters in this part of Eastern Canada meant that earthworks and other construction were generally only possible during the summer months as the upper 2m–3m of clay would freeze, essentially forming a "rock" type material.

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Desk study and ground investigation

Soon after being commissioned as project designer, Arup carried out a geotechnical desk study which collated existing information from the pre-tender studies procured by MTQ, and from other sources. A key part of this study was to develop an initial geotechnical risk register which identified potential hazards for earthworks and structure foundations arising from the ground and groundwater conditions along the route. The desk study was the first stage of a geotechnical risk management process that continued successfully throughout detailed design and construction[5].

The site investigations were procured in three broad stages. The first was by MTQ during initial project development before the PPP contract was awarded. Then, as is common on large infrastructure projects, the second stage was procured by the CJV for the detailed design, to supplement the data from the pre-award investigations. This was scoped by the designers, and CJV, and targeted the risks identified in the geotechnical desk study.

The third broad stage was procured by the CJV during construction to support value engineering initiatives, and it rendered significant returns in terms of the resultant cost and schedule savings. The total combined cost of the site investigations was some CAD$8M, or about 0.5% of the total civil engineering construction cost. Arup input the key parts of the site investigation information into an electronic geotechnical data management system, and this proved an efficient resource for the ground engineering design for use by all members of the CJV and designer teams.

Embankments

Most of the main line of the A30 is on low-height embankments, typically 2m–3m high. As already noted, higher ones were required at interchanges (Figs 28–29) and for side roads on the approaches to bridges over the A30. The highest embankments, (up to 11m) are at the Northern Interchange, where the A30 joins the existing A20 and A540 autoroutes. This coincided with the greatest thickness (up to 20m) of Champlain Clay along the route.

28. View looking west at Southern Interchange, October 2011.

29. Height of construction activity at the Northern Interchange, looking north, October 2011.

The greatest geotechnical hazards for the earthworks design lay in the soft, sensitive and compressible nature of the Champlain Clay which, if construction was not implemented and managed appropriately and carefully, could cause cost and schedule over-runs during construction and inadequate performance of the earthworks once in operation. The largest risks were associated with building high embankments on this clay; where they were greater than 2m–3m high, large primary (consolidation) and secondary (creep) settlements were predicted, together with potential temporary slope stability problems. Also, due to the clay's low permeability, the primary settlements would occur very slowly.

MTQ endeavoured to reduce the project risk associated with constructing high surcharged embankments on the Champlain Clay by building an 8m high advance embankment during the tender stage in 2006. This was constructed with vertical drains installed into the clay below to accelerate the primary settlements, stabilising berms and surcharge, and it was monitored for nearly a year. This gave much useful information to the detailed design process on the magnitude of the likely settlements, and the effect of vertical drains on the rate of consolidation, but there remained many uncertainties and thus risks.

As well as the risks associated with the Champlain Clay, other constraints needed to be addressed:

- The short construction schedule could only accommodate one consolidation period for the embankments built over vertical drains.
- Existing interchanges needed to be kept open to traffic throughout construction.
- The permitted landtake was often constrained.
- The CJV's preferred construction methodology needed the flexibility for embankments and bridges to be built concurrently.

Where there was sufficient clearance from existing roads and the construction schedule allowed, the high embankments were built using surcharging and settlement periods, as this was the most cost-effective method. Prefabricated vertical drains in the clay at close centres under the high embankments were used to accelerate the primary settlements. The team analysed the embankments' stability at each stage; stabilising berms were usually required.


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30. Installing vertical drains under permanent embankments at the Northern Interchange, April 2010.

31. Looking south-west along the A20 at the Northern Interchange.

The embankment fill thickness was calculated to include an allowance for ground settlement up to 3.5m (for the highest embankments) and also to provide some surcharge to the embankment to accelerate the primary settlements and reduce post-construction secondary settlements.

The original design for the high embankments at the Northern Interchange was for multi-stage construction with surcharge, berms (up to 25m wide), and vertical drains to achieve the required vertical alignment. This design required vertical drains to be installed under most of the footprint of the berms and permanent embankments (Fig 30) to achieve the required degree of consolidation and strength gain in the underlying clay prior to placing the next stage; this design also required two settlement periods.

As noted above, this solution would usually be the most cost-effective option for building high embankments on the Champlain Clay if sufficient construction time and space were available. However, at each stage of the embankment construction, there would have been uncertainties with regard to the anticipated magnitude of the settlements and more particularly with regard to the time required to achieve the required degree of consolidation.


31.

As the project developed, it became clear that the short Northern Interchange construction schedule could not allow more than one settlement period for the embankments built over vertical drains. During the detail design, therefore, Arup developed an alternative value engineering solution that required only a single stage of construction for the high embankments.

