1. The main terminal building, summer 2005.

Terminal 5, London Heathrow:

The main terminal building envelope

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Introduction

When Heathrow Airport opened in 1946, a group of tents and some phone boxes formed the first passenger terminal. Facilities at the airport have moved on immeasurably since then, but there is always room for improvement and so, at the end of the 1980s, BAA started to plan a fifth terminal.

The process of deciding what to build and getting planning approval was long and complex, but by early 2000, the project team had started work in earnest on the design of the new terminal.

T5 was to handle 30M passengers per annum and had to make a significant statement on the world travel scene. BAA wanted "the world's most refreshing interchange" and so, when the structural engineer suggested that the main terminal building could have a single-span roof that vaulted over all its disparate activities to enclose them in one space, the architects and BAA took up the idea with enthusiasm.

BAA set up the project team under a partnering contract and made Arup responsible for structural engineering of the buildings above ground level. The firm worked alongside the other "first tier suppliers" in a partnership where architect, contractor, engineer, and client took joint responsibility for the project's successful completion. The whole team worked in one place, on site, at Heathrow.

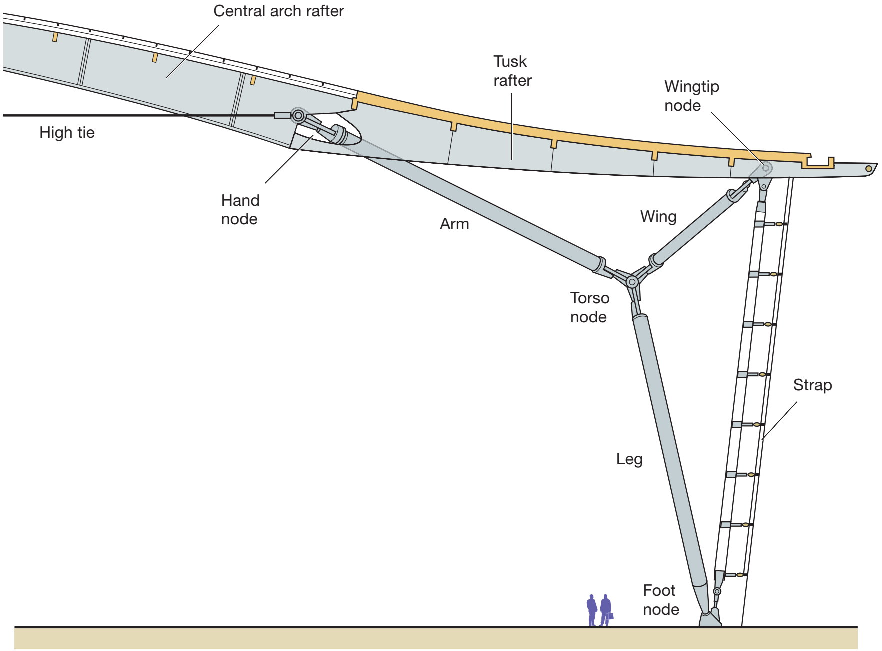
There is a lot to say about T5. The innovative computer-aided design tools have already been discussed[1]. This article covers solely the design and construction of the roof and façades of the main terminal building (Fig 1). Further aspects of the complex will be dealt with in future *Arup Journal* articles.

2. Dramatic full-height circulation space.

Main terminal building roof

The roof has a span of 156m, and is 396m long. It is supported by 22 pairs of 914mm diameter steel legs that reach down to apron level in dramatic full-height spaces just inside the façades (Fig 2). These spaces also form the main routes for passenger vertical circulation to and from the gates.

The span is formed from steel box girders at 18m centres: 800mm wide and up to 3.8m deep. These are tied at high level by pairs of 115mm diameter prestressed steel cables. 914mm diameter steel arms reach up from the tops of the legs to support the rafters, and solid steel tie-down straps from the rafter ends complete the 3D hybrid portal frame structure (Fig 3).



3. Main structural elements of the roof.

5. Minimal intrusion of façade vertical structure.

Single span

The three-storey superstructure of the terminal is completely separate from the roof and façades (Fig 4). BAA chose this bold structural arrangement because it gave several important benefits. The roof acts as a visually unifying element for the building. It is intended to give travellers a sense of place in the world as well as an intuitive feel for where they are within the terminal. The lines of the structure and roofing are deliberately simple and clean to impart a feeling of calm and purpose to the space.

