# The Arup Journal

1966

2016

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*The Arup Journal is our 'journal of record', documenting some of our more challenging projects and explaining how we approached them. The focus on technical detail is a hallmark of the publication and, in my view, the reason for its longevity.*

*Since its launch in 1966, the Journal has published more than a thousand articles, whose common thread is the quality of the work, reflecting the creativity and calibre of the people who worked on the projects.*

*I would like to especially thank and acknowledge our clients and collaborators who worked with us on the projects republished in this 50th anniversary edition. In every article I am reminded that successful design in the built environment is always a product of teamwork.*

**Gregory Hodkinson**
Chairman, Arup


# 1960s

**Sir Jack Zunz** joined Arup in 1950, and was Co-Chairman of Arup from 1984 to 1989.

*Looking back, the 1960s were very formative times to be an architect or an engineer. We didn't necessarily have the sophisticated tools, the variety or choice in materials or as much money as we have today, but exciting ideas and ideals were bubbling across the industry. New concepts were taking hold. Prefabrication was the perceived means whereby the country's construction industry could become more productive and in particular the housing crisis could be solved.*

*This was also the decade when engineers started using computers. During the 1950s we knew that computers were coming but were limited in practical applications. But by the 1960s some engineers had learnt to write their own programs. Computers were generally based at some universities and in the premises of their manufacturers. We used the machines made by Ferranti in their Newman Street offices, as well as one based at the Northampton Institute (now City University). Computers were in rooms full of cupboards housing large numbers of thermionic valves. One hired these computers by the hour, some 'runs' taking many hours. One of the many hazards were not infrequent power failures when one would have to start all over again.*

*As the 1960s progressed we took advantage of this rapidly developing technology and acquired our own computers. We were one of the first consulting engineering practices to do so and people would come and gawp at the seemingly amazing things we could get them to do. All this was many years before the concept, advent and use of personal computers.*

*It was an incredibly formative decade in other ways too. A consequence of Ove articulating his ideas about integrating architecture and engineering led to the formation in 1963 of Arup Associates, where these concepts were put into practice. It was also the decade when we were beginning to widen our horizons into infrastructure projects and a number of specialist disciplines.*

*But our work on Sydney Opera House probably dominated these years and the firm became known more widely. That Sydney Opera House happened at all is really quite miraculous. Jørn Utzon who won the international competition with a sketchy and ill-defined scheme left the project in 1966. Somehow, despite much controversy and many setbacks, it was completed in 1973 and is now a World Heritage Site. It simply couldn't happen today.*

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# Snape Maltings Concert Hall

Of all the projects Arup worked on during the 1960s, the transformation of a disused malt house into a world-class concert hall in the tiny English village of Snape, in Suffolk, must rank as one of the more unusual.

The project sprang from the need to create a new and permanent venue for the annual Aldeburgh Festival, founded in 1948 by composer Benjamin Britten, singer Peter Pears, and writer Eric Crozier. This popular event had outgrown the local halls and churches where it was originally hosted, so in a letter to Ove Arup in 1965, festival manager Stephen Reiss asked whether the firm could examine the potential of a recently closed maltings for conversion into a concert hall, with opera facilities.

Ove gave the job to Derek Sugden, an engineer and a partner in Arup Associates, the firm's integrated architecture and engineering practice. Derek later went on to found the firm's now well-established acoustics consultancy. The brief that Derek's team developed in collaboration with Britten and Pears defined Snape Maltings as it is today: a concert hall with distinctive and widely admired acoustics, in a building that respects its rural surroundings and industrial heritage.

**Defining features**

Several factors contribute to the acoustic quality of the hall:

First, the selection of the maltings building shell provided the classical 'shoebox' plan geometry for a concert hall that could provide excellent lateral reflections.

Second, the walls were grit-blasted, sealed, heightened and topped with a roof that is relatively steep for a concert hall to achieve the preferred hall volume. This resulted in a reverberation time of two seconds when the hall is occupied.

Third, the roof lining was stiffened to avoid excessive low-frequency absorption, and traditional cane chairs were specified, also to limit sound absorption.

In addition, all the mechanical and electrical works were designed to keep noise and running costs to a minimum.

Overall, however, it was the way the various elements of the project came together that created such an excellent balance of intimacy, reverberance, clarity and loudness.

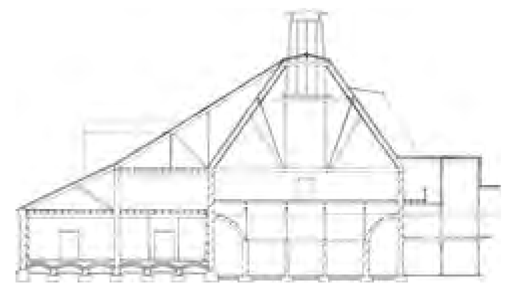
**How it all began**

Describing the project as it was seen at the start, in an *Arup Journal* article published in June 1967, Derek said:

"The brief was for a concert hall to seat between 700 and 800. It was to be provided with lighting facilities for opera, an orchestra pit, and with a removable proscenium. It was to have a restaurant and changing rooms. It was to be wired for the BBC for recording during the festival and for the Decca Record Co. for stereophonic recording... The stage was to be the full width of the auditorium, to be 40ft deep, 4ft above auditorium level and to have a 1ft rake."

The Arup team agreed with the festival committee that the hall should be designed specifically as a concert hall, with certain facilities for opera. It was strongly felt that the whole conversion, inside and out, should continue to reflect the character of the maltings and that as much of the existing structure as possible should be preserved.

The overall design called for the removal of the long wall between two galleries of the existing building, which in turn made it essential to relocate the ridge of the roof to the central line of the new auditorium space. It was agreed that the best solution to achieve the desired hall volume meant retaining as much of the roof height as possible. The slope designated for the roofline was, in fact, a compromise between the two existing rooflines (see diagrams).



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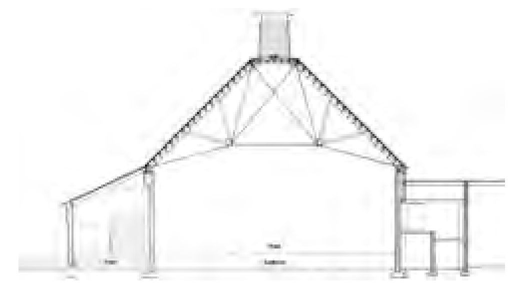

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The smoke hoods that were once functional for the barley malting process, and key to the character of the building, were retained as part of a low-energy ventilation system.

**Legacy**

Snape Maltings was a milestone project for Arup's work in concert hall design, and it paved the way for later acoustics consulting projects at Arup, including Glyndebourne Opera House (see page 42) and the Bridgewater Hall in Manchester.

Derek's philosophy for the project embraced the concept of total architecture. He said in his *Arup Journal* article:
"I believe it is also dangerous to talk about acoustics in an abstract way, to divorce them from their physical surroundings, because the whole architecture of the space in which music is made is as much responsible for our whole response to the music. It is as dangerous to talk about only the acoustics of a hall as to think we can rely on only our intellect for judgement."

This holistic approach meant the firm delivered a concert hall at Snape that is as effective today as it was when it opened to the strains of Benjamin Britten's specially written overture 'The Building of the House' in 1967.

Snape Maltings: arup.com/journal41967

1. The interior of the concert hall shows the sensitive transformation of a traditional malt house into a world-class classical music venue.

2. Cane chairs, made from locally sourced materials, minimised sound absorption.

3. The exterior was designed to align with the hall's historical context and rural location.

4. Before conversion.

5. After conversion: height was added to the walls and a relatively steep roof pitch gave the hall its required volume.

**Richard Cowell** is an architect specialising in acoustics and related specialist fields. In the 1980s, he co-founded Arup Acoustics with the late Derek Sugden.

*In my view, the enduring success of Snape Maltings Concert Hall is founded on Derek Sugden's passionate dedication to realise its purpose, together with the multidisciplinary support of his colleagues in Arup Associates. A careful amalgam of technical rigour and artistic insight created a performance space supportive of musicians and a listening experience for audiences that was of the highest standard. The acoustic reputation is first rate, and recognised globally.*

*The designers were pioneering when it came to sustainable design and construction. By reusing the maltings, use was made of valuable heritage. The ventilation system is low-energy, using natural air extract through modified forms of the original smoke hoods. Many materials, including bricks and the seating, were made locally. There was predominant use of local labour.*

*Simplicity and very effective integration of architectural and engineering disciplines, hallmarks of Arup Total Architecture, were fully realised here.*

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# York Minster

1. Foundations that were almost 800 years old needed to be strengthened.

2. Cutaway diagram demonstrating the prestressed concrete foundation solution.

When York Minster was built between 1225 and 1472 AD, procedures for calculating the required foundations were a thing of the future. So it's a tribute to the know-how of the late-medieval constructors, therefore, that the cathedral remained standing for so many years because in the mid-1960s, when Arup was asked to investigate cracks in the central tower area, the firm discovered the area of foundations was too small for the stratum of clay immediately underlying the building. The effective area of the footings was such that the factor of safety against shear failure in the clay was possibly as low as 1.3, and the masonry below floor level was badly deformed in bending, and cracked in shear.

To make the superstructure safe for the next millennium, the foundations of the four main piers supporting the central tower had to be strengthened. Each pier was carrying a vertical load of about 3,850 tonnes at floor level and with the masonry in delicate condition, it was essential to use a method of strengthening that would least disturb the existing footings. The scheme Arup selected had prestressing as its central element.

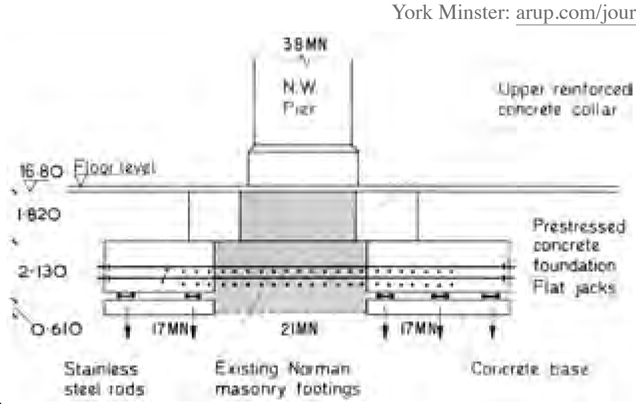
David Dowdrick, writing in *The Arup Journal* in 1970, detailed the work on the north-west pier which was largely replicated on the other four corners of the tower:

"It was decided to surround the Norman footings in concrete, incorporating the north-west pier and the adjacent nave and transept columns into one huge footing about 14.5m square. This would utilise all the cracked masonry footings as well as providing some completely new areas of footing in concrete. The total effect would be to spread the load from the columns over a much larger area of clay. The new average bearing pressure on the clay would be approximately 290kN/m$^2$, improving the safety factor against shear failure in the clay from about 1.3 to 2.5."

David explained that the new concrete and the ancient masonry were unified by prestressing them together. "There are four layers of main prestressing rods, two layers in each orthogonal direction passing right under the main pier, thus providing the tensile reinforcement necessary in the bottom of this large spread footing. This main part of the new foundation is 2.1m deep with an average compression due to the prestress of only 0.86 N/mm$^2$."

After detailing the remainder of the prestressing process, he went on to explain that the prestressing hardware was made of stainless steel, specifically manufactured for the purpose. It was recognised that this was, in David's words: "a once-for-all conservation operation with a life expectancy of hundreds of years."

York Minster: arup.com/journal31970

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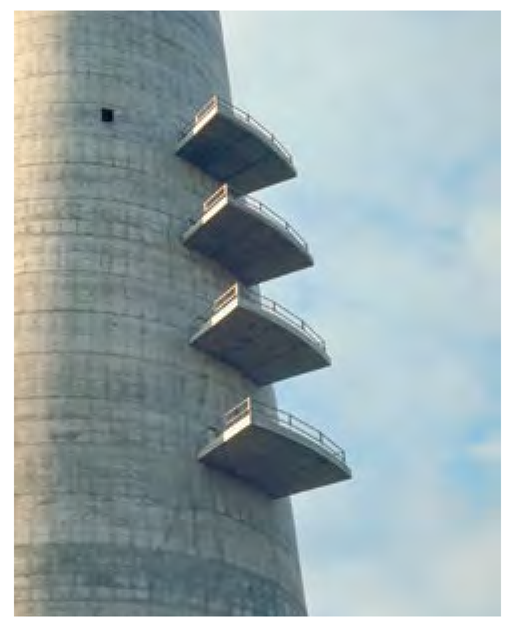
# Emley Moor Tower



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1. Emley Moor Tower has broadcast TV signals across the Yorkshire landscape since 1969.

2. The tower's reinforced concrete structure was designed after careful analysis of wind and vibration effects.

On a fine day, the Emley Moor television tower in West Yorkshire can be seen for miles around. At 330m, it is the UK's tallest structure (the top is higher than The Shard), and more than 1.5 million people rely on it for their digital terrestrial television channels.

Its height, in such an exposed location, makes the tower susceptible to the effects of ice and wind, yet research carried out by Arup in the 1960s means it is well equipped to withstand the forces of nature. Since it was constructed more than 40 years ago, it has proved sturdy and resilient.

The story of Emley Moor Tower goes back to 1969 when the guyed structure collapsed due to an accumulation of ice that increased the area exposed to wind. This resulted in the loss of television programmes in a large and densely populated area of Yorkshire.

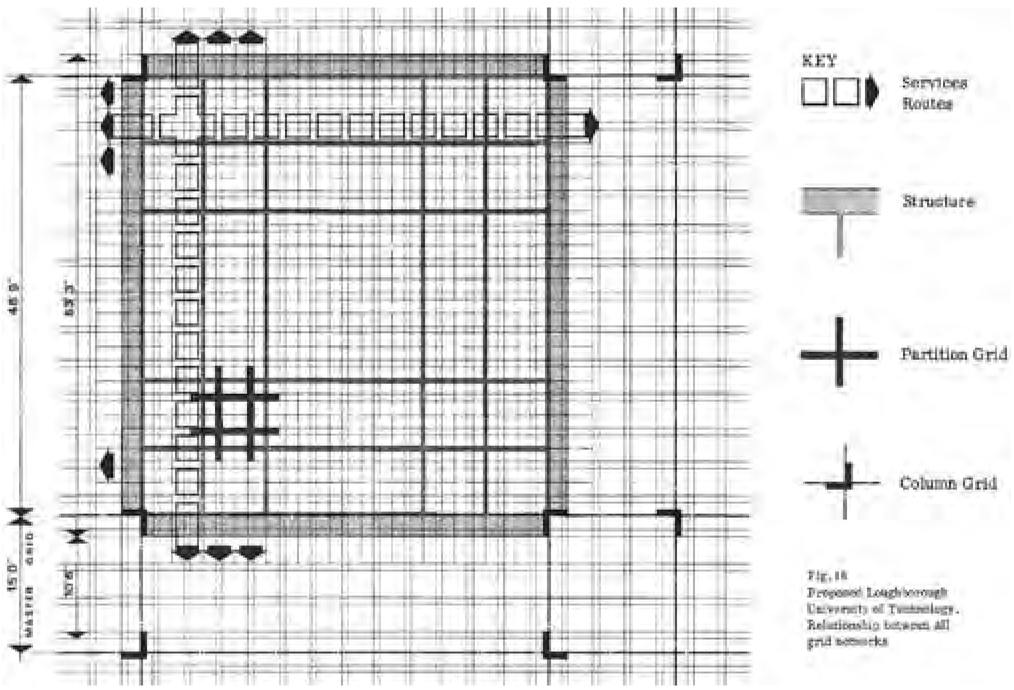
To restore the previous level of coverage and enable new services, the UK's Independent Television Authority immediately authorised a feasibility study for a new structure, inviting Arup to undertake the study. It was the start of a project that involved the firm in the fast-developing arena of telecoms and broadcast infrastructure.

Key considerations included working with ground conditions that incorporated sandstone and coal seams, and examining issues such as how to protect the tower from lightning in stormy weather and prevent ice formation in the latticed and guyed steel structures in cold weather. The analysis of wind and vibration measurements was careful and detailed, and led to the development of techniques that the firm would further refine in future years as the demand grew for tall structures.

Work on the project is recounted in two articles in *The Arup Journal*: 'The Emley Moor television tower' by Andre Bartak and Mike Shears, March 1972; and 'Wind and vibration measurements at Emley Moor' by Mike Shears, September 1974.

Emley introduction: arup.com/journal11972
Emley wind testing: arup.com/journal31974

# Concrete system building

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Opportunities to test and refine radical ideas for using concrete systems abounded in the fast-expanding higher education sector of the mid-to-late 1960s. Seats of learning as varied as ancient Oxbridge colleges, Victorian redbrick universities, and the planned campuses of entirely new institutions wanted inspirational new buildings to accommodate an influx of students. Teaching and living spaces built quickly and stylishly to a tight budget were in high demand.

Arup Associates' total architecture approach was well suited to meeting these briefs and there was no better test bed for applying industrial processes to construction. The construction methods refined during these years transformed techniques for the design and construction of large concrete buildings in ways that were easily transferable to other sectors, notably housing and office building.

**Metallurgy and Materials Building, Birmingham University**
This seminal building was conceived as an exercise to move the construction industry towards a modular approach. Completed in 1966, it was Grade II listed in 1993, and received a Certificate of Excellence in the Mature Structures Category of the 2011 Concrete Society Awards.

Sir Philip Dowson explained the fundamental principles of the construction method in a speech given to the RIBA in February 1966 that was later published in *The Arup Journal*:

"The construction method, based on an assembly of separate 17 ton, 20ft square, precast concrete tables, was radically different from anything we had ever attempted before.

"We had been thinking, for some time, in terms of 'deep' laboratories, with all the service rooms planned internally, to serve laboratories on the perimeter, as they do in this building. Coupled with this, we have been experimenting with a three-dimensional geometry of multiple grids, which were related but not co-incident, covering planning, services, structure and so on. This geometry is essential to the organisation of a highly disciplined and repetitive building of this nature."

The structural unit of the Metallurgy and Materials Building is a square tower,

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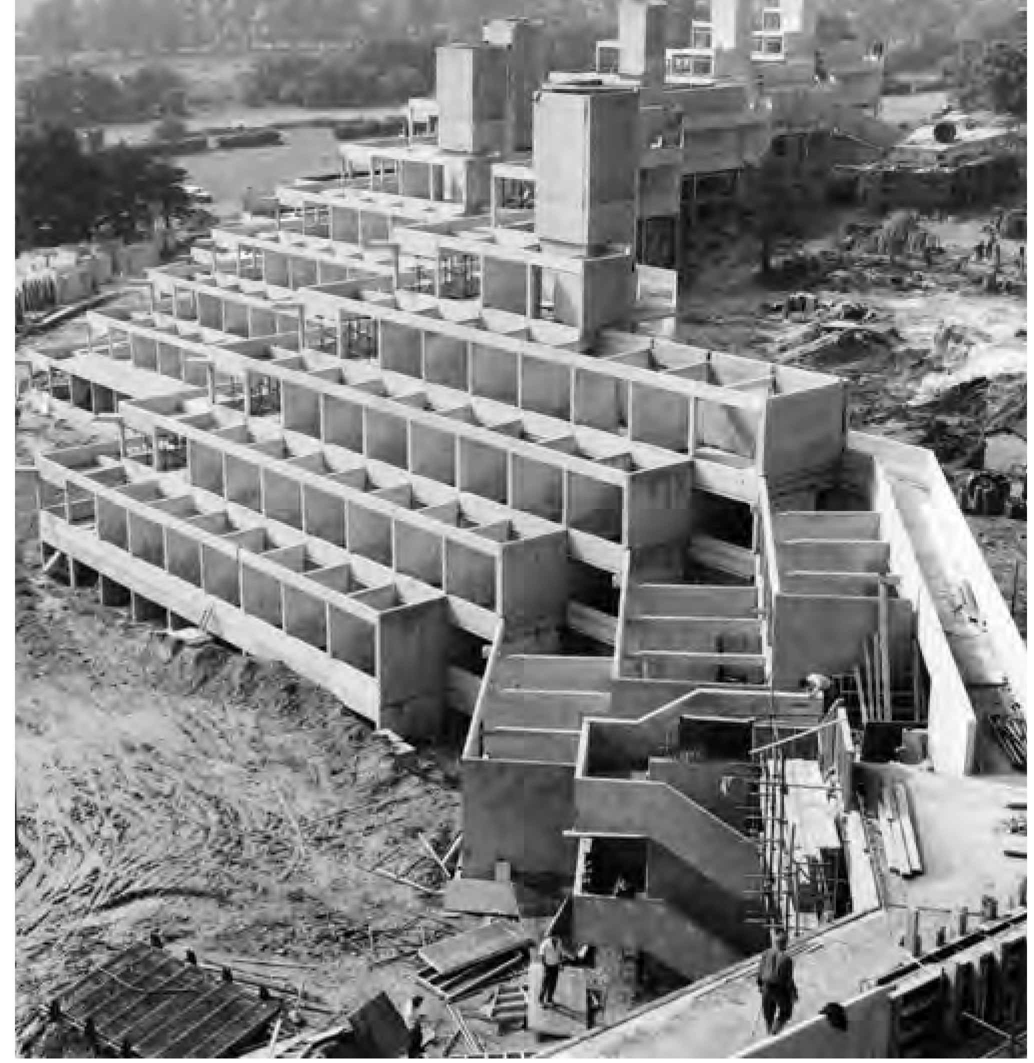
comprising single coffered slabs supported at each corner by a single column. The columns of adjacent towers are tied together. Services are run vertically at the centre of the column clusters, and horizontally between adjoining slabs. Electrical trunking runs in grooves under the coffer ribs. The towers are massed into squares five or six bays wide. Teaching rooms and laboratories are on the perimeter to maximise daylight and natural ventilation; circulation and dark rooms are at the core. The elevations echo the structural pattern:



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habitable bays are glazed, and service runs in concrete.Ventilation is by louvres, with pairs of opening lights in each bay to provide a current of cool air.