It also only required vertical drains under the footprint of the permanent embankments and not under the berms, and so reduced the amount of vertical drains by nearly 160 linear km. The embankments were topped off with a relatively small volume of lightweight fill, its cost offset by the reduction in the amount of vertical drains.

This option was selected. It was cheaper; it allowed completion of the section within the available time; it was less complicated and faster to construct; it was less dependent on weather; and it was less risky than multi-stage construction.

The embankments were monitored using settlement plates, piezometers and inclinometers through the settlement periods. The settlement results indicated that the consolidation rate was lower than expected and, to maintain the allotted window of time, extra surcharge was placed on some embankments to accelerate consolidation.

The Arup team predicted the magnitude of the final primary settlement which signified that acceptable consolidation had occurred, and the extra surcharge was removed once it had been reached. The highest embankments were then topped off with lightweight fill.

Expanded polystyrene (geofoam) lightweight fill was used for the higher embankments (Fig 32) where constraints, primarily construction time or proximity to an existing road, prevented a surcharged embankment solution. Lightweight fill was also used immediately behind bridge abutments to permit bridges and surcharged embankments to be built concurrently and also to minimise loads on the bridge piles (see below).

Value engineering by the CJV and Arup throughout design and construction enabled the volume of lightweight fill at the Northern Interchange and elsewhere to be optimised. This was achieved through targeted ground investigation, monitoring of the actual settlement regime, amendments to the highway alignments, adjustments to construction sequences, and more sophisticated geotechnical analyses.


32.

The main type of fill used for the highway embankments was site-won brown clay crust. MTQ's specification effectively excluded it as highway embankment fill, so using it here had to be enabled by a collaborative Arup/CJV value engineering exercise, which successfully combined Arup's earthworks expertise with the CJV's experience[6]. Other earthworks-related Arup/CJV value engineering included reducing the amount of excavation required in an old municipal landfill, reductions in the extent of excavate/replace ground treatments, and optimisation of surcharge extents.

Cuttings

Two major cuttings were built for the A30 project. One, for the approaches to the Soulanges Canal tunnel (Fig 33), was up to 11m deep — one of the deepest ever constructed in the Champlain Clay.
The other, at Châteauguay, was up to about 6m deep. This was in the lower, siltier part of the Champlain Clay and was subject to liquefaction issues that were resolved by careful investigation, laboratory testing and geotechnical engineering analysis[7].

33.


St Lawrence River bridge foundations

Overview

The St Lawrence River bridge has a single abutment on each bank of the river, and as each of its twin decks is supported by 41 piers, there are 84 individual foundation units. The decks are supported on single columns supported in turn by pad footings bearing directly onto rock. Each footing is anchored to the rock with drilled and grouted micropiles to resist lateral forces due to ice loading and to provide overturning resistance in the event of an earthquake. There are between eight and 28 micropiles at each footing, depending upon water depth and column height, and altogether more than 1400 micropiles were installed[8].

The foundation design

The reference design by others for MTQ formed the basis of the environmental impact study and approvals for the overall A30 project prior to bidding. Rock in the vicinity of the St Lawrence bridge was found at depths from as little as 0.2m to roughly 5m below grade, and the reference design included drilled shaft foundations socketed deep into the rock to resist the design demands while limiting the plan area of the foundations and permanent disturbance to the riverbed.

32. Lightweight fill being installed at the Northern Interchange, June 2010.

33. The Soulanges Canal tunnel.

34. Beauharnois Canal bridge eastern approach piers under construction, May 2011.

34.

The CJV judged this foundation solution to be expensive, so suggested spread footings founded directly on the shallow rock as a more economical alternative. The CJV additionally sought to avoid expensive over-excavation to recess the foundations into sound rock to resist sliding — a standard MTQ foundation detail.

Despite the reduction in seismic overturning moments realised by using FP bearings, the horizontal forces and overturning moments due to design ice and wind forces would still have required very large spread footings. Early estimates found that the area of riverbed disturbed this way could be much higher than considered in the environmental study, triggering the need for an updated environmental study with associated time delay and the possibility of permit refusal.

The solution to reducing the size of the spread footings and avoiding over-excavation into rock was to stabilise them against lateral forces by using micropiles, 150mm in diameter with 65mm diameter high strength bar cores. The micropiles were principally designed to act in tension in the event of lateral movement of a foundation and they also contribute to controlling overturning. The maximum tension load in the micropiles from the overturning moments was chosen to limit the elongation of the bars to less than 10mm, and the embedment length of 7m was controlled by grout-to-rock bond strength.

Micropiles were installed efficiently with a relatively small drilling rig, making them far more economical than drilled shafts, even when many are used. A substantial reduction in the size of the footings and reinforced tremie plugs was possible this way, achieving the CJV's goal of cost-effective foundations while avoiding environmental consequences.