BAA strives always to provide value for money by constantly fine-tuning the retail and passenger service offered within its terminals. This can lead to a lot of building work and inconvenience caused to terminal operations, but in T5's main building all this work will be internal, on the upper levels, and non-structural, so disruption to BAA's business will be minimized.

4. Structural separation of envelope and content.

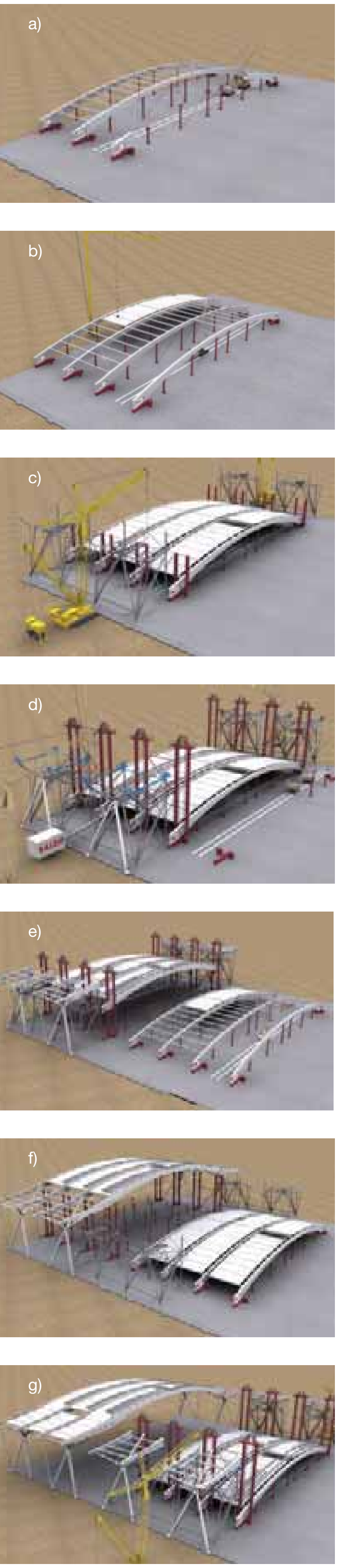
The construction critical path went straight from completion of basement slab to roofing and façades, which led to an early date to achieve watertightness. Moreover, the internal structure was constructed in a semi-indoors environment, improving build quality and reducing programme delay from bad weather.

Perhaps the most significant benefit has been the fact that design and construction of the roof and façades was free to go ahead completely unimpeded by any decision-making about the function or layout of the internal spaces. For instance, in 2003 BAA made huge changes to the internal layout of the building so that British Airways could move its whole operation into the terminal in one go, but that did not affect the roof team at all. The site programme continued to march forward, without even pausing in mid-stride.

Façades

A key part of the passenger experience in this building will be the ability to look out at the airfield and aircraft and get a taste of the excitement of air travel. The façades are thus fully glazed, and the design team strove to minimize the intrusion of vertical structural elements into oblique views through them (Fig 5).

The team decided to use the roof tie-down straps to support the façade wind loads. The straps are part of the roof structure: they run vertically and carry tensions from the roof of up to 9000kN. When the wind blows on the façade the straps will deflect,



6. Roof assembly sequence.

but as they deflect the tension tries to pull them straight again. This tension stiffening effect reduces bending moments and deflections, so the straps can be slimmer and less obtrusive than a conventional façade support.

Elliptical hollow sections span horizontally 18m between the roof tie-down straps. The weight of glass and steel is carried to apron level by a series of 139mm diameter steel props.

The façades on the gable ends of the building each consist of a simple grid of steel that carries gravity loads down to apron level and resists wind loads by spanning vertically up to the underside of the roof. There is a joint at the head of the gable façade that allows vertical and in-plane horizontal movement between the façade and the roof while still carrying wind load in the out-of-plane direction (Fig 7).

All the façade panels are 2m x 3m double-glazed and toughened with aluminium framing. *Brises-soleils* are used to reduce building cooling loads and consequent carbon emissions. On the "land side" of the building the glass is laminated, and the robustness of the framing, the fixing of the glass, the frame, and the steel connections are enhanced to resist blast loading from terrorist attack.

