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Contents

Front cover:
Second Avenue Subway
New York, USA.
Photo: *Wade Zimmerman.*

Left:
San Francisco Museum of
Modern Art, USA.
Photo: *Jeff Goldberg.*

1.

Second Avenue Subway, New York

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1. On new stations in Phase 1 of Second Avenue Subway, the platforms are accessed from a mezzanine, the high ceilings making the stations feel more spacious. This photograph was taken at 72nd Street.

2. The next three phases will extend the subway north to Harlem and south to Manhattan's Financial District.

3. Phase 1 construction was divided into ten contracts and delivered in just under ten years.

Introduction

Second Avenue Subway is the line that many New Yorkers believed might never be built. First mooted in the 1920s, its design and construction were beset by challenges that ranged from wars to economic crises. The project was continuously mired in financial stalemate, with construction going ahead on a start-stop basis that left plans incomplete and tunnels half-finished.

So when Phase 1 was opened to the public on 1 January 2017, its completion was a tribute to all involved in bringing it to fruition. Unlike a completely new subway system, this project was designed to tie into an extensive network below ground, a highly developed urban fabric above ground, and tunnels that had been built and closed up many years before. It was a gargantuan task that involved intricate stakeholder management and community outreach, as well as thoughtful engineering.

Arup has worked for the New York Metropolitan Transportation Authority (MTA) on this project since 2001, in a joint venture with AECOM that is currently known as AAJV (AECOM-Arup JV). New approaches to subway design have been developed that are now used widely around the world but were less prevalent during the early 2000s: this is particularly true of urban noise management and acoustic modelling of stations. The JV's overriding achievement, however, must be that it delivered a line that had confounded so many administrations, over so many years.

History

Second Avenue Subway will eventually run from 125th Street in Harlem, to Hanover Square in the Financial District, taking pressure off the overcrowded Lexington Avenue Line (statistics show that a significant number of riders have already switched from 'the Lex' to the newly completed Phase 1 section). First conceived in 1929, the subway was intended to replace the elevated lines on 2nd and 3rd Avenues that were demolished in 1942 and 1955. Most of the subsequent design and construction took place when post-war economic recovery was well under way in the 1960s, and three sections of the new tunnel were built before the New York City financial crisis stopped construction again in the late 1970s. These three sections (located between 110th and 120th Streets; 99th and 105th; and at Chatham Square, near the entrance to the Manhattan Bridge in Chinatown) were completed and closed up at that time.

In 1995, the Manhattan East Side Alternatives (MESA) study revived the concept of a new subway in this part of the city. In the years since the 1970s, work had progressed on the 63rd Street Tunnel Project which now connects Queens and Manhattan via the F Line, through a tunnel that at one time was supposed to be part of Second Avenue Subway. The MESA study concluded that with the overburdened Lexington Avenue Line carrying, at that time, approximately 1.3 million riders daily (now 1.6 million), the need for a new line to serve the east side of Manhattan was greater than ever, particularly as pressure would increase with completion of the East Side Access Project which would bring riders from Long Island to Grand Central Terminal.

- 8.5 route miles
- 16 new stations
- 1 renovated station
- Linked to existing Q Line

Phase 2 | 125th to 96th

Phase 1 | 96th to 63rd | **Opened**

Phase 3 | 63rd to Houston

Phase 4 | Houston to Hanover

2.

	Scope of work	Start date	Substantial completion date	Duration (months)
1	Tunnels and Launch Box	March 2007	March 2012	60
2	96th St Station (Heavy Civil)	May 2009	November 2013	54
3	96th St Station (Fit-out)	June 2012	January 2017 (final completion planned for June 2017)	55
4	63rd St Station	January 2011	January 2017 (final completion planned for June 2017)	72
5	72nd St Station (Heavy Civil)	October 2010	January 2014	39
6	72nd St Station (Fit-out)	February 2013	January 2017 (final completion planned for October 2017)	47
7	86th St Station (Utilities)	July 2009	November 2011	28
8	86th St Station (Heavy Civil)	August 2011	December 2014	40
9	86th St Station (Fit-out)	June 2013	January 2017 (final completion planned for August 2017)	43
10	Systems	January 2012	January 2017 (final completion planned for November 2017)	60

3.

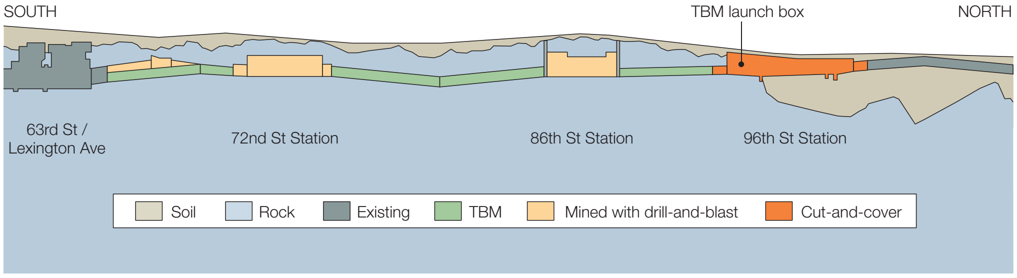
It was against this backdrop that in 2001, Arup, in a three-way joint venture with DMJM and Harris, was awarded the MTA contract options for engineering concept, preliminary engineering and detailed design of Second Avenue Subway. Soon afterwards, DMJM and Harris (operating as independent employee-held companies under a holding company called AECOM) merged to form a single entity under the AECOM umbrella that itself went public in 2007. This is what led to the JV's rebranding.

Design overview

The preliminary engineering stage consisted of devising an overall alignment, and stations concept, for a line running the entire length of Manhattan, with options for a northerly extension to the Bronx and a southerly extension to Brooklyn. The concept developed in the 1960s had been for a cut-and-cover approach for the entire line. This was reviewed, and the decision was taken to alter it completely, substituting a bored tunnel solution with deep cavern stations where rock existed. This avoided the politically difficult proposition of digging up the entire length of Second Avenue with all the socio-economic impact this would have had on business, the community and the environment. The line is designed to run underground from 125th Street in Harlem to Hanover Square, and for most of its length the alignment is directly under the Second Avenue roadway.

The design contract award was made at a momentous time for New York, just after the attacks on the twin towers of the World Trade Center in September 2001. It was a time of great uncertainty, and with federal funding unlikely to be made available immediately for the whole project, it was decided to recommend a phased approach. The intention was to provide a viable new service to the Upper East Side, beginning with the initial Phase 1 operating segment to bring in early revenue. Phase 1 would be built as an extension of the existing Q Line.

The phased approach was adopted, and after preliminary engineering was completed for the entire line (all 16 stations for a twin-track system stopping at all stations), final engineering of Phase 1 was started in early 2006. This comprised detailed design for refurbishing and expanding the existing station at 63rd Street/Lexington Avenue; developing two new mined cavern stations at 72nd and 86th Streets; and creating a new cut-and-cover station at 96th Street where there was the opportunity to re-open and refurbish the existing tunnel between 99th and 105th Streets that had been abandoned in the 1970s. It also included a contract for constructing the running tunnels between stations.



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Phase 1 was divided into ten construction contracts to enable more contractors to participate, increase bid competiveness, permit a better approach to staging, take into account the different types of work involved, and more readily satisfy federal funding requirements. The contract for the bored tunnels was awarded in 2007 to spearhead construction (see table at image 3). Construction of the two tunnels and three new stations meant excavating approximately 446,000 cubic metres of rock and 351,000 cubic metres of soil. Methods of construction included cut-and-cover, drill-and-blast and the use of a tunnel boring machine (TBM).

The tunnelling contract comprised construction of the TBM launch box, two circular shafts at 69th and 72nd Streets, and two tunnels from 92nd to 63rd Streets. The launch box was constructed by cut-and-cover in a section of the tunnel that lay between 92nd and 95th Streets, and the project was designed such that the launch box would become the southern portion of 96th Street Station where the rock/soil interface exists.

96th Street Station

This station structure was shallow in order to make use of the existing 1970s-built tunnels to the north, and the launch box which was situated across the full width of Second Avenue between 92nd and 95th Streets. The depth of excavation varied between 15.2m and 18.3m below grade, and involved removing rock and soil.

The top of rock dips dramatically from 92nd Street north towards 93rd Street, and is deep between 93rd and 95th Streets. This geology fixed the south wall location so that a rock boring machine could be safely launched. Relocation of the many utilities was staged to allow simultaneous construction of both the support of excavation (SOE) walls and the deck structure, with the deck installed one half at a time: east side of the road, then west. Once the SOE walls and deck were installed, work continued below the deck with traffic and pedestrians travelling above.

Where the top of rock is high between 92nd and 93rd Streets, the SOE wall functioned chiefly as support for the decking, and because it was temporary to construction of the permanent 96th Street Station structure, secant piled walls were installed. Between 93rd and 95th, however, the SOE walls were constructed in soil consisting of fill, over a 3m-thick deposit of organics, over sand/silty sand, over varved silt and clay, so reinforced concrete diaphragm walls (called ‘slurry walls’ in the USA) were selected and they became permanent walls for 96th Street Station. The diaphragm walls were excavated to a maximum depth of approximately 27.4m and also served as groundwater cut-off walls. The reinforcement cages were fabricated on site and lowered into the slurry wall trenches using twin-crane tandem lifting.

TBM tunnels

Two approximately 6m-diameter tunnels were bored to serve as running tunnels between the stations, with the drive lengths and sequencing arranged to coordinate with the award of the station contracts and compress the construction schedule.

The first drive was from the southern end of the launch box under the west side of Second Avenue, proceeding south on a straight alignment where it stopped blind-ended after 2,195m. The machine was then disassembled and walked back through the tunnel to the launch box and moved over for the drive under the east side of Second Avenue. From here it proceeded south until 69th Street from where it bored a curve with a radius of about 200m, finally holing-through at an existing bellmouth structure under 63rd Street. This drive was approximately 2.4km long. The depth of the drives varied from 13.7m to 25.9m, with a minimum rock cover of 4.6m, and were mostly through strong rock (between 34.5 MPa and 82.7 MPa), comprising competent gneiss and schist with occasional pegmatite and several fault and shear zones.

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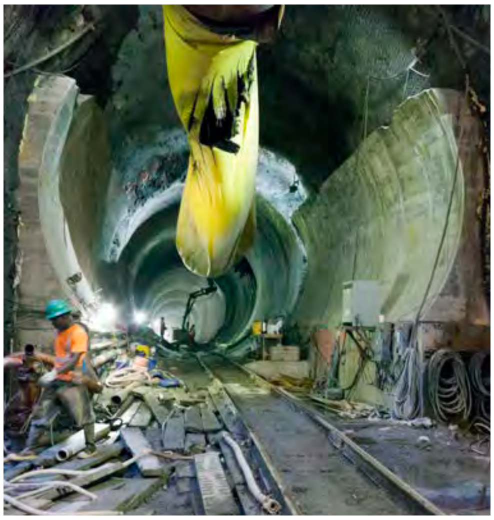

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The design team’s initial proposal was for a precast concrete segmental lining as the permanent tunnel lining, to be installed in the tailskin of a double-shielded TBM. A request from local contractors, however, led to a cast-in-place concrete lining being designed and it was this option that the low bidder chose. The lining was reinforced with steel fibres, rather than rebar, to facilitate

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construction and improve durability, and made use of a thermoplastic sheet waterproofing membrane.

The connection to the existing stub tunnel, south of 72nd Street Station, was developed from a combination of TBM tunnels, single-track mined tunnels, and two-track caverns. The two tracks at 72nd Street Station are side-by-side; therefore the geometry of the tracks from 63rd Street Station must take them from the vertical stacked stub tunnel to a horizontal side-by-side position. This geometry, combined with special track work required to connect Phase 1 to future Phase 3 tunnels, led to some challenging cavern configurations.

Above-ground work

Surface work was restricted to daytime hours six days per week to reduce disruption to the local community, though underground work was allowed 24 hours per day, seven days per week, with vibration constraints for blasting. The goal of a minimum of four lanes of traffic was met, and at the same time pedestrian and emergency access for buildings and sidewalks was maintained at a minimum 2.1m width. Ground settlement, air quality and other health, safety and environmental requirements were specified in the contract.

To further reduce impact on the community, muck-house enclosures were used over access shafts to the mined caverns. These steel-framed buildings contained gantry cranes that lifted filled muck bins from the tunnel for loading into trucks at the surface. The protection they provided limited noise and dust emission to the street. In addition, when concreting began, deliveries of reinforcing mat were lowered into the station cavern from the muck houses during the night, after the surface work restriction cut-off, saving time, reducing impact on the environment, and minimising inconvenience to the community.

4. Located approximately 25m deep, mostly in competent gneiss and schist, two tunnels were bored side-by-side, each approximately 2.5km long.

5. At 96th Street, the slurry wall reinforcement cages for the cut-and-cover station were lifted to vertical from a flatbed trailer, then lowered into the wall trenches.

6. 96th Street starter tunnel looking south, showing TBM guide walls and temporary ventilation.

7. Gallery excavation for a future machine room above the pre-bored running tunnels at the south end of 86th Street Station cavern.

8. 86th Street Station cavern excavation showing partially mined section for the top of the cavern above tunnels already bored.

9. Part-concreted station cavern showing thermoplastic waterproofing membrane in the roof.

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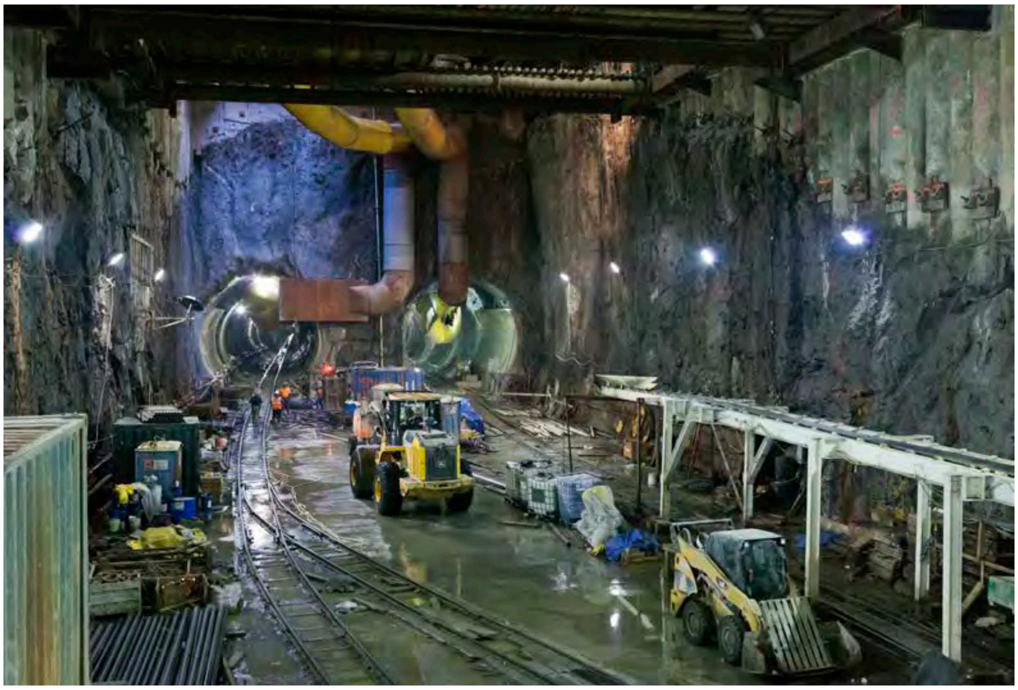

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Station design

The mined stations were constructed by drill-and-blast at a depth of approximately 45m. With the rock being of relatively low permeability, the decision was made to design these underground structures as drained caverns. The groundwater collection system runs behind the walls and under the invert, discharging into longitudinal collector pipes that are gravity-fed to pump stations.

Because the rock was good, it was possible to create column-free stations within the structural form of the caverns, and this proved an advantage in design terms. As the rest of New York's subway network was built pre-1940, all its other stations are column-supported. Designing 'column-free' results in open spaces that are more pleasant and safer for station users because sight lines are unimpeded.

The cavern construction meant the design of the new stations at 72nd and 86th Streets could feature high ceilings and mezzanine levels. The mezzanines contain the fare arrays where travellers buy tickets. Access to the platforms is via stairs or lifts (elevators) that pass through large central openings, and the roof is a curved, coffered design. The structure for these stations is cast-in-place reinforced concrete, with the mezzanines formed on beams that span the station at approximately 3m intervals, tied into the station's walls and lining with fixed connections to reduce their required structural depth. The platforms are flat slabs on cast-in-place walls.

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The column-free design was also implemented in the cut-and-cover station at 96th Street. This station is longer than the other three because it is the terminus for the Phase 1 and houses operations space for the New York City Transit Authority (NYCT). Some of this space will be used to accommodate the connection into Phase 2.

At 63rd Street, the 1970s-built station was partly in use, the remainder abandoned many years previously and in need of a complete revamp: complex sequencing was required there to demolish existing struts and install new walls. This station is not totally column-free, although the design is broadly similar to the other three.

The brightness created by the open mezzanines, and walkways underground,

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is complemented by blue canopy lighting at street level. The goal was to provide an iconic blue glow to guide riders to the entrances. Of particular note is the 96th Street Station entrance, designed at the very end of the project at the request of the MTA, which wanted this canopy infused with coloured light. A double strip of bright blue LEDs was designed to tuck neatly into the canopy to achieve this.

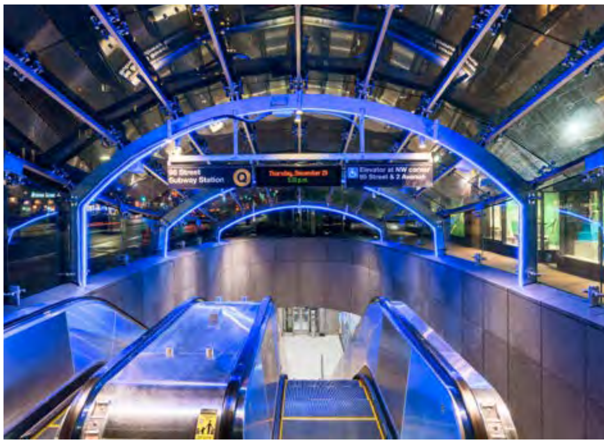
Adjacent buildings

Station entrances were created within the sidewalks or inside existing buildings. Where entrances had to be incorporated into older buildings, jacks were used as temporary supports until the loads could be transferred.

Protecting all existing buildings from the effects of construction, particularly the historic 'brownstones', was a priority. Newer buildings on piles or deep foundations were unlikely to suffer from movements caused by open-cut excavations, but could be affected by vibrations from rock excavation work: this was accounted for by setting construction vibration limits. Older buildings on masonry rubble, many with heritage features, needed greater care, and in some instances repairs and stabilisation measures had to be approved by New York State's Historic Preservation Office.

Historical information on some of the brick buildings was inconclusive. It transpired that brickwork façade ties were not always present, and some façades were leaning. A two-phased approach was taken to stabilise such buildings: temporary repairs were carried out to allow the subway excavations to continue, while a permanent repair was developed and implemented. The preferred permanent option involved building a timber truss within the floor depth, spanning horizontally to transfer load from the front façade to the brick side-walls. The truss was designed to withstand wind loads and leaning effects and it was formed using additional timbers twinned to, and strutted between, the existing joists. To comply with the requirements of local preservation organisations, star-shaped plates were used on the exterior. In addition to above-ground tie-backs, below-ground tie-backs were required in some locations: an external steel angle just below street level was used along the full length of the building, then tied back into the building by threaded steel rods to side walls and to the central supporting wall or beam.

Where necessary, construction methods were adapted to ensure the stability of existing buildings. At 96th Street, for example, the ancillary facilities could not be built on the slurry wall used for most of the station because of the sensitivity of adjacent buildings, so a secant pile wall was used both as the excavation support and as the permanent basement wall.



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10. 96th Street Station: lifts (elevators) to the column-free platform are accessed from the mezzanine.

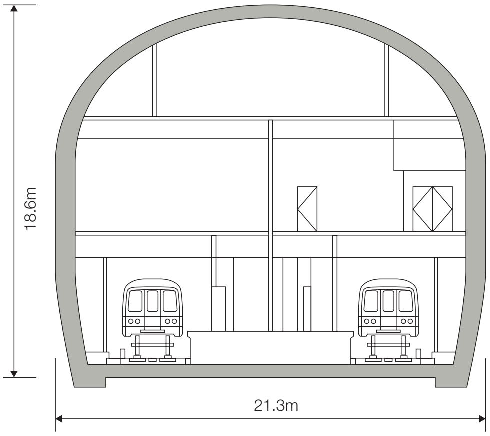
11. 96th Street Station: cut-and-cover excavation looking south, showing the rock/ soil interface. This was the TBM launch box.

12. Awaiting the first trains to run on the new line on opening night, 31 December 2016.

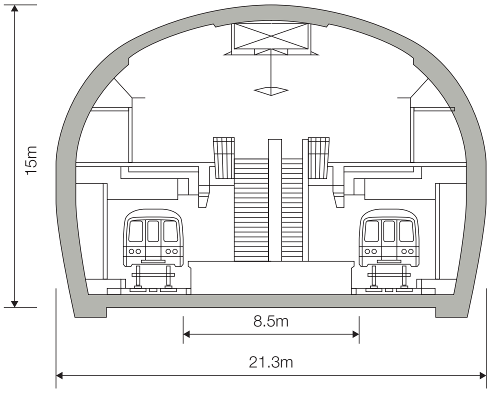
13. Entrances to 86th Street Station were designed into the sidewalk.

14. Star-shaped anchor plates were used on the exterior of 'brownstones' along the route: these are historic buildings that were reinforced with trusses and tie rods to prevent them being damaged by excavations for the new line.