**Rooms for students**
In his article 'Rooms for students' published in *The Arup Journal* in 1969, Tim Sturgis summarised Arup Associates' design work on residential buildings for five Oxford and Cambridge colleges, including Leckhampton House at Corpus Christi, Cambridge. Each project demonstrated how imaginative and expressive use of engineering systems results in unique and interesting buildings.

Leckhampton comprises two linked pavilions, glazed, so that there are views from one pavilion to the other, and through the corners to the gardens beyond.

**Loughborough University masterplan**
Developing the masterplan for the proposed Loughborough University of Technology provided an opportunity to test the modular approach on a large scale. The design work was done in the early 1960s and work on site started in 1965.

In his 1966 RIBA speech, as construction was just getting under way, Sir Philip Dowson said: "Our brief was very open. The university is to expand up to certain stages, over unpredictable periods of time and is to be fully residential… it can be built very rapidly, and may have to be at certain periods if funds are available. Speed, though, is not the primary consideration. The repetition of elements, carefully designed and embodying all the various functional requirements, should, we hope, enable higher performance standards to be achieved within the same cost limit. We have tried to exploit the richness and variety of space that can be created within the strict geometrical disciplines that are the reflection of an industrialised method."

Loughborough University was completed in 1970. *The Arup Journal* published a detailed article on the design in 1967 called: 'Loughborough University of Technology: growth change and grid disciplines' (David Thomas).

**University of East Anglia**
At UEA, the brief to create more than 600 rooms at speed resulted in 10 'semi-ziggurat' residential blocks of precast concrete units, ranged across a hillside, facing out into a river valley.

The external joints between units were left fully visible purposely to celebrate the prefabricated nature of the buildings.

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Architect's approach to architecture: arup.com/journal21966
Rooms for students: arup.com/journal31969
Loughborough University: arup.com/journal61967
University of East Anglia: arup.com/journal21968

1. Interwoven grids for Loughborough University.
2. Leckhampton House, a hall of residence building at Corpus Christi College, Cambridge.
3. Birmingham University Metallurgy and Materials Building.
4, 5. University of East Anglia: precast concrete halls of residence.

# A1 Viaduct, Gateshead

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Construction of the A1 viaduct started on site in Gateshead in March 1969. It was Arup's first urban motorway in the UK and, in their 1969 article, authors Smyth and Srinivasan said it was: "One of the most complex structures we have designed and the culmination of years of effort by a devoted team."

This stretch of motorway connects the north-east of England to the south and extensive calculations were required for every aspect of the project, including the initial decision over whether to build in prestressed concrete or, more expensively, in steel. With computer analysis still in its infancy, the team either had to take on many months of calculations by hand or commit to developing ways to program the computers to take on the burden. They chose the latter.

Many of the computer-based techniques developed on the A1 Viaduct would later help streamline Arup's approach to other infrastructure projects, including bridge building. However, as *The Arup Journal* article from the time made clear, in the early days using computers often involved more work, rather than less, as strategies were devised for handling the data generated:

"The prestressed concrete solution was obviously sensible in structural form, but difficult to analyse. We had to be able to satisfy ourselves that our structure would be safe, but we did not feel that analytical difficulties should stop us from designing the right structure for the situation.

"The really critical problem with our electronic allies is to find ways of generating the input so that the engineer fills in a small amount of data instead of a large amount, and of representing the output in such a form that the important information is readily available and doesn't have to be picked out with great labour from a vast jumble of numbers."

**Gateshead Western Bypass**
The road network was expanding in the 1960s. With the UK economy prospering, and increased transport of goods by road, came the demand for new bypasses to keep heavy traffic out of city centres.

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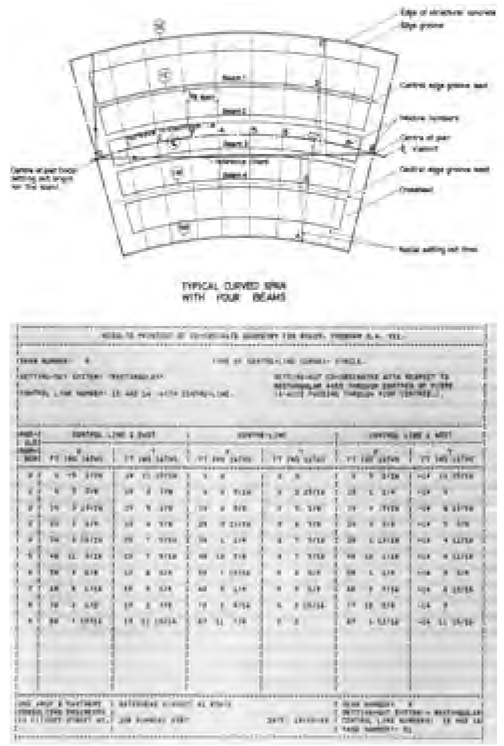


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Also in Gateshead, Arup was asked to design the Gateshead Western Bypass. It was the firm's first large road and bridge project in the UK, extending 5.5 miles from the new Scotswood Bridge carrying traffic from the A1 to the west and the Team Valley Trading Estate to the east.

The notable aspects of this project were the difficult ground conditions, including areas of old mine working, that complicated the design and engineering of bridges and underpasses along the route. Again, it was newly available computing power and the team's programming skills that played a large part in performing the necessary calculations.

Gateshead Bridges: arup.com/journal11970
Viaduct model tests: arup.com/journal31968
Gateshead Bypass: arup.com/journal41974
A1 Viaduct: arup.com/journal31969

1. The A1 motorway viaduct at Gateshead: a significant new connection in the nation's 1960s road network expansion.
2. An aerial view showing the smooth curves of the new roadway.
3. Computer analysis of data was integral and essential to the success of this project.

1.

# Shahyad Aryamehr

The monument of Shahyad Aryamehr, now known as the Azadi Tower, is Tehran's most well-known landmark and it marks the west entrance to the city. Arup worked on developing the geometrical forms used in the monument, all of which were inspired by the architect, Hussein Amanat of Tehran.

Constructed from reinforced concrete, in the form of an arch, the 45m-tall monument houses a museum, library and conference room. The surfaces are formed by slabs of marble as external cladding and the family of defining curves is expressed in the form of grooves running from top to bottom. The depth and width of these grooves vary in such a way that the ratio of depth and width to the horizontal extent of the surface at any level are constant.

The monument is a beautiful articulation of complicated geometry, first imagined by the architect, then developed and realised with the assistance of mathematicians and engineers.

Peter Ayres, writing in *The Arup Journal* in 1970, described this complex structural design project:

"The monument is essentially an external visual experience and the external surface geometry is thus of the greatest importance. Although the monument has the qualities of a piece of sculpture, considerable rationalisation of the details of the geometry has occurred during its development, with no loss of free form effect. The final geometry is controlled by a 3m (10ft) square module in plan and elevation, with overall proportions governed by a 21m (69ft) square grid."

Arup's work on the project started in 1967 and the monument was completed in October 1971.

Geometry of the Shahyad Aryamehr: arup.com/journal11970

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1. Shahyad Aryamehr.
2. Detail within the arch.


# 1970s

**Bob Emmerson** joined the firm in 1960 as a graduate, and was Chairman of Arup from 2000 to 2004. He instigated the firm's development as a multidisciplinary practice in the 1970s.

*By the end of the 1970s the world economy had been badly hit by two oil crises. In addition to the uncertainty this introduced to project work, it also demonstrated how energy use was becoming a critical issue in the design of buildings. At Arup we took this as an opportunity to develop lower energy use concepts for building design, like wind energy systems or orientating buildings so they could take advantage of early solar panels for heating water.*

*At the beginning of the 1970s we formed a multidisciplinary group to offer building engineering services: in other words, structural and service engineers working together with outside architects. We started this in 1971 and immediately got commissioned on some influential projects like the Carlsberg Brewery in Northampton and the National Exhibition Centre in Birmingham.*

*The 1970s was also the decade when desktop computers started to appear in offices for the first time. They were gaining in power and sophistication but across the industry there was still a shortage of useful software for the kinds of problems we needed to solve. Arup formed its own computing group and by the middle of the decade the team had developed CADdraw, an early computer draughting tool. The firm had opened an office in Hong Kong in 1976 and used CADdraw for the first time on a hospital design project in the city.*

*The firm grew considerably in this period, moving from a partnership to Trust ownership structure in 1976. Interestingly, we didn't fully appreciate how important this decision would become until much later. It's still rare for firms in our industry to use the employee-ownership model, but its benefits are considerable. It's very motivating; the Trust structure ensures our people feel that they're working for their own firm. And it also meant we could preserve the firm's unique character, avoiding the mergers and acquisitions that are typical of the industry.*

*By the end of the 1970s Arup had become an incredibly exciting, innovating place to work. Everybody who joined, stayed. It had become the sort of firm that you turned up and enjoyed working in. Despite the decade's difficult economic climate, we seized every opportunity to try new things.*

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1.

# Sydney Opera House

The history of Arup is inextricably linked with the Sydney Opera House. The defining feature of Jørn Utzon's now iconic winning entry for the Sydney Opera House competition was the roof structure: the sails, generally referred to as the 'shells'. Utzon resigned from the project before the structure was fully erected, and Arup continued working, now with New South Wales Government-appointed team of architects, Hall, Todd and Littlemore.

Utzon entered the international architectural competition without professional engineering advice. Yet to realise the complex configuration of the roof was a formidable task that involved working at the very frontier of existing engineering expertise. The challenges posed by the analysis and geometric definition of the roof structure, and by developing appropriate construction methods and techniques, were unprecedented.

So it was the use and applications of electronic computers, then hardly used in the civil engineering world, that was to have a lasting impact. Not only did they play a seminal role in solving the complex analytical and geometrical problems, but were also used on site for surveying the emerging structure and controlling the tightly specified tolerances.

**Designing Utzon's roof structure**
Utzon's competition-winning scheme of the roof's forms was sculptural, free flowing and intuitive, without any geometric definition or order. There were four main pairs of curved surfaces for each hall and these surfaces – or shells, as they were incorrectly called – were geometrically undefined and connected to each other by a further series of surfaces called 'side shells' (again named incorrectly). There were no obvious solutions to designing structures that would satisfactorily express the interplay between the many complex surfaces.

Thin reinforced concrete shell solutions, then popular, were ruled out early on. The pointed nature of the roof shapes implied forces that thin shells were unable to withstand. Solutions


2.

with simpler structural forms that could eliminate some of the large bending moments inherent in these roof shapes were considered: non-pointed arches, curved shells covering each hall, and a single roof without discontinuities over both. But all these potential options would destroy the essential sculptural quality of Utzon's concept.


3.

1. Sydney Opera House at sunset, October 2015.

2. This aerial view shows the spherical geometry that underlies the formation of the shells.

3. Sydney Opera House during construction.

4. On site at Sydney Opera House, from left: Michael Lewis (lead site engineer), Sir Ove Arup and Sir Jack Zunz.


4.

Many possible avenues were explored to find a viable structure, with a clearly defined geometric order that would keep the original building profile and roof silhouette. The breakthrough came when Utzon embraced the desire articulated by Arup's engineers, for an underlying geometrically regular shape from which the shells could be formed. He changed the roof profile, some say quite radically, to accommodate a spherical geometry. Computer analysis and model tests subsequently carried out over several years provided the needed information for the design and construction for the now-familiar structure .

**Making the calculations**
It is difficult to imagine how the calculations necessary to design the roof could have been made without computers. At the time, slide rules and calculating machines, both manual and electrically driven, were the engineer's basic tools. Access to electronic computers was limited and expensive. Early computers occupied large spaces and were driven by thermionic valves. Sydney Opera House was one of the first applications of this emerging technology. There was little or no relevant software available and Arup's engineers had to learn quickly which analytical approaches were best suited to the machines' capabilities and write the appropriate programs.

Early analyses relied on the Pegasus MK 1 machine. Each run lasted many hours with frequent breakdowns of the hardware. Results were in the form of punched tapes or reams of numbers that required expert interpretation, and the calculation and preparation of the input data would take several weeks. The analysis of a structure with 780 equations was thought to be a major breakthrough, as it was one of the first successful attempts in the analysis of frameworks in three dimensions.

Computers were also extensively used in drawing production, during construction, particularly in predicting the adjustments necessary to achieve the specified tolerances and general surveying. During the latter stages of the project, computer uses became more widespread and increasingly necessary tools, particularly for the design of the glazed walls. The skills and experience gained using computers on the project would transform the discipline of engineering design in subsequent years.

Opera House Special Issue: arup.com/journal31973
Sydney revisited: arup.com/ Journal11988

**Sir Jack Zunz** was the principal structural engineering designer of the Sydney Opera House.

*Most of us who were involved in the design and construction of Sydney Opera House knew that they were working on something out of the ordinary. But no one foresaw the magnitude of its social, architectural and technical impact, nationally and internationally. That it became a World Heritage Site in the lifetime of some of us has been astounding.*

*It has played a significant part in shaping the firm's history and deeply affected the lives of many. The story of its genesis is complicated. It was, and still is, the subject of books, films and even an opera.*

1.

# Carlsberg Brewery

With growing demand for its beer, Carlsberg commissioned Arup and Danish architect Knud Munk to design its new flagship brewery in Northampton, on land reclaimed from the River Nene. The brief was to build a 100m-litre p.a. brewery in just over two years that could double production capacity after the old brewery buildings were knocked down. The design of the brewery was required to express the best aspects of modern Danish architecture.

Although Arup's initial appointment was for the design of the civil and structural engineering work, together with mechanical and electrical utilities, the role was later expanded to encompass managing the whole project, including providing quantity surveying and cost control. In addition, the specialist nature of the facility meant that a very high standard of building finishes was needed, and the mechanical and electrical services had to be integrated to meet these requirements. This was now a project that required an integrated approach to working with architects and designers. In response, Arup established its 'Structural and Services' division – a prescient move because this was exactly the type of team that was required to work on the Centre Pompidou project which began not long afterwards (see page 20).

A new management contractual form was adopted, too, under which design and construction could proceed at the same time, and which would enable the advance purchase of equipment on long delivery schedules. In the first stage of the work, a small team from the management contractor, G.E. Wimpey, worked with Arup's designers to define the construction and installation sequence. Subsequently, Arup programmed all site activities of the project with the emphasis on flexibility of completion dates while maintaining meaningful targets. It was one of the first times that programme management methods from other industries – in this case the petrochemical industry – had been used on a major architectural building project.

Carlsberg introduction: arup.com/journal11974
Carlsberg completion: arup.com/journal41979

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1. Carlsberg Brewery, Northampton: ambitious industrial facility design.

2. Despite its scale and complexity, the new brewery was completed in 1974 after just two years.

# Byker Viaduct

The Byker Viaduct, 800m long and shaped in plan like the letter 'S', is one of the most prominent features on the Newcastle upon Tyne skyline, and a major feature of the Tyneside metro transport system. Completed in 1979, after a three-year build programme, the bridge won the Concrete Society Award for Civil Engineering in 1980.

The viaduct site was particularly challenging: it runs between two earlier structures (a road and a rail viaduct) and crosses a steep-sided valley with old mine workings underneath. The valley is also crossed by a fault and the Ouseburn river.

The viaduct design had to take into consideration the live loading conditions from passenger trains travelling quickly on both tracks, and from slower, but heavier, works trains. Centrifugal forces were particularly significant for the tall valley columns.

After evaluating several different design options, the Arup team focused on an approach involving segmental construction with matched casting for epoxy resin joints. The spans on Byker Hill were designed to be built as continuous cantilevers using temporary props.

Two prestressing systems were used: bars that are coupled at each joint and used to clamp segments together; and multi-strand cables threaded through ducts in a number of segments. Each segment was cast on site using the adjustable pallet technique, and because each segment was cast between a fixed stop end and the end of the unit previously cast, any measurement errors could be adjusted for in the next cast.

Much care was given to the design and proportions of the viaduct, including detailing it for weathering. As a result, the columns and parapets were given a vertically ribbed finish, with the outer face of the ribs tooled to expose the aggregate.

Byker Viaduct: arup.com/journal41977

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1. The S-shaped Byker Viaduct carves its way above and across Newcastle.

2. The columns and parapets were detailed with a vertically ribbed finish.

3. Tyne and Wear Metro system trains use the viaduct to cross the Ouseburn Valley.

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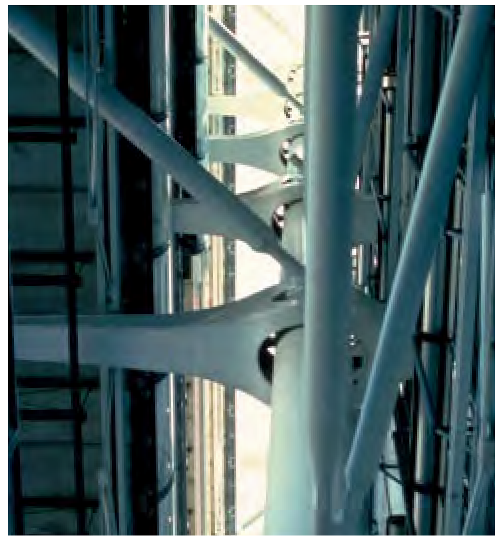

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1. The Centre Pompidou, Paris, still futuristic in appearance 40 years after its completion.

2, 3. Cast-steel gerberettes are a key element of the structure.

4. Air-handling units on the roof channel air through vertical ducts on the exterior of the main façade.

5. Colourful for a reason: the Centre's services use colours to denote function.

6. From external balconies, visitors have fine views of the city.


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# Centre Pompidou

The Centre Pompidou in Paris is one of France's most famous cultural landmarks, a still-relevant example of machine-age architecture. Its 'inside-out' design – with the structure and building services located on the outside – propelled Richard Rogers and Renzo Piano into the architectural stratosphere and reinforced Arup's reputation as a leading design collaborator. Arup played a major role in bringing the design team together, encouraging Rogers and Piano, who were then just merging their practices, to join Arup in putting together an entry for the French Government's international design competition.

The project was conceived in 1969 by the then president, Georges Pompidou, and the international competition was launched by the French Ministry of Culture in 1971. The brief was for a new library and modern art gallery complex to serve as a focal point for the regeneration of the Beaubourg area of Paris. The high-calibre judging panel, chaired by French master engineer Jean Prouvé, included American architect Philip Johnson, Sydney Opera House designer Jørn Utzon, and the Brazilian modernist architect Oscar Niemeyer. The competition attracted 681 entries from 49 countries.

The winning Rogers+Piano and Arup solution defined the Pompidou Centre as a cross between an information-oriented, computerised Times Square, New York, and the British Museum, London, with the emphasis on interaction between people, activities and exhibitions. In plan, the scheme encouraged strong pedestrian movement, with a high level of adaptability. So in order to create big expansive spaces, the structure, escalators and building services were placed on the outside of the building to provide flexible interior spaces that could be changed to suit whatever exhibition spaces were required.

**Key influences**

After winning the competition, the Rogers+Piano and Arup team were initially commissioned to develop their ideas further. A series of design iterations led to agreement on the façade, the proposal to locate escalators and stairs on the outside of the building, and the decision to construct much of the 10-storey structure in cast steel, in the tradition of Gustave Eiffel, the French civil engineer and architect of the Eiffel Tower. The modern reference was the space-frame roof of Osaka Airport, designed by Japanese architect Koji Kamiya, with cast-steel nodes machined for connection.

The spans involved are significant – 48m between each of the structural columns, with tension ties 6m outside the principal columns. The main horizontal circulation occurs in the space between. Between these tension ties and the column line is a cast-steel cantilevered piece known as the 'gerberette' (after Professor Gerber, a German engineering academic).

Because the steelwork is visible, the joints and structural elements become part of the architectural language of the building, and because cast steel is a flexible material, it is particularly useful in detailing. For example, the gerberettes themselves have a pin connection with a circular bearing between the gerberette and the column.

**Complex building services**

With its emphasis on large and flexible spaces, the Pompidou Centre's building services requirements were complex. Arup designed all services: heating, ventilation and air conditioning, electrical, plumbing and fire protection. A total of 24 air-conditioning plants were designed into the building, ranging from single ducts of cold fresh air to dual-duct variable-volume systems: the 13 air-handling plants on the roof serve the building's superstructure, channelling air through 12.8m vertical ducts on the exterior of the main façade. There are also electrical substations, extensive medium voltage and light current installations, and even plumbing systems for the provision of movable lavatories.

Given this complexity, it is a surprise to discover that some aspects of the design solution are remarkably simple. The well-known brightly coloured network of ducts on the outside of the building, for example, are colour-coded for ease of identification: blue for air; green for fluids; yellow for electricity cables; red for movement and flow (elevators, stairs) and safety (fire extinguishers).

After initial opposition to the project, the public was quick to embrace the Centre Pompidou. Since it opened in 1977, more than 150 million visitors have passed through its doors. It remains popular, and was reopened after renovation and enlargement in 2000.

Centre Pompidou Special Issue: arup.com/journal21973
IStructE award: arup.com/journal21977

# Bush Lane House

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Bush Lane House was a milestone project for Arup's fire engineering services, being the first application in the UK of fire protection by filling a building's structure with water. It was significant for another reason too: it demonstrated the importance of bringing performance-based fire engineering to modern building design, helping to combat the shortcomings of traditional fire safety methods and practices.

The client's requirement for Bush Lane House was that it needed to provide the maximum permitted usable floor area for a high-quality 'let-able' City office building. Not only were there constraints from planning restrictions and the relatively small plot, but the site's close proximity to Cannon Street station meant the substructure would need to be robust enough to allow tunnel and station construction to continue below the site. Arup Associates' feasibility report showed that these conditions could be met, and designs were commissioned to obtain planning permission.

The structural system for the building was based on a full-height lattice frame outside the building envelope, meaning that the office space is uninterrupted by the structure. In order to protect the lattice system, the tubular frames were water-cooled. Normally, structural steelwork is insulated to prevent it from losing its strength in fires and to keep temperatures below the critical value of 550°C. Calculations and tests showed that as long as water remains in contact with the steel throughout the fire, its temperature would not exceed critical values except under very unusual circumstances. The Greater London Council approved the Arup design.

