1. Heathrow's new air-traffic control tower in the airport context.

Terminal 5, London Heathrow: The new control tower

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The size and position of Terminal 5 necessitated a new central location for Heathrow's air-traffic control tower, which introduced challenges for the project team in the tower's design, fabrication, and delivery.

Introduction

This is the third *Arup Journal* article to deal with aspects of Arup's work on Terminal 5 at Heathrow Airport, London. It follows accounts of the project's 3-D and 4-D design environment[1], and the structural design of the main building[2].

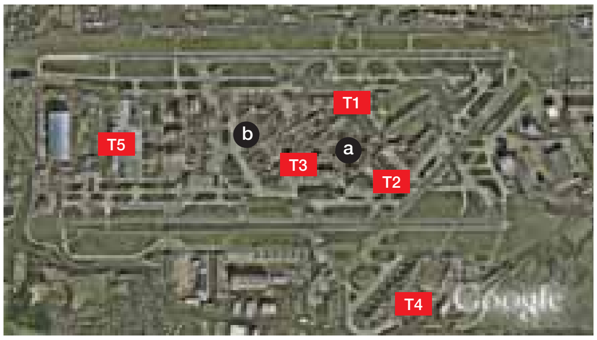
In March 2008, T5 opened, increasing further the size of the world's busiest two-runway airport, where in any one day the UK National Air Traffic Services (NATS) controls the movements of over 1000 aircraft approaching and departing, as well as managing the planes taxiing around (Fig 1).

Air-traffic controllers have to maintain constant visual contact with aircraft, and thus air-traffic control towers are crucial to ensuring that operations remain safe and efficient. T5 introduced obstructions to the required sightlines between the existing tower and aircraft using the new terminal, so a new location at a new height was needed. The optimum tower dimensions were calculated by assessing the sightlines to all taxiways and stands on the enlarged airport, whilst the best location was determined as the airport's geographic centre, at a height of 87m (Fig 2).

With the basic height and location requirements selected, the project team's task was to develop an efficient and elegant tower design, simultaneously addressing the considerable construction challenges of building on an island site surrounded by aircraft. A key requirement was to cause no operational disruption to the running of the airport; this had a significant effect on development of the design solution and the construction that followed.

Functionality

The location at Heathrow's centre necessitates full 360˚ views from the cab, whilst the taxiways and stands at the tower base need an extremely low viewing angle. To fulfil these requirements, the final design provides what is thought to be the largest cone of vision of any control tower in the world (Fig 3). However, the requirements of floor space for the controllers and their equipment had to be



2. Plan of Heathrow Airport showing location of (a) old and (b) new control towers.

balanced against the detrimental effects of increasing the size of the cab, which included reduced angles of vision for individual controllers, larger areas of glass, more solar gain, and wind drag on the tower. A great deal of detailed 3-D co-ordination between all design disciplines was needed to provide the most compact yet functional space possible (Fig 4).

The cab contains four levels, the highest being the visual control room (VCR), accommodating desks for 13 controllers. This floor is set back from the 10m high glass façade. At the base of this wall is a gallery space used to service the sub-equipment room containing communications and radar equipment. Underneath the sub-equipment level is the rest and recreation area containing a rest room, kitchen, toilet, and office. An external walkway here accesses a permanent cleaning cradle to service the entire cab glass wall.

The lowest level accommodates the air-handling plant as well as docking for the lift that travels up the outside of the mast. The mast structure itself contains stairs, an internal lift, and various risers for M&E and IT purposes. This rises through the middle of the cab and services every level.

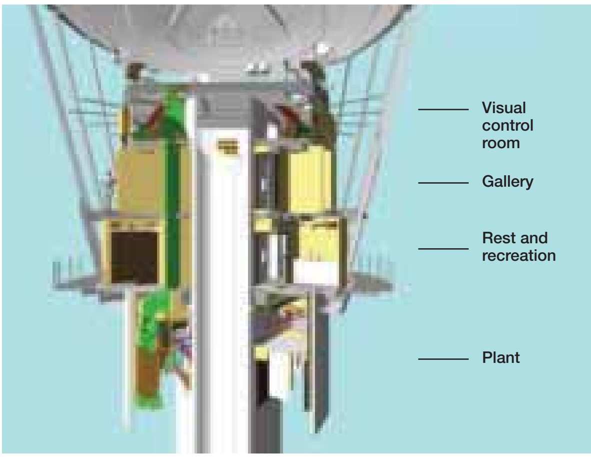
Finally, a three-storey building at the base of the tower contains the NATS offices, administration and training rooms, technical equipment areas, and main plantrooms.

3. The 10m high glass façade provides a large cone of vision.

Construction method

Importantly, the construction strategy was developed in parallel with the design. A key aspect of the project was the use of the T5 agreement, the form of collaboration contract used by BAA when appointing its design consultants and contractors. This allowed the tower design to be specifically tailored to suit the erection strategy, with designers and construction team working together from the outset.