15. The canopy entrance to 96th Street Station is lit with bright blue LEDs to guide riders into the station.



End of station – ancillary section



Middle of station – public section

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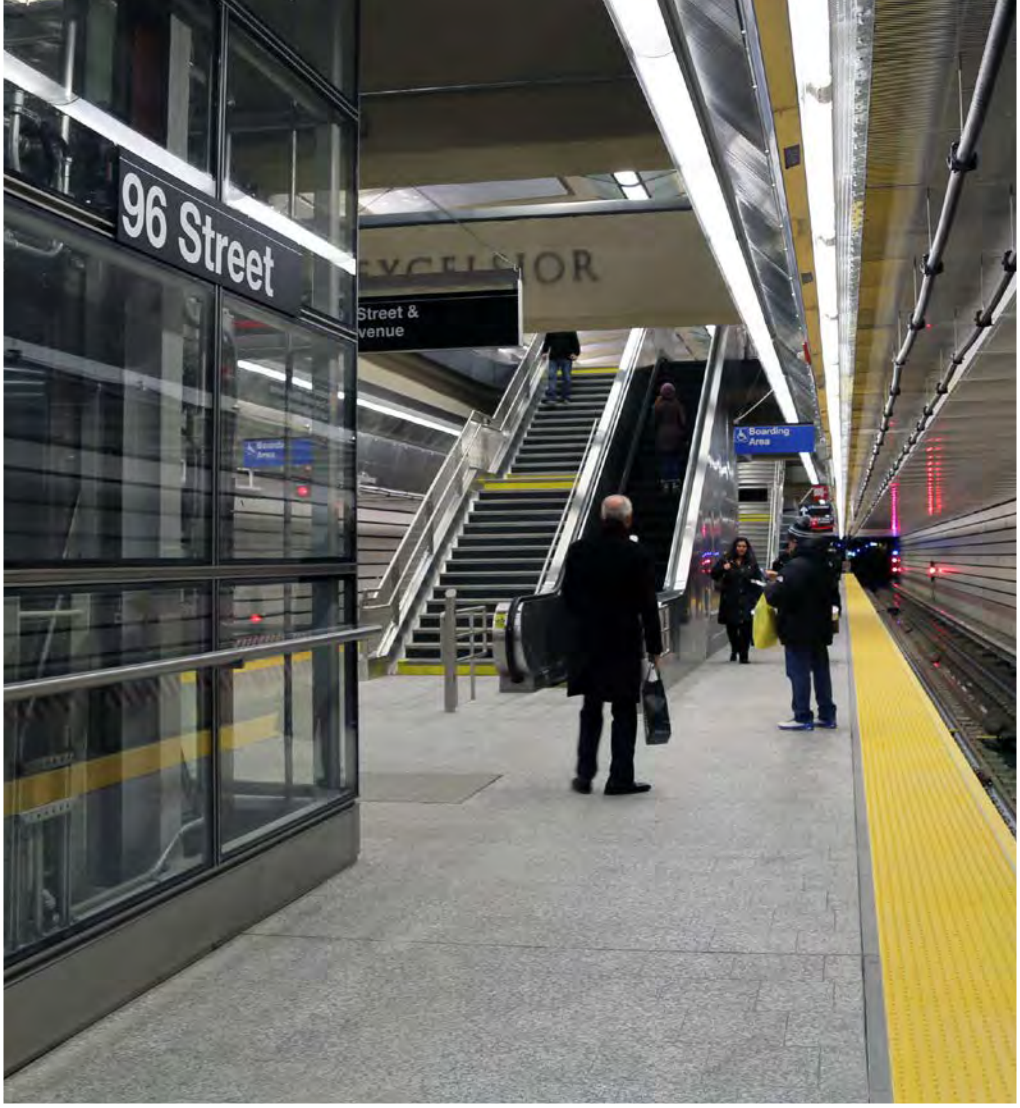

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16. The height of the ancillary sections of tunnel at each end of the new stations is higher than the mid-section of the station to accommodate the fans and associated silencers for the air-tempering system.

17. During New York's hot summer weather, cool air is delivered to the platform via the air-tempering system.

18. Computational Fluid Dynamics (CFD) analysis and Subway Environment Simulation (SES) models were used to ensure the air-tempering system can be operated cost-effectively.

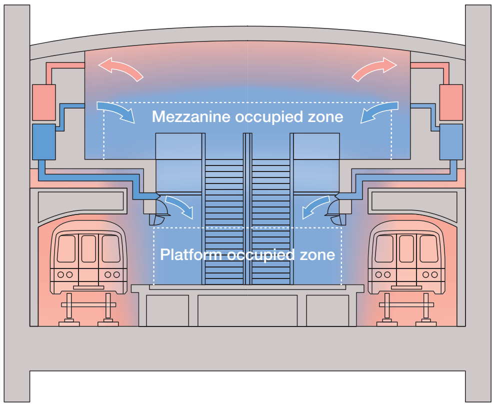
19, 20. The CFD and SES were also used to develop the fire engineering strategy.

21. Finished mezzanine-level architectural fit-out complete.

Air tempering

The ancillary facilities, built at either end of the three completely new stations, were new to the New York subway and important in terms of passenger comfort and safety: it is here that water chillers are located to cool air for an 'air-tempering system' and where fans are housed for controlling smoke in the tunnels in the event of a fire.

The air-tempering system was designed to create comfortable conditions in all seasons at an acceptable capital and operating cost. Simulation modelling of the thermo and aerodynamics determined that winter and mid-season cooling could be accomplished by using solely the overtrack exhaust system, provided primarily for smoke evacuation. But in hot summer weather, operation of the air-tempering system would be needed to convey cooled air through ducts onto the platform. The amount of cooled air required was determined by a Computational Fluid Dynamics (CFD) analysis that determined the airflow, and hence heat distribution, caused by the piston effect of trains entering and leaving a station. As a result, the air-tempering system was designed to direct cool air only where most needed (the platform), with temperatures allowed to rise higher in the mezzanine (a more transitory space), and higher still in the train ways.



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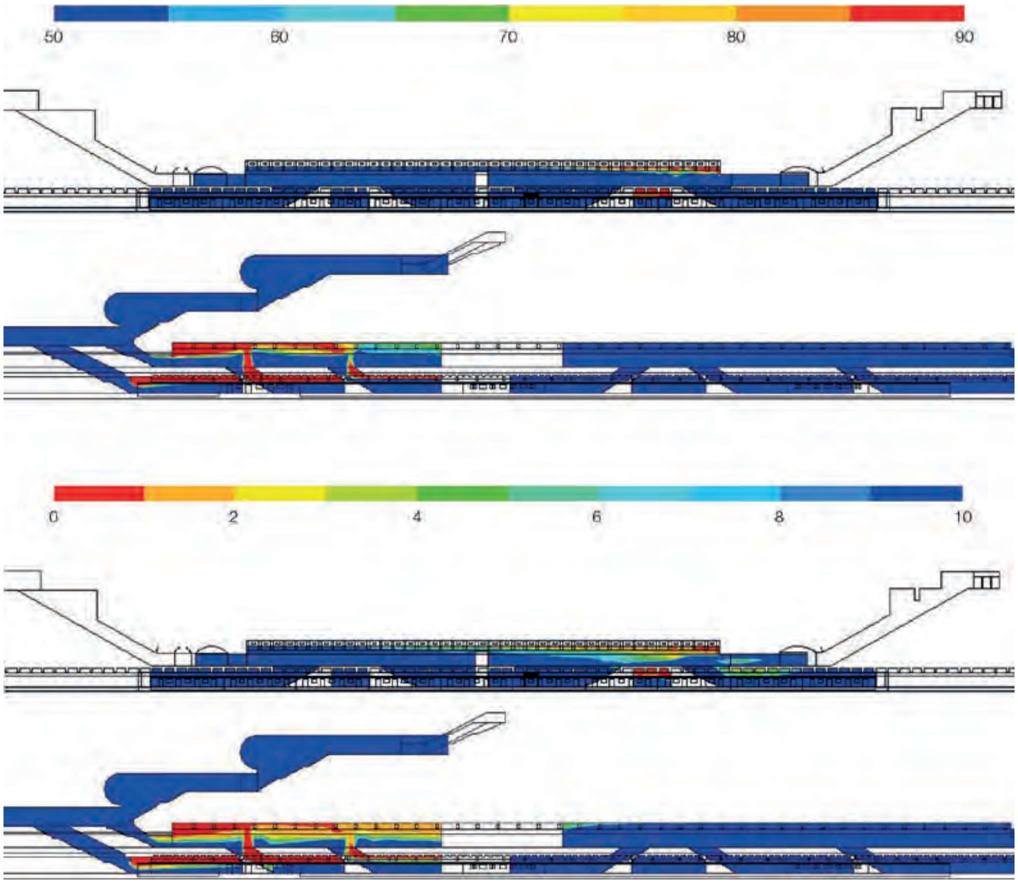
The system is novel in New York, where few of the stations feature air cooling (although the subway cars themselves are air-conditioned), and in the stifling heat that characterises the city's summer weather, it is a welcome innovation.



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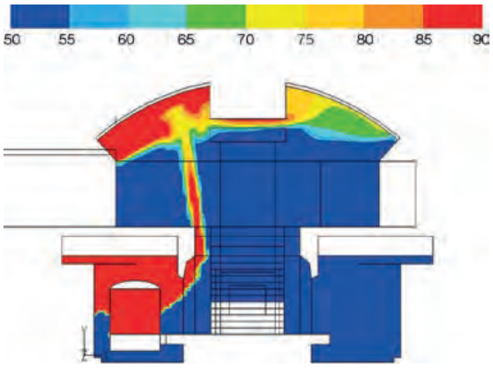

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Fire engineering
Fan plants, located within the ancillary facilities at both ends of each station, serve not only that station, but also the tunnels between stations. These are designed so that in a fire emergency, the following will happen:

- Within a station, semi-transverse ventilation will remove smoke-laden air via overtrack exhaust at the platform level, and via high-level exhaust at the mezzanine level to maintain tenable paths of egress.
- Within tunnels, fan plants at the two adjacent stations are configured to develop longitudinal airflow sufficient to achieve critical velocity, and at special track sections, such as crossovers, means are provided for semi-transverse ventilation to maintain tenability.

The design performance was verified through a combination of computational fluid dynamic and subway environment simulation modelling. Tenability was evaluated in relation to timed egress assessments that considered the potential availability of egress elements based on the location and size of the fire. Ventilation layouts were optimised based on considerations of cost, ease of construction, ease of maintenance, complexity of operation, reliability, and performance under fire conditions. The design demonstrated that the requirements for handling three separate and distinct emergency conditions – in stations, tunnels or crossovers – could be served by a single integrated plant, eliminating the need for dedicated ventilation systems.

Structural fire engineering methods were used to verify that existing partially encased steel beams at 63rd Street Station did not require full encasement because they met the two-hour fire resistance rating, and maintained their structural integrity under the design loading specified by the NYCT. The study investigated the behaviour of each of the beam types when exposed to a subway car fire and a standard fire test exposure. Two-dimensional finite element modelling was performed using the analysis software SAFIR. The structural capacity utilisation was analysed using the thermal profile of each beam after the prescribed fire exposure. This resulted in cost savings for the MTA while also maintaining the coffered ceiling and beam style.

Fire suppression within the stations was provided by means of fire standpipe (stations and tunnels), wet pipe sprinklers (various back-of-house spaces), Inergen (in select communication/signalling spaces), and water mist sprinkler systems (elevators/escalators and associated machine rooms, select communications and electrical rooms, and under-platform protection). Fire alarm systems are designed to enable manual operation in the public areas and automatic detection in the back-of-house spaces. The station public address (PA) system that is used to alert station users in case of emergency is supplemented by various means of visual notification in the public spaces.

Fire engineering scope was split across multiple contracts, so coordination among the design and construction team was paramount to ensure delivery of fully functioning systems, as well as access to equipment for future inspection, testing and maintenance.

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Acoustics

The intelligibility of announcements is clearly critical within stations and the new PA system developed for Phase 1 is noticeably improved compared with others on the New York subway network. This is due to a combination of factors, many of which evolved from an analysis of what was wrong with existing PA systems: it was necessary to do this because the new and existing systems had to be integrated. Using Arup's SoundLab, each part of the communication signal chain affecting the overall quality of the announcements was assessed: from the announcer's booth and the microphone, through amplifiers and cabling, to the speakers and geometric layout in the station.

Background noise was clearly one of the most significant problems, so sound-absorbing finishes were integrated into the station form. The most widely used were perforated ceramic and metal panels backed with a fibreglass core, inset into the concrete. Additional sound-absorbing finishes were applied at track level to reduce noise from wheels on rails, and also at the ends of stations to reduce train entry noise at crossovers and switches. Silencers were placed at each end of the ventilation system fans: large units that are 2.5m high, so they had to be designed into the ancillary facilities early to ensure there was space for the rest of the ventilation equipment.

24.

Vibration that causes the rumbling noise when trains pull into stations was a problem both below ground and above. So, before Phase 1 was built, site measurements were conducted to capture source vibration levels from existing lines, and this data was used to predict potential vibrations from the new line.

Various mitigation schemes were considered and the solution chosen was a Low Vibration Trackform (LVT) consisting of individual concrete blocks that fasten the track to the ground but are separated from the trackform concrete by rubber boots, to reduce the amount of rail vibration transmitted to the tunnel invert and buildings above. This was considerably more expensive than using traditional timber, but the resulting reduction in noise and vibration was significant.

The PA system is essential to the evacuation procedure in case of emergency, so a high-quality system was specified to meet intelligibility requirements mandated by the US National Fire Protection Association (NFPA), with speakers located strategically throughout the stations.

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IT, communications and control systems

Integrating new control systems design into an existing operating subway infrastructure, built by separate independent railway companies more than a hundred years ago, and adding intermediate updates and patching, proved both a challenge and an opportunity.

A SCADA (supervisory control and data acquisition) system was implemented, using technology based on direct digital control and programmable logic control, to integrate the systems for new station-based heating and ventilation, including the air-tempering system. Allied to this was a wider rail control system focused on ventilation within the tunnels (including emergency smoke management – should it be necessary), track and station drainage, traction power systems, high and low voltage power systems, and all station lifts (elevators) and escalators.

The entire control systems communication network design incorporates a system-wide IP-based converged network (SONET: Synchronous Optical Networking) that enables control and monitoring of systems both locally and remotely, so not only within stations but also from maintenance facilities, emergency response locations, and rail and power control centres, for example. This provides maximum redundancy and, most importantly, reliability for rail operations.

The thermal comfort in the stations is much improved by these systems compared with traditional NYCT stations. An added aesthetic value is that the station finishes are not cluttered with multiple conduits and service runs.

Pedestrian modelling

Intrinsic to the overall design of the stations was a comprehensive approach to modelling the way people would use them. As this was the first subway construction project in New York for more than 50 years, there were no existing design guidelines for passenger movements so in the early days of the Phase 1 project (2002–2003), design parameters and performance metrics were established with NYCT, many of them new to the system.

A model was developed that simulated 3,000 uptown and downtown train arrival combinations to better understand the effects of simultaneously arriving peak-loaded trains. The data was drawn from the existing Lex Line 4/5/6 trains and it focused on the number of entering and exiting passengers at peak times, and the delays that occurred regularly at Lex Line stations including queuing at escalators and stairs, with attenuation to the mezzanine, through the turnstiles and up through the exits. Where appropriate, models also included transfer passengers and movements.

22. Rails are fastened to the ground via concrete blocks that are separated from the trackform concrete by rubber boots to mitigate the rumbling as trains enter and leave stations.

23. Silencers – two at either end of each station – mitigate noise from the ventilation fans.

24. On the platform at 96th Street Station, the noise-absorbing panels made from ceramic, metal and fibreglass are clearly visible, inset into the wall.

25. Pedestrian modelling techniques helped determine the location of escalators, stairs and elevators. Here, plenty of space is provided in a brightly lit transit area that features some of the artwork that was designed for all stations. In peak hours, this area is busy as travellers ascend and descend between platforms and the street-level entrance/exit.

26. A new seating area and lighting at 63rd Street Station entrance: pedestrian modelling, combined with community consultation, helped to determine the location of sidewalk infrastructure.

27. The customer service area at 96th Street Station, sized to accommodate current passenger peak flows, plus future growth.

28. New station entrances, designed to be welcoming, are also sited to encourage housing and retail development in their vicinity. Integrated planning and place-making was an important aspect of the design.

29. Wayfinding and associated signage is designed to be intuitive. The pedestrian planning and circulation design was modelled and tested using analytical software for various scenarios including flows at peak hours and in case of emergency egress.

28.

Dynamic pedestrian simulation models were developed for Phase 1 and used as a design tool to optimise elevator, escalator and stair provision and layout, and also to evaluate emergency evacuation scenarios. The models were extended out at street level to help ascertain the locations for sidewalk infrastructure such as the lighting and signage related to the new entrances. The models proved very useful for community information meetings during the planning stages and during construction.

Summary

Selected by the American Society of Civil Engineers as its 2017 Construction Achievement Project of the Year, Phase 1 has already improved the way people travel around New York. Average weekday ridership, up every month since opening, had reached 176,000 by May 2017, with the trend continuing upwards as commuters discover the line's benefits. Congestion and related delays on 'the Lex' decreased over a similar time frame by 26% overall, and as much as 40% during peak morning hours, according to MTA statistics.

KPMG reported for the MTA that the estimated annual benefit of Phase 1 in the year 2030 (expressed in 2015 dollars) will be $265.4 million, the saving based largely on reduced travel time and traffic congestion, but also taking into account reductions in road accidents and emissions, and increased productivity. The estimated property value premium is a one-time amount of $4.71 billion (assuming 10% increase in value for property within a 0.5 mile radius of the four stations).

But it is about more than numbers because for individuals the time savings can contribute to better work/life balance. People living along the route can now ride to many destinations throughout the city without changing trains. Along the way, they can enjoy Wi-Fi availability in stations, artwork by renowned contemporary artists (commissioned by the MTA, it is the most expansive permanent public art installation in New York's history), fewer stairs (there are more escalators than in traditional stations), wider walkways and welcoming bright lighting. It adds up to a safer and more enjoyable travel environment.

New York State Governor, Andrew M. Cuomo, said in February 2017, just a few weeks after Phase 1 was opened: "The Second Avenue Subway has already become an integral part of the Upper East Side and the ridership figures show just how important this expansion project is to the neighbourhood and our economy."

Authors

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Project credits

Owner: *Metropolitan Transportation Authority Capital Construction (MTACC) and New York City Transit Authority (NYCT)* Prime design consultant: *AAJV (joint venture of AECOM and Arup)* Geotechnical engineering for conceptual and preliminary engineering design, soil

29.

and rock testing: *GZA GeoEnvironmental, Inc* Geotechnical engineering for conceptual and preliminary design: *MRCE* Architectural input for conceptual and preliminary design: *FXFOWLE Architect* Environmental services for conceptual and preliminary design: *Metcalf & Eddy, Inc.* Geotechnical support staff and peer review: *RIZZO Associates* Geotechnical engineering services: *YU & Associates, Inc* Environmental impact analysis: *AKRF, Inc.* Consultant construction manager: *WSP/Parsons Brinckerhoff* Launch box for TBM at 96th Street and tunnels to 63rd Street: *S3 Tunnel Constructors, a joint venture of Schiavone Construction Co. LLC, Skanska USA Civil, and J.F. Shea Construction, Inc* Heavy civil works for 96th Street Station: *Joint venture of E.E. Cruz & Company Inc. and Tully Construction Co. Inc.* Rehabilitation of 63rd Street Station: *Judlau Contracting Inc.* 72nd Street Station, cavern mining, and connecting tunnels between 72nd Street and 63rd Street Stations: *SSK Constructors, a joint venture of Schiavone Construction Co. LLC, J.F. Shea Construction, Inc. and Kiewit* 72nd Street Station finishes: *Judlau Contracting, Inc.* 86th Street Station excavation, utility relocation, and road decking: *D'Annunzio & Sons, Inc.* 86th Street Station, heavy civil: *Joint venture of Skanska USA Civil and Traylor Bros. Inc.* 86th Street Station finishes, MEP (mechanical, electrical and plumbing), ancillary buildings, and entrances: *Joint venture of Schiavone Construction Co. LLC and John P. Picone, Inc.* Systems, track, signal, and traction power: *Joint venture of L.K. Comstock and Skanska USA* Civil lead and asbestos surveys and design, support during hazardous material investigation and remediation design, and environmental and geotechnical survey: *Matrix New World Engineering* Project management, project controls, design leadership and management, geotechnical engineering, use of geographic information systems (GIS), tunnelling, civil and structural engineering, MEP, station design and architecture including façades and vertical transportation, fire engineering including ventilation strategy, rail information technology and communications, lighting, pedestrian modelling, acoustics, vibration, security, sustainability, energy consultancy: *Arup – Davar Abi-Zadeh, Robert Accosta, Kevin Acosta, John Alexander, Katie Alfredo, Jonah Allaben, Jarrod Alston, Joseph Appleby, Aidan Archer, Chris Ariyaratana, Stephane Audrin, Peter Ayres, David Balter, Alison Barmas, John Barrot, Alban Bassuet, William Baumgardner, John Beaumont, Jonathan Ben-Ami, Burkhard Bein, Peter Berry, Rinita Bhadra, Rami Bitar, Ryan Biziorek, Gillian Blake, Justin Bocian, Michael Brandes, Fergal Brennan, Peter Bressington, Cillian Brown, Ian Buckley, Jenny Buckley, E Bury, Lowell Cabangon, Yan Cai, David Caiden, Mellisa Capowski, Michael Capuzzi, John Caroll, Carlos Carranza-Torres, Bob Cather, Bianca Celestin, Eun-Ju Cha, Foram Chaliawala, Peter Chamley, David Charters, Ho-Yan Cheung, Helga Chmielowski, Jonalen Chua, Matt Clark, James Cohen, Neal Corridore, Anthony Cortez, Craig Covil, Helen Crosby, Casey Curbow, Richard Custer, Carmen Danescu, Star Davis, Juan De Los Rios, Frank Del Gigante, Mike Devriendt, Nicola Dobbs, Matt Dodge, Filipa Duarte, Glenn Edwards, Robert Egan, Khlaid Eid, John Elissa, Ed Ellis, Johnson Esho, Reynaldo Espiritu, Karim Ezzeldin, Steven Fairneny, Jin Fan, David Farnsworth, Ian Feltham, Chris Fesq, Marc Florestant, Paul Franklin, Marsha Fraser, Frank Freudenberger, Chad Fusco, Eci Garavito-Bruhn, Louis Gargiulo, Ken Garmson, Marc Gateau, Bethel Gebre, Graham Gedge, Amirreza Ghasemi, Shaaz Ghouse, Richard Giffen, John Gill, Ken Goldup, Rico Gomez, Graham Goymour, Richard Greer, Helga Gregory-Chmielowski, Tom Grimard, Don Guan, Nancy Hamilton, Andrew Harrison, Mike Hastings, Paul Heslop, Stephen Hill, Lucy Hirst, Bruce Hlvana, Chu Ho, Trevor Hodgson, Stuart Hodgson, Nicole Hoffmann, Robert Hoffmann, Ken Hope, Robert Hsu, Shuang Hu, George Hummel, Jon Hurt, Peter Ingato, Elisa Iribarne, Matt Jackson, David Jacoby, Ernesto Janica, Mateusz Jankowiak, Clare Judge, Deepak Kandra, Kai Kang, Mia Kang, Michael Keane, George Keeber, Tony Kelava, Tom Kennedy, Mahmood Khwaja, Daniel Kim, Jonathan King, Kevin Kleyla, Tatiana Kokorina, Jacob Koshy, Natalia Koupanou, Jaewook Kwon, Hannes Lagger, Iraklis Lampropoulos, Gary Lamonica, Susan Lamont, Barbara Lane, Matt Larson, Holly Lattin, Bob Lau, Matthew Lawrie, Adrian Lee, Seungwon Lee, Colin Leung, Adela Levy, J Levy, Peter Li, Shawn Li, Danny Lin, Hillary Lobo, Paul Longhurst, Sebastian Lopez, James Lord, Al Lyons, Filip Magda, Tom Maguire, Theresa Mahoney, Yazdan Majdi, Swarup Mandal, Chris Manning, Andrew Marchesin, Glennys Marmolejos, Chris Marrion, Ivan Martynenko, Nazir Mawjee, Chad McArthur, Pat McCafferty, John McCracken, Brian Meacham, Tali Mejicovsky, David Mellon, Alan Merrett, Ashraf Metwally, Vahndi Minah, Strachan Mitchell, Jessica Moeller, Carlos Molina Hutt, Erin Morrow, Wil Nagengast, LJ Nassivera, Barry Nicholls, Peter Oldroyd, James Olson, Robert Pallman, David Palmer, Lynn Pang, Wilfred Patrick, Jennifer Pazdon, Adrian Pena-Iguaran, Nicos Peonides, Daniel Peterson, Richard Petrey, Don Phillips, Sam Plourde, Seth Pollak, Richard Potter, Martin Preene, Mark Presswood, Richard Prust, Thomas Puttman, Craig Quaglini, Jim Quiter, Parisa Rajaei, Mahadev Raman, Rene Rieder, Robb Risani, Eric Rivers, Vicky Rom, Ron Ronacher, Jonathan Rose, Sarah Sachs, Stefan Sadokierski, Yet Sang, Maxim Sankey, Yuvaraj Saravanan, Rob Saunders, Yuliya Savelyeva, Kurt Schebel, Ian Schmellick, Nando Schmitt, Leni Schwendinger, David Scott, Eric Sekulski, Sheldon Sherman, Christopher Simon, Duncan Smith, Ernest Smith, Julian Smith, Marsha Smith, Tom Smith, Nik Sokol, Keith Solberg, Marina Solovchuk, Joe Solway, Brian Stacy, Robert Stava, Pascal Steenbakkers, Jimmy Su, Nick Suslak, Matt Sykes, Visha Szumarski, Mohammad Tabarra, Chris Taylor, Christopher Taylor, Ian Taylor, Larry Tedford, Maria Theodori, Bob Till, Neil Towell, Ed Tufton, Andrew Valente, Thomas Van Puyenbroeck, Aniju Varughese, Sasha Velic, Tony Vidago, Tom Wagner, Lorna Walker, Naor Wallach, Kim West, Jacob Wiest, Craig Wiggins, Daniel Wilcoxon, Patrick Wilfred, Michael Williams, Andrew Wisdom, Christopher Wood, Eileen Wood, Neill Woodger, Nerik Yakubov, Stephen Young, Yelena Zolotova.*

Image credits

1, 10, 13, 15, 21, 24–27 *Charles Aydlett*; 2, 12, 17, 19, 20 *Arup*; 4, 16, 18 *Martin Hall*; 6, 11 *Ari Burling*; 8 *Richard Barnes*; 5, 7, 9, 14 *AAJV*; 22, 23 *Joe Solway*; 28, 29 *Wade Zimmerman*.