Projects such as Bush Lane House showed how a fire engineering design approach could influence the early design of a building, with clearly defined fire protection objectives integrated at the start. This approach avoids the expense and inconvenience of patching-in measures at a later stage, and also makes the design more effective and more closely matched to the needs of the owner and users of the building.

Bush Lane House: arup.com/journal41976

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1. Construction of Bush Lane House's external lattice structure.
2. Prefabricated assembly of one of the lattice elements.
3. Bush Lane House, above Cannon Street station, completed in 1976.
4. The water-cooled steel structure ensures comprehensive fire safety.

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# OCBC Centre

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Completed in 1976, this 52-storey banking and office complex in the commercial heart of Singapore is the headquarters of the OCBC Bank. It was the tallest building in the country at that time.

The OCBC Centre has a distinctive appearance largely because of the design decision to place the lift cores and building services in two 20m-diameter semi-circular service cores, 35m apart at opposite ends of the building.

The architect for the project was I. M. Pei of New York, with BEP Akitek of Singapore. Two particular factors played a role in the architecture and construction methods for the building: first, the bank's wish that the banking hall be column-free and as imposing as possible; and second, its desire to construct as quickly as possible.

The banking hall is an impressive space with a mezzanine floor 3.6m above ground floor level. It appears to cantilever from the perimeter walls, but is actually supported on prestressed beams that span 30m. Two self-supporting circular staircases provide a simple yet attractive way to access this mezzanine floor.

For the tower itself, Arup proposed a construction method that involved service cores being slipformed ahead of the floor structure, so that transfer girders could be put in place as soon as possible at the 20th and 35th floors. This allowed three banks of typical floors to be built on the different levels at the same time, which took around a third less time than conventional 'from the ground up' construction methods.

OCBC: arup.com/journal31976

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1. The placement of the lift and services cores at either end create the building's semi-circular ends.
2. The completed building in 1976.
3. The OCBC Centre is still a prominent feature of Singapore's skyline.
4. The airy, open central areas of the OCBC Centre were a distinctive feature of its 1970s design.

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# Barbican Arts Centre

The centrepiece of the Barbican development for the Corporation of the City of London is the Barbican Arts Centre, a 2,000-seat concert hall, theatre, cinema, music and drama school. It was also one of the last major elements of the Barbican complex to be built, and Arup was charged with ensuring that its substructure could be created without affecting the existing foundations of the buildings around it.

As the Barbican redevelopment progressed, the brief for the Arts Centre changed, and the volume of the building increased several times. As a result, Arup's challenge was to design and construct an extremely large excavation in London Clay – roughly 190,000m$^3$ – in the centre of a development that included two 42-storey tower blocks and a realigned underground railway.

Complex calculations had to be made to predict the movements that were likely to occur, including finite element analysis, which showed that the amount of movement would adversely affect the surrounding buildings. The permeability of London Clay presented major design challenges, including differences in soil pressures developed against retaining walls. To overcome the notoriously difficult behaviour of the soil, the team developed a positive system of restraint that would also be used as much as possible in the permanent substructure.

Flat jacks were to be used in order to pre-load the substructure system horizontally in a north–south direction. Once the forces in the props had been raised, soil could then be taken out of the theatre auditorium completely, and the process could begin on construction of the foundation slab.

The jacking took place over two days in September 1974 and both the pulling of the cables and the raising of the pressure in the jacks was trouble-free. More significantly, the team monitoring levels on the 42-storey Cromwell and Shakespeare Towers as the jacking and excavations took place found no material difference in either the level or the inclination of the blocks – a significant achievement.

Barbican: arup.com/journal41975

1. Much of the Barbican Arts Centre is below ground, beneath the rectangular building in the centre of the picture which provides its entrance.

2. Entrance is from the terrace with its ornamental pool and fountains.

3. Stairs down into the building.

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# Bundesgartenschau, Mannheim

For the 1975 garden show – or Bundesgartenschau – in Mannheim, Germany, eminent architect and engineer, Professor Frei Otto, designed a lattice-shell roofed hall, the Mannheim Multihalle, to sit at the heart of the show site acting as its focal point and housing a restaurant.
A world-leading expert on lightweight structures, Otto, learning from Antoni Gaudí, had developed particular expertise in using hanging chain nets to define possible structures in which, when inverted, the self-weight would produce direct force only. Calculating and justifying the inverted compression structure which is prone to buckling is a complex matter.

The original structural engineer having resigned from the project, Arup was appointed to justify the structure just as the square lattice roof, using two layers of 50mm square laths, one in each direction, was sent to tender. The team had three weeks in which to provide preliminary analysis before the tender returns were due. While waiting for the geometry to be established from the hanging chain net using stereo photogrammetry, they built a 1/16th scale model of a simpler dome, at Essen, in Perspex strips to find out what could be learnt.

This Perspex model together with hand calculations showed that the roof as tendered, using 50mm-thick laths, would be unstable and that 100mm-deep laths could not be bent to the desired curvature. The lattice was changed to four layers of 50mm laths, two in each direction, bolted together with spring-loaded washers to clamp all four layers together where they crossed over. This structure was subsequently justified by its own Perspex model together with a bespoke non-linear computer analysis written especially for the project.

The loose, unclamped lattice was assembled flat on the floor then lifted using scaffold towers in the centre, and fork lift trucks that could both lift and move laterally around the perimeter. Once the lattice was in the correct doubly curved shape, which it could adopt because of the shear deformation allowed by rotation of the laths around the through bolt at each node, the bolts were tightened and the boundaries fixed to lock it in position.

The lattice roof is impressive for its unique construction process and for its design durability, given the technological limits of the time in which it was designed and constructed.

Mannheim: arup.com/journal31975

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1. The swooping lattice roof of the multipurpose hall and restaurant at the 1975 Mannheim Garden Show ('Bundesgartenschau').

2. A detail of the lattice.

3. Perspex model of actual Mannheim grid shell.


# 1980s

**Alistair Guthrie** is an Arup Fellow. He joined the firm in 1979 as a designer of building environments. He became a proponent of environmentally and socially responsible design.

*The 1980s was the decade when the hi-tech architecture of the 1970s matured, and the big architecture practices started to develop the style in new ways. Richard Rogers' Lloyd's Building was a continuation of the externalised services idea. But for Norman Foster's Stansted Airport design, hi-tech actually involved fewer exposed services, hid the services below the public level and used an innovative membrane roof. Similarly, Renzo Piano went from the very hi-tech design of the Pompidou Centre to something more measured like the Menil Collection gallery in Houston, which represented a quieter, more responsive approach to its immediate environment.*

*Actually, the Menil Collection was a formative project for me and probably everyone who worked on it. It continued our close relationship with Renzo Piano Building Workshop, one that endures to this day. This was the collaborative, Total Design approach in action, which was particularly key as we designed the multifunctional platform roof. Only by working in this very creative and open-minded collaboration could we have integrated the roof structure with the natural light, to enable the artworks to be displayed without damaging them.*

*The 1980s saw a continuing drop in the cost and simultaneous growth in the power of computers, and we were increasingly using them to solve engineering problems and take on more ambitious work. This also meant that we could start to model new dimensions of our work, including a building's environmental performance. Instead of using traditional rule-of-thumb assumptions about environmental conditions and lighting levels, we could use software to make more objective judgements about the experience that would be produced by a given design.*

*Despite the economic pressures of the 1980s, the firm had an optimistic atmosphere. As a young engineer, just starting his career, I was immediately struck by the freedom of expression everyone enjoyed within Arup. The firm liked to give you the opportunity to pursue new design ideas – it was never about simply repeating the past.*

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# HSBC Building, Hong Kong

As the 1970s drew to a close, Hong Kong's financial services sector was expanding rapidly. The Hong Kong Shanghai Bank (later HSBC) needed a new headquarters building, one that could physically express its ambition to be the best bank in the world. In response, Norman Foster and Arup collaborated on a truly revolutionary building, one that continues to mark out Hong Kong's individuality nearly four decades later.

The completed design was a powerful statement of high-tech architecture, a 200m-high steel-framed structure without a central concrete core. The building embraced flexible floor planning, connecting its highly sociable workspace 'villages' via escalators, creating a modern working environment.

The steel structure was suspended above the ground from eight steel towers, a daring design solution for such a large building at the time. Design ideas morphed through variations that included a triple chevron, a multi-chevron, and what was known as the 'coathanger' until the final iteration was settled upon (see diagram).

The coreless structure helped to link departments to each other, and the design favoured escalators over lifts, which led to a tremendous sense of movement throughout. It was also a design that would lift the building up, to maximise the public space at ground level.

At heart, of course, this is a bank, so in addition to a large banking hall and supporting offices, the substructure and basement function were designed to contain safe deposit space, with secure access and storage for bullion.

Construction of this highly distinctive landmark was complicated and drew interest from all quarters, right from the start. In addition to the difficulties of creating such a large steel building in a constrained space, the design also encompassed the boring of a 350m tunnel through granite, to bring in cooling sea water from Hong Kong bay as part of the building's air-conditioning and flushing system. Intensive ground analysis was also important as previous experience had established that Hong Kong's soil and granite base were susceptible to considerable movement under certain stresses.

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### Steel feats

The Hong Kong Shanghai Bank's structure represented the largest use of structural steel in a building outside the USA, particularly the very large tubes more typically used in the industrial, offshore and petrochemical sectors. The Arup team pushed the use of tubes to its limits, using steel tubes that were 100mm thick and rolled into a diameter of 1.5m. It was hard to get steel to form this way, so the team had to use different heating and rolling techniques, ones new to the construction industry. For the major connections, thick steels with high fracture toughness and spherical bearings were required. By completion, the new bank headquarters had changed the way in which massive steelwork could be crafted to form a visually minimalist suspended building.

### Space to work

Almost any construction site in Hong Kong is hampered by a lack of space, so off-site prefabrication of the steel elements was key. Given the then less-developed state of Hong Kong's own construction trades, the large-scale prefabrication would take on an international dimension that Arup had never attempted before. The plant rooms, toilets and storage facilities were constructed as 139 completed modules by a consortium of major Japanese companies, including Hitachi and Mitsubishi, and shipped and lifted into the steel frame as units. Steel elements also came from the UK by ship before being assembled on site. And with so many prefabricated elements being brought together from foreign countries into a highly constrained site, it was vital to institute a bespoke quality assurance system, to ensure everything worked first time during assembly. In this the team took inspiration from the defence, nuclear power and offshore energy sectors where this approach was more common.

The Hong Kong Shanghai Bank remains a forward-looking icon within Hong Kong's skyline, one that set new standards and expectations, from procurement to installation and operation.

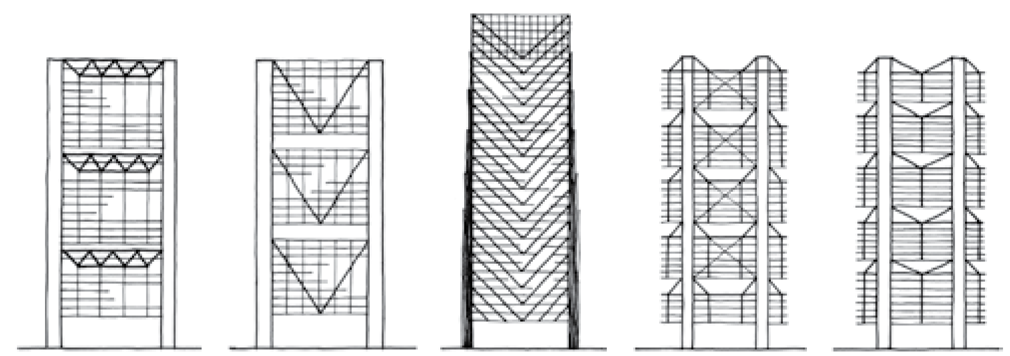
HSBC introduction: arup.com/journal41982
HSBC seawater intake: arup.com/journal41983
HSBC Special Issue: arup.com/journal41985

2.

**Mike Glover** was the project director for the HSBC Building.

*I understood, early on, that Norman Foster's brilliant and hi-tech design would challenge our knowledge on many levels. From the outset, research was vital. Norman always looked to push technology in his design solutions, which meant we had to be out ahead on issues like aluminium and high-strength steel technology and fabrication and fire engineering for expressed steel.*

*Also, you have to remember that most tall buildings were concrete at this point. To use steel on a high-rise building of this scale and sophistication was unheard of. Arup, or indeed anybody else, had never done anything like this before. We had to look at how steel was used by makers of oil platforms and in the nuclear industry to see what was possible, and stretch it a bit! On completion, the building definitely made the statement the bank wanted, and it also expressed something of our growing confidence and capability on the most ambitious of structures.*

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1. A powerful architectural statement: the HSBC Building is a 200m-high steel-framed structure, without a central concrete core.

2. The core-less design creates an open, integrated and sociable workspace.

3. Various schemes for the steel structure were considered.

4. Using escalators, rather than lifts, increases the feeling of movement within the building.

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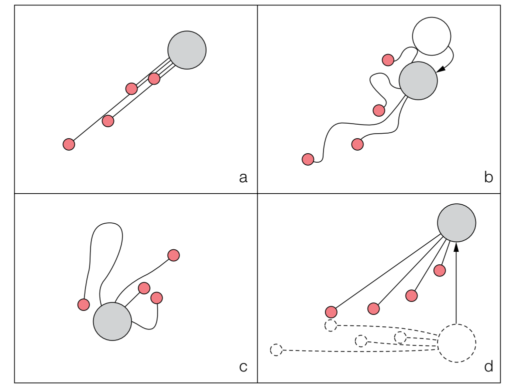


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# The British Library

1. The stepped, low-rise exterior of the British Library hides multiple below-ground storage levels.

2. Understanding the effects of differing soils via the analogy of someone pulling bricks on strings (see sidebar).

3. The light and airy entrance hall.

4. Contiguous bored pile retaining wall.

5. Cutaway of the soil structure showing the foundations.

The British Library is the largest library in the world, home to more than 170 million items, including books, maps, manuscripts, magazines, recordings and musical scores.

It was during the 1970s that the UK Government decided to commission a single home for the country's most important collections of books and research. At that time, the collection was kept in poor-quality storage on three separate and disparately located sites. A dedicated and centralised facility was clearly the answer.

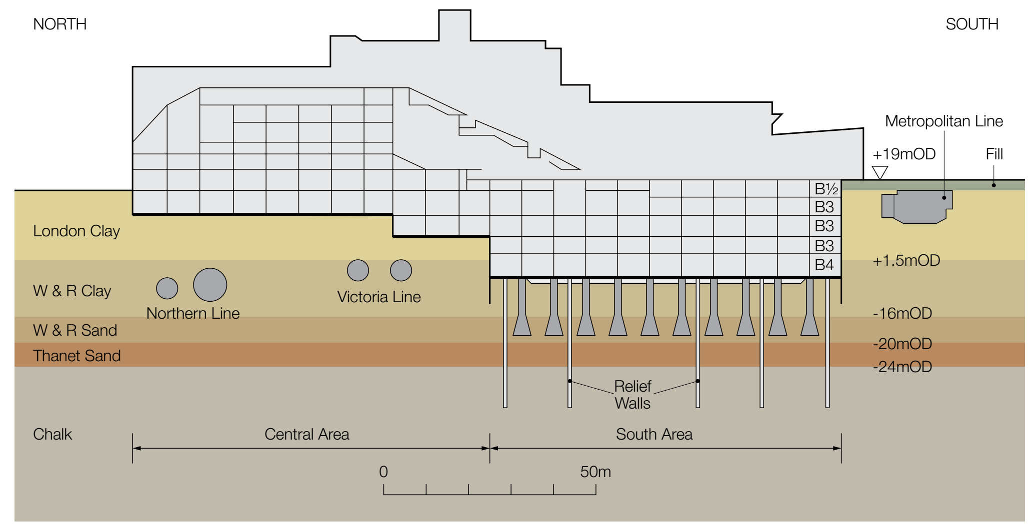
Working on a phased development programme, the first task for Arup's geotechnical engineers was to establish the limitations of the foundations, given that the site, on Euston Road adjacent to St Pancras station, was to be used for four basement storage levels, which must be capable of supporting seven storeys of public reading and office space above. Development of the site also had to take account of the nearby underground train line tunnels running into King's Cross station.

The geotechnical team immediately began testing the soil below the site, taking samples from more than 30m below. The clay basin and chalk layers, found under most of London's buildings, presented a particularly difficult challenge. The library's foundations needed to be strong enough to overcome clay's natural capacity to shrink and swell in response to water presence and vertical pressure.

**A pioneering program**

To ascertain the likely behaviour of the foundations, the team made extensive use of its own special finite element computing tool. SAFE was a computer program written at Arup that helped the team model and test the basement's viability. The program (still in use today) allowed a comprehensive and confident testing and analysis of how the basement's retaining walls would perform at the required depth.

And the team's analysis phase extended beyond the library site itself. Back-analyses were undertaken from a comparable project, New Palace Yard Underground Car Park,

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which became a useful benchmark for the likely performance of the new library's basement component. In order to successfully design the diaphragm walls and to predict the likely movements of the tunnels and surrounding buildings, the team had to understand the deformation behaviour of the structure, the response of the London Clay and other underlying strata, and the interaction between them.

Library London Clay: arup.com/journal11979
Library pile testing: arup.com/journal31979
Library introduction: arup.com/journal41978
Like bricks on strings: arup.com/journal41992

## Like bricks on strings

The Arup team learnt a lot about London Clay and soil behaviour during the British Library project. Indeed, Brian Simpson, an Arup geotechnical engineer who worked on the British Library, was asked to give the prestigious Rankine Lecture at the British Geotechnical Society in 1992 on this very subject.

In the lecture, Brian shared how the team had discovered that soil stiffness is high when strains are small but reduces as the straining proceeds. It turned out that this important feature of soil behaviour is strikingly similar to the movement of bricks attached to different lengths of strings. This physical analogy proved useful as the geotechnical team attempted to understand the volumetric and shear strains involved in the basement's construction.

Brian's findings were published in *The Arup Journal* in 1992, after the British Library had been completed.

# Lloyd's of London

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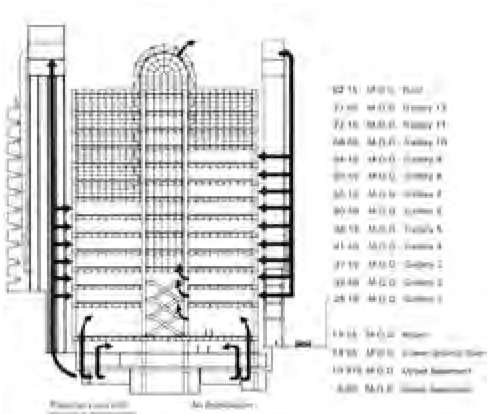

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1. Engineering as art: the Lloyd's Building makes functional elements central to its overall aesthetic.

2. Floor cutaway diagram showing services location and ventilation flow.

3. Physical model of the proposed Lloyd's Building.

Global insurance market, Lloyd's of London, has always been a unique operation, bringing together brokers and products from every conceivable insurance sector. Having expanded greatly in the 20th century, and being faced, once more, with increasing needs for space, Lloyd's decided to commission a new headquarters on the site of its existing Lime Street building dating from the 1920s.

The new Lloyd's Building, completed in 1986, gained Grade I listed status in 2011, and it echoes some of the inside-out structural philosophy Arup and Richard Rogers first employed on the Centre Pompidou in Paris. Once again, the idea of moving the building services to the perimeter was regarded as the best way to create spatial flexibility for the client. The air-conditioning system, described below, was revolutionary at the time and influential in the industry.

As a structure, a large and tall central atrium is enclosed within three main towers and three service towers, and escalators connect the highly modular floors that were designed to be reconfigured according to changing need. The main areas of insurance underwriting activity are busy, densely populated spaces, requiring large volumes of fresh air and good circulation. To achieve this efficiently, the building deployed a pressurised underfloor distribution system. With such a significantly sized vertical atrium, air currents become a challenge because air temperature differentials between top and bottom cause air turbulence within the space. Some of the used, but still cool, air from the underwriting levels was spilled into the atrium in a way that minimised this effect. Most of the return air was passed through the triple-glazed windows to reduce solar heat gain.

The signature style of the building is in part embodied by the services arranged in columns at the outside edges of the structure. Flexibility and ease of upgrade were designed into the services, meaning floors could be used in different ways in the future while retaining easy access to power, communications, lighting and related facilities sourced from the edges.

Lloyd's of London: arup.com/journal21982

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# 1 Finsbury Avenue

1 Finsbury Avenue was a key mid-1980s commission for Arup Associates. Unlike many of the signature structures of the decade, where occupier and architect tied their fortunes to the particular design of a building, this was a speculative development. Taking this as a cue to do something different and new, the Arup team came up with an eight-storey steel-frame and glass solution set around a fully glazed atrium.

The design was planned in three stages, and this, combined with its comparatively low-rise profile and central glazed courtyard, gave the sense that the project was more the design of an area than a building. Combining a subtle, confident appearance with appealing use of natural light and low energy usage made the building contemporary and popular.

The client, Rosehaugh Greycoat Estates Ltd, had an ambitious schedule, wanting to go from initial design to completion in just three years. In essence, this constraint helped make a big decision for the architects: the choice of a steel frame was a response to the need to meet this assured completion date. The 1,500 tonnes of steel made up the structural frame of the building and were put in place in just 13 weeks. This nimble solution meant that construction of the first 50,000m$^2$ phase took only 21 months in total.

Internally, the steel structure was encased in concrete and the ceilings fire-treated with sprayed vermiculite cement. High ceilings were another feature: a way of dealing with the growing need for space for technology and services beneath floors.

The building won the 1988 Structural Steel Design Award and a prize from the Royal Institute of British Architects (RIBA) in 1987. It was Grade II listed in 2015.