Beauharnois Canal bridge foundations

Overview

The Beauharnois Canal bridge twin decks have single abutments at each end. Each span is supported by single columns, with pairs of adjacent columns tied together at the waterline to form a single foundation element (Fig 34).

The 44 foundation elements for the bridge include: pad footings bearing directly on rock (in eight locations); piers supported on groups of 96 concrete-filled driven steel tube piles (at 16 locations); and piers supported by groups of 1.85m diameter drilled shafts socketed a minimum of 4m into rock (at 20 locations, with a total of 138 drilled shafts)[9].

Testing and design

A comprehensive pile load test programme was carried out to validate the foundation design parameters for the bridge. Full-scale static compression and uplift tests were performed on instrumented driven steel tube piles (subsequently filled with concrete).

In addition, two load tests were done on sacrificial, heavily-instrumented 1.18m diameter test drilled shafts using Osterberg load cells[10]. The results of the pile load test programme not only proved the method of pile installation, but enabled the final design of the driven steel pile and drilled shaft foundations to be optimised and value engineered.

The design of the piled foundations in the river involved conflicting criteria. The piles could not be too large in diameter or they would attract significant pressures due to static ice forces. On the other hand they had to be strong enough to resist seismic loads without being so stiff as to increase the loading. This led to heavy reinforcement cages within the piles — near the maximum allowable.

A significant enhancement in design strength was achieved by successfully demonstrating that strength reduction factors for drilled shafts should only be applied to the concrete while the reinforcement itself should be considered to have its full design strength.

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Other bridges

The bridges in Sections 1 and 3 are characterised by high curvatures and skews, generally because the interchanges had to fit into small land areas (interesting for a country with one of the highest amounts of undeveloped land in the world). The Arup team had to develop its own methodology for the seismic design of walls and abutments backfilled by lightweight fill.

The Section 3 bridges were generally conventional, mostly square and straight, while those in Section 5 formed a mix of types. Generally these were also geometrically simple, but in terms of structural type embraced decks of post-tensioned in situ concrete, prestressed precast concrete, prefabricated steel girders, and a steel truss pedestrian crossing. Most had lightweight backfill and piled supports.

The choice of foundations was determined primarily by the thickness of the Champlain Clay at each location — and most are in areas where it is relatively thick. Following local practice, these bridges were designed with 320mm diameter steel tubular piles driven closed ended, either vertically or raked to resist horizontal forces.

Typically the piles were driven either to the bedrock or, where the glacial till was thick, terminated in the till. The team undertook a programme of preliminary pile drives and testing, and subsequent optimisation of the foundation design[11].

The 28 other bridges by Section

Section 1: north of the St Lawrence River (11 bridges):

- A20/A30/A540 interchange – four bridges for links over the A20, A30 and A540 autoroutes; a bridge carrying one link over another link; a bridge carrying the A20 over various links/ramps; and three bridges carrying the A540 and one link over the Toronto-Montréal railway
- A30 over Chamberry stream
- side road Chemin du Fleuve over A30, immediately south of the Soulanges Canal tunnel.

Section 3: on Île de Salaberry (six bridges):

- side roads Chemin du Canal) and Montée Pilon over A30
- one for each carriageway of A530 over Boul Pie XII
- R201 at interchange with A530
- two links over A30 at southern interchange with A30

Section 5: from the Beauharnois Canal to Châteauguay (11 bridges):

- side-road Boul St Jean Baptiste over the A30
- side-road Boul St Joseph over A30
- A30 over Châteauguay River
- side-road Montee Bellevue over A30
- R205 over A30 at interchange
- cycle track over A30
- side road Chemin St Louis over A30
- one for each A30 carriageway over St Louis River
- R236 over A30
- R236 over St Louis River.

35. Looking east along the A30 across the Châteauguay River bridge.

36–37. Road bridges at the Northern Interchange.

38. Installing lightweight fill transition to bridge over the Toronto-Montréal railway at the Northern Interchange, early 2010.

39.

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Soulanges Canal tunnel

The historic Soulanges Canal, built to carry ships around some rapids on the St Lawrence River, opened in 1899. The canal crosses the A30 route north of the toll plaza (in itself a substantial construction (Fig 5, page 94) that had to incorporate many variable traffic signs, as well as accommodation for the operators that was appropriately built and serviced to handle the climatic extremes).

The Soulanges Canal operated until 1958, when it was replaced by the enlarged Beauharnois Canal and St Lawrence Seaway. It sits a few metres above natural ground level and is contained within two parallel, water-confining, side earth embankments.

As part of the A30 project, an 80m long, four-lane tunnel was constructed beneath the canal using a concrete cut-and-cover box structure founded in the Champlain Clay, which (as previously noted) is normally consolidated, compressible and sensitive. A floating foundation solution was developed by balancing the weight of the structure with the excavation of a significant thickness of clay.