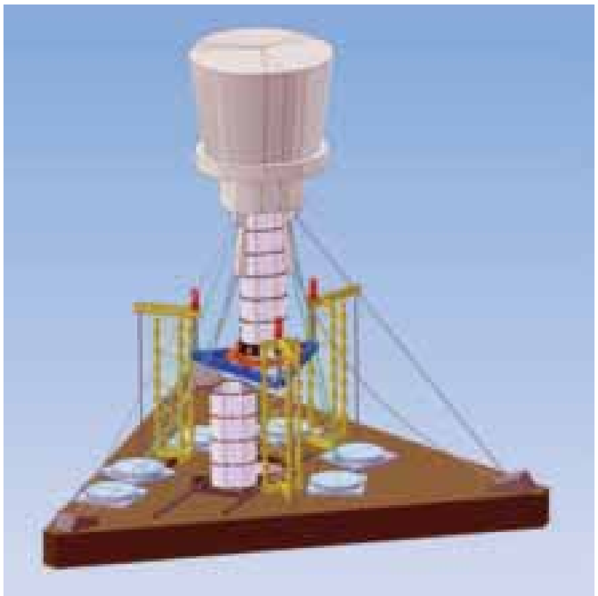
The design team considered using a traditional slip-formed concrete cantilever mast, but this would have required regular and uninterrupted concrete deliveries. Security, operations, and radar restrictions applying in the airport would also have necessitated an on-site batching plant, with cranes only usable in five-hour night-time airport closures. In view of this, the team decided on a cable-stayed steel tower, which could have half the mast diameter of an equivalent cantilevered mast structure. A steel tower could also be prefabricated and transported to site in 12m lengths, completely fitted out with stairs, lift cores, and mechanical-and-electrical risers, and then bolted together.



4. Section through control tower cab.

In addition, a small-diameter cable-stayed mast satisfied concerns about the visual impact of a traditional large-diameter concrete cantilever tower on the Heathrow skyline, as well as making it possible to construct the cab at ground level around the base of the mast, and later jack it up into position at the top. Building the cab at low level had several safety advantages, though significant challenges were also involved in making it structurally stable with the large hole through the middle for the mast.

These were met by using an idea from the petrochemical industry for erecting process plant (Fig 5). Its great advantage is that is allows the complete cab to be built at ground level without incorporating a temporary hole for jacking the cab up the mast. Understanding the prefabrication, transportation, and erection requirements was essential in defining the parameters to control the maximum diameter of the mast and the design requirements for the cab structure.



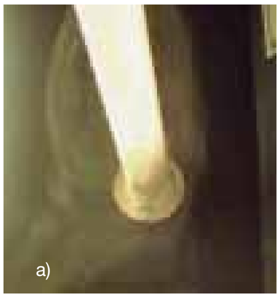
5. Tower jacking: three temporary works towers support strand-jacks and yoke system; the strands lift the yoke and mast off the ground via hydraulic jaws to allow a new section of mast to be inserted underneath.

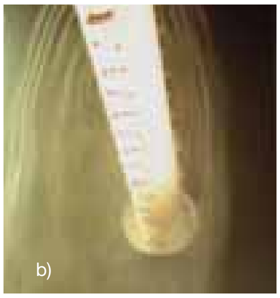
Dynamic performance

Alongside the erection strategy, another factor critical to the structural requirements for the mast was wind-induced movement of the completed tower.

Setting appropriate "comfort" criteria for tall buildings is more difficult than most design cases faced by engineers; here the tower's dynamic performance was critical to the comfort of the air-traffic controllers. In the case of wind-induced lateral movements, acceptable performance is both time-dependent and varies with occupier sensitivity. The more often movement occurs, the less tolerant are occupiers of the level of lateral acceleration they experience. In the case of Heathrow, which often experiences fairly windy conditions, the frequent lower-strength winds formed the critical design case.

6. Cab model in wind tunnel.





7. Airflow around 1:30 mast model in a wind-tunnel smoke stream without (a) and with (b) aerodynamic strokes.

During the early design stages, various levels of lateral acceleration were demonstrated to the air-traffic controllers on a motion simulator at Southampton University, and levels of acceptable movement of the control room were agreed. With these performance limits established, the design then focused on the tower's aerodynamic performance, stiffness, and damping.

Wind-tunnel testing

Extensive wind-tunnel modelling (Fig 6) was undertaken to optimise the tower's aerodynamic performance by reducing the drag and crosswind response of the design. These tests were used to develop a unique aerodynamically sculpted enclosure for the support rails and drive cables of the external passenger lift, reducing both the drag on the tower and improving the high-wind operation of the lift.