1 Finsbury: arup.com/journal21986

3.

1. A subtle, yet confident, Arup Associates design that proved popular in the City of London in the 1980s.

2. A spectacular skylight floods the atrium with natural light.

3. Internal walkways were airy and open to natural light within the building.

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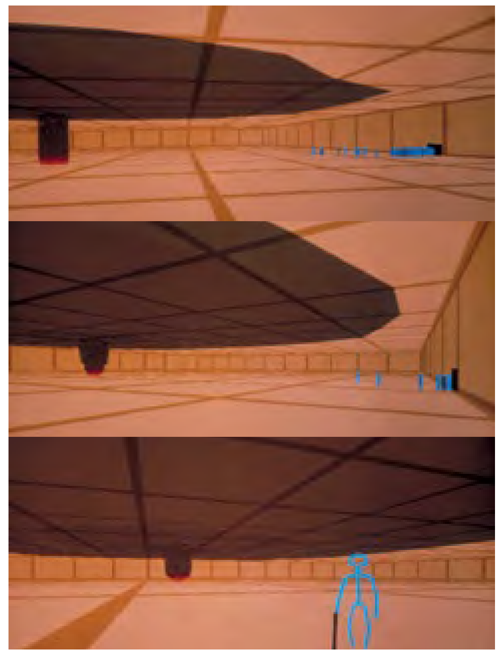

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# Stansted Airport

What is immediately striking about Stansted Airport, from both inside and out, is the vast canopy roof, overarching an airy open concourse. Less evident, but a critically important facet of the design, is the fire engineering concept that was essential to ensure safety in a large and busy public space that is 198m long, 162m wide and 12m high. With architecture by Foster Associates, the passenger terminal at this former military airbase in Essex, designed and built in the late 1980s, was innovative in many respects.

**Roof design**
The roof comprises a grid of 18m-square panels, which was pre-assembled and erected whole. It is supported by steel 'trees' placed in a grid at 36m intervals within the concourse, with branches above spanning out to 18m and service risers housed within each trunk.

Plant and service machinery was placed in underfloor storage below the concourse, rather than on the roof. And this meant the roof could be more lightweight and light-transmissive in design.

**The cabin concept**
Evacuation and egress modelling was important, and it was for this project that the fire engineering team developed the 'cabin concept' – a strategy that would contain smoke for sufficient time to enable escape. It was almost certainly the first time computational fluid dynamics analysis was carried out to assess smoke flow, and combined with people movement predictions it led to a solution that was widely regarded as a valuable new development in the world of fire engineering.

The diagrams (above) show how smoke spreads during an evacuation, how it spreads further, and how it looks at the point of 'last person out'. For a full explanation of the concept, please see the article 'Design for hazard – fire' – link below.

Stansted Airport: arup.com/journal11990
Design for hazard – fire: arup.com/journal21991

1. The roof panels are independent lattice domes consisting of intersecting orthogonal barrel vaults. Thus the cladding could be singly curved. These lattice shells rely on their out-of-plane bending stillness for stability.

2. Windows on all sides enable passengers to see the planes from the moment they enter the terminal.

3. Evacuation and egress models used to develop the fire engineering strategy.



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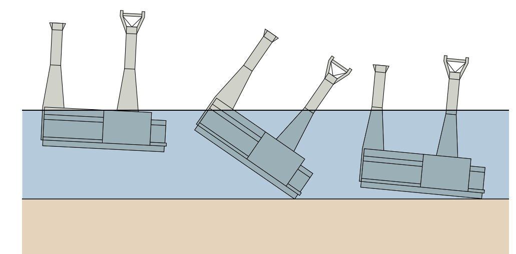

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# Ravenspurn North

1. Arup's first off-shore platform: an innovative CGS is towed out to the Ravenspurn North gas field.

2, 3. Angled installation, a cost-effective innovation on this project, later widely adopted in the industry.

The Ravenspurn North concrete gravity substructure (CGS), the firm's first off-shore platform, was simple to design and construct for certain sub-sea conditions.

Concrete gravity platforms were not uncommon in the North Sea in the 1980s, especially for deep water, but they had gained a reputation for being complex to build, and expensive. The Ravenspurn design was born out of a detailed assessment of such structures and how they could be designed for shallower water applications. The outcome was a simple rectangular arrangement, easy to build using conventional construction techniques and dry docks, and capable of receiving post-installation heavy ballast, thus significantly reducing the float-out weight.

The sub-sea conditions at the site of Arup's client, Hamilton Brothers, at Ravenspurn North in the southern North Sea, was ideal for a CGS design. And in 1987, following extensive commercial, construction and installation feasibility studies, the project moved forward to execution.

Parametric studies were undertaken to investigate the effects of the structure's geometry, weight and hydrodynamic performance movement. Mathematical models were then used to optimise and analyse the behaviour of the structure under the various conditions it would experience during its service life, including float-out.

There were, however, limitations to reliance on mathematical modelling because of the complexity of environmental loadings from wind and sea. To provide this additional assurance, extensive wave-tank testing was carried out to validate the design, float-out and installation.

With such structures, defining the size of the base is a key initial task as it needs to be sufficiently large to transmit the forces from the vertical shafts into the seabed soils, and capable of being floated out and installed with safety and certainty; the latter aspect was the central challenge of the project.

A particular innovation in the project was the use of an angled installation in which the structure was ballasted initially only on one side to ensure that there were no sudden changes in the hydraulic performance of the structure during sinking. If the structure had been sunk traditionally there would have been a sudden and destabilising effect at the moment the base became submerged. This installation technique was an extremely cost-effective initiative as it avoided having to design into the system additional floatation for this critical transition.

The outcome of the project, delivered on time and under budget, led to the firm designing and installing other concrete gravity platforms around the world, each posing different challenges, yet having the solutions that maintained the simplicity of the Ravenspurn North design. The project demonstrated that concrete gravity substructures could be highly cost-efficient where multipurpose platforms were needed, particularly for topside-heavy platforms based in relatively shallow water.

Ravenspurn North: arup.com/journal31989

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# The Menil Collection

In 1981, the Menil Foundation commissioned Renzo Piano to design a permanent home for the Menil Collection of art and historic artifacts in Houston, Texas. It was first opened to the public in 1987, and ever since has been a highly influential exemplar of gallery design.

The client, Dominique de Menil, had commissioned a gallery that could display her extensive collection of 20th-century art, lit naturally and predominantly from above by the ample and changing Texas daylight. The gallery roof design therefore had to conduct and control the sunlight without also damaging the works.

Daylight plays a powerful role in museums and galleries because it has a very full spectrum, making objects look like they should. It varies too, with the weather, the time of year, and the time of day. So the Renzo Piano and Arup team jointly experimented with different materials for the roof structure, to create a solution that transmitted yet controlled light within the space. The solution turned out to be rows of thin, ferrocement leaves which, combined with ductile iron coatings, form the roof structure, provide the shading, and carry the glazing. They also support and hide the ductwork.

The prototype developed by Renzo Piano showed promise, but manufacturing the leaves en masse was a challenge that involved approaching a specialist English ferrocement developer. Many models were constructed, including a life-size mock-up of a gallery and roof section. Dominique de Menil even brought in works of art to hang within it, to test the visual experience.

Arup's Peter Rice also saw that ductile iron could be used to make the frame that combined with the leaves to make the structure because the material offered more fluidity during casting than steel. The result meant it was able to flow more easily into the fine and detailed shapes with the required strength.

The Menil Collection remains a touchstone project for Arup's firm-wide commitment to design and engineering, with an innovative and sensitive approach to materials and design throughout.

Menil Collection introduction: arup.com/journal31983
Menil Collection roof: arup.com/journal21987

1, 2, 3. The leaves of the precisely engineered roof are made of ferrocement, a material traditionally used for boat building, and certain other thin-wall, free-form structures. Ferrocement consists of a number of fine steel meshes, impregnated with a cement-rich mortar, and it exhibits properties sufficiently different from normal reinforced concrete to be classified as a separate material.



# Lord's Mound Stand

1. The multi-section canopy roof at Lord's Cricket Ground.
2. The stretched fabric roof creates a lighter form of protection from the elements.
3. Walkways underneath the coated PVC roof.



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For its new stand at Lord's Cricket Ground, in London, the Marylebone Cricket Club (MCC) staged a design competition.

Architects Michael Hopkins and Partners worked with Arup on the winning solution that envisioned replacing the ageing steel and asbestos-roofed Lord's Mound Stand with an elegant and translucent fabric canopy, while retaining elements of the existing structure beneath.

The cricket season was a constraining factor that had to be considered by the programme, and the MCC. insisted that the chosen solution should take place in a single off-season. By building around the existing terrace, the team had a solution that saved the time and cost of demolition. The retention of some elements of the stand had the secondary and pleasing benefit of maintaining some of the original stand's 1930s character. Off-site prefabrication was another way to save vital time.

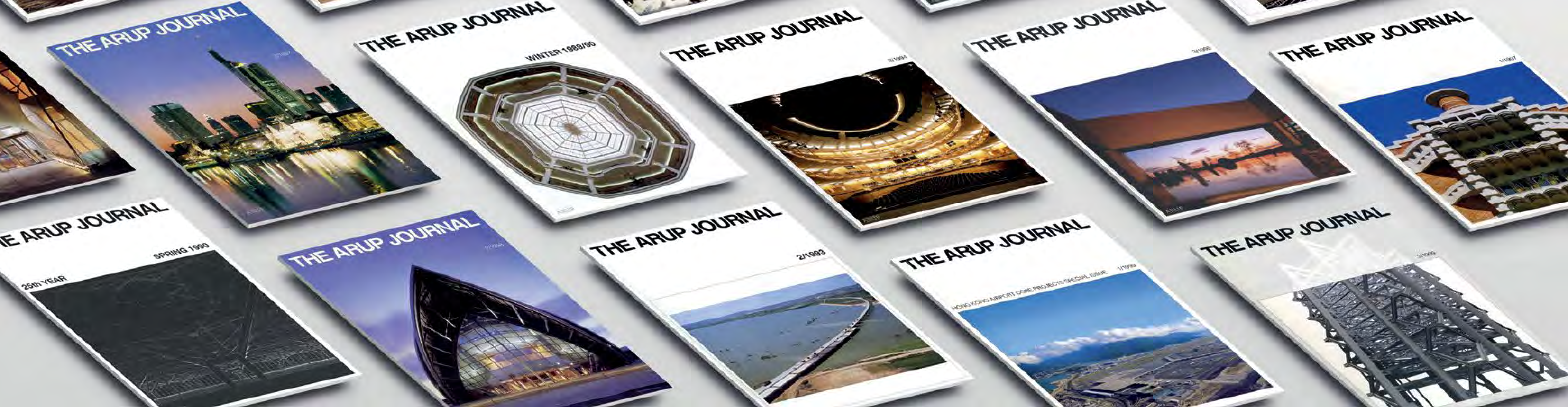
Perhaps the most significant part of the upgrade was the translucent fabric roof, which would provide an improved visual experience within the stand, while providing shelter from the sun and rain. And as a design choice, the fabric of the roof harks back to summer marquees on village greens, very much a cricket-friendly choice.

The fabric roof went through various design refinements, to keep costs down, as well as to simplify the amount of structural framing needed in order to preserve the elegance of its appearance. Eventually the team refined the number of cables, masts and pickups needed to hold the fabric in place, a great example of how reduced budgets can actually drive scheme innovation and design excellence.

The roof fabric itself went through various iterations, the final choice being polyester coated with PVC (polyvinyl chloride) and treated with PVDF (polyvinylidene difluoride) on its upper surface to improve durability. Despite PVC's limited lifespan, its low cost meant that even at replacements at 15-year intervals the roof would cost no more than a PTFE (polytetrafluoroethylene) equivalent.

The stand continues to be regarded as an elegant and inviting place to watch cricket.

Lord's Mound Stand: arup.com/journal31987




# 1990s

**Peter Chamley** is a member of Arup's Group Board and is the firm's Infrastructure leader.

*As the 1990s began, the UK's speculative office building boom finally came to an end and there was a pretty bad recession in the construction industry. It affected the firm significantly, but looking back I think we interpreted tough times as a chance to diversify and broaden the nature of our work, particularly in infrastructure.*

*Fortunately, publicly funded infrastructure projects have such long lifespans that they often buck these kinds of commercial economic headwinds. In the UK in the 1990s work on the Channel Tunnel Rail Link was therefore a pivotal project. Beyond the core value of the programme as a series of transport and connectivity improvements, we had a feeling that this project had the capacity to be quite transformative if the route was chosen correctly.*

*In the face of initial opposition from institutions like British Rail, the government and others, we were able to establish the value of an engineer's viewpoint, and in 1993 the changes to the route we suggested were accepted. The finished route for HS1, as it became known, has driven immense social and economic benefits along its route through Stratford and into King's Cross ever since. The route's regeneration effects in east London also ended up strengthening the country's successful bid for the London 2012 Olympic Games, and the improved rail services through Stratford were central to the visitor access strategy. It reminds us that the definition of engineering's remit should always encompass the potential social, environmental and economic value of design choices.*

*The 1990s was also the decade when construction's environmental performance came under increasing scrutiny and regulation. Across the world, environmental impact assessments were becoming a lot more detailed and rigorous, and as a result the firm's consultancy services expanded to offer planning, land contamination expertise, flood protection and many other related disciplines.*

*Returning to the possibilities of infrastructure, I also have to mention our design work on the Øresund Link between Copenhagen in Denmark and Malmö in Sweden. Øresund's success wasn't just the bridges, tunnels and artificial islands that created a road and rail link between these two nations. It also lay in something else that we've always pioneered: the conviction that a truly collaborative and cooperative relationship between client and designer will always lead to greater achievements. To have been able to deliver the Øresund Link three months ahead of schedule is testimony to that cooperative approach.*

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1.

# Øresund Bridge

1. The rising form of the bridge, viewed from the Swedish shoreline.
2. One of the cable-stayed bridge sections.
3. The bridge sections were prefabricated and lifted into place from barges.
4. The railway runs beneath the road deck.

The busy Øresund strait between Denmark and Sweden had long posed the question: could these two near nations be joined by an actual physical link? As far back as 1888, a submerged tube tunnel had been proposed and the idea was refined and reworked throughout most of the 20th century. With Denmark's accession to the EU in 1975, and Sweden scheduled to join in 1995, a formal agreement to create a physical link was finally signed in 1991.

Arup was involved from the start of the design competition, working in joint venture with SETEC of France, and Gimsing & Madsen and ISC Consulting Engineers of Denmark. The selected scheme was a unique combination of a 3,500m undersea tunnel, two artificial islands and a cable-stayed bridge with two side-spans, a creative response to one of the client's central aims: that the new link should not damage the environment, fishing or shipping.

In an approach that had strong resonance with Arup's total design philosophy, the client, Øresundskonsortiet, adopted an innovative planning, design, contracting and construction management process that emphasised trust and cooperation. The design-and-construct contract developed by the client worked well, allowing the contractor teams to find ways to solve problems without slowing down the project or creating unforeseen additional costs. Commitments to the aesthetics and the quality of workmanship required of the project, already defined within the contract, left enough flexibility for the contractors to adapt and succeed.



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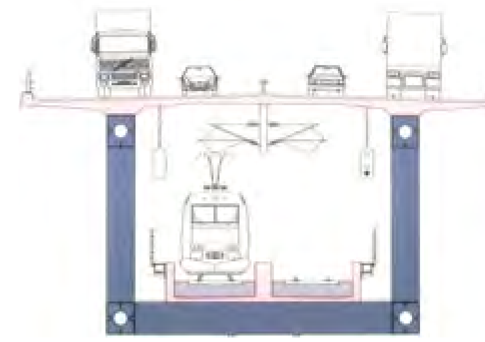

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**Design and delivery**
Despite the original brief's requirement for a side-by-side road and rail arrangement, the consortium settled instead on a two-level design, with trains travelling below the motorway above. In addition to this simplification, the team suggested a curving design to provide a more dramatic and beautiful visual experience for people crossing the bridge.

A project of such scale, taking place in incredibly busy shipping lanes, could only be achieved with extensive use of on-shore prefabrication. During the design phase, the team established that the programme could best be met by incorporating factory-type prefabrication for the largest sections of each element.

The watertight retaining caissons, for example, were built on shore in Malmö, Sweden, before being towed into place. These 2,500–4,700-tonne structures formed the basis for the piers and pylons supporting the bridge above, and as no existing crane ship was strong enough to carry the bridge's two main 19,000-tonne caissons, they had to be moved from dry dock into position on a bespoke, specially constructed catamaran. Complete bridge spans, including the concrete decks, were also constructed on land in Malmö. A variety of benefits resulted from this: quality assurance, speed, and health and safety were all improved by working in this controlled manner. Arup was deeply involved in the quality assurance part of the construction process, vital if the bridge was to meet the requirements of a 100-year lifespan.

The completed bridge opened on 1 July 2000 and was finished on time without cost over-runs, an incredible achievement for an infrastructure project of this scope and scale. The project won the coveted Outstanding Structure Award from the International Association for Bridge and Structural Engineering in 2002.

Øresund introduction: arup.com/journal11996
Øresund completion: arup.com/journal32000

**Alain Marcetteau** was the head of geotechnics on the Øresund Bridge project.

*A moment that I remember, as if it happened yesterday, occurred during the first visit to the site in Malmö, Sweden. I stood on the shore where the bridge abutment would eventually be, cleaning my glasses staring out over the Øresund strait and realised that I couldn't see where the bridge would end. That was the moment I realised how big it was really going to be!*

*We were lucky to work with such an enlightened client. During the bidding phase, Øresundskonsortiet went out of their way to set things up well, carrying out their own highly detailed ground investigations, doing foundation tests looking at friction and lateral movement issues. They then handed every bidding team this information and said: 'These are the given ground conditions all bidders must assume. If you carry out any additional research that shows these assumptions are not valid, we will pay you for any extra construction work.*

*This really set up the project effectively, and they were a pleasure to work for.*

1.

# Glyndebourne Opera House

1. The acoustic quality of the 1,200-seat venue, is highly regarded.

2. This diagram shows how air flow was optimised.

3. The seat base design assists the air flow strategy.

4. Traditional materials in complementary colours create continuity between the new opera house and the existing manor.

The music may be timeless, but concert venues must sometimes change to keep pace with audience expectations. By the end of the 1980s, Glyndebourne, the annual opera festival staged by John Christie in his country house in Sussex, had outgrown its existing 300-capacity auditorium, so Christie's son, George, commissioned a dedicated opera house in the grounds of the manor.

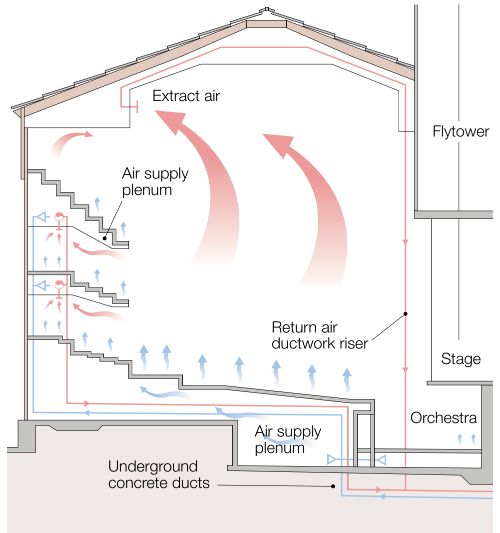
Since its inception in the 1930s, the Glyndebourne Festival has brought together music, people, social occasion and experience in a way that goes far beyond staging operas in a performance space. Arup's involvement in the concert hall was similarly broad ranging as it involved integrating engineering and acoustic design with the architecture, in a thoughtful and innovative way that set new standards for concert venue design while retaining the magic of Glyndebourne.

Every aspect of this project was a balance of practical and aesthetic considerations. A key requirement, for example, was that the new venue would be isolated from the aviation noise from nearby Gatwick Airport.

**Attention to detail**

Hopkins Architects and Arup developed a scheme that involved carving a horseshoe-shaped building into the hillside, in brickwork sympathetic to the manor house. This made the choice of materials critical to every aspect of this project, from the colour and acoustic properties of the bricks to the type of mortar needed to absorb differential movements between frame and cladding.

Attention to detail extended into the complexities of the acoustic design. George Christie wanted the new auditorium to improve on the existing facility's combination of clarity and resonance, so the team set about creating the perfect balance between performer and listener experience.

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Listening tests were conducted in Wagner's Bayreuth opera house and London's Coliseum, as part of their research.

**The technology**

Designing a space for opera involves striking a judicious balance between creating clarity for the high frequencies inherent in the sung-words, and the need to create volume and resonance for the orchestra. The distance between pit orchestra and performer is pivotal. And the reverberation time of the music decreases with every additional seat and audience member soaking up the sound waves. The scale of the new 1,200-seat venue at Glyndebourne therefore posed complex issues of acoustic performance, air flow and temperature.

Working together with Glyndebourne's director Anthony Whitworth-Jones, the team planned to design a space that would provide a richer orchestral sound than is typical in opera houses, one that would provide a 25% increase in reverberation at lower frequencies (cellos, basses, deeper brass). Solid pine was used around the space for its ability to reflect and enhance bass frequencies.

A great acoustic performance is also about what's missing, and achieving a near-silent air-conditioning solution was as important as the sound on stage. Arup designed an air-ventilation system into the seat pedestals, which draws cooler air into the auditorium without affecting the acoustic performance of the space. The mechanical parts of the air-conditioning system were placed at a distance outside the auditorium to preserve the PNC15 quietness rating.

An exacting testing phase was vital. The individual seat designs were assessed for their effects on the movement of sound throughout the space, and 1,250 100W lamps were deployed around the space at one point to mimic the heating load of a full house. Tracing smoke helped the team to establish the air flow effects. In addition, the London Philharmonic, led by Andrew Davis and Bernard Haitink, conducted test performances, which were extremely useful in settling on the correct geometry for the performers' rostra.