Erection method

Arup strives for quality of a building in its widest sense rather than merely achieving the "best" design in each individual discipline. This, of course, includes its construction as well as its systems, aesthetics, usefulness, and sustainability. Here the construction was a major consideration, and so the Arup team was delighted to work with the steel supplier Watson, the architects Richard Rogers Partnership, the heavy lifting specialists Rolton, and the rest of the construction and design team to tailor the frame design to suit a safe and efficient construction method. They, in their turn, were also keen to tailor the construction method to suit the design -so much so that it is now hard to say where the "design" ended and the "construction method" began. This was made much easier by the partnering contract that BAA set up for the T5 project and by the co-location of all concerned in dedicated offices at Heathrow.

The roof was assembled in five phases of 54m and one of 18m. The central arched section of each phase was assembled, clad and prestressed at ground level, and temporary works frames used to position the abutment steel for each phase accurately (Figs 6a-b). The centre section was then jacked 30m vertically into position and bolted to the abutment steel (Figs 6c-e). Once each phase was complete the temporary works frames were rolled north by 54m ready for the next phase (Figs 6f-g).

7. Joint at head of south façade.

8. Rafter section arriving on site.

Transport factors

The dimensions of this structure are such that almost every design decision included some reference to how the steel would be transported to site. There was no space for storage and so every load had to be planned so that it could arrive on site and be unloaded directly onto the work face.

The largest sections of rafter weighed around 50 tonnes and were up to 3.8m high. Other rafter sections were 27m long. They were fabricated in Finland and brought to the UK by ship, where they took to the road (Fig 8). The torso nodes were slightly lighter at 38 tonnes, but they did require purpose-made transport frames so that they were in the correct orientation for assembly as soon as they arrived on site.

9. Roofing material in place prior to erection.

10. Jacking of roof elements.

The low-level assembly of the central arch sections was a key decision, and had three main benefits:

- It reduced the risks of working at height for both the steel erectors and the roofing installers. All the cladding for the central arch sections and the aluminium roofing material for the whole width of the roof was placed on the central sections before they were lifted into place.
- It minimized the height of the props needed to assemble the arch.
- It allowed the whole operation to be carried out by cranes whose tops were below the airport radar ceiling.

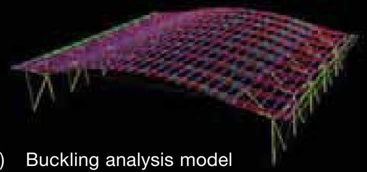
The construction team planned the whole process meticulously at the start, and refined its plans as the job progressed. Arup members of the design team observed the prestressing and jacking processes and so were able to take an active part in the construction process and in problem-solving on site. Overall, the construction went very well and it was a pleasure to have such close involvement in it (Figs 9-11).

11. Central section clad and prestressed, May 2004.

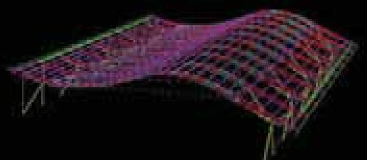
Modal buckling analysis

The T5A roof is a massive arch and carries huge compression forces. It is essential to prevent buckling both of its individual parts, and of the structure as a whole. In the past, engineers typically used rules of thumb, simple calculations, and educated guesswork to design against buckling, but here, the team carried out a modal buckling analysis (Fig 12) to predict the most critical possible buckling modes, and then processed the mode shape data to give sets of design forces. Designing for these forces ensured that there is a consistent reserve of strength against buckling, without wasting money on providing strength where it is not needed.

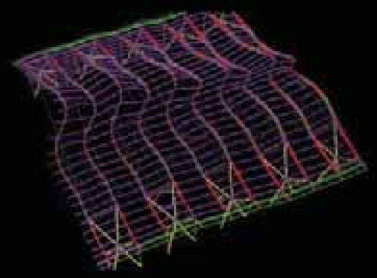
This method gives safer and more realistic results than the use of traditional notional restraint forces for the rafters in their minor axis, and enabled slimmer leg and arm sections because of the partial fixity provided at main nodes. Moreover, it allowed Arup to quantify the effective length of the major axis buckling mode of the main rafters rather than just taking an educated guess.



a) Buckling analysis model in GSA.



b) Simple buckling model predicted by the analysis.



c) Complex buckling mode predicted by the analysis.