National Forum of Music

Location
Wrocław, Poland

Authors
Ed Arenius Kelsey Eichhorn Tateo Nakajima

1.

1. The main concert hall at the National Forum of Music is designed using coupled volume acoustics to prioritise both clarity and reverberence.

2. A distinctive building within Wrocław's old town, the concept for the NMF was devised by Kurylowicz & Associates.

3. The measured background noise levels of this chart show how the N1 criterion is the measure of the most ambitious acoustic environments.

Introduction

The National Forum of Music (NFM), a new performing arts centre in Wrocław, Poland, is garnering widespread acclaim for the world-class acoustics of its four concert spaces. The project is a cornerstone of the city's economic development strategy and a catalyst for the vibrancy and remarkably fast growth of Wrocław's musical community, which provides a variety of events and educational opportunities for local residents. For its work on the project, Arup was awarded a commemorative medal recognising the firm's contribution to the cultural life of the city.

Opened in September 2015, the NFM integrates a 1,800-seat symphonic concert hall and three smaller, flexible concert venues. As the acoustics and theatre designers, Arup's scope included visioning, programming, site selection, construction cost modelling, pre-architectural acoustic and theatre concept development, strategic business case development and operations planning, architect selection support, and traditional design and construction responsibilities. In addition, the firm was construction engineer for the project, and provided post-commissioning artistic operations support during the NFM's first year.

Client advisory role

In 2002, the Mayor of Wrocław, Rafał Dutkiewicz, proposed an ambitious regional development plan in which culture was framed as a major asset and economic driver to attract foreign investment.

Initial market assessment by Arup showed that Wrocław's musical community was involved in many internationally recognised festivals, spanning opera, baroque, choral and contemporary music, and jazz. The assessment concluded, therefore, that a new facility serving this broad constituency could be transformative. Working closely with the client, the firm defined programme options and helped explore different funding routes, ultimately selecting an approach that leveraged European funding to provide a reasonable, yet limited, budget.

Construction cost

Recent projects worldwide have demonstrated how cost management is particularly challenging in major concert hall developments, with projects often delivered very considerably over budget. As part of Arup's strategic advisory service, the firm undertook a robust cost-modelling process during programming. A rigorous client review of the key characteristics of the technical concepts was an important part of the decision-making process, recognising that these spaces were both the leading success driver of the facility, as well as the most costly components.

Ongoing cost management was handled by the City of Wrocław, with the robustness of the initial modelling enabling them to require the design and construction teams to meet appropriate quality levels within budget. The approach was highly successful: the NFM was delivered at a construction cost fully in line with the initial estimates.

Design challenges

The technical design of the concert halls meant developing auditoria that would accommodate the facility's eleven resident ensembles and seven resident festivals without acoustical or operational compromise, as well as achieve an aspiration for the large concert hall to be acclaimed internationally for a uniquely recognisable sound signature. Combined with the limited budget, these challenges necessitated innovative, refined and efficient design solutions.

2.

Quiet spaces

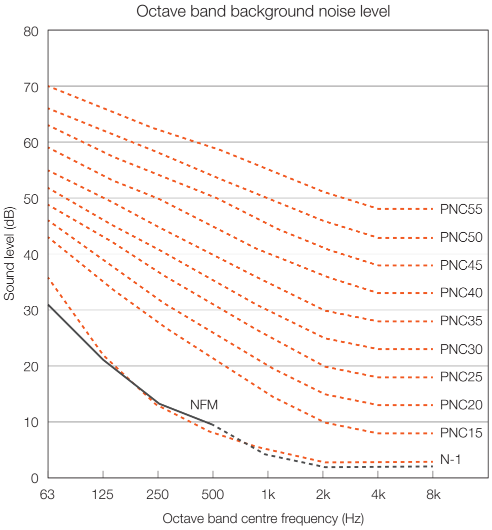
Acoustic intimacy was a key goal of the project and the team agreed from the outset that the starting point was a 'silent' concert hall based on the N1 criterion, which is derived from a subjective research study on the threshold of hearing published in 1964: D.W. Robinson and L.S. Whittle, 'The Loudness of Octave-Bands of Noise', *Acustica,* vol. 14, 1964, p.33.

Achieving N1 requires building systems to be extremely quiet, including an underfloor air supply through specially designed seat pedestals in the concert hall and careful design and layout of the mechanical and electrical systems.

Structural isolation of the large concert hall from the surrounding building through a series of natural rubber and steel composite pads was also necessary to ensure that no external vibrations cause audible disturbance within.

Airborne noise isolation planning required two massive layers of concrete construction separated by airspace between the hall and any source of noise, while all entrances were isolated by 'sound and light lock' vestibules.

The three smaller performance spaces in the facility were likewise isolated so that all spaces could be used simultaneously for recording, rehearsal or performance.



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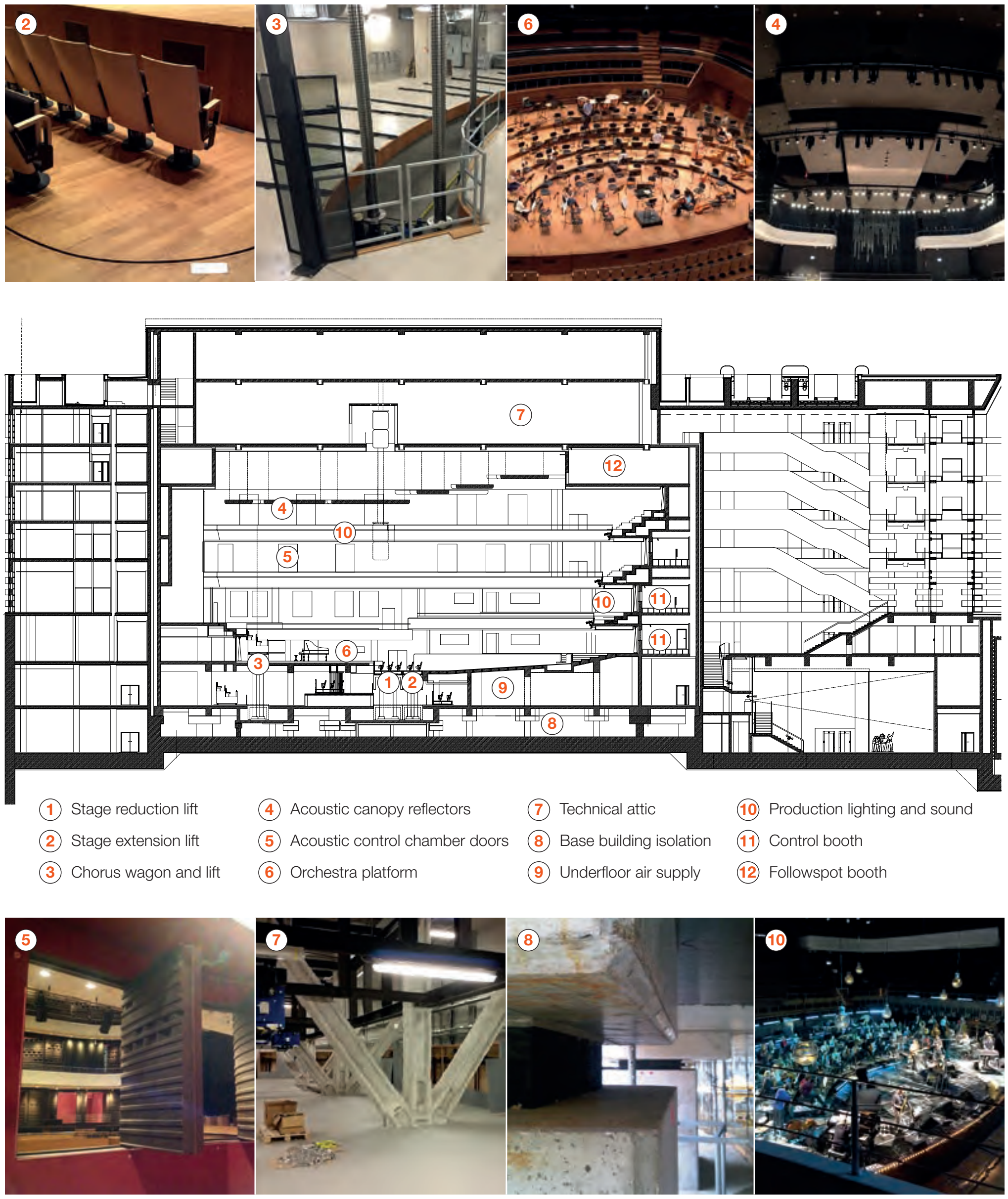

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4. A cross-section diagram of the main concert hall illustrates a number of the key technical aspects that create the tailored acoustic experience of the hall.

5. Musician's perspective from the stage of the main concert hall.

6. The main concert hall before a performance.

7. Coupled volume acoustics control chambers.

8. Removable castored seating wagon.

9. The acoustical signature of the main concert hall.

Wide range of use

Arup's work also focused on shaping spaces that are functionally and operationally viable for all intended uses. To do so, the team designed a system of adjustable elements:

- a system of 22 independently motorised sound-reflecting canopies spanning the entire hall, allowing fine-tuning of the sound reflection sequence over the orchestra and audience, and visual adjustment of the environment to the ensemble scale
- a motorised system of sound-absorbing curtains and banners that can be deployed to cover part, or all, of the wall surfaces and change reverberation and surface reflectivity
- a variable orchestra platform with an extension lift and reduction lift
- an extendable choral/audience seating area at the rear of the performance platform
- audiovisual and lighting systems for amplified music and gala cinematic events, recordings and broadcast

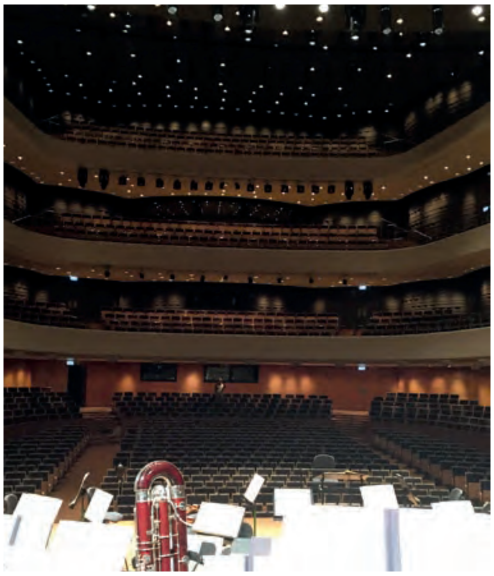
Tailored acoustic experience

Finally, the Arup team drew on accumulated experience with coupled volume acoustics to build the sound signature. A coupled volume acoustics environment is a complex space that allows the variable coupling of a primary acoustic volume with secondary acoustic volumes. This approach allows the simultaneous achievement of a high level of clarity and reverberence: two attributes that naturally sit at opposite ends of the spectrum. The couplings of these volumes are controlled via motorised concrete panels (or doors) for lateral acoustics control chambers as well as the canopy reflectors above. Arup has unique global expertise in coupled volume concert halls.

Dr Andrzej Konsendiak, General Manager of the NFM and a highly experienced conductor, worked with the team to develop a common understanding of the desired acoustic signature. He wanted a sound that reflected Wrocław's deep roots in baroque and classical music, its ecclesiastical tradition, and its dynamic and optimistic outlook.

Unlike many recent contemporary halls that focus on clarity over a rich, blended sound, this concert hall needed to achieve a sound signature reminiscent of icons such as the Musikvereinssaal in Vienna and Tonhalle in Zurich, as well as Wrocław's magnificent cathedrals. In addition, it had to reflect the expectations of a younger audience steeped in the comparatively louder, immersive and high-impact experiences associated with mobile and home entertainment systems.

The team tailored the acoustical and visual experience, by carefully shaping the geometry and dimensions of the hall, the proportions between primary and secondary volumes, the shape and sizes of the canopy reflectors, the number and positioning of the acoustic control chamber doors (here decreased from a typical 100+ to 34 doors),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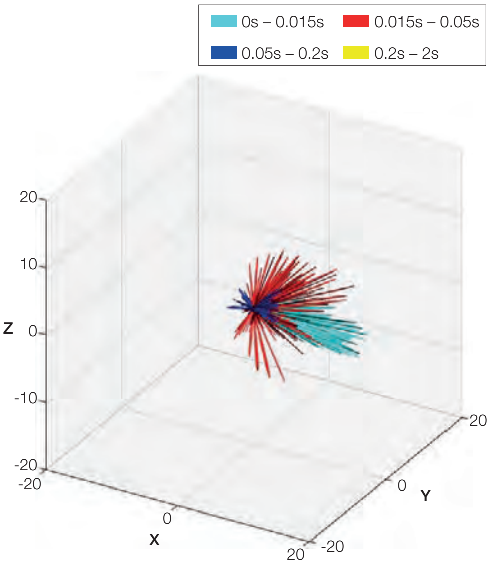

9.

the location and coverage of the cloth systems, and the materiality, macro and micro shaping of the hall. The technical concept was developed during pre-design, and subsequently further developed with the project architects.

Summary

The result of a 12-year client advisory relationship with the City of Wrocław, the NMF opened in time for the city's year as European Capital of Culture in 2016.

Paul McCreesh, founder and director of the Gabrieli Consort which performs internationally, said of the new venue: "…one feels immediately a great warmth in the sound and a natural balance in the large space, and yet for the audience the feeling is one of intimacy."

Dr Konsendiak concluded: "We chose Arup for the amazing track record they have in concert hall design around the world and they've delivered a fantastic facility for us. They've been a great partner in this project."

Authors

Ed Arenius, Associate Principal in the New York office, co-led auditorium design and facility planning.

Kelsey Eichhorn is Senior Communications and Storytelling Specialist in the New York office.

Tateo Nakajima is Director/Principal, arts, culture and entertainment, New York and London. He was Project Director and co-led the auditorium design and facility planning

Project credits

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1, 2, 8 *Lukasz Rajchert (NFM archives)*;
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1.

Sacred Heart Cathedral, Kericho

Location
Kericho County, Kenya

Authors
James Beer Katherine Coates Edward Hoare Jacob Knight Caroline Ray

1. Sacred Heart Cathedral serves a diverse community in Kericho, in Kenya's tea-growing region.

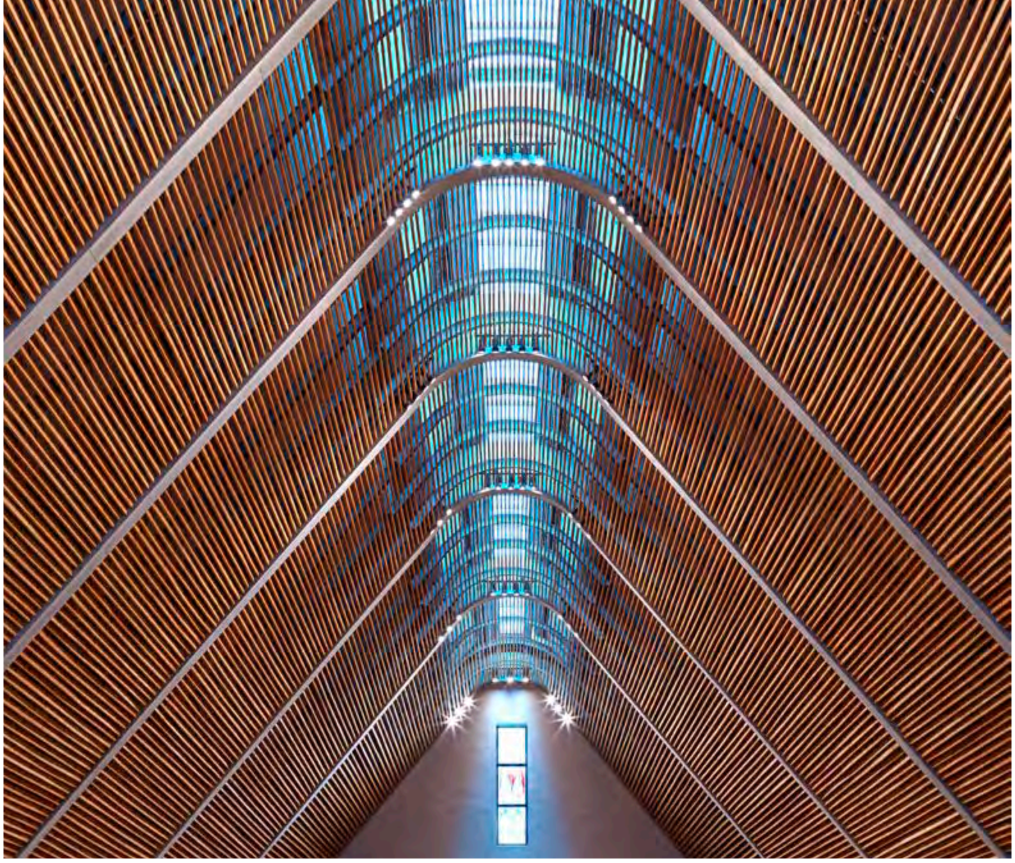
2. The roof is designed for light, but not heat, to filter through it.

3. Kericho is situated east of Lake Victoria in the seismic East Africa Rift.

Introduction

When the bright African sun filters through the roof of the Sacred Heart Cathedral, it bathes the congregation in a consistent, serene light. The roof is quietly elegant in its simplicity, straightforward in its design and engineering concept, yet there is much to be admired in the way it has been delivered, with natural lighting and ventilation creating cool calmness on the hottest of days.

Although this is Kenya's second-largest cathedral, there is nothing showy about this building. Instead, it demonstrates quality: in the geometry of its structure, in materials made by local craftspeople, and in the careful engineering that has developed the structure such that it will be strong in the event of an earthquake in this highly seismic zone.



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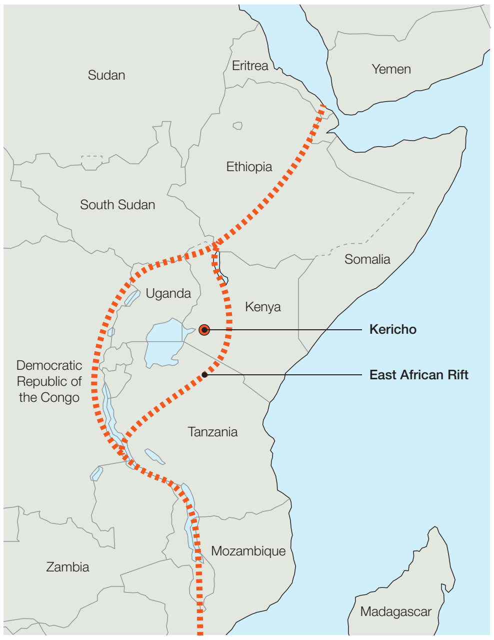

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Context

Kericho is in the heartland of Kenya's tea-growing industry, 250 miles north-west of Nairobi, high in the Rift Valley. The plantations attract workers from miles around, making it a diverse community that has experienced some political and civil unrest in recent years. Church is a source of unity, so the Roman Catholic Diocese of Kericho decided to replace its existing building with a new and bigger cathedral that would seat a congregation of up to 1,500 people.

Bishop Emmanuel Okombo wanted a building that was spacious and airy, with surrounding gardens that could accommodate additional worshippers on special occasions. John McAslan + Partners were appointed as the architects and McAslan invited Arup to help them develop the design.