More than 20 years later, Glyndebourne remains a cornerstone of opera house design, one that consolidated Arup's reputation for integrated design of high-performance venues.

Glyndebourne: arup.com/journal31994

1.

2.

# Stockley Park

Stockley Park shows how integrated design thinking turned a vast area of derelict land into a landscaped business park set within an extensive country park. It is a good example of how environmental engineering, successfully applied, creates land value.

The business park, just north of Heathrow Airport, was developed in phases. Phase 1 meant transforming the landfilled gravel pits into parkland, playing fields, a golf course and the commercial development area. Most of the landfill was transferred to the north of the site to create the parkland, and it was replaced by structural fill to create safe, stable building sites, thus avoiding the necessity of providing the piled foundations and ventilated undercroft space normally required when building on polluted sites. The transferred landfill was constructed as semi-permeable membrane for ease of methane gas release: graduated layers of old landfill and site clay, and a final layer of 'manufactured topsoil' formed with sludge cake and clay.

The office buildings in Phase 2 of the development, designed by Arup Associates, are notable because their distinctive double skins were unusual at the time they were built. Also, the buildings are quite different from each other in appearance to enable tenants to reinforce their corporate identities. Arup Associates' designs involved the use of glazing, shading and natural materials to create sophisticated low-energy environments that were ahead of their time.

For each building, the commonly used central atrium or 'U' shaped office plan was inverted and floor plates were planned with a central core similar to a typical high-rise building. Each plan was developed from a cruciform shape to generate a long external window for maximum views of the park. The 'umbrella' or 'rain jacket' of the external wall was separated out in a single-glazed square skin. This made it possible inside the skin to use materials for the office walls that were not necessarily weather-proof: warm timbers and richly patterned stone, for example. This approach was environmentally efficient, cost-effective and it contributed to each building's distinctive appearance.

The business park quickly became popular, particularly with firms from the information technology and media sectors that were burgeoning in the 1990s. While its location near the airport was a factor, so was the leading-edge nature of the office design. Stockley Park remains a prestigious address, the design concepts it pioneered having stood the test of time.

Stockley remediation: arup.com/journal11987
Stockley Phase1: arup.com/journal11990
Stockley Phase2: arup.com/journal31998

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4.

1, 2. The double-walled construction of No.2 The Square meant the office could be clad in maple wood. Its entrance foyer lies within the double walls, and the outer screen comprises aluminium glazing elements on a lightweight steel frame.

3, 4. The masterplan for Stockley Park and an aerial view of the development in the 1990s before Phase 2 was constructed.



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# Phoenix Central Library

In the 1990s, Phoenix, Arizona, was one of a group of American cities undergoing a period of expansion and renewal. This led to demand for improved cultural facilities within the city, including developing a new home for Phoenix Central Library.

Local architect Will Bruder, in collaboration with DWL Architects, worked with Arup on a building that mirrored and respected the desert environment in its appearance. It is an intentional echo of the mesas, the flat-topped hills with steep sides that are prevalent across the state.

The client, the City of Phoenix, wanted a 'library for the 21st century' – designed to accommodate digital resources, as well as books, a public reading room and special collection spaces. Yet they also wanted a building that was inexpensive to build and cost-effective to run. Off-site prefabrication of most of the concrete components kept build costs down, while the key to containing operational costs lay in finding passive or design-based solutions to mitigate the effects of the sun.

The key innovation was dubbed the 'saddlebags' – service areas hanging off the sides of the building's steel frame (a metaphor for the bags where a cowboy keeps everything he needs while he rides his horse). The saddlebags held the fixed service functions: elevators, stairs, rest rooms; the mechanical and electrical rooms; and the lateral framing for the structure. They embraced the east and west façades and, combined with heavyweight, dense, concrete walls, reduced heat gain.

Glazing on the north and south walls opened the library to views of Phoenix and brought in the necessary daylight for reading. Heat gain was minimised through the use of external vertical sail shades.

The saddlebags concept also allowed for floor-by-floor air-conditioning units that minimised cost through limited duct distribution and increased library flexibility.

The building that resulted from this innovative approach was cost-effective, pragmatic, and at the same time a poetic response to the Arizona landscape – an intentional echo of the mesas.

Phoenix Library: arup.com/journal41996

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4.

1. External vertical sail shades minimise heat gain.

2. The polished stainless steel skin above the entrances looks like a canyon cutting through a flat-topped hill.

3. The reading areas benefit from passive air cooling.

4. Extensive glazing brings daylight flooding into the building and affords attractive views of the city.

# Yapi Kredi Bank, Turkey

1.

Yapi Kredi Bank, one of the largest private banks in Turkey, had outgrown its headquarters in central Istanbul by the early 1990s. With more space needed for a combined headquarters and datacentre complex, the bank opted to move 50km south of the city to Gebze and, in so doing, develop one of the largest financial buildings in Europe. Arup's Istanbul office was appointed as prime agent for the project, in charge of masterplanning, concept definition, detailed design, tender and construction phases.

Arup's multidisciplinary skills were used in a variety of ways on this project: buildings, façade, fire, acoustics and communications engineering were among the services the firm offered in collaborating with architects, John McAslan & Partners. The final design captured the client's varied requirements, including a focus on utility and flexibility, within a contemporary aesthetic in keeping with the bank's brand. During the design process the client's aspirations for the project grew, and the resulting building is sophisticated as well as functional: a grid structure with internal, glazed streets that provide an echo back to the traditional Turkish city experience.

2.

Arup's project management skills proved pivotal throughout, running an adapted version of management contracting, operated as a multi-package scheme, so that progress could be made as soon as possible after designs were completed.

The finished complex became an exemplar for Yapi Kredi, a benchmark for future real estate developments within their portfolio. On its opening the then Turkish president, Süleyman Demirel, who prior to politics had worked in dam construction, commented approvingly: "As I approached the complex I could see as an engineer that this was a masterpiece of architecture and engineering."

Yapi Kredi Bank: arup.com/journal11998

3.

1. Combined headquarters and datacentre for Yapi Kredi Bank, Istanbul.

2. The entrance to the office building..

3. Internal walkways and stairways within the buildings are light and airy.

1.

1. Of the 18 viaducts, the longest was the 2km Karasu Viaduct, pictured here.

2.The Agadere Viaduct.

3 A section of the Camlica–Gebze stretch.

2.

# Kinali–Sakarya Motorway and Karasu Viaduct

The Kinali–Sakarya motorway project in Turkey, which took 10 years to complete, was truly a project where east meets west. The resulting 247km roadway connects Sakarya province in the east, with Kinali in the west, via Istanbul. This extensive project comprised four separate contracts for sections of motorway that involved different mixes of infrastructure elements beyond the basic roadway, including tunnels, cuttings, bridges and viaducts.

Arup was engaged to provide geotechnical advisory services on two sections of the project. These were: the Camlica–Gebze section, designed by Arup and ENET, comprising 45km of dual three-lane motorways and 15km of dual-lane roadways, across both urban and rural areas; and the 70km of motorway from the west of Izmit to the east of Adapazari through hilly terrain and low-lying rural land. In addition, Arup was engaged on structural engineering of the largest viaduct of the project: the 2km-long Karasu Viaduct.

Turkey's geology is complex, tectonically dynamic, and the clay layers and high natural groundwater table in the west were challenging. The team mitigated this by redesigning the vertical alignment of the motorway to reduce the maximum cutting depth, flattening the side slopes where needed. Instabilities in the hillsides through which the motorway was cut proved complex to deal with, requiring metres of rock to be added in some places to avoid dangerous landslips.

On the Agadere Viaduct, Arup's geotechnical appraisal took on urgent relevance when a 4.5 Richter-Scale earthquake caused a 40m pier to move out of place. Stabilising caissons proved to be the answer, and the foundations for the viaduct were extensively redesigned.

By working alongside local engineers in Turkey on this project, Arup was able to share knowledge and transfer skills and technology, to mutual benefit. Much was learnt about designing and building motorways in seismic locations.

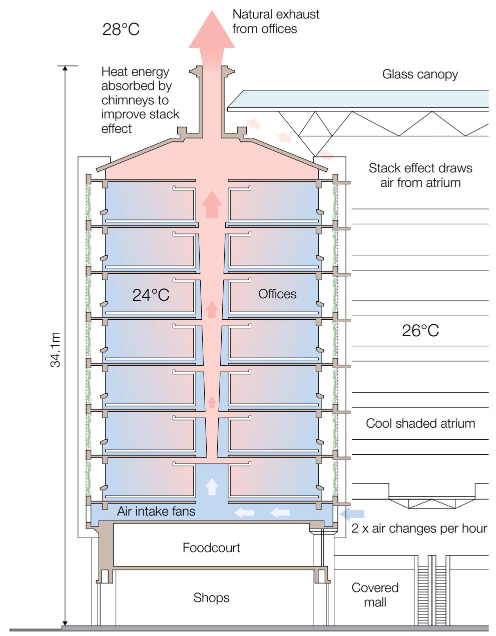
3.

Kinali–Sakarya: arup.com/journal21993

1.

# Eastgate, Harare

2.




3.

At its most intuitive, engineering is a creative response to a project's context. The Eastgate building in Harare is a major retail and office building in Zimbabwe's capital city, developed in the mid-1990s. At over 30,000m² Eastgate's adaptation to the local climate, energy-use profile and ongoing operational costs were key factors in the design. The client brief was a bold combination of requirements: a building without air conditioning, aesthetically impressive and yet inexpensive to build. Architect Mick Pearce and Arup's structural, mechanical and electrical engineering team collaborated to produce the largest naturally ventilated, passively cooled building in the world at that time.

Harare, nicknamed the 'Sunshine City', sits in a subtropical, temperate zone with high levels of sunlight. For such a large building the chosen form presented various trade-offs: a shorter, squat building with lower surface area would be less susceptible to the effects of sunlight but require more continuous and expensive use of artificial lighting; a taller, narrower building would have better access to natural light but cost more operationally (for lifts, sprinklers, air conditioning, etc).

Eschewing the modern staple of a large glass and steel tower, Eastgate is a creative solution: an eight-storey concrete structure, with only 25% external glazing to mitigate the strong effects of solar glare. The most innovative feature, though, is the passive cooling system, which was a central driver of the overall design.

A pattern of air shafts and air voids was defined that would draw cool night-time air through the building from the mezzanine floor 10m above ground, creating a natural stack effect, supported by fans to ensure a controlled experience throughout. At the top of the building, chimneys conduct the natural air exhaust out of the building, a design that was further developed a few years later in Portcullis House at Westminster, London.

Eastgate remains a powerful example of how engineering can bring together design and function to create environments that are well aligned to their context.

Eastgate: arup.com/journal11997

1. Eastgate's design combines affordability with references to vernacular architecture, supported by a commitment to low running costs.

2. Inside, the design makes significant use of natural daylight.

3. Eastgate's chimneys, a key part of its natural ventilation and cooling system, the largest in the world at the time.

# Heathrow Transfer Baggage System

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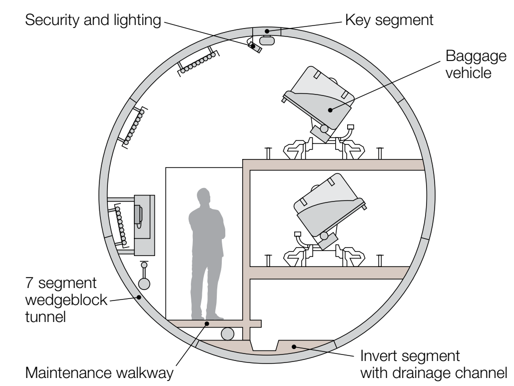
2.




3.

Airports are a focus for our sense of both distance and time. For airport operators, being able to provide an efficient and effortless travel experience is essential, and a rapid connection is vital for long-distance passengers on business or leisure flights.

London's Heathrow Airport is vast, and by the early 1990s BAA had realised that connecting baggage between terminals by road was too slow to keep the airport competitive. A feasibility study suggested a tunnel-based automated baggage transfer system could be achieved, and Arup was appointed as lead design consultant in 1993.

This project combined a number of challenges, including geotechnical engineering and tunnelling in London Clay and working within the constraints of live, airside logistics. The scheme selected was a sophisticated system of tunnels and underground bogey-mounted hoppers, each containing one piece of luggage travelling on a narrow gauge railway between Terminals 1 to 4, and vice versa.

Wherever possible, it was preferable to avoid tunnelling under existing buildings, yet at the same time it was clearly more economical to keep the tunnels as short as possible. And, as the tunnels are supported by ground access points, electricity supply infrastructure and ventilation support, it was better for them to be as close to the surface as possible.

The team adopted the New Austrian Tunnelling Method (NATM) for both speed and simplicity. This involved applying a sprayed concrete and steel mesh directly to exposed soil to minimise the overall excavation volume required. The project was completed successfully in 1997.

Baggage tunnel: arup.com/journal31996
Baggage system:arup.com/ Journal21998

1. A micro-sized metro system for luggage.

2. A narrow gauge railway runs between terminals.

3. A maintenance inspection platform runs the length of the tunnel.


# 2000s

**Alan Belfield** is Chairman of Arup's United Kingdom, Middle East and Africa region, and led the development of the firm's consultancy services during the 2000s.

*In retrospect every decade has its ups and downs, but the 2000s were particularly prone to dramatic swings, socially and economically. This was an era that began with the anxious scramble to solve the issue of the millennium bug and its fears of systemic risks, before being buffeted by more concrete social, political and economic change, particularly after 9/11 and the 2008 global financial crash.*

*But amid all the unrest it was a good time to be an engineer. We're not scientists or purists – we're interested in finding practical solutions to complex challenges and we're used to collaboration. Somehow this meant that in the 2000s it felt like our time, an opportunity for design and engineering to step up and solve bigger problems.*

*Clients' attitudes to project delivery changed during these years. Big organisations started to run their own procurement departments. And they got better at assessing value-for-money and more rigorous in their bidding processes. These were changes that challenged everyone in the industry to work more transparently and efficiently than ever.*

*The 2000s were also a decade when engineering's role grew in scope and scale, to tackle business operations more broadly. We'd gained the confidence to say that if engineers are great at understanding complexity, then that complexity doesn't have to stop at the structural or mechanical or electrical aspects of a project. The next logical step was to understand the business context better, which of course also helps you do a better job of designing the technical element of a project.*

*We carried out this business-plus-technical role during the purchase out of administration of the British car manufacturer MG Rover by Nanjing Automotive of China. It probably surprised a lot of people at the time, but our thinking was simple. We understood the car design and production process, we understood how factories are designed and built, we had the management consulting and financial transaction advisory expertise, and therefore we would help our client to make a success of this car company. It was a step into a wider world, one that we've been operating in ever since.*

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1.

2.

# Arup in Beijing

1. Beijing's 'Bird's Nest' stadium adopts a Chinese crazed pottery style in its structural design.

2. The National Aquatics Centre, known as the Water Cube, was creatively designed, with energy efficiency in mind.

3. The form of the Water Cube's EFTE façade was the imaginative result of combining 19th-century research into soap bubble formation with 21st-century computer modelling capabilities.

In 2001, Beijing won the right to host the 2008 Olympic and Paralympic Games. It was a pivotal moment for the People's Republic of China, setting in train a series of building and infrastructure projects that would together symbolise the nation's coming of age and offer the country an unrivalled opportunity to present itself as a major cultural and economic force in the world.

**The projects**

Arup worked on several Olympic-related projects, including the 91,000-seat National Stadium and the National Aquatics Centre. These two buildings became instantly recognisable to billions of people as global symbols of the XXIX Oympiad.

The firm's work in Beijing in the early 2000s also included the structural design of the China Central TV headquarters; two major transport interchanges: Terminal 3 at Beijing Capital International Airport and the Beijing South railway station; and the design of the Beijing Convention Centre, a prominent world-class exhibition centre at the heart of the Olympic Park.

Collectively, these projects have helped to transform Beijing and affirm China's position on the world stage.

**The 'Bird's Nest'**

The international competition for the design of the National Stadium – known widely as the 'Bird's Nest' was won by Herzog & de Meuron Architekten AG, Ai Weiwei and Arup, with a scheme inspired by local crackle-glazed pottery and veined scholar stones, symbols of China's cultural, sporting and economic renaissance.

Like most modern stadia, the design began with the stadium bowl comprising the competitive field and the seating stands around it. The challenge was to balance the needs of the spectator to have an unrestricted view of the field as close to the action as possible, with the needs of the stadium developer to fit in as many seats as the budget allowed. The Arup team worked with the International Olympic Committee and local organising committees to streamline and rationalise the on-field activities, creating a more compact stadium bowl with less distance between the spectators and the track.

Once the form of the bowl was set, along with the seating, the shape and structure of the roof could be designed. It needed to meet rigorous local seismic design codes, and be stable enough to support a moving roof (later omitted). As a result, the design team decided to keep the bowl structurally separate from the façade and the roof structure.

3.

Acoustic performance is widely-regarded as a particularly successful feature of the venue – vital in creating atmosphere and drama. Contributing factors include the elliptical form of the bowl, the depth of its structure, the acoustic reflectivity of its envelope, and a special lining below the ETFE (ethylene tetrafluoroethylene) roof membranes.

**The 'Water Cube'**

Sharing centre stage on the Olympic Green with the Bird's Nest, the National Aquatics Centre is often referred to as the 'Water Cube'. This rectangular blue box made of ETFE 'bubbles' provides a colourful counterpoint to the circular red stadium next door and is often described as one of the most innovative buildings in the world.

The Water Cube uses resources efficiently. It needs 90% less potable water than an equivalent structure and uses 55% less artificial lighting. It also captures 20% of the incident solar energy and uses it to heat the swimming pools.

The design for the Water Cube was based on the natural formation of soap bubbles, which create the most effective subdivision of three-dimensional space. This produces a highly repetitive and buildable geometry, while appearing random and organic. Although the space-filling patterns on which the structure is based are regularly seen in nature, particularly in biological cells and mineral crystals, they hadn't been used previously in a major structure.

To make the design buildable, the integrated design team used advanced 3D design tools to create the required structural elements. The end result was an inherently strong and lightweight structure that is earthquake-resistant.

The Water Cube was designed and built by a consortium comprising Arup, PTW Architects, and China Construction Design Institute.

**Michael Kwok** is the Arup director who led the firm's Beijing Olympic projects.

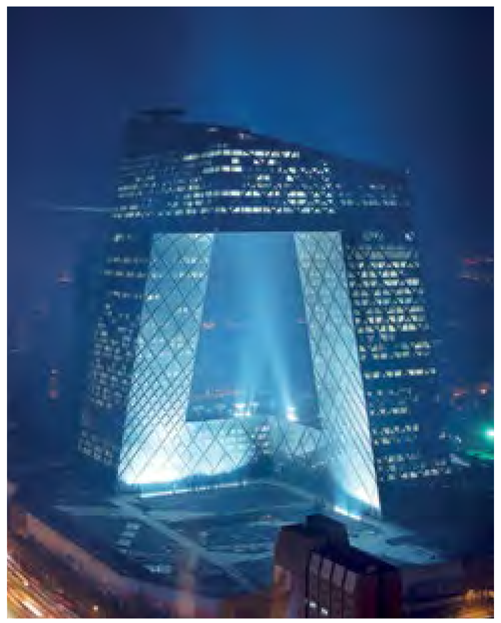
*Our Beijing office was opened in the same month that Beijing was awarded the hosting of the 2008 Olympic and Paralympic Games. I remember the moment when the announcement was made by the International Olympic Committee. The whole city went wild and celebration on the streets carried on until the next morning. I was sitting in our small office thinking we'll be very busy in the coming years. Gladly, I was right. We were awarded many of the high-profile Olympic-related projects and the office grew to more than a hundred people within a few years.*

*Preparing the city to host the Olympics led to an acceleration in creativity that involved lots of new ideas in design, architecture, masterplanning and engineering. It was a great moment in time and Arup played a significant part in it.*

4.

5.

6.



7.

4, 5, 6. Constructing the CCTV building posed considerable technical challenges. The tower is propped and stabilised by the overhang at the height of the 36th floor.

7. The CCTV building at night, the offices in the overhang clearly visible with the lights on.

**CCTV HQ**

With the 2008 Olympic Games as a catalyst, China's main state-run broadcaster, China Central Television (CCTV), commissioned a new headquarters building that would combine its entire television-making process into one facility. The winning design – by architects OMA and Arup – is based on a revolutionary building form that redefines the concept of high-rise buildings.

The building's structure is created from a single loop of interconnected activities, divided around the four main elements of the building: the nine-storey base, the two leaning towers that slope at 6 degrees in each direction, and the overhang that is suspended at the height of the 36th floor and provides nine to thirteen storeys of further floor space.

The technical challenges inherent in achieving this astonishing design included the fact that the entire façade structure had to be harnessed in order to provide the necessary structural stability. This created, in essence, an external continuous tube system.

Convincing CCTV and the Chinese Government that the design would withstand seismic activity was important. So Arup proposed a performance-based design approach from the outset, adopting first principles and state-of-the-art methods and guidelines to achieve set performance targets at different levels of seismic event.

Constructing the building presented further unprecedented challenges. The two halves of the overhang, which prop and stabilise the tower in its final condition, had to be connected when they would not be moving relative to each other due to wind or solar expansion of steelwork. So two massive steel beams were site-welded together just before sunrise.

**Beijing Airport Terminal 3**

With capacity for 35 million passengers a year, this is the world's largest airport terminal building. It has very few changes of level, short distances between destinations and quick transfer times. It was designed to be as welcoming and easy to use as possible, as well as one of the world's most sustainable airports.

Foster & Partners was the architect for this project and Arup's design team created a central distribution system for the terminal building which simplified the distribution of the building's services, creating large open spaces for passengers. Natural daylighting is complemented by angled roof lights that capture the thermal energy used to heat the building on winter mornings and reduce cooling needs during warm summer months. Beijing T3 opened in March 2008.

**Beijing South station**

This is the largest railway station in China and Arup worked with Terry Farrell & Partners Ltd and the Beijing authorities to design an upgrade that would significantly improve the capital's inter-urban and high-speed rail infrastructure, ahead of the 2008 Olympic Games.