12. Modal Buckling analysis.

13. Bracing in roof plane and abutments.

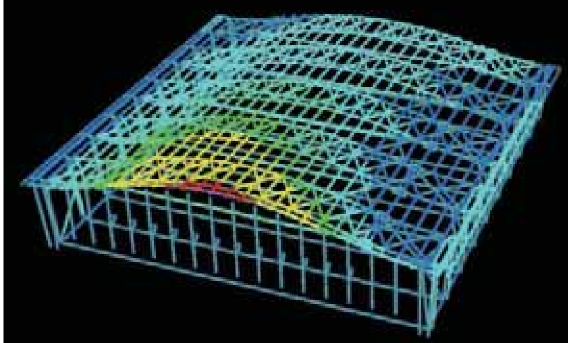
Structural action

The structural action of this roof lies somewhere between the stone vaults of a cathedral and the portal frame steelwork of a retail warehouse. As in a cathedral roof vault, the self-weight of the roof and the steelwork generates compression in the rafters and legs, and the feet push outwards and downwards on the apron level slab. This outwards force is resisted by steel beams in the apron level structure. This “arch action” in the rafters massively reduces the bending moments they would otherwise have to resist.

Wind loads or other asymmetrically applied loads in the east-west (lateral) direction are resisted by portal frame bending action in the rafters. In the north-south (longitudinal) direction, wind loads are carried to the abutments by lines of bracing between adjacent pairs of rafters. At the abutment, the wind loads are transferred to ground level through X-brace action in the legs and arms (Fig 13). The bracing in the roof plane also restrains the rafters against minor axis buckling.

The high-level prestressed steel cable ties have a similar action to the apron level tie. The tension in the ties creates upward bending moments in the rafters that almost exactly balance the downward moments from the self-weight of the rafters and roofing materials. During the jacking process, the central section of the roof becomes a perfect arch spanning the 107m between lifting towers.

The east and west façades have movement joints at 36m centres to co-ordinate with joints in the aluminium framing system. The roof also has movement joints at 36m centres, starting at the eaves and cutting into the roof plane by around 30m. These dramatically reduce the forces that are induced in the abutment steelwork by differential thermal expansion of the roof and the substructure. The joints provide flexibility to the roof plane but do not divide it into sections, and so the whole frame can be mobilized to resist north-south loading.



14. Single frame from time history dynamic wind analysis.

Dynamic time history wind analysis

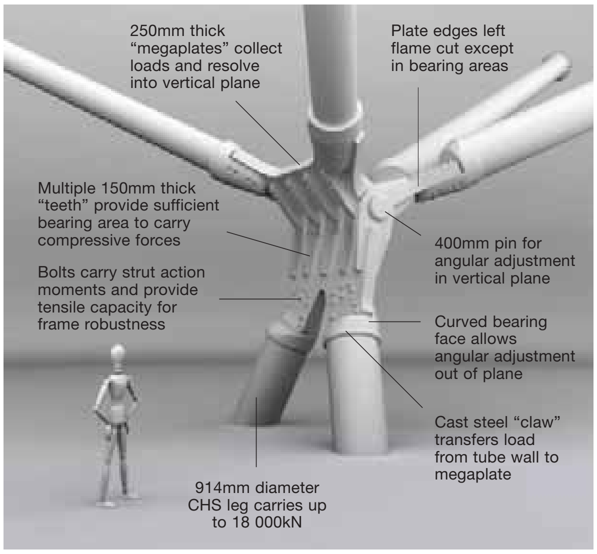
This structural form moves most under asymmetrical or uneven wind loading. The team had to protect the façade and roofing from damage by excessive movements, but it would have been uneconomical to make highly pessimistic assumptions about how wind pressures might be distributed.

Data acquisition and processing technology have advanced enormously in recent years, and it is now possible to record how wind pressures vary from second to second across an array of pressure taps on a wind tunnel test model. Arup’s Advanced Technology Group took this data and built a computer model (Fig 14) of how the roof would move from moment to moment, taking into account the varying wind pressures, its structural behaviour, and its inertia. This new technique gave a more accurate estimate of deflections in service than was ever possible before. As a result, the team saved 800 tonnes of steel by reducing the rafter flange thickness from 85mm to 70mm.