The resulting building is approximately 1,375m^2, and up to 25m high, tapering down to 10m at the entrance. The ceiling of concrete arched frames is interspersed with timber ribs and the inclined roof is clad with locally made clay tiles. Its base is clad in the most durable of local stones: Nairobi blue stone.

Arup provided civil, structural, building physics, acoustics and lighting consultancy to develop the design of the building, then supported Kenyan engineering firms to complete and deliver the building through to completion, with specific inputs to the fair-faced concrete construction, and acoustics and lighting commissioning. Skilled local artisans were involved in developing artworks in and around the cathedral, including a natural-stone wall mosaic designed by artist John Clark.

Working in a seismic zone

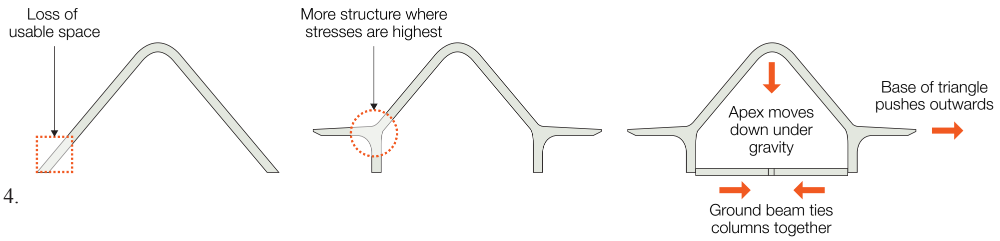
Located close to the eastern branches of the East African Rift System (EARS), Kericho is in a seismically and volcanically active zone. The geology of the site is largely volcanic in origin. A thin layer of topsoil less than 200mm thick overlies a band of red clay that is about 20m thick. Beneath the clay is weathered phonolite tuff (a volcanic rock) of unknown depth. The red clay is approximately 80% clay and 20% sand.

Buildings in Kenya are typically built to comply with a code of practice that dates back to 1973: a document that contains reasonable seismic design advice in broad terms, but was not well suited to a large, unusual structure such as the cathedral and, at more than 40 years old, no longer reflective of current seismic engineering practice.

A seismic hazard desk study was carried out, therefore, to establish seismic design criteria appropriate to the Kericho site. This was regarded as essential because the cathedral will be a building of cultural significance, with a design life of 100 years, during which time an earthquake may well occur. The study was conducted by collecting existing geological, tectonic and seismological data, reviewing published seismic hazard studies and performing deterministic seismic hazard analysis (DSHA) of the site.

The DSHA was used to compute the hazard level. A median peak ground acceleration (PGA) of 0.2g was estimated using the maximum possible magnitude earthquake on the rift, and, on the basis of the study, a bedrock PGA of 0.2g with a return period of 475 years was recommended as a moderately conservative value appropriate to progress engineering design. A brief view of other geo-hazards was undertaken and the potential for liquefaction, shakedown settlement and slope instability was considered to be low.

The desk study was linked to a paper Arup was developing to bridge the gap between the existing Kenyan code of practice and more recent and comprehensive seismic design standards, which would be applicable to all future projects in the region. This paper was published at the 2014 European Conference on Earthquake Engineering and Seismology and may be incorporated in a National Annex to the relevant Eurocodes that are currently under development in Kenya.



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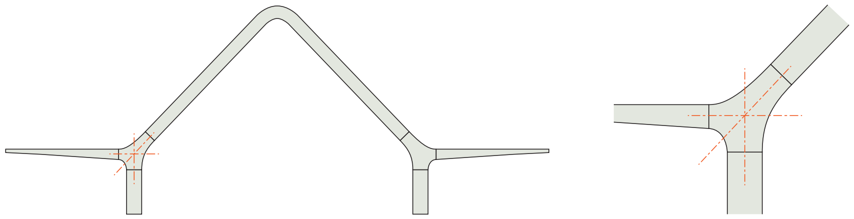

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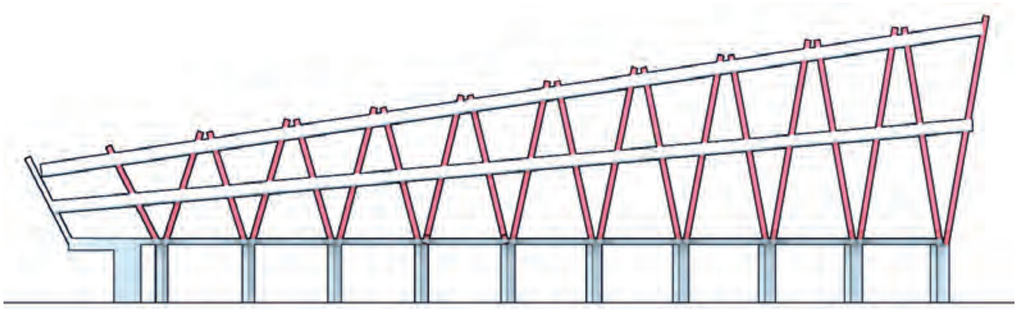

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4. Exploring the options for ‘grounding’ the simple vertical frames.

5. Forces are gathered at the curved node where the arch and cantilever meet the column.

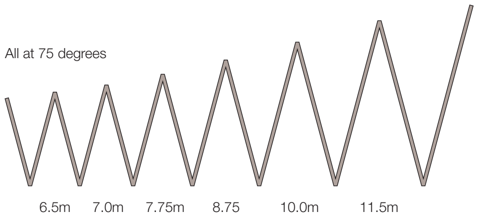
6–8. The ‘kissing arch’ geometry was complex to draw and model, which led to concerns over buildability.

9. Continuous concrete pour of the larger arches took 12 hours.

10. The concrete edges of the columns were so sharp that the contractor hand-chamfered them.

11. The contractor developed a strong but flexible inner formwork to enable the shutter to be struck without damaging the concrete.

12. A table-top model was used to explain the structural skeleton to the architect, client and contractor.



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8.

Structural engineering

The team considered various structural materials for the cathedral, a key project aim being to make delivery as local as possible to Kericho. Timber, the initial first choice, was rejected on the basis that scale and complexity of manufacture would make offshore design and/or fabrication the most likely outcome. Steel was rejected due both to the challenge of transporting sections over a long distance from a Nairobi fabrication yard, and the need for heavy cranage on site. Concrete was the material of choice because it could be produced in batches on site and is the most common building material in the region, so both supply chain and design and construction expertise were already in place.

For a significant period during the concept stage, the structure was targeting a ‘kissing arches’ geometry. This involved inclined arches, touching only at the apex. But the complexity of the geometry proved challenging to draw and consistently threw up questions over buildability and detailing because of the many varying aspects: arch height and beam cross-section, for example. The structural design was primarily driven by the desire to keep the sections relatively slender, but the large spans meant that they had to be tied together in order to control buckling behaviour. As a result, the elegance of the structural solution was in danger of being lost.

So, in order to recapture the cleaner lines of the original design intent, the design team decided to adopt a simpler geometry. Vertical arches were agreed and, after investigating a number of bracing/tying options, they settled on the simplest of structural forms: a Vierendeel truss.

On this basis, the most efficient structural form would have been a pure triangle, with the pitched rafters extending down to ground level. This was found to be impractical, however, as it would have created significant areas of unusable space and would have obstructed circulation space within the building. The triangular form was modified in response, by cranking the bottom end of the inclined rafters to create vertical columns. Thus the superstructure consists of a series of structural frames that are tied together by beams below the ground floor slab.


9.


10.

Stability is provided through different mechanisms in the two primary directions. Laterally, the concrete frames are inherently stiff because of the triangular form above the column head level. Forces are therefore delivered to the column heads, where a large bending moment is developed to prevent the column rotating when subjected to those forces. This moment could be carried at ground level, but would have resulted in substantial substructure works and columns that were at their widest at ground level. The adopted solution, therefore, was to carry the moments at the column heads, leading to columns that are widest at the top and are doing relatively little structural work below ground. Longitudinally, the roof carries stability forces to the column heads, where they are transferred into a concrete slab which, in turn, transfers them into the external wall line.

The roof frames need to be joined in such a way that sufficient stiffness is developed. In non-seismic regions, this direction is usually less critical because the lateral loads due to wind load are relatively small. In a seismic region, such as this one, the dominant lateral load is related to the total weight of the building, so is equal in both directions. The structural form in this direction was therefore more challenging to resolve than might otherwise have been the case.

The concrete skeleton

Given the prominence of the concrete skeleton in the finished building, achieving a high-quality, 'as-struck' finish was essential. The contractor, Esteel, progressed through two sample sections of the curved arch, to creating their own flexible 'kerfed' or notched inner shutter for maximum flexibility when removing the formwork after the skeleton had gained sufficient strength.

The arches were each cast in a single day pour to avoid day joints. On-site batched concrete was used, made from single-source stockpiled river sand and aggregate to achieve colour consistency. Progressive shuttering of the top surface of the arch enabled good, consistent vibration of the concrete at each stage of the continuous pour which, for the larger arches, took every minute of the equatorial 12 hours of daylight. The result was consistent, unblemished concrete, with edges so sharp that the contractor hand-chamfered the lower corners of the columns to avoid harm to the small children who regularly play in the aisles during the church services!

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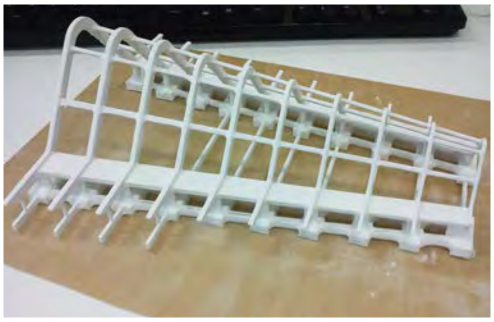
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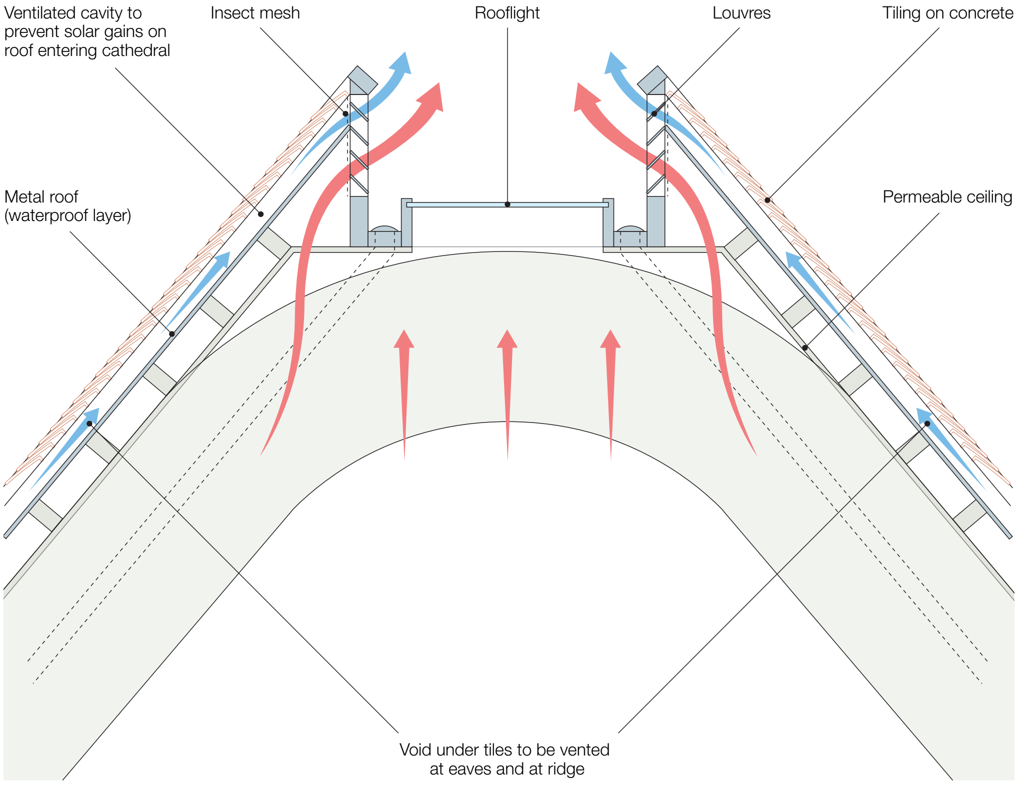

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Building physics

Although only a few kilometres from the equator, the climate at Kericho is moderated by its high elevation. As well as suiting the cultivation of tea, this makes it possible to design naturally ventilated spaces that remain reasonably comfortable even during the hot season.

Thermal modelling of the main space was carried out using hourly data from Nakuru, which was the closest match to the monthly weather data for Kericho. The data showed that the temperature rarely drops below 10°C and rarely exceeds 32°C, and humidity is low.

The challenge, therefore, was to design a building with a passive, natural ventilation system so that it would remain comfortable without either heating or cooling, and with congregations from 50 people to 1,500 on different occasions. The team worked hard to see if there was a vent area that could be left permanently open to allow the cathedral to cool down after a service and during the night, while not becoming uncomfortably cold in the morning during the cool season.

The design of the high-level vents required close collaboration with the architects. The principle adopted was to lower the central roof-light strip to form a walkway with the louvre vents on each side. This arrangement avoided the need for complicated opening/closing mechanisms or regular access to the vents.

Low-level ventilation is provided simply by opening the multiple doors that lead out to the gardens along both transepts. The heavyweight floor and furniture also provide thermal mass that helps slow the inevitable temperature rise when the cathedral approaches full capacity.

Since solar gains are extremely high, and thermal insulation is rarely used in Kenya (it has to be imported, making it very expensive), the solution was to use the architect’s vision of a clay tile roof as an outer skin, protecting a waterproof inner layer made from ubiquitous metal roofing sheets. The gap between the two layers was well ventilated to dissipate heat build-up and also to reduce impact noise from the heavy rainfall that happens most afternoons. An inner, white plasterboard ceiling was mainly for aesthetics to provide a backdrop to the timber slats and reflect daylight, but was detailed so as not to impede airflow out through the roof.

Lighting

Light sources are embedded in the building fabric: the central roof skylight runs the length of the building, widening to illuminate the altar in a shaft of light, with supplementary light coming from side windows and doors. Light levels vary considerably in this high altitude, from intense zenithal sunlight, to overcast rain-filled skies. The skylight design provides consistent ambience, despite these variations, with a diffusing glass interlayer scattering sunlight to protect the wooden fixtures and fittings inside the building and prevent the brightness acting as a distraction from services.

Lighting simulations and climate-based daylighting techniques were key to understanding the performance of the skylight and other daylighting components, particularly the interaction with the concrete arches and timber slats. At night, architectural lighting is used to create a rhythm of light and shadow between the slats that shows the simplicity of the architectural form.

Both the daylighting components and electric lighting work to reveal the surface qualities of the timber and concrete. The scheme is low-energy, economically sustainable, and

13. Diagram of the roof section showing airflows as part of the natural cooling and ventilation system.

14, 15. Locally made clay tiles form the outer skin of the roof. The waterproof inner layer is made from metal sheeting lined with white plasterboard to provide a light-reflective backdrop to the timber-slatted ceiling.

16. The louvre vents are on each side of the central roof-light strip.

17. Doors leading out to the gardens along both transepts are sources of light and natural ventilation.

18. Loudspeaker layout concept.

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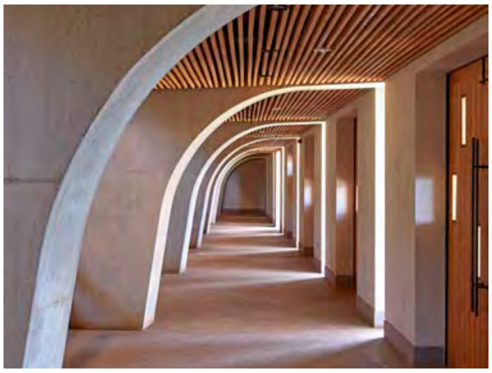

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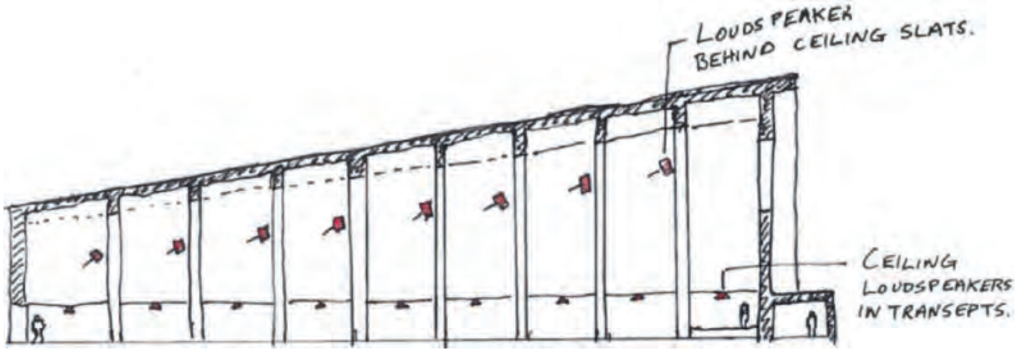

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part of the cathedral's character. The electric lighting is now controlled remotely from a tablet computer so that it can be switched on or off during a mass, as required, from within the congregation.

Acoustics

From the earliest stages of the project, the aim was to develop acoustics that combined the divergent themes of: 'family at table' (curved seating around the altar, common in African Catholic tradition); a single, unifying volume; clarity of speech delivered from anywhere within the cathedral; and a lively acoustic ambience to encourage participation in the service.

The resulting design limits the room volume relative to a European cathedral of similar capacity, but creates a space that naturally provides an appropriate acoustic environment without significant intervention to the form or materiality.

A sound system was essential, however, for two reasons: even the strongest voices struggle to carry past 20–25m, and the cathedral is more than 50m in length; plus, the clergy wanted to be able communicate with crowds of worshippers in the surrounding landscaped gardens when the building was full on special occasions.

Sound systems for cathedrals and large traditional churches are typically based on tall directional column loudspeakers. However, to protect the aesthetic simplicity in the cathedral, the team selected smaller units that could be hidden in the building finishes. Rows of loudspeakers are located behind the slatted timber ceiling, with distributing speakers down the length of the building for even sound coverage and good speech quality. Ceiling speakers in the transepts are intentionally located near open doors to spill sound into the grounds to serve larger crowds, and additional connections are provided to extend the system to temporary external loudspeakers, if required.

To keep down costs, the design was based on widely available products that could be installed by local contractors. A digital processor is provided to time-align the output of each row of loudspeakers and manage levels, and the system generally operates automatically, though it can be operated wirelessly, when required, for larger services.

Commissioning and tuning was managed over several months by local Arup engineers with support from the UK.

19. The landscaped areas include seating that can be used during and between services as the sound is relayed outside.

20, 21. Sacred Heart Cathedral is now part of community life in Kericho.

19.

20.

Summary

Sacred Heart Cathedral was consecrated in May 2015. The service was led by the Archbishop of Kenya, and attended by the Nuncio to Kenya and South Sudan, several bishops, and a congregation of thousands of people from miles around, who packed into the building, the grounds and surrounding streets. Choirs from neighbouring areas joined together to lead the singing.

The cathedral is exceptional in the way it has been delivered in a relatively remote region. The international and local teams have worked well together to harness best practice in seismic engineering, structural design, natural ventilation, acoustics and lighting, while at the same time respecting the local environment and the needs of church and community. The quality is notable, with local teams demonstrating outstanding skill in delivering a structure larger and more complex than they would usually work on, to an exceptionally high standard.

The Civic Trust, which organises Europe's longest-established built environment awards for projects that provide cultural, social, economic or environmental benefit, presented one of its 2017 Special Awards to the Kericho Cathedral team. In addition, the project was a winner in the Surface Design Awards (light and interior surface) and received the Judges' Special Award at the British Construction Industry Awards 2016.

Most importantly, however, the Diocese of Kericho has gained the cathedral it wanted to help serve and unify its congregation into the long-term future.

Authors

James Beer is a Senior Consultant. He guided the sound system commissioning.

Katherine Coates, Associate Director, Infrastructure, has been instrumental in developing Arup's knowledge of seismic design criteria in East Africa.

Edward Hoare was the Project Manager and lead structural engineer.

Jacob Knight is an Associate with the firm. He is a mechanical engineer and building physicist.

Caroline Ray was the Project Director, and she is a structural engineer. Working from Arup, Botswana, and later in Kenya, Caroline delivered Arup's input to the site phase of the project.

Project credits
Client: *Roman Catholic Diocese of Kericho* Architect: *John McAslan + Partners* Executive architect: *Triad Architects Ltd* QS: *Barker and Barton* Electrical and mechanical engineering: *EAMS* Structural engineering: *Arup and Eng Plan* Building physics (natural ventilation), lighting, acoustics, sustainability advice: *Arup* Main contractor: *Esteel Construction Ltd* Furniture design and entrance doors: *Studio Propilis* Stained glass and artworks: *John Clark, Glasspainter*.

Arup – Pavlina Akritas, Francesco Anselmo, James Beer, Junko Inomoto, Alison Gallagher, Edward Hoare, Unoda July, Jacob Knight, Ziggy Lubkowski, Boster Matenga, Olise Mhone, Rohit Manudhane, Caroline Ray, Sam Wise.

Image credits
1, 2, 17, 20, 21 *Edmund Sumner;* 3, 5, 6, 7, 13 *Martin Hall / Arup;* 4–12, 15, 18 *Arup;* 14, 16 *John Clark;* 19 *Tim Vaulkhard / Triad.*

San Francisco Museum of Modern Art

1.

Location
California, USA

Authors
Denis Blount Joshua Cushner Star Davis
Raj Patel Eric Rivers Leonie van Ginkel

Introduction

At San Francisco Museum of Modern Art (SFMOMA), a dramatic expansion to the existing building reimagines the gallery experience and provides a new gateway into the city. It seeks to engage local conditions and communities, thus realising the museum's goal of being a welcoming centre for arts education and an important public space for the Bay area.

The new expansion runs contiguously along the back of the existing building, allowing for a seamless integration of the two structures that doubles the exhibition space while also expanding the un-ticketed gallery areas and outdoor public spaces. And it is part of a design that makes the most of a tight urban site – the new building rises out of a relatively small footprint, its frontage just 25m wide, then broadens, higher up, to create space for artworks, events, conservation and administration. Other facilities include two multipurpose performance spaces, the White Box Theatre and the Wattis Theatre.

Arup provided fully integrated services in acoustics, audiovisual and theatre consulting; lighting and daylighting design; façade consulting; pedestrian and people flow, including MassMotion simulations. This article focuses on the work Arup did for SFMOMA, in collaboration with Snøhetta, EHDD Architects and other partners.