8.

The project involved engineering one of the largest roofs in the world to create column-free spaces for the platforms at the station. The elliptical shape was designed to mirror the tiered roofs of the 'Temple of Heaven' complex, an important cultural reference. It is split into two halves by the separate large-span, flat-topped roof over the central departure hall area.

The unique structural system and complex shape of the building meant the design team had to convince the approval authorities, at both the preliminary design stage and the construction design stage, that the scheme would work. As with CCTV, a performance-based approach to design was taken, and it led to approval at both stages. In just 37 months, the scheme went from design competition to opening, in time for the Olympic Games.

**Beijing Convention Centre**

Working with architects RMJM Hong Kong Ltd, Arup provided structural, acoustic, fire, façade, civil and geotechnical engineering services in the construction of the Beijing Convention Centre. The venue for fencing and pentathlon events, and the international broadcasting and media centre, during the Olympics, it subsequently became an exhibition, convention, banqueting and retail centre. The curved roof shape pays homage to traditional Chinese architecture and acts as a giant rainwater collector. Water is channelled into a treatment facility and used around the site.

9.

Traditional air conditioning is replaced by an innovative energy-saving system based around a garden that is 7m below ground level. Because the garden is cooler than the interior of the building, it acts as a passive cooler to the indoor space, saving almost 400,000kW of energy per year.

CCTV services: arup.com/journal22005
CCTV structure: arup.com/journal32005
CCTV: arup.com/journal22008
Beijing National Stadium: arup.com/journal12009
Beijing South station: arup.com/journal12011

8, 9. Beijing South station: its elliptical roof is delicately designed, inside and out, to create a tiered effect that resembles the roof of the Temple of Heaven in the Forbidden City.

1.

# Channel Tunnel Rail Link

The first new railway in the UK for more than 100 years and the country's first high-speed rail line, Channel Tunnel Rail Link (CTRL) was opened in November 2007. Operating under the High Speed One (HS1) name, it provided the infrastructure for international services from London to Paris, Brussels and beyond, together with high-speed commuter rail services from the south-east of England, to London, via Stratford International station.

Arup was involved in the design and construction of the project, with key roles in planning, project management and engineering design across the length of the 109km railway. What many regard as Arup's most significant contribution occurred many years earlier, however, when the firm helped the government to select the route for the CTRL.

**Initial ideas**
The process for linking the UK to mainland Europe began with the 1986 Channel Tunnel Act, the legislative framework for a short-term upgrade of existing rail infrastructure. It fell short of granting the powers required to build a brand new rail link, but prompted the then publicly owned national rail operator, British Rail (BR), to begin a consultation process that resulted in the publication, in March 1989, of its preferred route for international-only trains from the Channel Tunnel to Waterloo, passing under south-east London.

On its own initiative and at its own cost, Arup dedicated a small team of economists and planners to examine BR's proposal. They concluded that alternative routes should be explored to overcome some of the difficulties of the proposal and suggested building a new international railway that maximised the use of existing rail and road corridors. The other driving force for the different route was that it could provide opportunities for substantial urban regeneration.

**The right route?**
Arup published its proposed alternative in March 1990 and after considerable lobbying, negotiation, discussion and the deliberations of a commission, the government decided, in October 1991, that 'the Arup route' should be selected. This route expanded the scope of the train link beyond a simple international connection between London and the continent, developing the concept of a domestic high-speed commuter service that would share the line with international trains.

Three urban areas would be regenerated as a result: north Kent, Stratford in east London, and King's Cross in London. This would encourage wider private-sector interest, in addition to political support, and grant-funding for public facilities, from the government. The regeneration aspect transformed the project into a feasible, sustainable, and economically attractive proposition. Although no one knew it at the time, the regeneration of Stratford and King's Cross was also later to become a significant factor in London's successful bid to host the 2012 Olympic Games.

**Project creation**
It took four further years of consultation after the route was selected, and a Parliamentary Bill, before the concession to finance, build and operate CTRL was granted. Arup worked with the winning bidder, London & Continental Railways Ltd, in developing its strategy, and subsequently set up the Rail Link Engineering consortium with Bechtel, Halcrow and Systra to take on the project management, consenting, design, procurement, construction management and commissioning of the CTRL.

2.

3.


4.

It was a major multidisciplinary project requiring substantial technical commitment in the primary and detailed design of tunnelling, foundations and earthworks, bridges and structures, rail permanent-way, overhead line electrics, signalling and communications, highways, utilities, architecture, building structures and services, and environmental engineering, particularly in ecology and acoustics.

**More than design.**
CTRL was significant in introducing many new initiatives into the UK construction industry, particularly with regard to procurement, quality management, and communications and IT within major projects.

Non-design roles for Arup staff included project management, cost control, engineering management, risk management, project planning, environmental management, and the consents processes. The firm also led the engineering management, including the major geotechnical, structural, tunnelling, building engineering, and architectural disciplines.

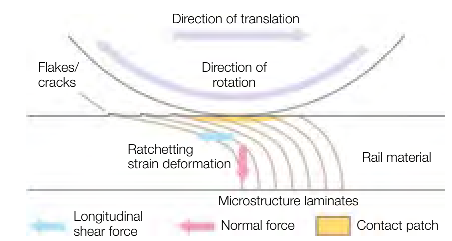
**The full story**
A special issue of *The Arup Journal* was published in 2004, which details how the CTRL project took shape. To read it, follow the link below.

CTRL Special Issue: arup.com/journal12004

## Why rails crack

Arup's contribution to the UK's rail network is wide ranging, spanning infrastructure strategy, project delivery and safety issues. A good example of this, recorded in detailed articles in *The Arup Journal*, is the work done after a high-speed train derailed at Hatfield on 17 October 2000 leading to four deaths and over 30 injuries.

It soon became clear that cracks on the running band surface of the rail had penetrated to the base of the railhead, causing the track to disintegrate over a 30m stretch. So the rail infrastructure operator at the time, Railtrack, appointed Arup to look at the risk of track failure across the rest of the UK network.




Together with Transportation Technology Center Inc, the team's five-year study found that the Group Standards for tracks and rail vehicles weren't enough to prevent rail contact fatigue (RCF) happening and that Sustainable Operational Limits were necessary to reduce RCF to acceptable levels.

Arup's work helped Railtrack create a practical solution to rail safety that was also affordable.

Why rails crack 1: arup.com/journal32005
Why rails crack 2: arup.com/journal12006

1. The Channel Tunnel Rail Link (CTRL) created the infrastructure for a high-speed connection between London, Brussels and Paris, and high-speed domestic commuter services to London.

2. St Pancras International station became the London terminal for the CTRL.

3. New tracks and tunnels were built to speed trains between London and the south coast of England.

4. Arup helped redefine the route of the CTRL.

# Hudson River Park

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3.

Spanning 550 acres, and extending five miles along historic waterfront, Hudson River Park is the most significant park development in New York City for several decades. In progress since 2000, the project is regenerating the waterfront area west of Manhattan and providing public access to the river. Very nearly completed, and with the benefits already clear, work continues in 2016 on the final stages of the project.

Arup was appointed by the Hudson River Park Trust (HRPT) in 2000 to work with Bovis Lend Lease in a project management role, providing design coordination services and employing 19 sub-consultants across a wide range of disciplines. The scope of the Arup team included establishing overall design guidelines for all aspects of the project to ensure consistency in meeting the Trust's goals and standards park-wide. This included adherence to HRPT's target of a 50-year design life for all materials to ensure durability and sustainability, and keep maintenance and operational costs low.

Early in the project, Arup supervised four sub-consultants to survey the bulkhead over most of the park length, and inspect the front face above and below the waterline. The design teams then used these surveys to rehabilitate the bulkheads to satisfy the required 50-year design life. The history, ecology and culture of the river and its surrounding areas are reflected in the masterplan, with 13 existing or former piers reconstructed for passive and active public use. This includes venues for concerts, art performances and other public events.

Along West Side Highway to the pier-head line, bikeways and walkways provide public access to the Hudson from a landscaped waterfront esplanade. Boat piers and water taxis encourage water-based activities, with floating platforms, get-downs and beach areas allowing contact with the river's edge for recreation, sailing and canoeing.

The waterfront has become a vibrant environment over the past 15 years. Dynamic new connections have been forged with nearby neighbourhoods, improving access to, and enjoyment of, this majestic river.

Hudson River Park: arup.com/journal22006

1. Piers 45 and 46 of the Hudson River Park, looking west to New Jersey across the mouth of the Hudson.
2. The green open space on Pier 45.
3. Pier 95 at Clinton Cove Park.

1.

2.

# Druk White Lotus School

Set high in the Indian Himalayas, the Druk White Lotus School was commissioned by UK-registered charity the Drukpa Trust, and designed as a model for sustainable modernisation that could be emulated in similar locations in other parts of the world. Though the project is a local initiative, it has an international context, with funding from charitable donations in Europe, as well as the local community.

Arup and Arup Associates started work on the project in 1997, on a largely pro-bono basis, providing masterplanning, concept and detailed design services. The first phase of the school opened in 2001 and work has been ongoing ever since.

The school is located in a remote, seismic, high-altitude (3,700m) desert region, cut off by snow for around six months of the year, with winter temperatures dropping as low as -30°C in some areas. Yet in summer, the hot sun and snowmelt from the River Indus bring the rich, fertile valleys alive. With the site encircled by peaks rising to over 7,000m and overlooked by two important monasteries, the masterplan achieves a unique sense of place for the school buildings.

The ecological context is fragile, so the site strategy aimed to ensure an entirely self-regulating system for water, energy and waste management. Arup's design for the school combines sustainable local materials and traditional construction techniques with leading-edge environmental design. There are gardens and extensive tree-planting, and the related water infrastructure is drawn from a borehole by a solar-powered pump. Classrooms face the morning sun to make the most of natural light and heat and the school is largely self-sufficient in energy.

The design team embraced the project in a culturally-sensitive way, developing designs and construction methods that would fit with local skills, techniques and traditions.

Druk White Lotus: arup.com/journal22002

3.

1. Masterplanning for the school was sensitive to its high-altitude setting, close to two important monasteries.
2. Sustainable local materials and traditional construction techniques were allied to leading-edge environmental design.
3. The school educates up to 750 pupils, the youngest of whom are nursery age.

1.

# The Eden Project

The Eden Project, one of Cornwall's most popular visitor attractions, is the result of transforming a 60m-deep, disused china-clay pit into a spectacular climate-controlled botanical environment. It features a series of biomes that follow the contours of the former quarry, in which major global habitats – from mediterranean to tropical – are recreated on a huge scale for education and research.

Working with Nicholas Grimshaw & Partners as architect, and Anthony Hunt as structural engineer, Arup advised project founders – horticulturist Tim Smit and Cornish architect Jonathan Ball – on their initial ideas for what is effectively the biggest greenhouse in the world. Also, after the first proposed site was discounted for being structurally unstable and not sufficiently well orientated to exploit sunlight, the firm worked with them on the business plan that would make their new alternative location commercially viable and popular with the public, and enable applications for funding to the National Lottery and the European Union's regional funds. Work to deliver the successful business case was as far-reaching and significant as the creativity needed to deliver the designs for the project within the capital spending limits.

Sustainability was a major consideration on this project, well before it became a common prerequisite on building projects. Eden's environmental effects were analysed and presented in three separate studies: Environmental Statement, Traffic Impact Assessment, and Planning Supporting Statement. Arup also conducted specialist studies of water resources, geology, ecology, landscape, noise, air quality, cultural heritage, socio-economics and construction impact. Energy use on the project was a major consideration, as was the material used to create the striking biomes, with the transparent film material, ETFE (ethylene tetrafluroethylene) co-polymer, chosen to help create the necessary environmental conditions to grow the plants.

After opening in March 2001, the Eden Project's visitor numbers reached two million in its first year, showing that it had certainly captured the public's imagination.

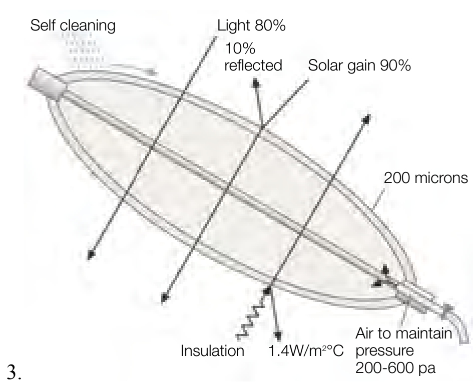
Eden Project: arup.com/journal12002

1. The Eden Project is a public greenhouse complex, able to recreate different growing environments.

2. The biome's ETFE roof structure conducts sunlight to help generate each zone's individual climate experience.

3. The ETFE bubbles transmit light and heat and keep the space warm.

2.

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# BedZED

Beddington Zero (fossil) Energy Development (BedZED) is one of the earliest and most influential examples of community-scale sustainable housing in the world. Built on a brownfield site in south London, the project was conceived in the late 1990s to show a sceptical construction industry how sustainability is possible and can be cost-effective. With 83 mixed-tenure homes and around 1,500m$^2$ of live/work spaces, the low-carbon development is an influential showcase for the One Planet Living concept, developed by environmental consultants BioRegional. The concept addresses the sustainability 'triple bottom line' – social amenity, financial effectiveness and reduced environmental impact.

Appointed to the design team in 1999 by UK housing association client, the Peabody Trust, Arup continued its long-standing work on the ideas exemplified at BedZED with the architect Bill Dunster, an environmental design specialist, and Pooran Desai of BioRegional. The project was completed in 2002, offering occupants the opportunity to live a carbon-neutral lifestyle in a practical and replicable way.

Techniques to harness renewable natural resources, and achieve closed-loop material use and site resource autonomy, were developed. Renewable energies were matched to energy requirements by mapping demand and availability. And homes were designed that had no need for conventional room-space heating. Bio-fuelled combined heat and power (CHP) encourages local community autonomy.

2.

BedZED featured a major advance in the use of heat-recovery wind cowls. The solution used had been developed by Arup over a 10-year period to harness low-velocity wind for heat recovery. Positive and negative wind pressure can therefore be used to deliver and extract air. Enough pressure is generated for it to be ducted into the building, delivering preheated air to each living room and bedroom, and extracting air from each kitchen, bathroom and toilet.

BedZED was also designed to reduce demand for treated drinking water by more than 50% and to treat waste water on site, with less resources used and the water available for recycling. Within a year of the development being finished, monitoring studies showed that hot water heating was 45% less; electricity used for lighting, cooking; and all appliances was 55% less; and water consumption around 60% less. BedZED continues to show how low-carbon living can work in practice.

BedZED: arup.com/journal12003

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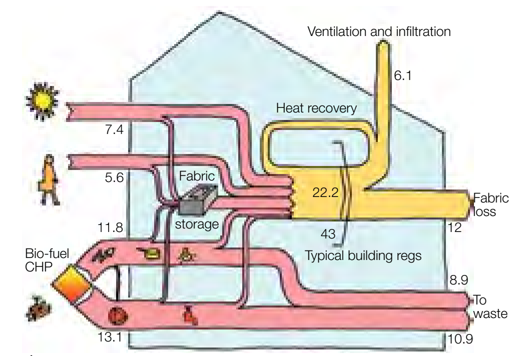


4.

1. From its solar-panelled roof down, BedZED set new standards for affordable sustainable social housing.

2. BedZED's homes feature sustainable materials combined with passive solar energy.

3. A typical home interior from the estate.

4. Energy flows through the development.

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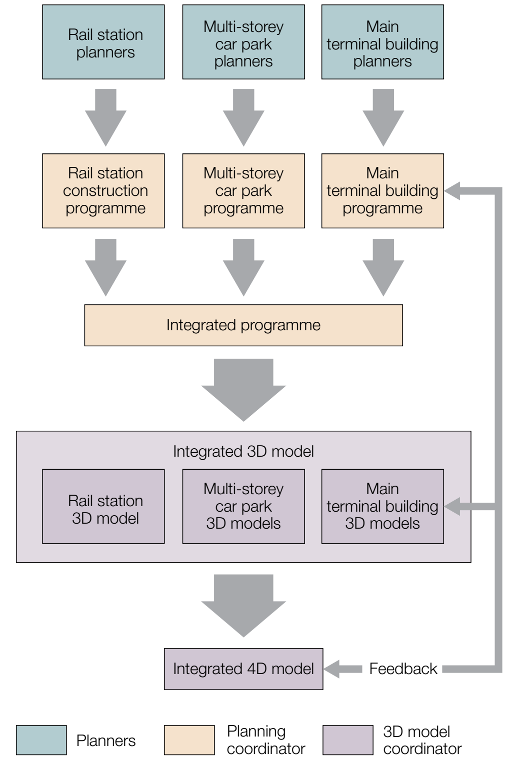


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# Heathrow Terminal 5

On Heathrow Airport Terminal 5, the British Airports Authority (BAA) set up a project team intent on putting into practice the recommendations made in Sir John Egan's 1998 'Rethinking Construction' report that aimed to improve the efficiency of the UK construction industry by establishing partnerships in which architect, contractor, engineer and client took joint responsibility for the project's successful completion.

On the Terminal 5 project, Richard Rogers Partnership was the architect and Arup was the structural engineer. Arup also supplied a range of specialist services and design management across the entire programme.

The popularity of the terminal with passengers is testament to the successful outcome of the collaborative approach. Since it opened, it has regularly been voted the winner of a variety of travel industry awards indicating how well it meets the needs of travellers and those who work or do business there.

**Modern methods of construction**
BAA wanted the new terminal, with its capability to handle more than 30 million passengers per year, to create a significant statement on the world travel scene.

The project included the main terminal building, two smaller satellite terminals, an extension to the rail lines for the Heathrow Express and London Underground Piccadilly line, 60 aircraft stands and associated airfield infrastructure, a 4,000-space multi-storey car park, a control tower, an energy centre and a 600-bed hotel.

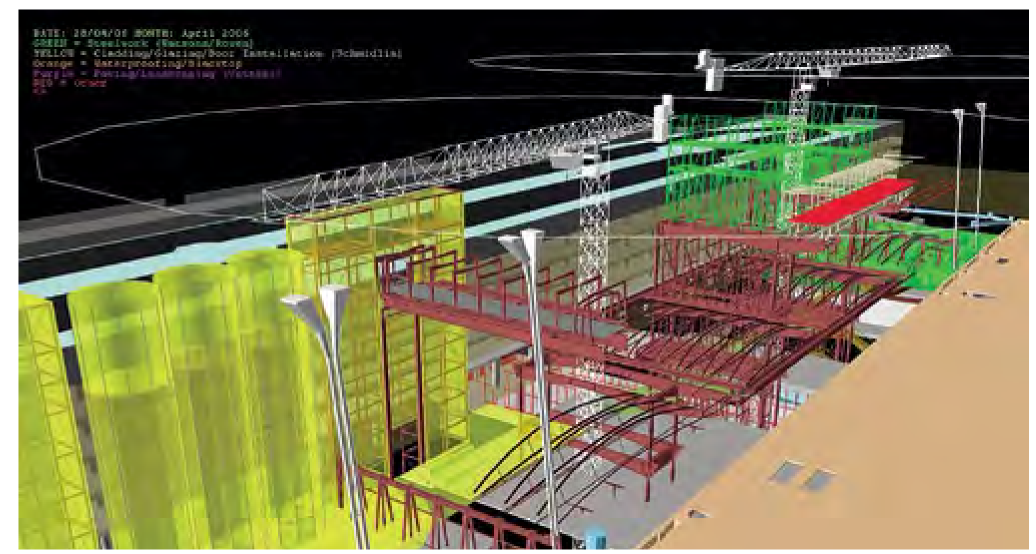
The main terminal building, the most prominent and well-known element of the project, has a single-span roof enclosing many activities in a single space. By adopting 'Design for Manufacture and Assembly' (DfMA), the construction process could be optimised and built safely and efficiently. In fact, the frame design was carefully tailored such that it was hard to say where the design ended and the construction method began.

The structure and its connections and details became sculptural objects in themselves, the language of exposed welds, as-cast steel surfaces, and visible bolts giving a feeling of scale and a grain to the building. Above all, the DfMA approach led to reduced site programme risks and cost. Roof construction started on site in December 2003 and the building was watertight by November 2005, beating the programme milestone by three months, and coming in on budget.

**Single Model Environment**
From the outset, BAA wanted to harness the collective experience of each CAD team to develop an effective tool for computer-aided design, draughting, and manufacture. The system should not only help design coordination and drawing production, but also help plan the terminal's construction and future maintenance. Central to the whole enterprise was the creation of a single CAD system to create, store and share data, called the Single Model Environment (SME). When the concept design process began in 2000, no such system existed, so with BAA's vision and the support of their supplier partners it was developed.

Fundamentally, the SME is a simple concept: a set of directories and folders that store the CAD data for every discipline on the project. Folders are protected to ensure that each discipline maintains authorship over the information it produces. Any discipline can access the information of another for its own purposes, but only after that information has been officially released by the author. The key to the SME is organisation. Although simply stated, it is difficult to achieve in practice because CAD users from different organisations use different standards, limiting the benefits of sharing data. It only works if everyone adheres rigorously to one set of standards and processes. In practice, this approach helped with decision-making by consolidating information and presenting it in a clear and consistent way

**Time saved, time gained**
Additional tools such as 4D planning were used in a number of areas and one prime example was at the Terminal 5A interchange plaza. This area was complex because it was at the interface of the terminal, rail station, car park and landside teams and it was difficult to reconcile the needs of the different teams in this relatively confined space. The tool linked CAD data from the different schedules, helping to identify potential clashes between contractors, and saved £2.5m in the first nine months of use. Because the 4D models could be viewed in standard digital formats, everyone involved in the project could see several years of work unfolding in less than a minute and could resolve issues in advance.



5.