Design for manufacture and assembly

The way the building design was chosen to optimize construction has already been touched upon. This fundamental aspect of the partnering contract was carried through the entire design almost to the last nut and bolt. The paragraphs below give examples of how this “design for manufacture and assembly” led to reduced site programme time, risks, and cost.

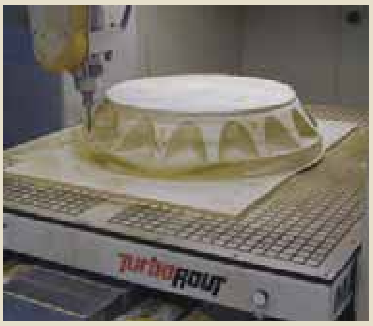
Having said this, one might expect to find that visual quality or usability had been compromised because the design team was focusing on construction issues. On the contrary, the architects used this focus as an opportunity to express the building’s engineering visually. The structure and its connections and details became sculptural objects in themselves. The language of exposed welds, as-cast steel surfaces, and visible bolts gives a feeling of scale and a grain to the building, and speaks of the human hands that have brought this huge structure into being.



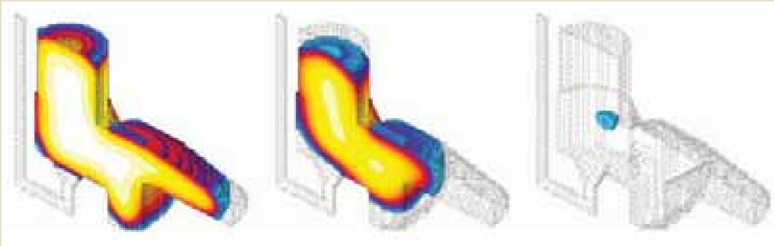
15. The torso node.

16. Connection of arm to torso.

17. Casting removed from sand mould.



18. Cutting of timber patterns.



19. Computer modelling of casting solidification.

Casting structural steel

The success of a structural steel casting depends on its shape because the steel shrinks as it solidifies, and it is essential to allow new molten steel to flow in to make up for the lost volume. The ideal would be a carrot shape with molten steel flowing in from a header at the thick end. The shapes of all the cast components were developed in consultation with the foundry (William Cook); the design team developed 3-D computer models and Cook then used its numerically controlled five-axis cutter to cut timber patterns directly from the computer files.

The torso node

The geometry of the abutment steel generated its own engineering challenge: how to connect the 914mm diameter circular hollow sections so that they could carry compressive loads of up to 18 000kN but still be easy to assemble on site into the required geometry.

The team looked at past solutions to this type of problem. Oil rigs, with similar geometries and steel sizes, generally use fully-welded structures and very large steel castings for the more complex nodes. Site welding was to be avoided, however, because it can be dangerous and prone to error, and is relatively slow. The team wanted to maximize work at the factory to streamline the site process and, where possible, avoid any welding of steel over 50mm thick - even at the factory - because of the complex welding procedures required and the risk that repair of any significant flaws could delay the project. A different solution had to be found.

The abutment steels carry loads that are (almost) always compressive, so direct bearing of steel on steel is an efficient way of transferring forces. However, any tiny error in the angle of machining a bearing face could throw the far end of a 22m long member seriously out of position. We had to find a node design that would allow the angle of each of the arms and legs to be adjusted independently on site.

The final node design (Fig 15) took inspiration from those old-fashioned wooden puzzles that you might find in your Christmas stocking. The nodes are made from pieces of steel plate that are flame cut to shape and slotted together. The bolts provide robustness but do not carry the primary forces (Fig 16).

20. Connection of arm to torso.

21. Adjustable connections.

22. Conjunction of rafter with top of abutment frame.

The geometry and fit of the parts were optimized with Corus Process Engineering, the supplier, to make the best use of its production facilities and the manufacturing process run as smoothly as possible. For instance, the teeth are 150mm thick but the Arup team set them out at 154mm centres because plates from steel suppliers are never exactly 150mm thick. The nominal 4mm gap allows for this tolerance. This removes the need for the plates to be machined to the correct dimension and saves time and money in the workshop. The partnering contract allows gains like this to be passed on to the client.

Design for assembly

The most obvious example was the way all stages of the construction sequence were analyzed and designed for at the same time as the final state analysis was carried out. In addition, all the site connections (Figs 20-22) were designed by the original design team at the same time as the overall frame.