The project

When the original SFMOMA, designed by Swiss architect Mario Botta, opened in 1995, its location in the SoMa (South of Market) district was less salubrious than it is today. Botta's approach reflected the gritty nature of the neighbourhood with a fortress-like design that was inwardly focused rather than openly welcoming. The tech booms of the '90s and '00s have since changed the area's character. Now home to internet businesses, shops, restaurants and clubs, SoMa is busy, fashionable and pedestrian-friendly, so when it came to transforming the museum, a key aspect of the brief involved attracting passers-by to enter and look around, in keeping with the new mood.

The expansion had to address the challenges that face contemporary spaces for modern art: it had to be infused with natural daylight, provide a sonic journey through space to subconsciously delight the senses, seamlessly integrate technology to support the developing needs of audio-visual art and associated education, while gently encouraging the flow of visitors shaped by the architecture.

The façade

The façade undoubtedly makes a statement on the skyline. What is less evident is the material from which it is made. Although white stone comes to mind, the building billows outwards, like a ship's sail, in a shape that conveys lightness and flexibility. This is because, working with the international architecture firm Snøhetta, and composite materials specialists Kreysler & Associates, Arup developed the façade using glass fibre-reinforced plastic (GFRP) panels affixed to a curtain wall system. These panels, which are lighter than precast concrete, glass fibre-reinforced concrete (GFRC) or stone, enabled a sculpturally complex approach. And the bow-shaped eastern façade comprises 700 of the uniquely shaped panels, embedded with silicate crystals, hence the stone-like appearance.

With budget consideration a major driver throughout the project, material and system selection was critical to success. The design team's challenge was to find an effective, elegant, yet cost-effective solution that would create the desired complex geometry in combination with large floor-to-floor spans at the gallery levels.

2.

Studies conducted during the early stages of the project assessed the suitability of various materials to achieve the free-formed panels that would become the ripples of the east façade. The geometry of the wall did not allow for any repetition, and with this in mind the design team recommended the use of GFRP as an alternative to GFRC.

The lay-up process of GFRP provided flexibility in the geometry and allowed the moulds to be easily fabricated out of styrofoam. Sand mixed into the gel coat helped achieve the architectural aesthetic of a cementitious finish, while allowing for a flexible fabrication process and lightweight solution. Using GFRP panels, rather than

1. The façade of SFMOMA is embedded with light-reflecting silicate crystals.

2. Streaks of electric light encourage passers-by to enter the building, as well as being part of a strategy to guide the flow of visitors around SFMOMA.

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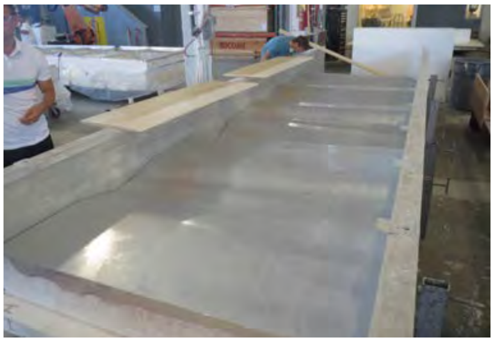

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3. The panels that ripple on the east façade are made from glass fibre-reinforced polymer (GFRP).

4. The GFRP panels were developed to be weather-tight and easy to install.

5, 6. The panel moulds were milled out of styrofoam blocks at Kreysler & Associates' workshop.

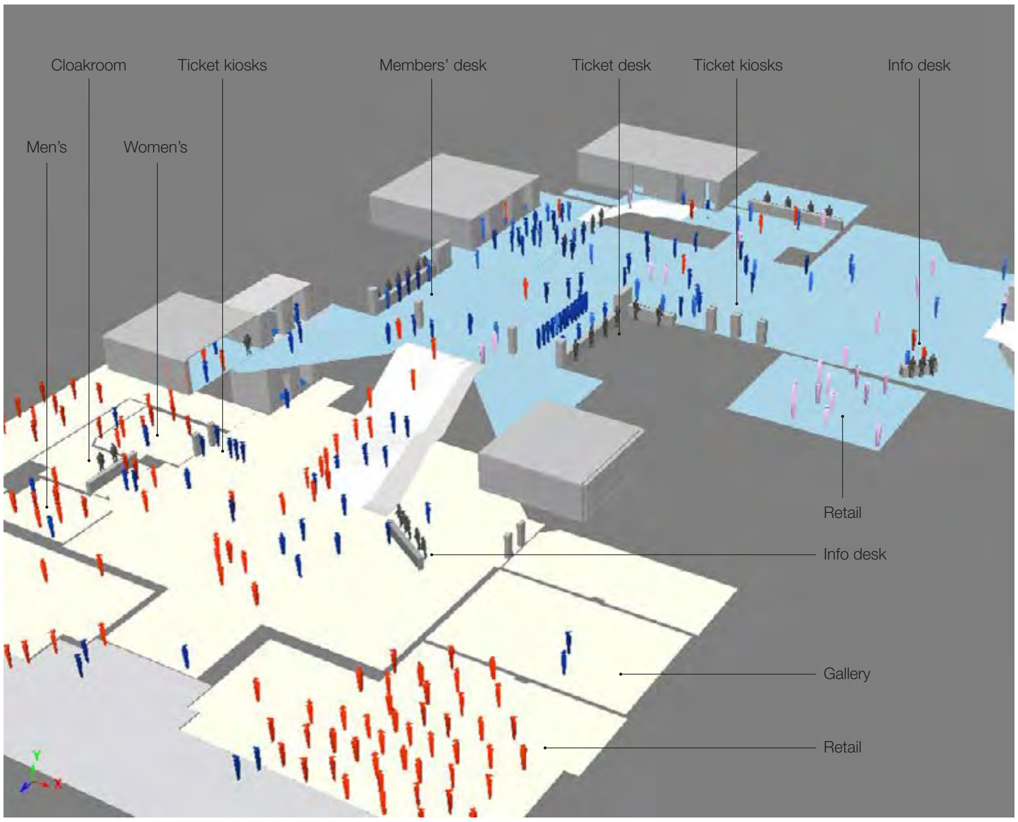
7. MassMotion modelling enabled the team to fully understand the visitor experience and plan for forecast increases in visitor numbers in future years.

GFRC or precast concrete, dramatically decreased the overall weight of the façade and therefore lessened the demand on the building structure. In fact, despite being approximately three times larger than the original SFMOMA building, it is estimated that the new addition weighs less overall.

Specifying GFRP introduced extra steps into the façade design process. The material had not been widely used for architectural applications previously in the USA, so certain complexities had to be overcome during the manufacturing process to ensure that a durable solution was developed that also met all code requirements. To get early feedback on feasibility and pricing, therefore, the design team held preliminary discussions with manufacturers and, as a result of this, recommended engaging in a 'design assist' process using performance-based design drawings and specifications. The process included mock-ups and validation tests to ensure the GFRP façade material would perform as well as expected both aesthetically and technically.

GRFP's fire rating, required by code, can be achieved dependent on the material design, which should optimise the percentage of glass fibres and fire-retardant additives to the matrix. The material fire tests carried out by the team included ASTM E-84 and assembly fire tests in which the cladding panels were installed onto the weather wall system to satisfy the requirements of the National Fire Protection Association test, NFPA 285.

The team also had to develop panels that were weather-tight and easily installable. To fulfil these performance criteria, the GFRP panels were installed onto aluminium strong-back framing, supported from a unitised curtain wall panel, and it is this panel that provides the weather and airtightness of the façade. In addition, as the museum has stringent interior humidity levels for art conservation, thermal performance was an



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important consideration in the selection of the weather wall to prevent condensation from occurring inboard of the vapour barrier.

A unitised curtain wall system was selected over a stick-built approach because it provides advantages in terms of speed of installation and sequencing, and quality can be controlled during fabrication in a factory environment. Each weather-tight curtain wall panel follows a simplified geometry to allow interlocking of the joints while supporting a free-formed GFRP cladding panel using aluminium brackets, resulting in a high-performance, yet sculptural envelope.

Pedestrian modelling

To enable the project team to fully understand every stage of the visitor experience, Arup's pedestrian planners helped Snøhetta think through the arrival sequence from street to galleries, then plan points of visitor interaction and service, vertical circulation, restrooms, retail nodes, and areas for rest, reflection and respite.

MassMotion pedestrian simulation software was used to demonstrate how the museum might perform under different levels of activity. Various lobby arrangements were simulated, showing how visitors could move through ticketing, cloakroom, then on into the art spaces, and how queues and crowding responded to different staffing and operational schemes. MassMotion was also used to demonstrate the effects of a flow of visitors up to 20 years into the future, based on anticipated attendance numbers for normal days, peak days and a 'blockbuster' show.

These simulations influenced the design. The pathways from all public entrances converge at the second-floor Helen and Charles Schwab Hall, a spacious gathering place with views to the vertical garden. It is from here that visitors move upwards from the ground-floor exhibition spaces into the second- and upper-floor galleries.

MassMotion modelling was critical to the design process and to achieving buy-in from stakeholders with different perspectives. The museum director, his immediate stakeholders and the board of trustees, for example, were primarily concerned with the proposed layout, the design and construction schedule, and their need to know that the plan would work for visitor experience in a way that would enable continuous development. MassMotion modelling demonstrated for them that the lobby's performance in a dynamic environment could respond to substantially increased attendance, while maintaining very positive user experience.

The operations team, however, was more concerned with forecast attendance increases and the effect this would have on points of interaction such as ticket counters and the information desk. Videos taken from the MassMotion models demonstrated for the operations team how staffing levels could change based on queue length and waiting time performance criteria. Specifically, the models showed that current operations would not serve the future building adequately, so the operations team would need to revisit its approach to staff deployment and training.

Lighting

The comprehensive lighting design (including daylighting) was seamlessly integrated within the architecture to provide a journey through the museum. It is a sophisticated design that is highly energy-efficient. On the ground level, sharp lines of light cut through the soft ceiling form, moving from a regular pattern of dashes to randomised streaks that transition the visitor through the space. Then, moving upwards through the building, the ceiling form, lighting and volume of the galleries are tailored to the collections.

Of particular note is the lighting arrangement on the fourth and fifth floors, where the galleries have a sculpted ceiling with light quality similar to that of a gallery lit by daylight from above. The walls are free of shadows or striations, and the lighting of the ceiling emphasises the voluminous curves. The ceiling brightness is in keeping with the ratios found in the natural environment. The form of the coffer was optimised for efficiency and aesthetics, the exact curvature optimised using Grasshopper software and the radiance through a ray tracing calculation, thus ensuring the most efficient geometric form to deliver light.

The sixth-floor galleries have a different custom-sculpted cove, much more geometric in form, the design playing with the perception of boundaries and the volume of the space above. The seventh-floor contemporary galleries take on a completely different aesthetic and sense of place: custom extrusions reinforce a 'raw' gallery typology in keeping with the studio spaces where many of the artworks were developed.

8.

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In all these spaces the coves serve multiple functions: lighting, acoustic, life safety, and mechanical systems are incorporated and seamlessly integrated within the forms.

An important journey through the gallery spaces is the city gallery that runs along the north-east end of the building across all floors. Here, an open stairwell and many large picture windows provide views to the city and the balance of daylight and electric lighting has been finely tuned to meet art conservation requirements, together with a level of brightness and contrast which naturally guides visitors through the space.

The design of any gallery space must balance many priorities because exhibitions are constantly changing. With this in mind, and ceiling heights in the SFMOMA expansion ranging between approximately 5m and 10m, the lighting allowance for the track is typically designed to provide the capacity to light any object, in any place.

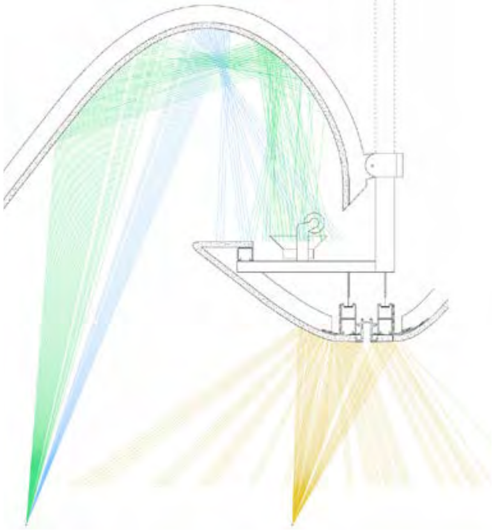
High ceiling heights require higher-power lighting to deliver the same quantity of light. Yet the team designed a solution that could provide maximum flexibility without requiring excessive power. Their solution, which required multidisciplinary collaboration and a customised programming of the relay panels at each floor, was a track load limiting solution, monitored floor by floor. Typically, track limiting is done within the gallery space, with a physical device attached to individual runs of track. Programming the track limiting to be done at the panel achieves much lower lighting power density, less than a quarter of that provided in galleries with similarly soaring ceilings.

This innovative energy-saving solution allowed for reduced circuiting, and was awarded a LEED point for design innovation. The museum's commitment to LEED was essential to this design idea being successfully employed and adapted.

Acoustics and AV

The acoustic design for the public areas creates comfortable spaces for quiet contemplation. Gallery spaces include sculpted glass fibre-reinforced gypsum (GFRG) panels that scatter both light and sound to avoid harsh reflections that may otherwise detract from a comfortable viewing experience. In the high-density entry area, strategically located sound-absorbing finishes control the build-up of noise from visitors, helping to keep the ticketing experience calm and comfortable. The amount of sound absorption required was determined using proprietary acoustic models based on the architecture and anticipated occupancy.

In the large column-free gallery spaces where the museum can vary configurations using temporary walls, it was necessary to address the issue of sound transmission between adjacent exhibition areas, because some of the museum's exhibits, particularly for media arts, feature sound and video. It was also important to create the ideal sound environment for these exhibits, so the media arts acoustics, tailored for audio reproduction and sound isolation, include:



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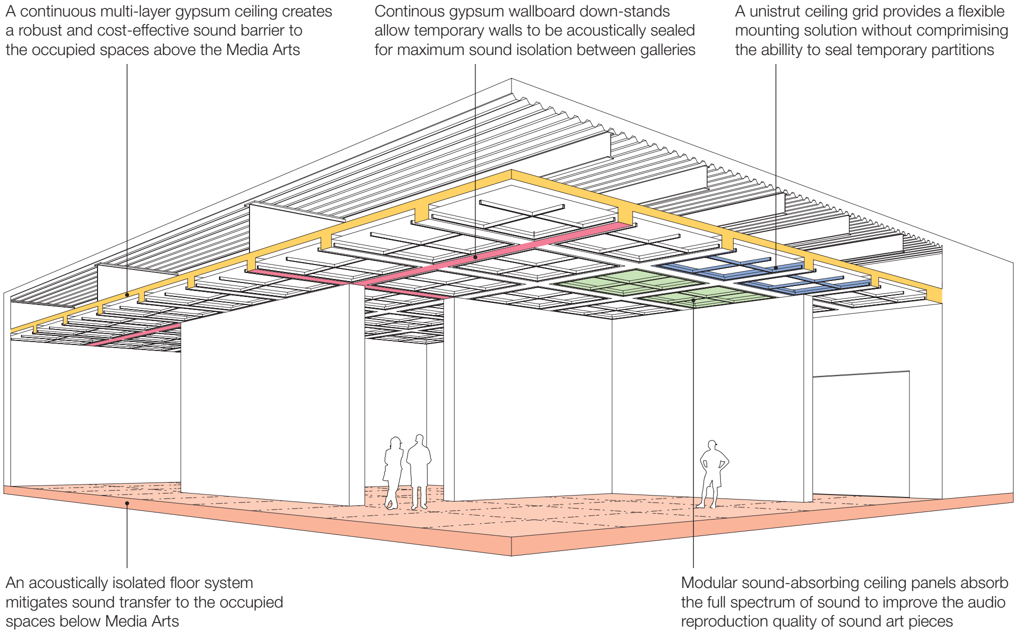
- 100mm-thick sound-absorbing ceiling panels that reduce reverberance, improving audio fidelity, especially in the lower/bass frequencies
- sound-isolating floor, ceilings and walls designed to contain sound and avoid disturbing neighbouring spaces
- low-noise heating, ventilation and air-conditioning (HVAC) systems to improve the detail and dynamic range of audio content.

Outside the building, the acoustic impact of the new expansion on the surrounding urban environment is minimal. Site noise levels were benchmarked over a 24-hour period and whisper-quiet fans for the cooling towers, and attenuation packages for relief fans, were specified.



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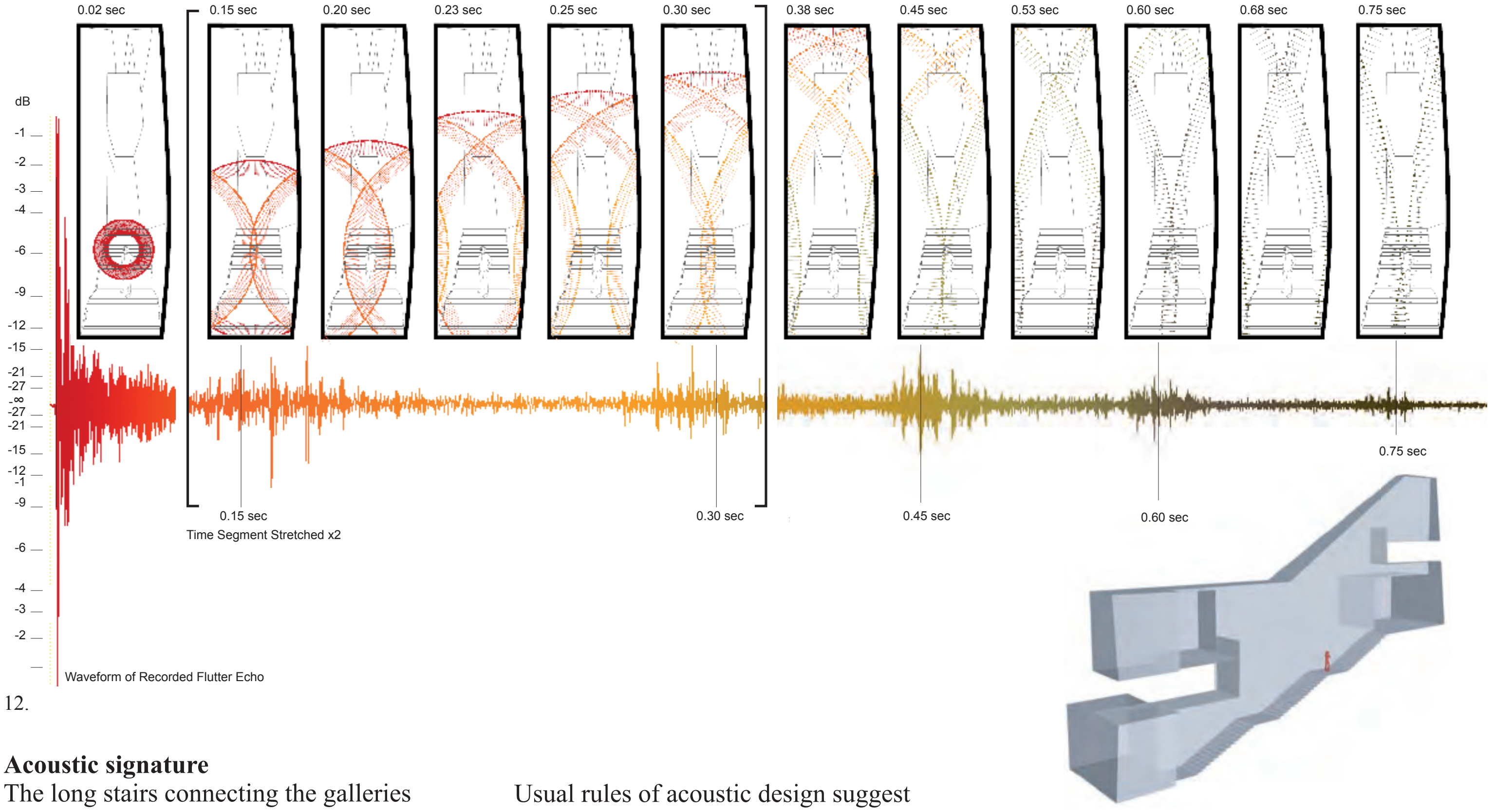
8. Daylight and electric lighting are finely balanced in the stairwell.

9,10. The sculpted ceiling design is optimised for both light and sound dispersion. The sound component has two primary features: the upper concave portion focuses sound into the return air plenum above the ceiling to reduce overall reverberance and sound energy in the gallery space; the lower convex portion scatters sound to provide a more diffuse sound field, reducing harsh/specular sound reflections from the ceiling.

11. Acoustic design features of the Media Arts galleries.

12. Acoustic signature of city gallery stair.



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Acoustic signature

The long stairs connecting the galleries exhibit a natural ‘flutter echo’ giving each stair a unique acoustic signature, which is activated by the sounds made by visitors: footsteps and whispers, for example. In essence, each sound creates a unique sonic artwork. This acoustic signature can be specifically activated by artists should they choose.

Usual rules of acoustic design suggest adding sound-absorbing material to neutralise these artifacts, but the team decided to retain them to create additional engagement and tell a story around design and multi-sensory experience of spaces.

13.

The Wattis and White Box Theatres
The Wattis Theatre at SFMOMA, the well-known cinema within the original Botta building, was completely renovated as part of the expansion project. The Arup-led design includes architecturally integrated acoustic features that both recreate the acoustics of the original theatre, and support an active architecture system that can electronically alter the acoustics of the room for different performance types. The ability to vary room acoustics at the push of a button enables the museum to present a wide range of events.

The White Box Theatre is an entirely new space for live performance, accommodating theatre-in-the-round configurations, multi-screen projections and special installations. It means that for the first time SFMOMA has the full range of flexibility and infrastructure necessary for performance-based work, allowing artists to explore movement and film in new ways. The design of this space provides support for performances that are suited neither to the separation of a proscenium stage, nor to a gallery with acoustic bleed that may contain art with particular conservation needs. This space fosters works that call for continuous action over long periods of time, or live pieces rooted in intimate audience-performer exchange and group dynamics.

Arup collaborated with Snøhetta on the initial design of the room to integrate the theatrical, acoustics and lighting design needs, part of the White Box fit-out with architect EHDD. The fixed technical grid, control room, and audio-visual and theatrical infrastructure designed by Arup, support a wide variety of performances, installations, board meetings and rotating artworks.

Summary
SFMOMA’s distinctive – and, in this case, it is probably fair to say, iconic – new expansion is innovative not only in its appearance but also in the design and engineering that underpin the effectiveness of its galleries and performance spaces. Arup worked consultatively across the entire project, providing specific expertise in particular disciplines.

The expansion project features what is believed to be the largest architectural GFRP façade application in the USA. Architecture and engineering were carefully coordinated, options explored, and appropriate materials selected to inform the development of the GFRP panels. By leveraging modern materials, the team delivered a façade that has all the elegance of a natural material, such as stone, yet offers significant further benefits, particularly in terms of sustainability and cost-effectiveness.