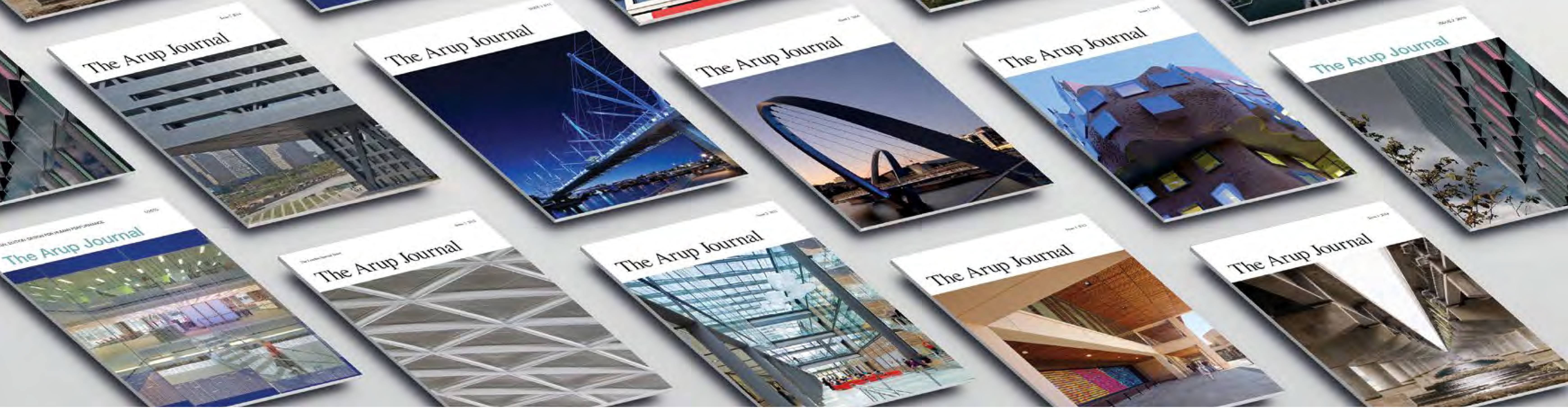
In essence, this project witnessed the first successes of Building Information Modelling (BIM), an approach that gathered pace quickly from the early 2000s and is now becoming standard practice on most projects.

3D and 4D design: arup.com/journal12006
Terminal Building: arup.com/journal22006
Control Tower: arup.com/journal22008

1. Structural engineering of Terminal 5's curving single-span roof was a central challenge of the design.

2. The control tower: one of the most technically challenging aspects of the project (see link).

3, 4 and 5. Designing and constructing the Terminal 5A interchange plaza: the flow chart and BIM model led to the efficient construction of this important link between terminal, car park and rail station.



# 2010s

**Tristram Carfrae** is Deputy Chairman of Arup having joined as a graduate in 1981. He has pioneered the use of computers in design and is widely known for his work on the 'Water Cube' for the Beijing Olympics.

*This has been the decade when digitalisation has really started to redefine and transform the way we design and engineer projects, accelerated by revolutionary consumer technology that has leapfrogged business IT to set new standards for connectivity. As an industry, built environment design and construction wasn't made much more productive by the first micro-computer age in the 1980s. By contrast, the new digital era is bringing together visualisation, operational data and analytics to allow us to become much more ambitious in our work.*

*We're seeing the effects of the digital revolution most clearly in our work in cities. The data we now have is making cities far more intelligible to designers, engineers and their citizens. We're able to shape public transport projects using public data, able to pinpoint the best route for trains or metro services. We have projects where anonymised phone data or Twitter heat maps can tell us in incredible detail about people's behaviour and needs. So in this new era designers and engineers are able to understand land use in multiple simultaneous dimensions. This in turn is changing the nature of our work, expanding engineering's horizons from the individual project level into true 'systems thinking'.*

*This decade has crystallised several long-term global trends. Sustainability and climate change have both become accepted facts of life, ones that we're responding to in our work. Sustainability has expanded and grown as a concept to encompass overall resilience to threats economic and social, as well as natural and physical. Tackling these issues requires the kind of multidisciplinary approach Arup is well-organised to deliver.*

*And in an era of rapid change it's also worth saying something positive about continuity. For 50 years, The Arup Journal has been dedicated to explaining the processes that go into our work, capturing the specifics of our projects. As our work deepens in its scope, sophistication and meaning, the role of The Arup Journal in sharing what we've learnt, is as critical as ever.*

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# The Fulton Center

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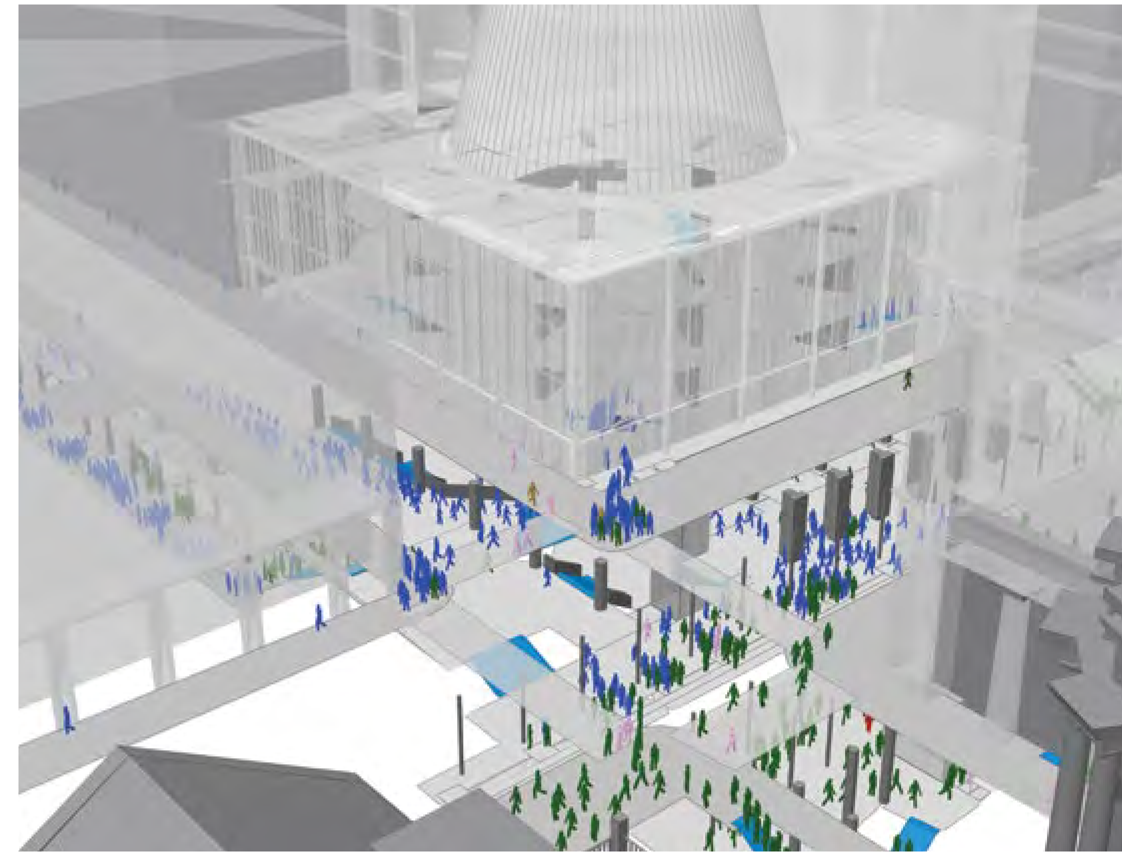


3.

On the corner of Fulton Street and Broadway, the Fulton Center unites 12 subway lines and six stations beneath Lower Manhattan into a single transit hub. Arup created MassMotion pedestrian simulation software specifically to understand how people would move through this complex interchange. The connections developed between the lines, as a result, enable commuters to negotiate it with ease, leading to a smooth flow of people.

Above the stations, the Fulton Center offers multi-storey retail crowned by a distinctive circular cone and glass skylight – the oculus – that has become a city landmark. The cone is lined with a stainless steel cable net, a permanent art installation of almost 1,000 reflective panels that direct light downwards to illuminate the subterranean space.

Next door, and attached to the Fulton Center, is the historic Corbin Building – Manhattan's tallest when it was built in 1888. Lavishly decorated with ornamental terracotta and steelwork, it had fallen into disrepair and was scheduled for demolition until it was restored as part of the project.

Arup was commissioned by the Metropolitan Transportation Agency (MTA) as prime consultant for the project, to provide overall planning, project and design management, engineering and risk advice.

**Corbin Building**
Retention of the Corbin Building depended on whether it could be made compliant with modern building standards. One of the first challenges was how to structurally integrate it with its new neighbour. Initial investigation of the site established that it would have to be supported. So Arup developed two 3D structural analysis models to interrogate and predict the building's movement and stability given its limited foundations and the need to connect it to the new transit hub.

Ultimately it was decided to build a new lateral stability frame attached to the Corbin's west edge, to support it by absorbing some of the lateral shear forces created by the new Fulton Center, and also provide a location for the Corbin's upgraded services. Given the narrow wedge shape of the building, there was little flexibility to remodel the interior for these upgrades, so an external frame was beneficial in this regard. And as the models predicted, the dead weight of the new frame added greatly to its stability.

Arup's role as lead consultant helped significantly in fostering a creative collaboration that fully involved the client, the approving authorities, and the several architectural firms that worked on the overall development.

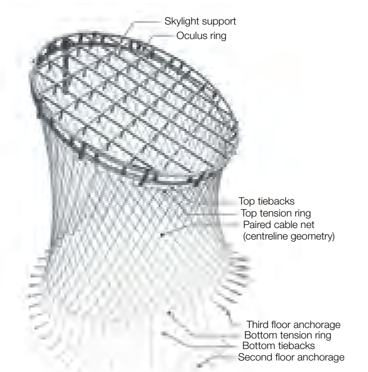
**Oculus and Sky Reflector-Net**
The superstructure of the Fulton Center, designed by Grimshaw Architects, is a three-storey glazed pavilion set around a central eight-storey cone structure surmounted by the inclined circular skylight known as the oculus, which collects and redirects sunlight through the building. The central space beneath the dome and oculus is occupied by a large-scale artistic installation – the Sky Reflector-Net.

The Sky Reflector-Net is the result of an engineering, architectural and artistic collaboration between Arup, Grimshaw and James Carpenter Design Associates to develop a reflective lining that is independent of, and offset from, the dome's interior. The result is a steel cable net structure supporting nearly 1,000 coated aluminium infill panels using flexible, universal node connection assemblies.

4.

Extending the full height of the central space, the cable net is suspended from 56 connection points around the compression ring of the oculus and anchored to as many cantilevered beams at levels 2 and 3. It is a skewed hyperbolic paraboloid, or hypar, in form; but, unlike a regular hypar, it has double curvature. Moreover, the skewed form has only one axis of symmetry, so each four-sided infill panel has a unique shape, defined by the lengths and intersecting angles of the cable segments along each side.

Arup worked with architect and artist to understand how factors such as air pressure,




5.

interior temperature and building movement would influence the movement of the net, then developed 815 unique scenarios that each produced a slightly different cable net shape. Finally, Arup analysed the intensity and distribution of the light that would filter into the space below. The result is a bright, uplifting space that welcomes visitors and cheers the daily commute of thousands of New Yorkers.

Fulton cable net: arup.com/journal22013
Corbin Building: arup.com/journal12014

**Craig Covil**, was the project director for the Fulton Center.

*We had such an important undertaking, extensive in scale and lengthy in project duration, that for me the epitaph has been the journey to becoming a trusted advisor to our client. We were allowed to engage in things way outside our original brief, and our holistic strategies, robust and rational, endured the many vicissitudes of project delivery. It's a privilege to work for clients and earn their trust, it empowers and enables us to do greater things.*

1, 2. Many thousands of people transit through the Fulton Center every day. The exterior blends the modernity of the glass frontage and oculus skylight with the historic redbrick Corbin Building.

3. MassMotion pedestrian simulation software was developed specifically to understand how people move through the levels down to the station platforms underground.

4. Even in the base of the station, commuters can look up through the oculus to see the sky.

5. The steel cable net structure of the Sky Reflector-Net that gathers light from the oculus to illuminate the spaces below.

1.

3.

5.

# London in 2012

The London 2012 Olympic and Paralympic Games meant the eyes of the world were focused on the UK capital that year, and beyond the Games there was much to celebrate in the revitalised infrastructure of the capital. *The Arup Journal*, in a special issue of the magazine, showcased projects that demonstrate how Arup's reputation for collaborative innovation made the firm a player in many of the city's milestone achievements.

**Masterplanning for London 2012**
The opportunity to redevelop land east of London was spawned many years previously by Arup's plan for the Channel Tunnel Rail Link (CTRL) route (see page 56).

When the UK government adopted the firm's proposal to run CTRL into the north of London from the east, it not only connected the UK with the European rail network, but also made available three large sites of largely derelict land at King's Cross, Stratford and Ebbsfleet. Arup's range of roles in transforming these sites included the masterplan for Stratford, the regeneration principles for King's Cross, and preparing the cost–benefit study for the government that paved the way for the Olympics.

CTRL and the revitalisation of east London were significant factors in winning the Games; and CTRL, now known as High Speed 1 (HS1), has reconfigured London's transport landscape. The shift in its centre of gravity towards the north and east is a lasting legacy, both socially and economically.

**Stratford and the Olympic Park**
The masterplan for Stratford and the Queen Elizabeth Olympic Park was developed with the intention of leaving a lasting legacy: a vibrant residential and business area that would thrive after the Games.

And this was to be done on a site scarred by years of heavy industry. In the south of the Olympic Park – an area that became an urban park after the Games – planning focused on how to redevelop the complicated landscape of existing watercourses, roads and railways that were interwoven along the border of the new Stratford City development. Contaminated land and groundwater was an issue in many parts of the site and remediating successfully, swiftly and comprehensively was a crucial element of the plan, essential to the success of the Games and to underpin the legacy proposals.

Infrastructure for the new Stratford City retail development was reclaimed from former railway land. With the bare minimum of existing infrastructure on the site, Arup drew up a plan encompassing earthworks, bridges, retaining walls, highways, drainage, lighting and utilities, including combined cooling, heat and power (CCHP).

2.

The firm's visualisations showed plans for the Olympic Park site in realistic detail and this helped the design teams and stakeholders to make important decisions. Using bespoke software, Arup brought together information from across the park to create virtual and physical models, animations and still visualisations.

Initially, the visualisation supported the structures, bridges and highways workstream: clear communication was essential to achieve planning permission, and visualisations enabled planners to see exactly what was proposed. This worked so well that later in the project Arup built a coordinated computer model of the whole Olympic Park site, set in a wider model of London, bringing together information from architects, engineers, landscape designers and other specialists.

4.

Employing powerful gaming technology, the team used this model to create a real-time simulation that let stakeholders 'fly through' the park. The simulation proved an ideal tool to help choose between options and for stakeholder and public consultation.

**King's Cross**
In addition to masterplanning for the King's Cross area, Arup worked on the modernisation of the station. The original Victorian façades were retained and a vaulting canopy roof over the western concourse was added.

The roof was described approvingly by architectural critic Kieran Long as "like some kind of reverse waterfall". Arup's GSA structural analysis software proved an important tool in establishing the viability of the roof design, given the massive loads to be supported, and the firm provided multidisciplinary services on the project.

Other projects featured in *The Arup Journal* 2012 Special Issue include:

**The Shard**
A striking addition to the London skyline, The Shard's spire-like shape, 310 metres tall, with constantly varying geometries, presented unique challenges in terms of the position and implementation of its services, including the requirement for additional high-speed evacuation lifts. The ever-decreasing floor plate sizes meant the Arup team that worked on this project had to design plant and MEP functions that worked compactly.

**Evelyn Grace Academy**
Zaha Hadid's ambitious Evelyn Grace Academy, Lambeth, provides accommodation for two schools in a three-storey curving shape. Arup, as structural engineer, made the design workable within the tightly constrained budget. Natural or passive ventilation keeps down the building's operating costs.

**Leadenhall Building**
Arup worked with Rogers Stirk Harbour + Partners on this project, known to most Londoners as 'the cheese-grater'. A massive steel diagrid-framed building tapering to a narrow summit, it presented challenges in terms of location and layout of its building services. Arup's solution was to integrate them into the architecture of the building from the outset.

**Crossrail**
While there were many eye-catching designs on the city's skyline, a big story was shaping up underground. Crossrail – the most extensive civil engineering project in Europe – was finally hitting its stride. This is an Arup tunnelling project and by mid-2012 two of the tunnel boring machines (TBMs) began their journey from Royal Oak, near Paddington in the west, to Farringdon in the east. Arup is involved in many parts of the continuing programme, including the new station within the deck of Canary Wharf.

The London Special Issue: arup.com/journal22012

1. Stratford City in the foreground with the Olympic Stadium beyond.
2. A model of the approved masterplan for Stratford City.
3. The new King's Cross station roof.
4. Evelyn Grace Academy, a challenging structure Arup delivered with Zaha Hadid Architects.
5. Design and implementation of the building services and communications infrastructure on The Shard meant creating solutions that tapered with its shape.

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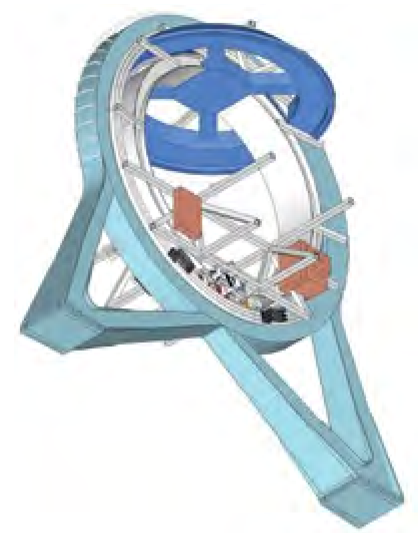

3.

# The Vegas High Roller

In a city as visually arresting as Las Vegas, it takes a remarkable structure to make an impact. The 550ft-high Vegas High Roller, opened in 2014, is an elegant response. The structural design of this giant observational wheel, particularly the 'V frame' that attaches cabin to rim, is deceptively simple and highly efficient.

The wheel was commissioned by Caesars Entertainment for its LINQ development on the Vegas Strip, and Arup worked in collaboration with specialist contractors, fabricators, suppliers and other consultants to deliver the project's aspiration: an unforgettable passenger experience. The firm's involvement followed its success in engineering two similar observation wheels – the London Eye and the Singapore Flyer, the latter being a close comparison for the High Roller at 541ft tall.

In the absence of a full design-build contractor, the client asked Arup to develop the design of the wheel, its structure, the platforms and foundations. The scope of works called for a highly integrated response to the reference design, using many connected disciplines: structural wheel design, wind engineering and occupant comfort assessment; geotechnical engineering and foundation design; the High Roller's drive mechanism and controls; cabin design including glazing and heating; fire engineering and safety systems; acoustic and noise consulting; failure mode analysis and documentation.

Beyond the structural engineering of the wheel itself, it was clear that the cabin experience would be critical to making the High Roller a success. So, as the wheel operates the cabins are designed to actively rotate relative to the rim, ensuring the passengers experience a continuous flat-floored experience. Each of the 28 cabins is suspended from a V-frame that connects back to the rim of the wheel.

The cabins were extensively prototyped for manufacturing ease, performance and stability, and safety was a major driver within the design: the Roller features full redundancy, a backup 'sloth mode' in the case of general power failure, and emergency supplies for passengers in each cabin should they get stuck for an extended period.

Vegas High Roller: arup.com/journal22014

1. After the London Eye and the Singapore Flyer, Arup designed and delivered the Vegas High Roller.
2. The rotational cabins in production, the result of many design iterations and prototyping.
3. CGI model of the cabins, showing the V-frame connecting to the main rim.



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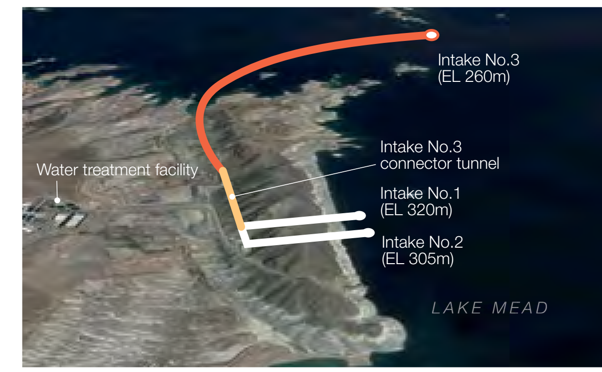



3.

# Lake Mead Intake No.3

Orchestrating the design and construction of the world's highest-pressure subaqueous tunnel, bored down into the bed of Lake Mead reservoir, South Nevada, involved Arup's international tunnel engineering team working under an unprecedented 17 bar from above. The tunnel takes water out of the bottom of the reservoir into the water supply system for Las Vegas.

With water levels in the lake falling drastically over the past 10 years through drought and increased demand, the two existing intake tunnels were placed too high to offer continued access to quality drinking water, so a third deeper intake was deemed vital. For Arup, this was an eight year tunnelling project, a perilous operation to bore through the bottom of the lake.

A precise and innovative methodology was defined to excavate the 5km-long, 6.1m-diameter tunnel safely, given the pressure from above and the need to avoid flooding the new tunnel before the connection was complete. The Arup team opted to prefabricate the intake structure in a hole at the bottom of the lake, surround it with concrete, and bore the tunnel towards it, connecting intake and tunnel using a remote access vehicle only when both were complete.

An initial access tunnel was built, wide enough to allow assembly and operation of the 1,500-tonne tunnel boring machine (TBM). As the TBM moved slowly forward, 2,400 precast concrete rings, each weighing 30 tonnes, were lowered into place behind it to form the tunnel. Meanwhile, the concrete and steel intake was fabricated on shore before being floated out on the lake and sunk to the concrete base already installed on the lake bed.

The new intake won't draw more water from the lake than before, or make the surface level drop any faster, but it will keep the water flowing even if drought-stricken Lake Mead drops to its lowest-ever levels. It will ensure quality and security of water supply in Nevada, and the knowledge gained on this project has informed other Arup tunnelling commissions around the world.