The challenge consisted of temporarily cutting a section of the canal without flooding the surrounding area, building high retaining walls at the tunnel portals to make way for the walkway and for Route 338 alongside the canal, and tying the new canal lining to the clay dikes of the 100+ year-old Soulanges Canal. In addition, the design had to accommodate the design effects resulting from the passage of canal ships without restriction. Finally, all of the works, including the cut-and-cover tunnel under the canal, had to be designed to resist the intense freezing inherent in Québec climate.

Watertight temporary bunds were first constructed to dam the canal on each side of the tunnel, the length of canal in between was drained, and the water-confining side embankments removed. Then a cutting was formed to construct the tunnel section, and the tunnel box structure was built in two stages between temporary sheet pile walls (Fig 39). The tunnel was backfilled, the water-confining side embankments were replaced, and the canal was then reinstated above the tunnel.

The requirement to reconstruct the canal embankments without inducing excessive differential settlement was achieved by incorporating expanded polystyrene lightweight fill within the embankments immediately adjacent to the sides of the tunnel. To ensure watertightness of the new canal water-confining side embankments, a combination of mineral liner, geocomposite, and high-density polyethylene (HDPE) liner was used.

39. Construction of the Soulanges Canal tunnel, October 2010.

40. High embankments contain the Soulanges Canal above the tunnel.

Other project challenges — on and off site

For numerous reasons, the project as a whole had many unusually demanding aspects. At the most basic level, it was quite long; at around 42km overall it took over an hour simply to travel from end to end. The great mix of engineering challenges throughout has been covered in this article, but in addition Arup had to work hard to ensure full compliance with the engineering laws in Québec, while at the same time meeting the demands of a fast track PPP design-and-build contract. Also, as the contract ran in French, some of the team had to polish their language skills. Finally, the contractor's workforce was highly unionised, and more used to traditional working practices.

And then, of course, there was the climate. Temperature extremes ran from +30˚C in summer to -30˚C in winter, with high snowfall and restrictions on working caused by the frozen ground and temperature control on materials, especially concrete. The fact that the rivers froze prevented deliveries by water, while the spring thaw brought weight limits on access roads, limiting the inflow of materials. (A more intangible benefit, however, was the beauty of much of the location, with the glorious colours of nature in the fall.)

Despite all these factors, the project was completed on time thanks to the huge and positive efforts from all involved.

Conclusions

Seismic loading dominated many aspects of the design of the St Lawrence River and Beauharnois Canal bridges, and it became apparent that the CHBDC design spectrum has a very significant level of conservatism, particularly for long period motion. The team regards the seismic design criteria adopted for this project as conservative and it is hoped that future revisions of the standard will state more clearly for all stakeholders the expected seismic performance criteria for bridges and give designers more flexibility to adopt rational design approaches to meet those criteria, using internationally recognised site-specific hazard assessment methodologies.

The two major river bridges adopted several innovative design features to tackle the complex design and construction constraints. Although their individual spans are not great, their overall length required significant resources to be expended in construction. As there is no clear winner between concrete and steel when considering embodied carbon content, for capital-intensive infrastructure projects such as these simple value engineering goes a long way to reducing carbon footprint. The A30 designs aimed for efficiency, economy, and environmental responsibility without compromising function, durability and safety, together with less risk and achieving the very tight construction schedule.

The ground engineering was particularly challenging, primarily because the route crosses the deep deposit of soft, sensitive and compressible Champlain Clay. The largest geotechnical risks were associated with building high embankments, the design and construction of which required careful team co-ordination.

Following the project's completion on time and opening, the Nouvelle Autoroute 30 consortium is now responsible for the operation, maintenance and rehabilitation of all elements of the eastern and western portions of the A30 corridor.

Upon completion of the concession period in 2042, the highway will be handed over to the Government of Québec.

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Project credits

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41 Northern Interchange.

42. Beauharnois Canal bridge western approach (overleaf).

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Key statistics

- 42km of dual two-lane highway
- 23 road bridges
- seven river bridges of which two are major bridges
  - — the 1.86km St Lawrence River bridge (Serge Marcil Bridge), the first new bridge crossing of the St Lawrence in almost 50 years
  - — the 2.55km Beauharnois Canal bridge, one of the longest "launched roadway" bridges in the world
- two highway-to-highway interchanges
- eight interchanges between the highway and the local road network
- one 80m tunnel under the Soulanges Canal
- one toll plaza
- over 900 precast concrete NEBT beams (representing 37km in length)
- 1.7Mm^2 of asphalt
- more than 6M man hours to deliver the project.

42.

About Arup

Arup is a global organisation of designers, engineers, planners, and business consultants, founded in 1946 by Sir Ove Arup (1895-1988). It has a constantly evolving skills base, and works with local and international clients around the world.

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With this combination of global reach and a collaborative approach that is values-driven, Arup is uniquely positioned to fulfil its aim to shape a better world.

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