Lighting, acoustics, audio-visual and theatre planning strategies that maximise flexibility and minimise power use are also seamlessly integrated into the architecture, and the MassMotion analysis provides SFMOMA with insight into how the museum will manage visitor footfall up to 20 years into the future. The expansion of SFMOMA will undoubtedly influence similar projects, its outcome having set new benchmarks in several aspects of museum design.

Authors

Denis Blount was the Project Manager and lead acoustic and AV designer for the project.

Joshua Cushner, Associate Principal, acoustics, AV, theatre consulting and team leader for the Wattis and White Box fit-out designs.

Star Davis is a Senior Lighting Designer.

Raj Patel was the Project Director. He is an Arup Fellow, and the firm's global leader for acoustics, AV and theatre consulting.

Eric Rivers, an Associate in the Integrated Planning team, is an expert in pedestrian movement and modelling.

Leonie van Ginkel, Senior Consultant, Façade Engineering and Building Physics.

Project credits

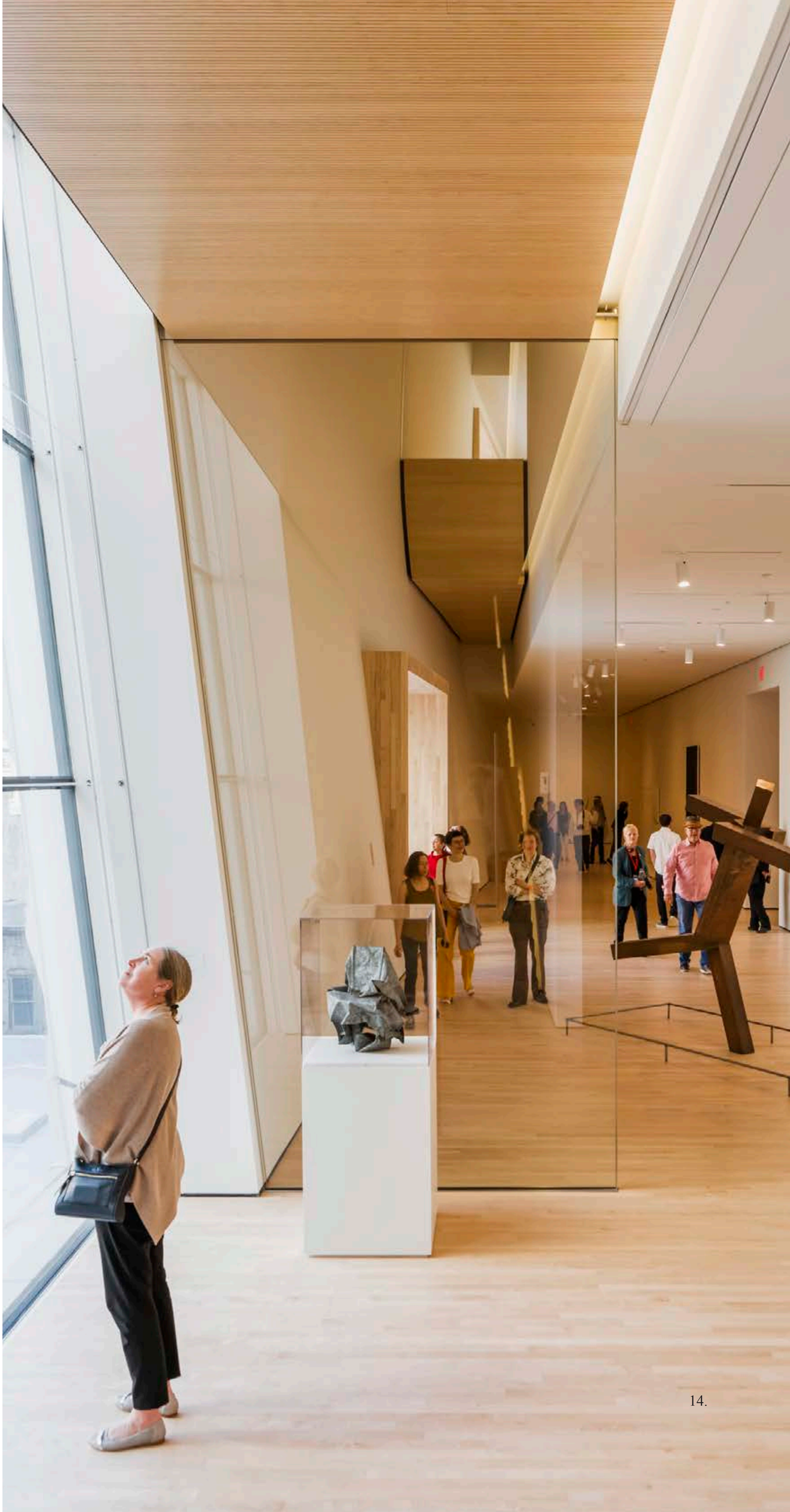
Client: *SFMOMA* Architects: *Snøhetta, international architecture firm based in New York, Oslo and San Francisco, and EHDD* Façade: *Kreysler & Associates and Arup* Arup's New York team supporting *Snøhetta* was led by *Denis Blount* and *Raj Patel*. Arup's San Francisco team supporting EHDD was led by *Joshua Cushner and Fiona Gillan*. *Arup – Sammy Aglipay, Denis Blount, Joe Chapman, Karine Charlebois, Clarissa Cruz, Joshua Cushner, Star Davis, Fiona Gillan, Clara Hie, Stephanie Hillegas, Carla Jaynes, Jerrod Kennard, Christine Lee, Rok Lee, Trent Lethco, Toby Lewis, Jack Lim, Matt Mahon, Shane Myrbeck, Lj Nassivera, Raj Patel, Eric Rivers, Jacinda Ross, Cesar Sanchez, Markus Schulte, Ricky Shum, Brian Stacy, Nathan Stroud, Leonie van Ginkel, Felix Weber, Robert Young.*

Image credits

1 *Iwan Baan*; 2, 3, 9, 10, 13, 14 *Snøhetta/Jeff Goldberg/ Esto*; 4 *Felix Weber*; 5, 6 *Kreysler & Associates*; 7, 8, 11, 12 *Arup*.

13. Live performance in the White Box Theatre.

14. In the City Gallery, picture windows afford the visitor fine views over San Francisco and the balance of daylighting and electric lighting is finely tuned to meet art conservation requirements.



14.

1.

Hong Kong International Airport Midfield Concourse

Authors
Mark Cameron Alice Chan Jerman Cheung Franky Lo Mark Swift

Introduction

Hong Kong International Airport (HKIA) is one of the world's busiest, connected to more than 190 destinations through more than 1,000 daily flights. To meet future demand and strengthen Hong Kong's competitiveness as a regional and international aviation hub, further expansion was necessary. The Airport Authority Hong Kong (AAHK) tendered the detailed design of Phase 1 of its Midfield Development project in 2010, a project that was completed in December 2015.

Located to the west of Terminal 1, between the two runways, the midfield was the last piece of land on the airport island available for large-scale development. A core part of this expansion comprised the design and construction of the Midfield Concourse (MFC). Arup, in joint venture with Mott MacDonald, was selected to provide full multidisciplinary design and construction support.

Building Information Modelling (BIM) was an important key to the success of this project and the way BIM was used resulted in awards from both Autodesk and Bentley, key providers of software to architecture, engineering and construction professionals. This article focuses largely on the role of BIM in developing the MFC.

The project

The new five-level MFC with a total floor area of 105,000m² features an architectural style that complements Terminal 1. Its large, open-span steel truss roof, high headroom and extensive use of glass create a sense of light and space. Passenger access to Terminal 1 is via an extension of the existing automated people mover (APM) system.

The MFC adds 19 contact aircraft parking stands, two of which can accommodate Code F aircraft, such as the Airbus A380, significantly expanding the airport's capacity enabling it to serve in excess of 10 million additional passengers per year.

Within the detail design JV, Arup's scope included structure, façade, sustainability, airport systems, APM, baggage handling system, MEP (mechanical and electrical engineering and plumbing), fire, acoustics, specialist lighting and logistics planning.

BIM overview

The MFC was one of the AAHK's first major BIM projects. Although BIM is increasingly regarded as a standard facet of integrated design engineering, this project began back in 2010 when BIM usage was less well-established. The advantages of BIM became evident as the project progressed, resulting in better coordination between disciplines and earlier identification of clashes, or design issues that required rectification.

The JV, in conjunction with architect Aedas and sub-consultant Atkins, deployed multiple software platforms to deliver the optimum solution. A variety of 3D design software was used; for example, Autodesk Navisworks as a common platform for showing and assessing information in 3D and helping to advance the complex 3D geometry design of the curved roof of the concourse.

In addition, a robust BIM workflow was defined, describing how the various software from Bentley, Autodesk and others would be used, exchanged and integrated, and where conversions to other formats would be required. The software integration enhanced project-wide collaboration allowing rapid information exchange and helping to significantly improve inter-disciplinary coordination, resolving clashes and other issues well in advance of construction.

The project won the Bentley 'Be Inspired' BIM Awards 2011 and Autodesk Hong Kong BIM Awards 2013 due to its early adoption of BIM for both building and external works (airfield) design.

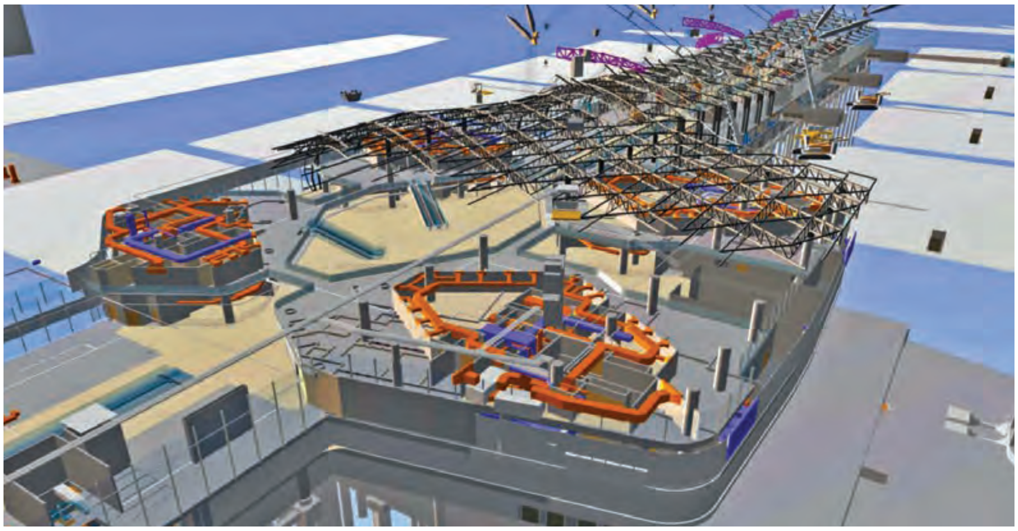
Another key challenge was for the design team to manage multiple, and sometimes conflicting, requirements from various stakeholders, including the AAHK, airlines, security, customs, immigration, police and retailers. The project team skilfully navigated the design phase, understanding the various stakeholder requirements, and then coordinated and transferred these requirements into the technical design.

In the construction phase, the project team had to work on building in the midfield of an operating airport. This was achieved by essentially creating an island within the airfield where the contractor was allowed to operate. During the construction stage, the contractor took over the design team's BIM model and further developed it to include fabrication and installation details for their and their subcontractors' use.

Parametric modelling of the roof

Use of parametric modelling and design streamlined the steel roof structural design process. Rhino was used to manipulate the structural and architectural geometries of the roof and ceiling profile, thus ensuring effective communication of design intent and details between architect and engineering teams and speeding up design coordination and development.

The roof spans approximately 42m across the width of the MFC to provide a column-free interior. Both sides of the building are fully glazed, with roof skylights angled towards the north – a key architectural design consideration.



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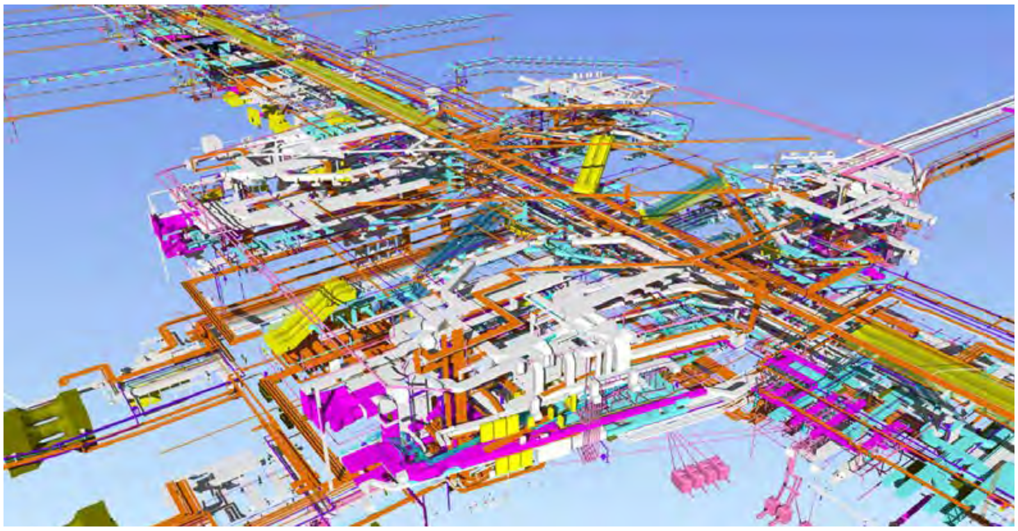


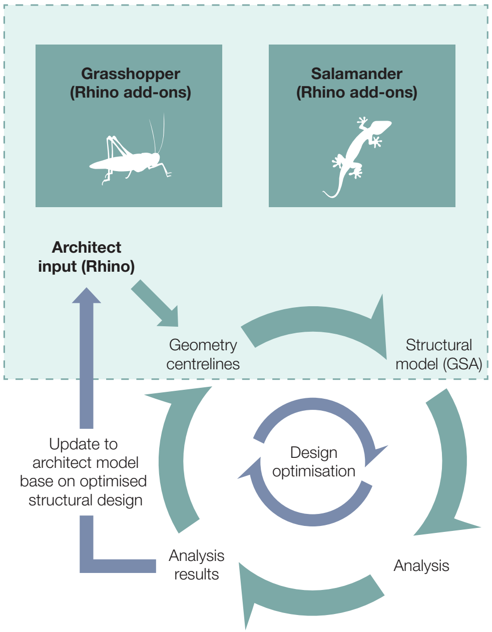
3

1. The MFC adds 19 contact aircraft parking stands, two of which can accommodate Code F aircraft, such as the Airbus A380, significantly expanding the airport's capacity and enabling it to serve in excess of 10 million additional passengers per year.

2. 'Buildability' simulation for review of construction activities.

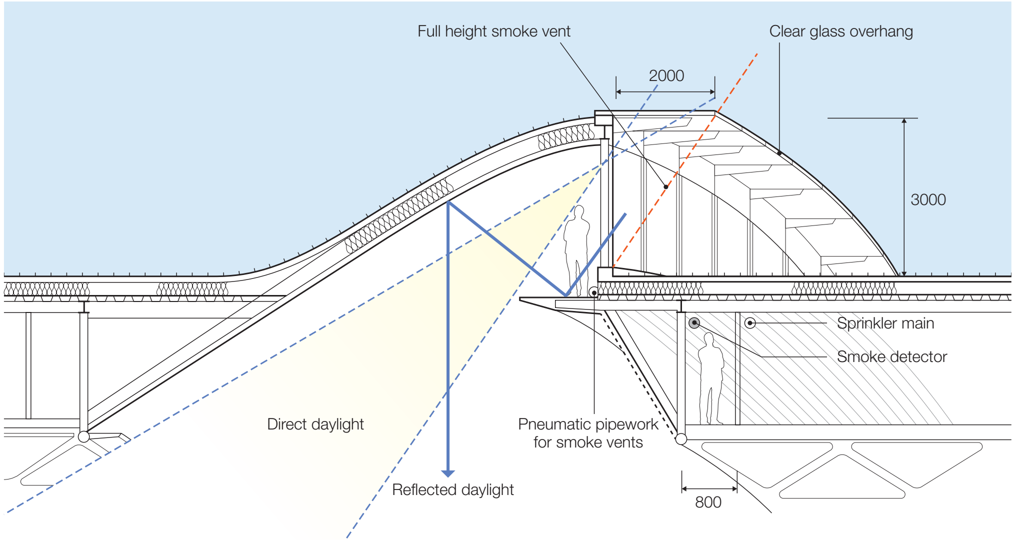
3. A 3D model of the integrated building services and airport systems.

4.



5.

Vertical loads, including gravity loads and wind uplift, are transferred from the roof panels to the secondary steel beams (orientated longitudinally). Diagonals rise from the bottom chord of the trusses to the secondary beams to provide lateral restraint to the bottom chords of the primary trusses. The steel trusses are supported by steel A-frame columns at one side and RC columns at the other side. The trusses are arranged in a one-way spanning truss system with the span direction skewed with the principal direction of the concourse axis to cope with the angled skylight orientation. Lateral load resistance is provided by the RC columns at one side and the A-frame column at the other side.



6.

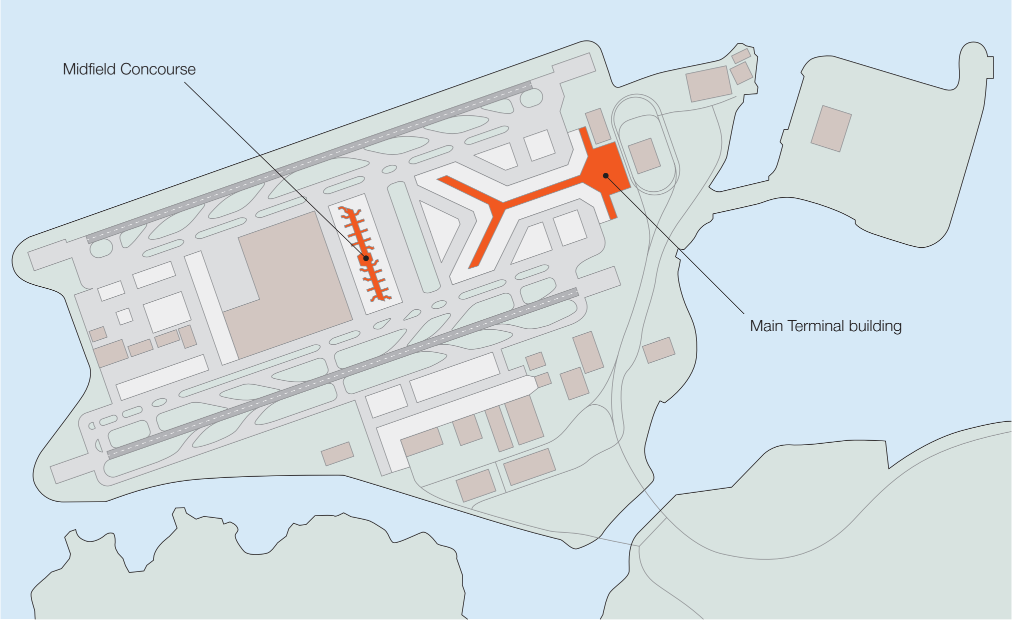
The main truss components comprise a combination of circular hollow sections and open I-sections (UB / UC). The top chord is piecewise linear which changes direction at the connection with the secondary beams. The bottom chord of the main truss is exposed as an integral part of the aesthetic ceiling. The CHS member provides a cleaner connection appearance. Regular UB or UC sections were chosen for hidden truss members for cost-effectiveness in view of the high cost premium on circular sections and the relative ease of connections.

Similar configuration is provided for the node area which has a larger dimension in the transverse direction. Two lines of internal columns are provided for maintaining the span of the node trusses to be the same as those in the concourse area. In order to provide a column-free space along the centre line of the node, transfer trusses are provided.

The span of the main roof trusses is skewed in line with the skylights that are located in each alternative bay between the main trusses, and feature a curve-shaped cover, shaped like an eyelid. The volume under the skylight is clear of obstruction by structural members. The profile of the trusses is rationalised to match the roof and ceiling profile. The bottom chords are again circular.

Sustainable design
In line with AAHK's pledge for Hong Kong Airport to become one of the world's most environmentally efficient airports, the MFC has achieved BEAM Plus Gold accreditation in the Hong Kong Green Building Council's environmental performance scheme. Arup's sustainability team worked with AAHK to determine which practical targets could be achieved, focusing on energy and carbon, materials, and water usage.

Passive design measures to reduce energy use relate to the building geometry, orientation and fabric performance.



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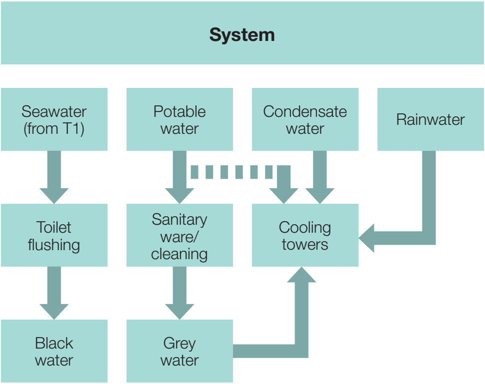
8.

The design team recommended orientation along the north-south axis to avoid large solar gain from the south and used parametric optimisation analysis to develop the distinctive shape of the building. Glazing on the east façade was maximised to bring in natural light, and also provide a view of Terminal 1, creating a sense of connection to the main concourse. Conversely, glazing on the west façade was minimised to reduce heat gain, and it was covered by an overhang with shading devices. On both façades, high-performance glazing was used to reflect more than 40% of solar heat. In the roof, north-facing skylights bring in diffuse natural light to reduce the need for artificial lighting during the day.

Active and renewable design measures adopted to reduce energy consumption include:

- Water-cooled air conditioning with high-efficiency chillers: the cooled air, provided to the MFC via binnacles, sinks from the top of the binnacles to form a ‘blanket’ above the floor, enabling efficient local cooling for occupied areas rather than the entire space.
- More than 1,200m² of integrated photovoltaic panels on the skylight structure.
- Fixed ground power for parked aircraft to reduce reliance on auxiliary power units; regenerative power from the APM system and lifts; and on-demand walkways that reduce energy consumption when not in use.
- LED lighting with ultra-low energy consumption, coupled with daylight and occupancy sensors. Arup’s lighting team developed a high-performance LED down-light product range with super low-glare optics specifically for this project.
- Materials that were regionally sourced (within 800km of the site), recycled, or renewable wherever possible. More than 20% of materials came largely from South China, Taiwan and Hong Kong. More than 50% of the timber used came from renewable sources certified by the Forest Stewardship Council. More than 60% of the construction waste was recycled. Furthermore, MFC was designed for flexibility so that the space could be adapted and changed in the future, if required, with minimal structural works and re-strengthening.
- Grey water from restrooms and kitchens, as well as rainwater and condensate water, collected, treated, and used as makeup water for the cooling towers. Other measures include low-water consumption fittings and sensors for taps.