The connections had to fulfil three requirements:

- The piece size had to be chosen to suit cranage and space available at the works, as well as transport restrictions and the limits imposed by cranage on site.
- The steel had to slot together on site in a positive way with a minimum of direct human intervention. This would reduce the risks of injury and falls for the steel erectors and speed the site process.
- The connections had to be well proportioned and elegant, because they are potentially the most visible part of the structure.

In the case of the rafter splices in the central arched section the splice is almost completely invisible but is very quick and easy to build (see panel below). Watson was able to off-hire two crawler cranes when it discovered how quickly the units went together. This alone saved the client a six-figure sum over the duration of the contract.

23. Close-up of shear key.

24. Rafter assembly.

Rafter splices

One of the more subtle advantages of the prestressed high ties is that the splices in the central arched section of the rafters always carry significant net compression. Therefore, they can transfer forces from section to section in bearing, rather like the joints between the stones of a gothic cathedral. No welding is required. 120mm diameter “male” and “female” shear connectors interconnect during erection so that the whole rafter fits together like giant Lego bricks (Figs 23, 24). Some bolts are required for extreme wind load cases but these can be accessed from inside the rafter section after assembly and off the critical path.

25. The main terminal building in summer 2005.

Tolerances

When components are manufactured, the dimensions of the finished piece are always slightly different from those on the drawings. The team knew that when all the pieces of the roof went together, their dimensional deviations would add up and could throw the frame out of position. Under a traditional contract, this often leads to recriminations and remedial works and, very often, delays to the rest of the project.

Because the project team had decided on an erection sequence, such problems could be designed out by providing adjustable connections in the frame. Arup carried out a statistical analysis of the probable combined effect of all the individual dimensional deviations of the elements, and designed a set of connections with packing plates, threaded rods, and friction grip bolts in slotted holes that would allow the frame to be adjusted back into an acceptable geometry.

Conclusion

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. This was a testament to the hard work, professionalism and, above all, team spirit of all involved. Everyone on that team was focused on designing and constructing a great building and doing it in the best, safest, and most efficient way they knew.

Reference

(1) BEARDWELL, G, *et al*. Terminal 5, London Heathrow: 3-D and 4-D design in a single model environment. *The Arup Journal*, *41*(1), pp3-8, 1/2006.

Credits

Client: BAA **Architect:** Richard Rogers Partnership Assistant architect: HOK **Multidisciplinary engineer:** Arup - Graham Aldwinkle, Andrew Allsop, Jolyon Antill, Trevor Baker, Mike Banfi, Kathy Beadle, Dan Birch, David Bloomfield, Isobel Byrne-Hill, Simon Cardwell, Mark Collier, Andrew Cunningham, Lee Cunningham, Pat Dallard, Tony Fitzpatrick, Brian Forster, Damien Friel, Ian Gale, Clare Gardiner, Florence Gautron, Kathy Gibbs, Chris Godson, Lee-Zane Greyling, Ray Ingles, Barney Jordan, Tarsem Kainth, Vince Keating, Richard Kent, Steven Luke, Steve McKechnie, Ian McRobbie, David McShane, Pablo Marsh, Astrid Meunzinger, Dervilla Mitchell, Phillip Moneypenny, Gareth Mooney, Chris Murgatroyd, Paul Nuttall, Deirdre O'Neill, Gabriele Presot, Steve Roberts, Joe Spatola, David Storer, Martin Tarnowski, Gursharan Thind, John Thornton, David Trelease, Rebecca Wright **Cost management:** EC Harris/Turner and Townsend **Steel supplier:** Watson Structural Steelwork Ltd **Heavy lift consultant:** Rolton **Team management and programming:** Laing O'Rourke **Steel foundry (castings):** William Cook **Machining and heavy assembly (nodes):** Corus Process Engineering **High tie supply and stressing:** Bridon **Wind tunnel testing:** RWDI **Checking engineer:** Flint and Neill **Roofing:** Hathaway **Strand jacking:** PSC Fagiolet **Building control:** BAA Building Control **Images:** 1, 2, 4-7, 9-11, 13, 24, 25 BAA; 3 Nigel Whale; 8, 17, 18, 20 Richard Rogers Partnership; 12, 14, 16, 21-23 Arup; 15 Arup/Richard Rogers Partnership; 19 William Cook.