Lake Mead Intake: arup.com/journal12016

1. The new intake tunnel runs deep below Lake Mead to supply Las Vegas with water.
2. Boring the tunnels was complex and difficult work, performed under immense pressure of up to 17 bar from above.
3. Schematic of the first two shallower intakes, with Intake No.3 placed further offshore in one of the deepest areas of the reservoir.

1.

# Hong Kong's waste-to-energy plant

1. With a flowing roofline, the structure blends elegantly into its surroundings on Stonecutters Island, Hong Kong.

2. The plant fits into the undulations of the roof.

3. BIM model showing flue gas treatment area and support steelwork coordination with equipment.

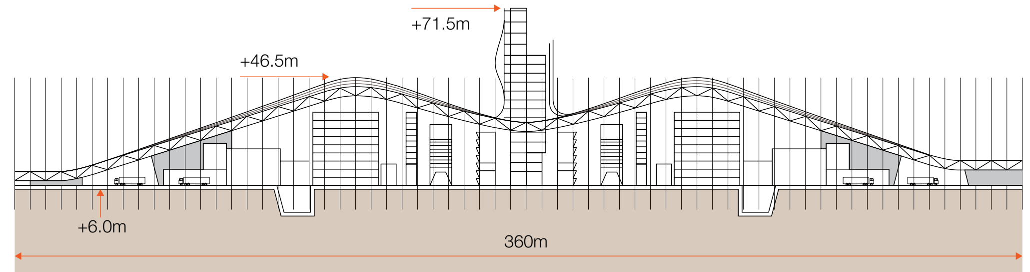
4, 5. Comparison between as-built flue gas duct and 3D BIM model of the same area.

6, 7. The pipe bridge, after construction and as a 3D BIM model.

Hong Kong's waste-to-energy plant at Tsang Tsui Ash Lagoons, is a critical element of the Hong Kong Government's strategic approach to managing sewage sludge. Arup worked with the Veolia–Leighton–John Holland joint venture and Vasconi Architects to devise and deliver what is the world's largest sludge treatment facility of its type.

Operational since early 2015, the plant processes 2,000 tonnes of waste daily and is a model of sustainable infrastructure, diverting its own heat into power generation and reducing the amount of sludge that goes to landfill by 90%. The heat generated by the treatment process is sufficient to power steam turbines that create enough power to run the facility and export to the grid. At full operational capacity, an excess of 2MW of power is available daily. The site has also committed to a zero fluids discharge policy: water recovered from desalination is used on site for drinking and industrial processes, and all wastewater is reused.

Designing and constructing the new plant meant closely integrating civil, structural, geotechnical, process and power generation disciplines. Having won the tender in 2009, Arup mobilised a team from different parts of the firm to work on delivering this technically challenging waste treatment facility.




2.

**Buildings Information Modelling (BIM)**
BIM techniques played a central role in this multidisciplinary project. BIM proved key to understanding how the design would deliver on requirements and represent a viable solution for all stakeholders. With so many complicated and interconnected technologies and structural elements within the design, these 'buildability' insights were invaluable. The entire design process followed a detailed 3D BIM model that could coordinate packages, simulate operation of key features and help define a successful construction process in virtual space. It also meant the team could resolve issues with the design implementation dynamically, inside the computer, at every stage.

This project was an exemplar of how powerful a comprehensive use of BIM can be. The modelling tools comprised detailed designs of the entire project from the geotechnical engineering at the rock head, to the engineering and mechanical design of high-pressure pipework, power and lighting – all within a single model.

**Site formation and foundations**
The seven hectare site of the facility, in Tuen Mun district on the northern coast of the New Territories, is in an area that had been used for disposing of pulverised ash fuel (PFA) from the nearby Black Point Power Station.

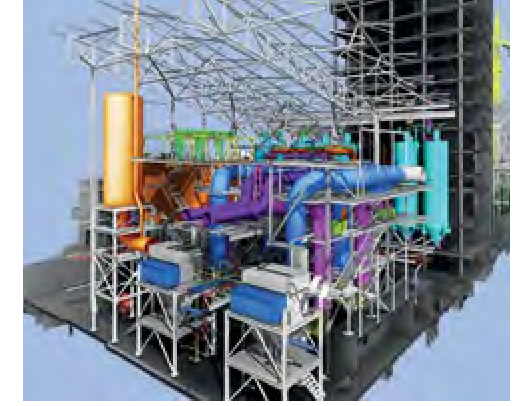
Since none of the PFA material could be exported off site, the nominal site formation was carefully selected so that PFA could be used as fill in low-lying areas. Once it was established that the corrosive qualities of the fuel ash layer would not damage steel piles over time, a combination of 15m- and 30m-deep driven H-piles was selected as the most appropriate solution.

**Architecture**
Inspired by Chinese mythology, the building's flowing roofline is fashioned in the shape of a dragon's wings or the rising waves of the sea. And the design is intensely practical, its shape ideally suited to the linear production line within. The 400m-long roof spans over, and unites, the two incinerator plants and the centrally located administration tower. In the longitudinal direction, the roof height varies from 6m to 35m above ground level, with the highest points housing two incinerators. To achieve natural light penetration into the building, a series of varying-height north-lights project from the roof surface, forming a stepped profile to the transverse roof cross-section.

**Fire engineering**
Fire safety design was an important facet of this project for Arup. As well as the industrial plant, the sludge treatment facility has a visitors' centre, so strategy had to be developed with public access in mind. In addition, the high-temperature incineration that is part of the sludge treatment process is new to Hong Kong. Prescriptive fire codes could not be applied fully to the facility and therefore fire engineering assessments were conducted to demonstrate the appropriate fire safety level. The fire engineering aspect of the project is detailed in the full *Arup Journal* article.

**Sustainability**
Hong Kong's waste-to-energy sludge treatment facility combines state-of-the-art engineering with a stylish architectural approach. A key building block in the Hong Kong Environmental Protection Department's sewage treatment strategy, it will play an important role in protecting sea water quality and also provide a steady supply of electrical power to the residents of Hong Kong.

Sludge treatment facility: arup.com/journal22015



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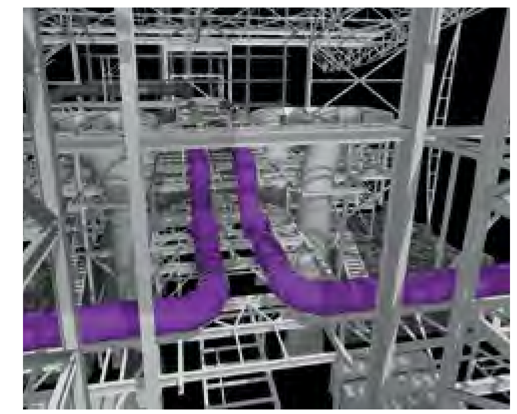

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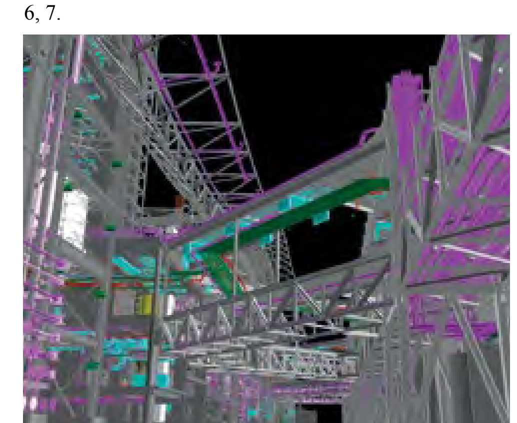

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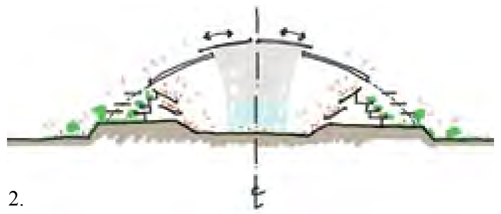
# Singapore Sports Hub



2.

1. A panoramic view of the Singapore Sports Hub in its waterfront location. The National Stadium at the heart of the development is oriented to provide a magnificent view of the city when the roof is opened.

2. A conceptual sketch of the stadium.

3. The seating bowl is designed for optimised viewing of football, rugby, cricket and athletics: 30,000 of the seats are retractable.

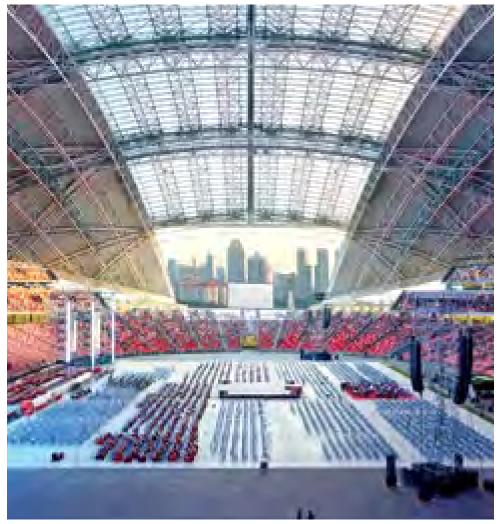
4. Detail of the cladding systems between the fixed roof of the stadium and the giant louvres that shelter the promenade around its perimeter showing how the structure is reduced to something more in keeping with the human scale at ground level..

Singapore celebrated the opening of Asia's first integrated sports, leisure, entertainment and lifestyle destination – the Singapore Sports Hub – in June 2014.

Located on a 35-hectare waterfront site, within easy reach of the city centre and international airport, the Sports Hub is key to the Government of Singapore's urban development plan and central to its 2020 vision for a sustainable, healthy and expanding population. Since opening, the venue has been in use for at least 100 days per year, demonstrating its popularity as an event facility.

At the heart of the Sports Hub is the new National Stadium conceived as a unifying protective canopy that connects all parts of the Sports Hub masterplan. The dome to the stadium has a span of more than 310m, making it the largest free-spanning dome structure in the world – an awe-inspiring event space. Air-cooled, and designed with a movable roof and retractable seating for a wide range of sport and leisure events, it is a state-of-the-art stadium.

Within the team that developed this project, Arup's client was Dragages Singapore. Arup Associates worked with DP Architects on the architecture.



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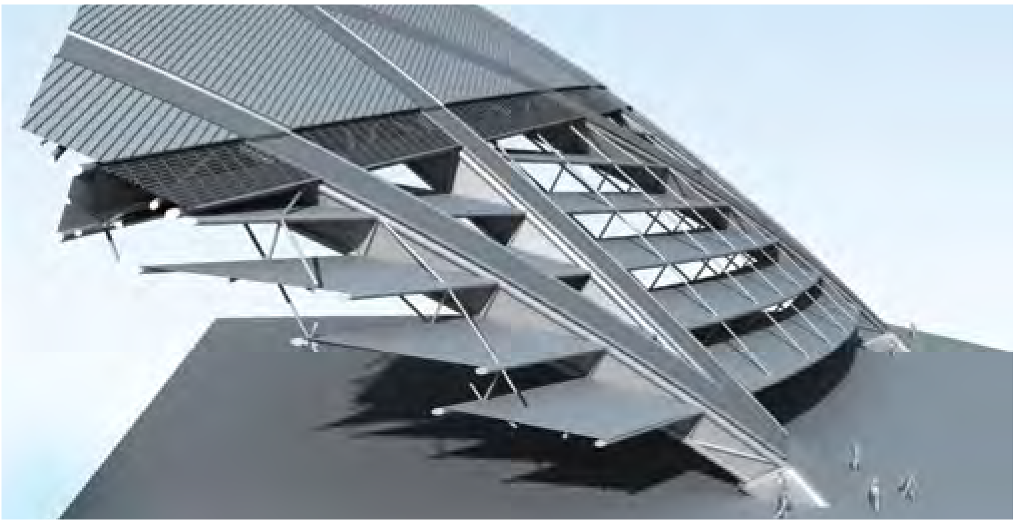
The dome roof form was chosen as it is structurally the most efficient for a roof structure of this scale, especially one that integrates a retractable roof. Singapore is a unique location – no seismic activity, low wind and no snow load – so it presented the Arup team with a unique architectural and structural opportunity.

**Parametric model**

The latest parametric modelling software was essential to the integrated architectural design and engineering of the Sports Hub, particularly the stadium roof. So a model was built that allowed the roof structure to be assessed structurally and redefined as the design developed.



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The model was used to control a multitude of other relationships between elements, which would have been impossible to achieve using conventional software. Each parameter was treated in the same way – structural and architectural requirements were considered, an optimised parameter agreed and inserted into the geometric control model for the roof.

In time, a fully editable 3D model of the stadium roof was completed that defined every constraint imposed on the roof and could be used independently by every member of the team.

**Roof design**

The initial target was to reduce steel weight by leveraging the inherent efficiencies of the shell roof form. One outcome of this was reduction in the depth of the primary structure as it came to ground. Two control surfaces were established to define this – one sphere to the top and an offset sphere to the bottom surface – with the roof structure reducing from a maximum depth of 5m to the centre of the dome, to 2.5m at the base. This optimised structural solution provided an architectural benefit at ground level as the proportions of the structure reduced to something more in keeping with the human scale.

Reducing dead load wherever possible was a key goal and the team estimated that for every 10kg of weight added to any part of the shell structure, a further 4kg would need to be added to hold it up. This was a strong influence in the design of the moving roof structure as well as the moving/fixed roof cladding design. The result is a dome that uses one-third of the steel weight per square metre compared with other large-span structures of this scale.

**Moving roof cladding**

For the moving roof, Arup's architects wanted a lightweight cladding system that provided shade to the seating bowl and reduced solar heat gain. At the same time the team wanted the moving roof to appear translucent to create a naturally lit event space during the day.

A multi-layer ETFE pillow was chosen to meet these design requirements and at the same time provide the opportunity to illuminate the moving roof at night. Sized at 20,000m$^2$, the moving roof is one of the largest addressable LED screens in the world and an unmistakable feature on the Singapore skyline.

Singapore Sports Hub: arup.com/journal12015

# BIQ House

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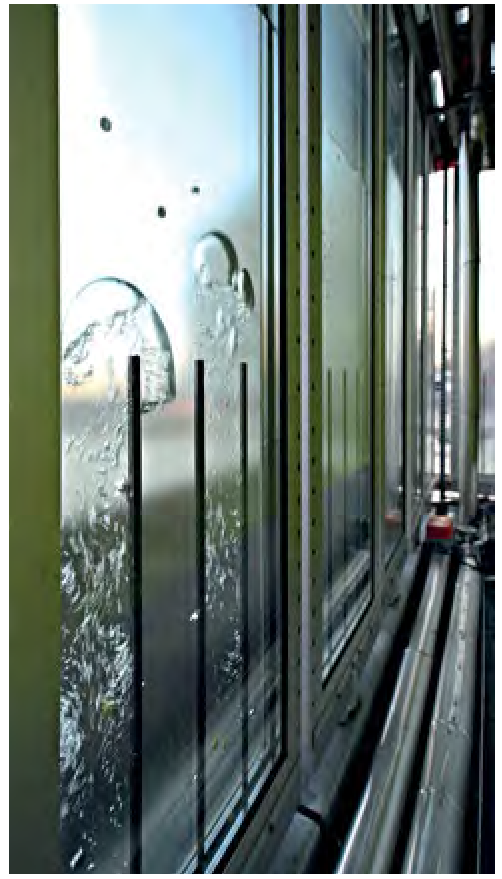

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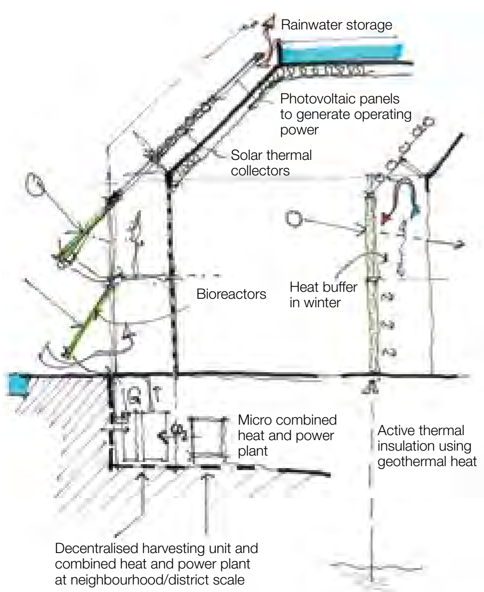


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1. The SolarLeaf panels that clad the exterior of BIQ House.

2. Using natural biological processes the cladding panels generate heat and power from sunlight

3. The BIQ House: the completed, fully assembled competition entry was a successful proof-of-concept.

From heating to lighting to air conditioning, buildings are some of the biggest consumers of energy. As building design embraces net-zero carbon goals, the race to create new post-carbon energy sources is under way.

The BIQ (Bio Intelligent Quotient) House, built in 2013 for the IBA International Building Exhibition in Hamburg, Germany, is a four-storey residential apartment block with a bio-responsive algae façade to generate heat and energy.

The façade technology, now marketed by Colt International as 'SolarLeaf', is the result of a collaborative project launched by Arup and Austrian architects Splitterwerk when they came together to develop an entry for the IBA 'Smart Materials House' competition. The work they started resulted in a working prototype within just two years.

Arup and Splitterwerk brought together hydrobiology specialists Strategic Science Consult GmbH, with Immosolar GmbH, to develop flat-panel bioreactors, similar to solar thermal collectors. SSC's technology created air bubbles within the panels to stimulate the absorption of carbon dioxide and light, thus boosting the production of biomass while simultaneously washing them clean from the inside. Up to 40% of the incident solar energy is recouped from the hot water in the panels and burning the algae that's grown.

When other partners, including Colt International, with their expertise in façade and climate engineering components, came into the collaborative partnership, the team finessed the panels. The resulting façade component was a glass louvre the height of a whole storey of the BIQ House, which pivots to track the position of the sun. The frame containing the supporting technology includes a pressurised air supply, inlets and outlets.

The BIQ House was the first pilot project and Arup developed the energy concept, the energy control centre and the mechanical systems for it. The success of the apartments, which are now occupied, has been widely heralded as a great example of the rethinking needed to decarbonise building design.

BIQ House: arup.com/journal22013



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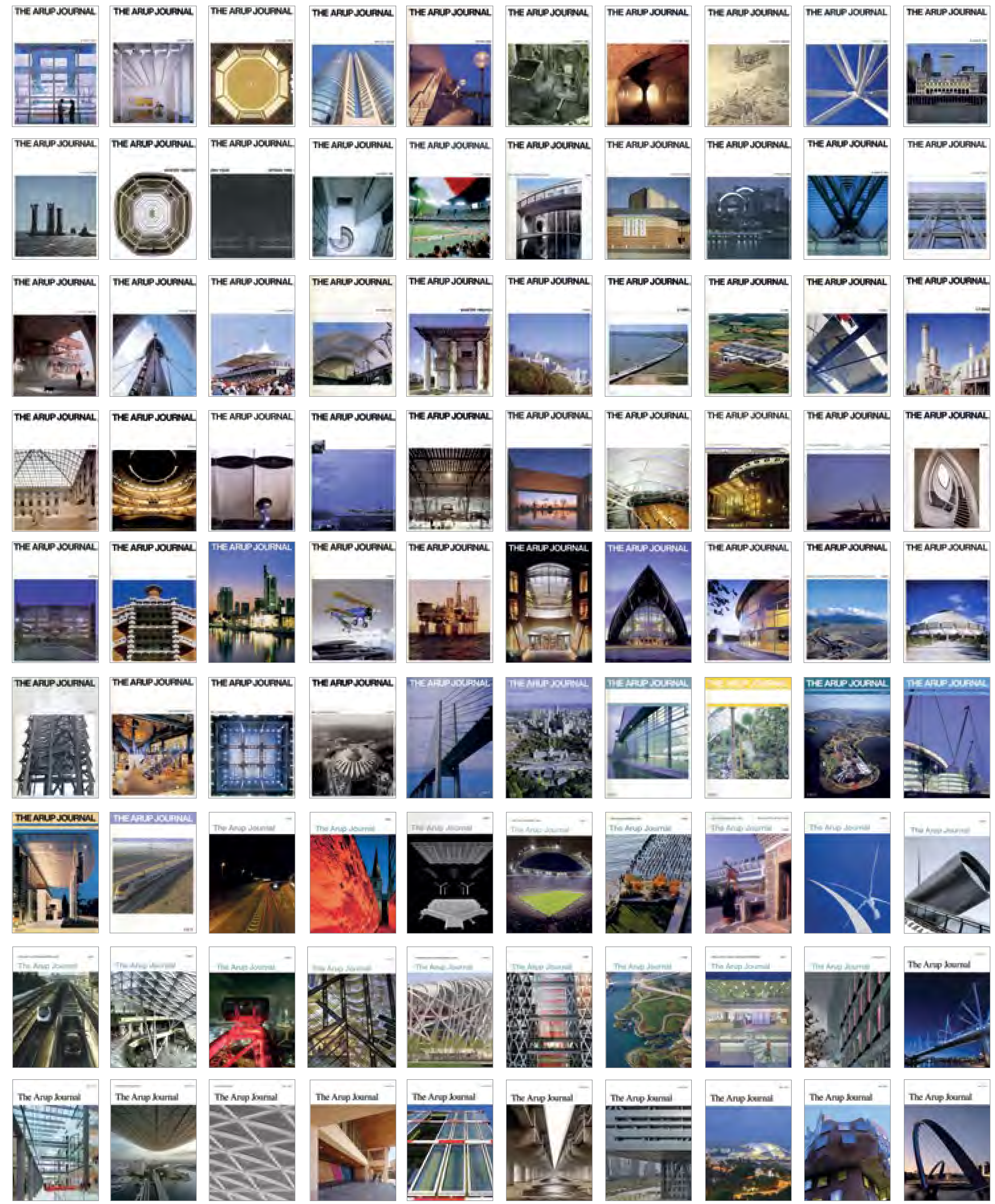


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