MFC won the ‘Grand Award in New Buildings – Completed Projects’ category in Hong Kong’s Green Building Awards, 2016.



9.

4. Structural BIM model with roof geometry.

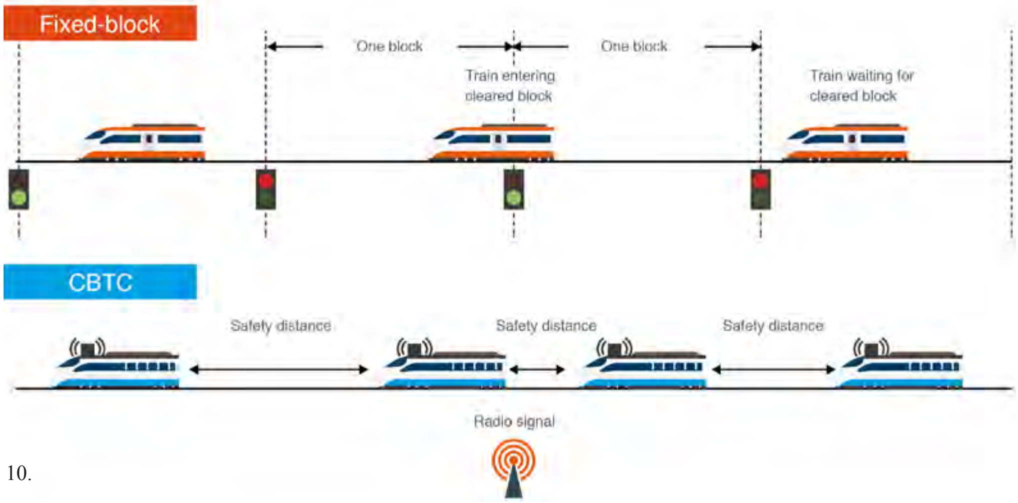
5. Parametric structure model.

6. Concept of Skylight, with its ‘eyelid’-shaped cover.

7. Location of the Midfield Concourse at HKIA.

8. Ultra-low energy LED lighting, coupled with daylight and occupancy sensors, illuminate the MFC: the super low-glare optics were developed specifically for this project.

9. A comprehensive strategy to minimise water use.



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Automated people mover (APM)

The 1km extension to the existing Terminal 1 line of the APM includes a new station at the MFC, a route recovery line and the creation of an associated light maintenance area. Arup's rail team upgraded the existing APM signalling system on this line from fixed-block to communications-based train control (CBTC) to increase capacity.

The fixed-block system divides the line into blocks, only permitting a train to enter a block when the previous train has cleared. CBTC uses bi-directional, train-to-wayside data communications to continuously monitor and calculate a train's status, including position, speed, travel direction and braking distance. This data is communicated so that the speed of the trains adjusts automatically in order to maintain a safe distance from the preceding train. As a result, trains can travel closer together, reducing the headway and increasing the system capacity.

The upgrade involved installing a new signalling system on the APM vehicles and tracks, and ensuring continuous APM operations. This was done as an overlay in parallel with the existing system: the fixed-block system remained functional during the day, with the APM switched to CBTC at night for testing. Equipment installed included on-board automatic train operation (ATO), automatic train protection (ATP) and automatic train supervision (ATS) systems, wayside ATP system and radio network communication system.

This was Hong Kong's first CBTC overlay project. Now, Arup is assisting with upgrading the Terminal 2 line to CBTC.

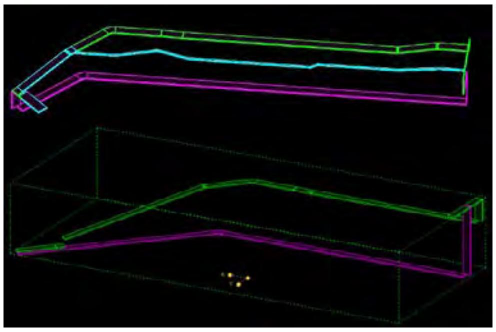
12.

On the APM system expansion, Arup also carried out tunnel structural design and the design of an associated light maintenance facility, tunnel ventilation design, fire engineering and passenger flow analysis.

Airport systems design and BIM

The APM system expansion meant modifying existing airport systems in Terminal 1's West Hall. New cameras, cables and access control doors were integrated into the system, existing devices were retained, dismantled or relocated, and Arup devised a strategy to divert the existing communication cable containment to make space for the new APM platform. Since these cables support systems used in the air traffic control tower, this diversion work was extremely important to the operation of the whole airport.

The cable containment design was verified using the BIM model to ensure the route distance was shorter, providing sufficient slack to relocate the existing cables, and avoiding the need to splice and reconnect the cables. An assessment was developed to identify the risks, the possible failure effect and migration methods.



13.

As equipment and cables in the West Hall radio room had to be relocated for construction of the APM platform, a methodology was prepared for relocating the operators' radio equipment without disrupting the service and the Arup team worked closely with mobile operators during construction to ensure smooth implementation.

Summary

The MFC project developed the further adoption of BIM by the AAHK to the benefit of the JV partners and the client. BIM is now transforming the way projects such as this are carried out and the value of the learning from the Hong Kong MFC project was recognised in the awards that it won from leading software providers.

Authors

Mark Cameron was Sustainability Leader on the project.

Alice Chan is an Associate Director, Rail.

Jerman Cheung was Communications Leader on the project.

Franky Lo, Associate Structural Engineer, worked on the roof design.

Mark Swift is Associate Director, Aviation.

14.

Project credits
Client: *Airport Authority, Hong Kong (AAHK)* Detail design consultant: *Arup and Mott MacDonald*; *Arup – Pavlina Akritas, Ming Au-yeung, Jeng Ang, Francesco Anselmo, Raymond Au, Gerry Banks, Raquel Brito Dias, Stuart Bull, Noah Burwell, Vicente Cabrera, Mark Cameron, Anne Carnall, Alice Chan, Alvin Chan, Che-cheong Chan, Henry Chan, Isaac Chan, Jimmy Chan, Karissa Chan, Li-san Chan, Man-him Chan, Raymond Chan, Roy Chan, Simon Chan, Spencer Chan, Jason Chen, Harold Cheng, Ping-mun Cheng, Durand Cheung, Eric Cheung, Evelyn Cheung, Vincent Chiu, Michael Chow, Carrie Chu, Celsius Chung, Clement Chung, Ricky Chung, Andrew Cowell, Jim Daly, Mohammed Danish, Bernard Dason, Reynaldo De Guzman, Daniel Duan, Matt Ellis, Anthony Fan, Chauncey Fan, Pengcheng Feng, Raymond Fok, Siu-man Fong, Ronald Fung, Charlie Green, Patrick Hanggi, Mark Hayman, Kenneth Ho, Lawrence Ho, Wing Ho, Kenneth Hon, Marco Huang, Henry Hui, John Hui, Emily Hung, Lewis Hwoi, Jeff Ip, Grammy Jiang, Soo Jin, Gigi Kam, Ming-chan Kang, David Keast, Ricky Kwan, Chris Kwok, Patsy Kwok, Karen Lai, Otto Lai, Florence Lam, Jack Lam, Joe Lam, Larry Lam, Mai-yin Lam, Penny Lam, Andy Lau, Carol Lau, David Lau, Hilary Lau, Tony Lau, Joey Law, Angus Lee, Frieda Lee, Jason Lee, John Lee, Kam-tim Lee, Manson Lee, Siu-yuen Lee, Benny Leung, Gary Leung, Gavin Leung, Patrick Leung, Wai-ho Leung, Joyce Li, Ricky Li, Sasa Li, Vivian Li, Rick Liu, Shirley Liu, Andy Lo, Franky Lo, Ivan Lo, Norman Lo, Mingchun Luo, Ross Lyons, Carlos Ma, Phillip Ma, Raymond Ma, Michele Mak, Andrew Mole, James Musgrave, Derek Ng, Kenneth Ng, Nick Ng, Simon Ng, Trevor Ng, William Ng, Ryan Ngai, Vincent Ngai, Jessica Pawlowski, Ray Pang, Simon Pearce, Simon Pickard, Cynthia Poon, Mark Richardson, Thomas Richardson, Renee Ren, Jonathan Roberts, Kin-pui Shum, Christopher Simon, Dicky Siu, Ho-kwan So, Mark Stapley, Mary Sung, Mark Swift, Fiona Sykes, Osward Tang, Ian Taylor, Chris Tidball, Alex To, Nicholas To, Michael Tomordy, Peter Thompson, Jimmy Tong, Man-him Tong, Sherine Tsang, Vincent Tse, Mark Turner, Tony Vidago, Aura Wang, Johannes Wirtz, Daniel Wong, Dicky Wong, Edwin Wong, Emily Wong, Hilton Wong, Jacky Wong, Jonathan Wong, Ken Wong, Raymond Wong, Sai-kee Wong, Steve Wong, William Wong, Zoe Wong, Patrick Wu, Glen Xie, Dong-lei Xu, Jimmy Yam, Keji Yao, Raymond Yau, Tak-cheong Yau, Shelley Ye, Anna Yeung, David Yeung, Ronald Yeung, Rumin Yin, Bernadette Yip, Charmaine Yip, Grace Yip, Jess Yip, Kevin Yip, Kim Yong, David Yu, Yuki Yu, Jessy Zhang, Jian-xin Zhang, Li-ping Zheng.*

Image credits
1, 11 *KerunIP / AAHK*; 2, 3, 4 *AAHK*; 5 *Arup / Martin Hall*; 6 *MAJV / Arup / Martin Hall*; 7, 8, 14 *Marcel Lam*; 9, 10, 12, 13 *Arup*.

10. Hong Kong's first communications-based train control (CBTC) overlay project uses data to control speed on the APM and thus increase capacity.

11, 12. For the extension of the upgraded APM, new trains were specified.

13. BIM was used to verify the route of a new strategy for airport systems cable containment: the cable support system was relocated to make way for the new APM platform.

14. The new APM platform.

1.

Planning Britain’s second high-speed rail line, HS2

1. HS2 will accommodate up to 18 trains per hour, travelling at speeds up to 400kph.

2. This map shows the route HS2 Phase 1 will take from London to Birmingham, and its link into the West Coast Mainline to enable travel further north.

3. The passenger experience on an HS2 train was modelled using virtual reality techniques.

Authors
Paul Johnson Colin Stewart

Introduction

Construction of HS2, Phase1, is now underway after the High Speed Rail (London – West Midlands) Bill gained Royal Assent in February and the main works civil engineering contracts were awarded in July. It will be Britain’s second high-speed rail line providing a new transport ‘backbone’ for the country with the potential to regenerate cities and provide new opportunities for communities. By delivering extra rail capacity and connectivity, it will ease congestion on the existing network and unlock opportunities for economic growth.

Extensive planning, design, and environmental studies, which informed both the route selection and wide-ranging stakeholder consultation, were a prerequisite to preparing what was the largest and most complex hybrid Bill ever presented to Parliament. The resulting legislation permits construction of Phase 1, the London to Birmingham stretch, of a line that will be extended further north, to Leeds and Manchester, in Phase 2.

The seeds of HS2 were sown in 2001, when Arup undertook a study for the Government into the potential for a high-speed link from London to the north. This was in the years after Arup developed the route for HS1, the Channel Tunnel Rail Link (CTRL), which opened in 2007. However, it was not until 2009 that High Speed Two (HS2) Ltd was formed as a result of a review of the UK rail network instigated by Lord Adonis, who was then Minister for Transport. It was at this point that Arup was engaged to undertake the initial studies for a new line, the locations it might serve, and the routes that could be followed.

Developing HS1

Arup’s appointments to HS2 contracts, particularly in the early feasibility phase, are largely due to its pivotal role in route selection for the CTRL. Dubbed ‘the Arup route’, this high-speed link from London to mainland Europe, first mooted in the late 1980s, also provided high-speed local commuter services and opened up brownfield sites for homes and commercial property, thus creating jobs and associated economic growth. Derelict land in areas

2.

Why a hybrid Bill?

Major infrastructure projects of strategic national importance fall outside the UK's standard planning procedures and require their own Act of Parliament, attained via the Bill process.

- Public Bills (the most usual) change the law as it applies to the general population.
- Private Bills change the law as it applies to specific individuals or organisations.
- Hybrid Bills are for legislation that affects both public and private interests. A hybrid Bill was the mechanism the Government chose to obtain planning permission and acquire the land to construct HS2.

Subsequent phases of HS2 will require separate legislation.

around King's Cross and St Pancras in central London, Stratford in east London, and Ebbsfleet chalk quarries in Kent were transformed such that thriving, growing communities have taken root there.

Many regard the route selection and development as the most important aspect of HS1 because the regeneration it brought made it environmentally and economically attractive. Stratford later became an important key to London's successful bid to host the 2012 Olympic Games.

Options for HS2

Arup was appointed early in 2009 for route engineering studies between London and the West Midlands. The scope included investigating:

- more than 2,000km of route alignments, in around 30 corridors
- more than 35 station location options, in inner London, outer London and Birmingham
- options for connecting to Heathrow Airport
- options for connecting to HS1
- broad options for extending the line to cities north of Birmingham.

3.

HS2 Ltd reported its initial findings to the UK Government at the end of 2009 and was then given the go-ahead to develop the design and undertake further public consultation in preparation for the UK Secretary of State (SoS) to make a decision on the preferred route.

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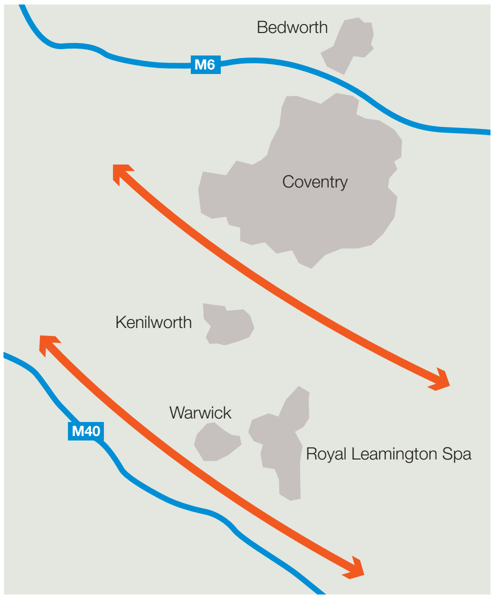

5.

4. Visualisation of a new interchange station close to Birmingham International Airport and the National Exhibition Centre.

5. The routes that offered most options for linking to northern cities ran alongside the M40 or in a narrow corridor south of Coventry and north of Warwick on the approach to Birmingham.

6, 7. Conducting ecological surveys.

Phase 1 route feasibility: 2009–2011

Key outputs at this stage were to identify feasible combinations of speed, journey time, engineering complexity, environmental impact and cost, in order to make the business case for a track optimised for speeds of up to 360kph, with an alignment future-proofed for up to 400kph. Previous studies had drawn only highly indicative lines on very small-scale plans, with broad arrowheads pointing to desired destinations. During the feasibility process, genuine 400kph alignments were drawn to determine whether previously suggested concepts could be designed and engineered. Operating up to 18 trains per hour at speeds up to 400kph has yet to be achieved anywhere in the world, yet infrastructure proposals made in the feasibility study had to meet this challenge.

The brief from HS2 Ltd specified that options following transport corridors, which were already in developed areas, should be included. This raised many issues. Following the M1 corridor, which runs north, and then west along the M45 corridor constrained the options for linking to the northern cities of the UK. The alternative M40 corridor had been developed as a gently curving alignment, but with curves too tight for a high-speed line to follow, and furthermore, the route around High Wycombe had been developed up to the motorway boundary. Whichever route was adopted would essentially require the crossing of the Chiltern Hills, an Area of Outstanding Natural Beauty. Further north on approach to Birmingham, the three major conurbations of Stratford-upon-Avon, Warwick and Coventry straddle the various corridors. Coupled with this were the hundreds of environmental constraints which were illustrated on a ‘measles map’ showing how hard it would be to thread the route though and minimise the impact. More than 70 route options and segments were considered.

Furthermore, studies were undertaken to see how a 300kph solution would differ from a 400kph route and how viable that might be. The outcome showed that in terms of weaving around environmental and property constraints, little could be achieved because such routes only shifted challenges from ‘Place A’ to ‘Place B’. In addition, a 300kph route would cost almost as much as a 400kph route to build (approximately 8% cheaper), insufficient to offset the long-term economic disadvantage of a lower-speed line. Station options had to be considered also, and this assessment was done in parallel with the route studies, the key finding being that the large footprint required for 400m-long trains made few choices immediately apparent.

Nevertheless, by mid-2010, Arup had gathered enough data to draw geometrically correct route and station options, then create a node-link diagram to allow a process of ‘paired comparisons’ against the major comparison headings. This process led to three major routing choices:

- Route 2: along the M40 corridor
- Route 3: a central route through Buckinghamshire, Oxfordshire and Warwickshire, to a triangular junction east of Birmingham, then into central Birmingham, and out northwards through Staffordshire, to join the West Coast Main Line, near Lichfield
- Route 4: largely parallel to, but not actually adjacent to, the M1.

These potential routes that either followed the line of an existing transport corridor, or were on land that could accommodate long, straight sections of track (such as the now

6.

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disused Great Central Railway line), were ranked according to environmental impact, cost, journey times and constructability, and Arup advised HS2 Ltd on the merits of each.

HS2 Ltd selected Route 3 as its preference, and Arup assisted in an initial public consultation, asking firstly if respondents felt that a new high-speed line was appropriate for the UK, and secondly their views on the preferred route. This stage of planning was brought to a conclusion when the SoS announced both the preferred route and the decision to proceed towards a hybrid Bill.

Delivering the hybrid Bill

The project to prepare the Bill was broken into manageable sections, and contracts were let in February 2012. The civil and design work was split into five geographical lengths of the route. Arup took on:

- developing Euston Station, and regeneration of its surrounding area
- approaches to Birmingham, including Birmingham Interchange Station, the terminus at Curzon Street, and the depot for rolling stock maintenance at Washwood Heath.

Work to create the Environmental Statement (ES) was split into four geographical sections for the purposes of Environmental Impact Assessments (EIAs). In addition, an Environmental Overview Consultant (EOC) role was established with responsibility for setting the environmental standards, bringing the EIA outputs together, and delivering the ES. Arup, assisted by AECOM and Corderoy, won the EOC contract, and independently won the EIA for the Birmingham Metropolitan area.

The countdown had now started on a highly complex process to submit the hybrid Bill by the end of 2013, as HS2 Ltd required. It meant that preliminary engineering and design, stakeholder engagement and consultation, EIAs, and compilation of the formal ES by the EOC needed to be completed within less than two years. A significant proportion of the content of the Bill – in particular that which rested on the consultation to shape, implement and deliver the public ES documents that were pivotal to gaining consent – was carried out by Arup, in partnership with firms that included AECOM (formerly URS), Grimshaw, Wilkinson Eyre and Costain.

The preliminary design was developed to include environmental mitigation, to propose the limits of land to be acquired to build the project, and as input for the EIAs. In the Birmingham Metropolitan area, although this was let as separate contracts for design and EIA, the Arup teams worked together as one integrated holistic team to maximise efficiency and reduce timescales, a successful way of working that was adopted by HS2 as the standard for subsequent contracts.

The Environmental Statement (ES)

The ES was the largest ever produced in the UK, and if anything truly defines the EOC contribution to Phase 1 it must be the single, fully integrated delivery programme it developed to encompass the activities of multiple organisations, producing hundreds of reports and documents, on diverse topics. Had the EOC role not been successfully executed, the hybrid Bill process – and therefore, the project start – could have taken substantially longer than it did.

As a first step, the EOC had to establish methodologies for the EIAs, as well as the standards and scope that would define their work. In itself, this element of the EOC role was complex because the emerging design would clearly influence the scope. Furthermore, the EIAs would need to be supplemented by the EOC's pan-route assessments of issues including operational noise and vibration, the socio-economic effects on potentially affected communities, waste management and carbon footprint during and after construction, and the resilience of the proposed railway: its ability to keep functioning during out-of-the-ordinary events such as severe flooding.

To ensure that all relevant issues would be properly assessed and consulted upon within the 26 community forum areas that HS2 Ltd had established along the preferred route, the EOC prepared a draft scope and methodology report for consultation. This provided the public, and interested organisations such as Natural England, the Environment Agency and Historic England (formerly English Heritage), with the opportunity to input into how the EIA was undertaken. When their feedback was absorbed into the draft report, and agreed by HS2 Ltd, work started on the EIAs (a process described more fully later in this article). The EIAs' output was collated by the EOC into a draft ES that was published online for consultation in May 2013. Six months later, the subsequent document that included amendments made as a result of the consultation was submitted to Parliament as part of the hybrid Bill process. Dubbed 'the main ES', this was published in hard copy and online and its 50,000 pages comprised five volumes and various supporting documents:

- Volume 1: introduction to HS2, the EIA process, and the alternatives considered to transform cities and communities at strategic, regional and local levels.
- Volume 2: EIAs for the 26 community forum areas on issues such as agriculture, air quality, community effects, cultural heritage, ecology, construction noise, local traffic and transport, and water resources.
- Volume 3: route-wide issues, such as climate effects, operational noise and waste management.
- Volume 4: off-route issues, such as effects on stations and depots remote from HS2.
- Volume 5: technical appendices.
- Supporting documents included the draft Code of Construction Practice, the Health Impact Assessment and the Equality Impact Assessment – all produced by the EOC and subject to public and stakeholder consultation in their draft and final forms.

8.

8. Arup SoundLab was used during consultations to enable members of the public and government ministers to listen to auralisations of the noise impact of the railway and the effects of mitigation.

9. An animated aerial visualisation was produced for public consultation and to assist the Select Committee in their deliberations. This image is a typical snapshot of the route: near the small village of Quainton, Buckinghamshire, it shows mitigation including balancing ponds which are used to collect surface water prior to controlled discharge to local watercourses.

Hybrid Bill process

HS2 is one of the largest single infrastructure projects the UK has ever undertaken: at 225km, it is more than double the length of HS1. The Government's chosen consenting mechanism – the hybrid Bill – meant that not only did the EIA processes and the ES have to comply with EU and domestic legislation, and be made available for scrutiny and comment (as is usual for large infrastructure projects), but there was also a 'petitioning period' after the ES was submitted.

The petitioning period, managed by Parliament through its officials and elected members (MPs), ran from November 2013 to February 2014, and during this time any individuals, groups or organisations that could demonstrate they were directly or especially affected by the proposals could oppose any aspect of the Bill, though not the principle of the project. Petitions were considered by a Select Committee of representatives drawn from the two Houses of Parliament (the Commons and the Lords) who had the power to change the Bill if they agreed with the objections.

In response to petitions and other public representations, the design and EIA teams, working with the EOC, prepared design modifications (known as Additional Provisions), each accompanied by additional ESs that were made available for public consultation. During 2014 and 2015, the EOC prepared five supplementary ESs for consideration by the Select Committee. Public engagement was integral to the entire process.

Public consultation

HS2 Ltd, supported by the design team, the EOC and the EIAs, consulted with the public in many and varied ways: through presentations, individual and group meetings, multi-party forums, public exhibitions, the internet, and via online media, for example. In all these forms of consultation, the visualisations and sound demonstrations developed by Arup using its 3D visualisation techniques, and SoundLab technology, proved an immensely valuable asset.

Using SoundLab it was possible to generate verified demonstrations of how HS2 might sound at various locations along the route, then present this to local stakeholders neutrally, to allow them to make up their own minds about the impact. As part of this process, SoundLab was used to demonstrate the effect of noise reduction measures: more than 75% of the surface sections of HS2 have

9.

The timetable from route feasibility to Royal Assent	
2009–2011	Route feasibility studies.
2012–2013	Design development, Environmental Impact Assessments (EIAs), draft and main Environmental Statements (ES) and supporting documents. Hybrid Bill documents submitted November 2013.
2013–2014	Petitioning period. Consideration by Parliamentary Select Committees (Commons and Lords).
2014–2015	Additional Provisions. Consideration by Select Committees.
2016–2017	Select Committee report February 2016. Further consultation work before Bill had its final reading in the House of Lords, then received Royal Assent to become an Act of Parliament in February 2017.

been designed to include noise barriers such as cuttings, fences and landscaped earthworks.

The demonstrations, which were based on recordings, and rigorously tested and reviewed by independent panels of specialists, were available in three verified forms: in SoundLabs at Arup's offices, via the portable SoundLab Lite which could be moved to locations anywhere along the proposed route, and in special sound booths installed at public exhibitions during the consultation period. The demonstrations illustrated what high-speed trains might sound like at different places along the route, and at different distances from the line, with and without noise mitigation.

In addition to the visualisations that were created for inclusion with the sound demonstrations, Arup 3D visualisation techniques were used to create 300 verified images of the railway showing before and after construction images. The 3D models were also used to develop a helicopter fly-through of the entire route for the public to see, and to assist the Select Committee in decision-making.

The passenger experience was simulated in virtual reality, enabling a virtual journey along the route to aid design considerations.

Route-wide waste management

The EOC recommended that most of the earthworks material excavated during construction of the route be used either for engineering purposes or, where practicable, in the landscape design to integrate and blend the railway into its surroundings. This strategy (derived from a similar successful approach to managing construction waste on the HS1 project) would also minimise construction traffic on local roads, minimise the carbon footprint of the project, and provide the most economical and sustainable solution.The strategy was adopted within the hybrid Bill and will be implemented when construction begins.

Environmental Impact Assessments

Work on the Birmingham Metropolitan EIA was very similar to the detail of all the other EIAs, so it is worth considering how it was approached. It included detailed agricultural, community, ecological, local traffic and footpath surveys within the community forum areas, and it was also designed to aid the integrated route design and assessment process so that impacts on the environment and local communities were avoided, minimised or mitigated.

Where possible, improvements were suggested, for example by re-connecting fragmented areas of woodland close to the proposed route. Other mitigation measures included providing extensive noise barriers, wildlife habitat creation, and planting trees and hedges to act as visual screens.

Smartphone applications were developed to capture survey data in the field that included specific apps for bat, badger, reptile and amphibian surveys, and a general app that enabled the location of any species to be recorded, while simultaneously enabling users to look up relevant conservation status when working in the field. The app meant that data was captured in a secure and consistent manner.

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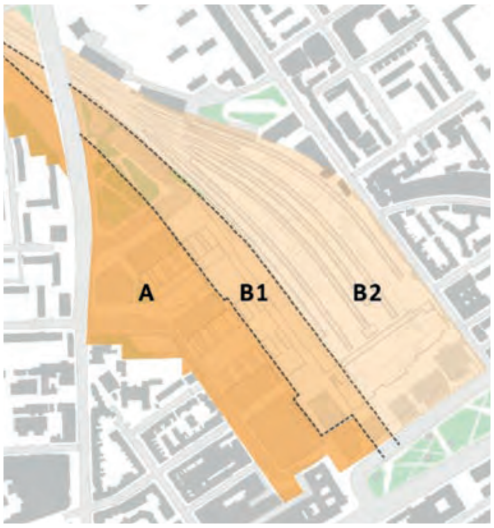

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10, 11. Euston Station: how it might look and how the station will be delivered in three separate phases.

12. This diagram shows the need for deceleration lanes to enable high-speed trains to stop at stations, without impeding other trains travelling at high speed on the same line.

13. A tapered design for porous portals will limit pressure as HS2 trains enter tunnels.

14. Porous portal: scale model testing.

Design and engineering

Developing the route options and preliminary design demanded innovative technical analyses and detailed planning. Of particular note are the following topics, each of which is discussed further in the remainder of this article:

- Euston Station: designing a high-speed station to operate within a busy conventional rail station
- Aerodynamic assessment of tunnels
- At station approaches, designing state-of-the-art acceleration/deceleration tracks to enable trains to leave and join the HS2 line
- Managing the Rayleigh wave phenomenon
- Curzon Street Station: parametric modelling for the proposed roof
- Washwood Heath: selecting the site for the rolling stock maintenance depot
- Future-proofing: a plan for developing the links to Phase 2.
- How 4D models benefited the Employers' Requirements Design process

Euston Station and regeneration

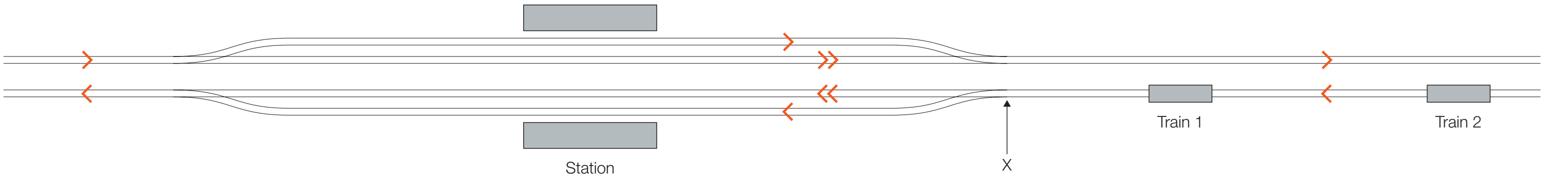
Euston is currently the fifth-busiest rail terminus in London serving the West Coast Mainline to the north of England and Scotland, and regional services north of London. With extensive connections to London Underground, the second-largest bus station in London, and plans for a station for Crossrail 2 running east to west across the city, it has the potential to provide the connectivity needed for the new HS2 London terminus.

The design and construction challenge relates to the tight urban fabric surrounding the station. Redevelopment will require acquisition of adjacent properties and significant work, above and below ground, to connect it into the existing transport network to create an integrated multi-modal transport interchange for trains, buses, taxis, cycles and pedestrians, with links to the busy nearby King's Cross and St Pancras Stations complex.

The vision that Arup, with Grimshaw and HS2 Ltd, worked to develop is that it must become a 21st century terminus that creates value in the immediate environs and gives rise to regeneration opportunities. Arup influenced, guided and advised on the design of the station, and the plan for the surrounding area. This meant leading a multidisciplinary team of specialist engineers, architects, planners and consultants and working closely with HS2 Ltd to foster a collaborative environment with other partners on the project. The outcome is a plan for the staged delivery of Euston to match the joint service level requirements of both HS2 and the existing conventional railway.

The projected increase in the number of trains and passengers to be accommodated through Phases 1 and 2 is significant and delivery has been planned accordingly (see image 11):

- The initial Stage A station will be constructed alongside the existing station and scheduled to open for service in December 2026, as part of HS2 Phase 1, with six platforms.



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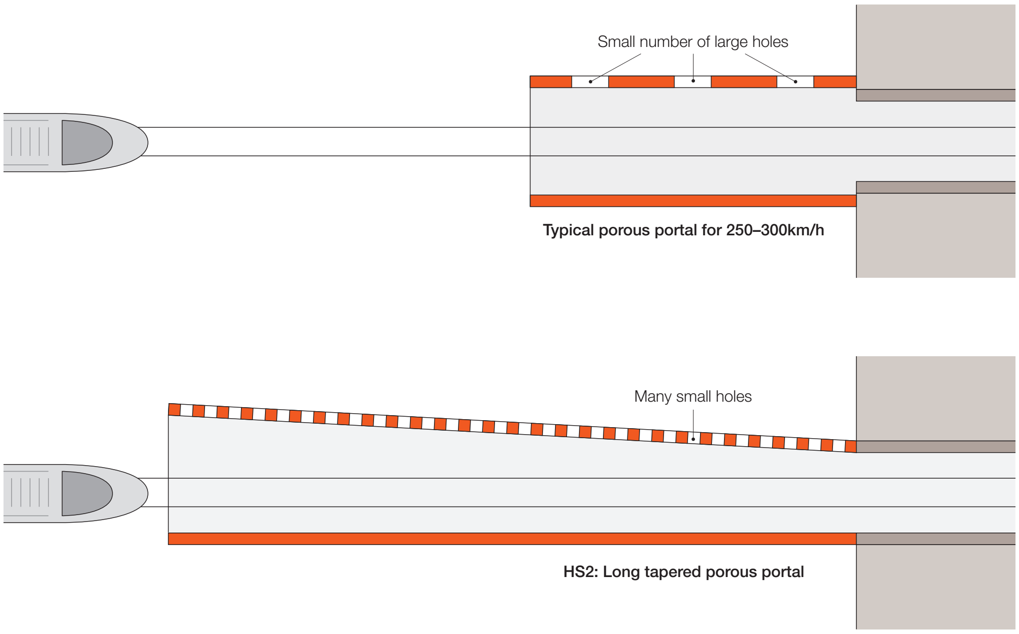

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- The Stage B1 station will be constructed within the curtilage of the existing station (platforms 14–18) taking advantage of the reduction in conventional services resulting from migration of services and passengers to HS2. This will open in December 2033 as part of Phase 2.
- The completion of Euston with renewal of the existing station (13 platforms) will follow as Stage B2 (outside the Phase 2 Act works).

Aerodynamic assessment of tunnels

Trains will run through tunnels on HS2 at higher speeds than anywhere else in the world. This will mean unprecedented challenges relating to air pressures in the tunnels, sudden changes of which may cause discomfort or injury to passengers. Using specialised aerodynamic analysis software, Arup quantified the trade-offs between increasing tunnel sizes (leading to higher construction cost), versus specifying rolling stock with greater pressure-tightness (which can limit choice of suppliers and/or increase cost).

High speed also means that sonic booms arising from pressure waves inside the tunnels can be emitted from the tunnel portals. These can be prevented by providing a perforated entrance region (porous portal) to limit the build-up of pressure when the train enters the tunnel. As the entry speed will be so high, HS2 tunnels will require exceptionally effective porous portals which will be delivered through a novel tapered design developed by Arup in collaboration with Professor Alan Vardy of the University of Dundee. The design has been validated and optimised through 1:25 scale model testing, leading to definition of the portal length and geometry for the project.

Station approaches

The number of stations on a high-speed rail route affects both the running speed and capacity. In order to maximise both, trains that need to call at an intermediate station must do so without impeding the passage of non-stopping trains running at full speed. The HS2 design speed of 400kph is the first in the world, so there was no existing blueprint for running such a service and an innovative approach was required. Arup developed models to examine what could be done.

At a speed of 400kph, and with trains following each other at three-minute intervals, there is a physical gap of 20km between trains. So it is critical that the infrastructure design enables stopping trains to decelerate enough to leave the main line, and accelerate enough to join later in a subsequent gap, without disruption to flow. The scenario is shown in image 13, where Train 1, which needs to stop, can begin to slow down on the main line until the headway reduces to two minutes, the minimum possible without impeding the progress of the non-stopping Train 2. By point X, Train 1 is still travelling at 230kph, but it now has to move out of the way of Train 2, and a set of points capable of operating at 230kph is needed. Train 1 then needs a further 2.0–2.5km to stop, so its deceleration lane is quite lengthy. The same principle applies to trains departing from the station as they accelerate to full speed.

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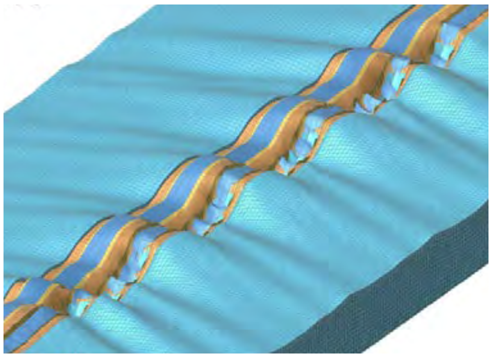

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15. A proposal for the station at Curzon Street, Birmingham, with an innovative flowing roof form.

16. The Rayleigh wave phenomenon relates to ripples in the ground surface caused by train passage and accentuated by high speed. Typical deformations are illustrated here, magnified for clarity.

17. The Wendover Dean Viaduct in Buckinghamshire will maintain the rail alignment as the railway crosses a valley. An animated 4D construction sequence was created to assist in decision-making.

The Rayleigh wave phenomenon

Moving trains cause ripples in the ground surface known as Rayleigh waves that travel away from the train at a speed that depends on the soil stiffness. If the train speed approaches or equals the soil wave speed, a harmful resonance-like dynamic condition ensues. Mitigation involves stiffening or replacing the soil, or providing an engineered structure to support the railway. Arup's dynamic analysis, based on the work of Professor Peter Woodward at Heriot-Watt University, provided increased understanding of how Rayleigh waves might affect the HS2 railway design and how they could be avoided. The analysis helped to quantify the acceptable properties for in-situ soils and materials used in embankments and evaluate various mitigation measures.

Curzon Street Station

The Birmingham terminus at Curzon Street, east of Birmingham city centre, will be located partially on the site of the former Birmingham Station, a Grade 1 listed building, built in 1838 and closed in 1966. It was once a hub of activity linking Birmingham to London, and when HS2 Phase 1 is completed, it will resume that role. The regeneration in the surrounding area is predicted to create 36,000 jobs and 4,000 homes.

Arup, with Wilkinson Eyre, planned the station and developed an architectural concept for the roof of the new Curzon Street Station to show the type of innovation that may be possible there. The concept features an inclined decaying sine wave. The building grids are 'out of phase' with each other to generate a skewed undulating appearance for the roof structure. This concept was established by using the Grasshopper plug-in to Rhino to take on the architect's surface profiles and further develop them into the structural geometry, including relevant offsets and engineering rationalisation.

Washwood Heath maintenance depot

The proposed site of the HS2 rolling stock maintenance depot, on land formerly occupied by a large engineering manufacturer, was the subject of much debate. Opponents of HS2 Ltd's proposal maintained that if the site remained earmarked for manufacturing, rather than train maintenance, it would create more jobs in an area where they were needed. Arup worked with HS2 Ltd, using GIS 3D modelling techniques, to reshape the proposed depot such that it would take up almost a third less land than originally envisaged. This meant the size of the site remaining for redevelopment would be approximately 50%. Following a review ordered by the Parliamentary Select Committee, HS2 Ltd and the landowners agreed to the compromise which it is estimated will create up to 3,000 manufacturing jobs.

Future-proofing

When Phase 1 opens in 2026, the maximum operational service level will be 10 trains per hour, each carrying up to 1,100 passengers. The projected increase for Phase 2 is a maximum operational service level of 18 trains per hour on the Phase 1 route, which equates to the absolute maximum line capacity for a two-track high-speed railway. The designs for the stations, junctions and approaches make provision for the completion of Phase 2 and beyond. At Euston, this manifests itself as a grade-separated junction at the head of the approach, which increases the station operational capacity from 14 trains per hour to 18 trains per hour. At Birmingham Interchange, these service levels are achieved by grade-separated junctions north of the station.

Employers' Requirements Design

In parallel with the latter stages of the hybrid Bill process, HS2 requested preparation of an Employers' Requirements Design (ERD)

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to increase confidence in all aspects of the planning, design and construction of the works, in order to inform the Invitation to Tender (ITT) documents for the main civil works, Early Contractor Involvement (ECI) contracts, and the next stage of design procurement for the stations. The ERD also furthered the process of mitigating effects on the environment. Arup developed 4D models to help HS2 Ltd better understand the construction sequence and therefore better explain it to stakeholders. In some instances this helped to remove or lessen objections to the scheme.

Summary

Developing the design, environmental assessment, and mitigation measures and preparing the Bill submission have undoubtedly enhanced and extended learning from HS1. It has clearly strengthened knowledge and understanding of how to develop high-speed rail links in settings that are new to the concept.

Arup is proud to have been a key part of this project so far, and looks forward to the construction and opening of HS2 as a user-friendly and visionary transport system that, as a result of its speed, will change how people choose to travel and where they live and work.

Authors

Paul Johnson, Arup Fellow, was Arup Global Environmental Leader and Head of Environment for Rail Link Engineering on HS1, and Project Director of the EOC on HS2 Phase 1.

Colin Stewart is Global Rail Leader. He was the initial Technical Director for HS1, and has led all Arup HS2 work from 2009 to 2017.

Project credits

Client: *High Speed 2 (HS2) Ltd* Project owner: *Department for Transport, UK* Partners: *AECOM, Grimshaw, Wilkinson Eyre, Costain, Corderoy* Route location and alignment, transport planning, requirements management, bridges, tunnels, geotechnical engineering and earthworks strategy, rail engineering and systems, highway design, flood and drainage, cost management, station planning and design, architecture, landscape design, acoustics, aerodynamics, operational planning, construction planning, risk management, GIS, visualisation, stakeholder engagement and consultation, environmental impact and assessment: *Arup – Musa Abbass, Muhammad Abdullah, Melody Ablola, Roman Acha Valls, Obie Achigbu, George Acuna, Lisette Adams, Paul Adams, Jenny Adams, Ekpes Akpanudoh, Thomas Aldridge, Steve Allen, Eloise Allsop, Mohammed Al-Sharif, Richard Ames, Daniel Amir Siassipour, Lucy Anderson, Sachin Anshuman, Matt Antrobus, Fernando Aparicio Banere, Tom Armour, Andrew Armstrong, Mike Ashford, Linn Aspinall, Ben Aston, Oliver Atack, Clive Aubrey, Mark Ayers, Chris Ayerst, Chris Baines, Bob Baker, Chris Baker, Ian Bakewell, Andrew Bamforth, Jorge Barbeito, Paul Barlow, Alison Barmas, Daniel Barnes, Oliver Barnett, Mat Barnett, Imelda Barry, Bonnie Bartlett, Souman Barua, Marynet Bassily, Adriani Bastouni, Alan Beadle, Faye Beaman, Joseph Bearne, Anne Bearne, Claire Beedle, Chris Bellingham, Jonathan Ben-Ami, Rosie Bendix, Lee Bennett, Stephen Bennett, Nicholas Berg, Harry Betts, Olly Bewes, Megha Bhavsar, Ian Biddlecombe, Rachel Birrell, Alys Black, Kim Blackmore, Robert Blair, Sue Blanch, Max Blatiak, Rosalind Blewitt, Jessica Boath, Simon Bone, John Border, John Bourke, Paul Bourke, Emily Bowden-Eyre, Daniel Boyce, Alistair Boyce, Richard Boyd, Ian Braithwaite, Ross Bramley, Hal Bransby, Grainne Breen, Simon Brimble, Sam Brizzell, Dave Brogan, Luke Brotherton, Claire Brown, Richard Brown, Tansin Brown, Carol Brownridge, Chris Bruce, Alex Bryson, Justin Buchanan, Cem Budak, Michael Bull, Chris Burgess, Jody Burley, Lindsay Burt, Diane Burt, Jonathan Burton, Ian Burwood, Stephen Bussell, Mark Buttimer, Mike Byrne, Yan Cai, Alison Caldwell, Simon Camm, Rory Canavan, Jamie Cardoso, Matt Carlson, Jenny Carrington, Stephen Carter, Phil Carter, Ross Carter, Seb Cartmell, Mersade Cartwright, Luke Casey, Roberto Castagnari, Sarah Cauldwell, Ringo Chan, Drew Chapman, Deirdre Chapman, Tim Chapman, Steph Chapman, Steve Chapple, Odetta Charles, Wayne Charles, Riz Chattha, Vululami Chauke, Danielle Chen, Alex Chen, Man-Yiu Cheuk, Noble Chigwedere, Annie Choi, Paul Clark, Andrew Clarke, Chris Clarke, Phill Clay, Harry Clements, Tom Clifford, Scott Clyne, Brian Coles, Adrian Collings, Jaki Collison, Mike Colman, David Connolly, Steven Cook, Danny Cooley, Antony Cooper, Jackie Corbett, Tom Corke, Nathalie Cornilleau, Riccardo Corti, Noel Cotter, Jeremie Coullon, Tian Coulsting, Peter Court, Ben Cox, Tim Cresswell, Kevin Cressy, Mike Crick, Jamie Crispin, Livvy Cropper, Paul Cruise, Wilma Cruz, Sebastian Cumpatescu, George Cusworth, Artur Czarnecki, Harry Dade, Paola Dalla Valle, David Dallison, Edgars Damlics, Rob Davies, Paul Davies, Helen Davis, Ian Davis, Matthew Davis, Reem Dawood, Ken Day, Richard De Cani, Milagros De La Cruz Gonz, Brian De Mello, Vinicius De Siqueira, Alan Dean, Balduino Del Principe, John Dell, Mike Devriendt, Kiran Dharni, Jessica Dias, Simon Dicken, Paul Dickens, Tim Dixon,*

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1 Hong Kong Midfield Concourse: Kerun Ip /AAHK; 2 Second Avenue Subway, New York: Arup; 3 Sacred Heart Cathedral, Kericho, Kenya: Arup; 4 Second Avenue Subway, New York: Ari Burling; 5 Ecological surveying for HS2: Arup; 6 San Francisco Museum of Modern Art: Jeff Goldberg; 7 National Forum of Music, Wrocław, Poland: Lucasz Rajchert; 8 Sacred Heart Cathedral, Kericho, Kenya: Edmund Sumner; 9 Hong Kong Midfield Concourse: Kerun Ip /AAHK.

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