Small aerodynamic strakes (stabilisers) were also developed in the wind tunnel. Attached to the side of the mast, these control vortex-shedding and significantly reduce the cross-wind response (Fig 7).

Mast stiffness and damping

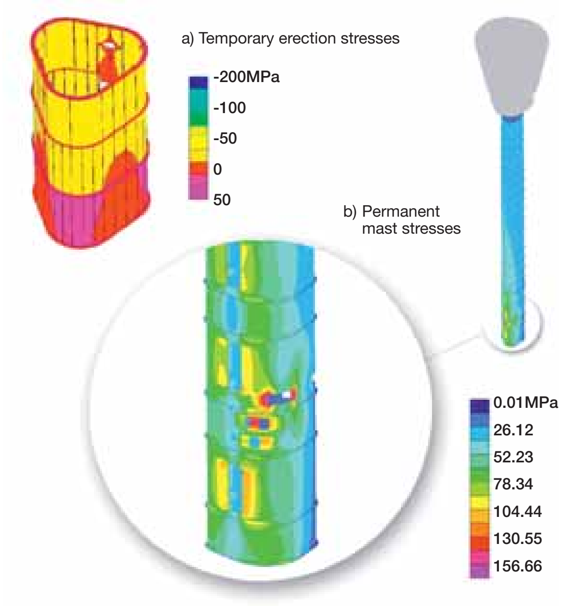
The tower's lateral stiffness and mass define its natural frequency. The amount of wind energy available to cause motion, and the sensitivity of the tower occupants, are both frequency-dependent.

In developing the Heathrow tower design, the diameter, type, geometry, and pre-tension of the main stay cables was critical to its final performance. The 150mm diameter locked coil cables, stressed to a 10th of their normal working capacity, give the axial stiffness needed to control the head of the mast and also provide considerable reserves of strength, allowing the tower to operate safely if cables ever need to be removed for replacement. The cable natural frequencies are governed by the cable mass, axial stiffness, and the degree of pre-tension. Coincidentally, the optimum pre-tension for overall tower stiffness resulted in cable natural frequencies very close to those of the tower system as a whole. De-tuning the cable pre-tension would have resulted in a much less efficient structure.

The final engineering factor that determines the tower's dynamic performance is its damping. The natural damping of the steel mast and cables is low (0.5%), so small viscous dampers were attached to the main cables to damp their lateral vibration, to prevent unpredictable and uncontrollable transfer of energy between the cables and tower dynamic modes, and to and lift the overall tower damping to 1.5%.

Finally, two hybrid mass dampers (Fig 12) were installed at the head of the mast immediately below the control room floor. These have both passive and active operational modes. In normal higher-wind situations, accelerometers in the cab detect tower movement and the control system then activates the dampers, moving the 5 tonne suspended masses in the appropriate direction to counteract the wind-driven tower movement. These raise the overall damping of the tower to levels in excess of 10% critical damping. Arup was instrumental in developing the design and validation of both the passive and the active damping systems.

8. Prefabricated mast section before installation of stairs and lift risers.



9. Mast stress diagrams.

Structural design

The steel mast was built in eight sections, normally 12m in length, with a 30mm thick outer steel skin, vertical longitudinal stiffeners, and horizontal stiffener hoops. The stresses induced in the steel mast during the temporary jacking cycles (Fig 9a) were very different from those it experiences in its permanent erected state (Fig 9b), and so it was designed to resist these considerable stresses during erection. Apart from the obvious compression loads carried by the mast, the critical additional design loads were generated by concentrated load from the lifting jaws during erection and by locked-in thermal stresses in the permanent state.

The high axial stiffness of the cable stays generate unusually high thermal stresses, as they restrict the tower's natural tendency to sway sideways under differential solar-induced thermal expansion on one side of the mast. A grey glass-flake epoxy paint, with low solar absorption, was used to limit the locked-in thermal stresses in the mast.

Thermal-stress modelling by Arup also showed that even a small air velocity makes a big difference to the steel temperature gradient around the mast. Back-analysis of UK Meteorological Office data showed that, even on the hottest days, there is always a small amount of background wind, and this was duly added to the thermal model.

To maximise usable floor space, the cab has no internal columns. Radial trusses in the roof act with each of the 24 façade mullions to form a 3-D portal frame. Floors within the cab span between the perimeter mullions and the steel mast. At the lowest cab level, structural loads in the mullions are transferred to the red-coloured structural steel skin spanning between the three support points offered by the main cable anchorages (Fig 11).

Construction co-ordination

One construction issue remained: prefabrication of the cab structure at ground level would require cranage. This would limit construction to night time only as cranage limitations were in force during airport operations. However, it was realised that as the cab structure was designed to be lifted by strand jacks attached to three points on the temporary works jacking frame, the same points could be used to lift and transport the cab from a remote site using multi-wheeled transporter units able to lift and transport large loads, as is the case in the petrochemical industry.

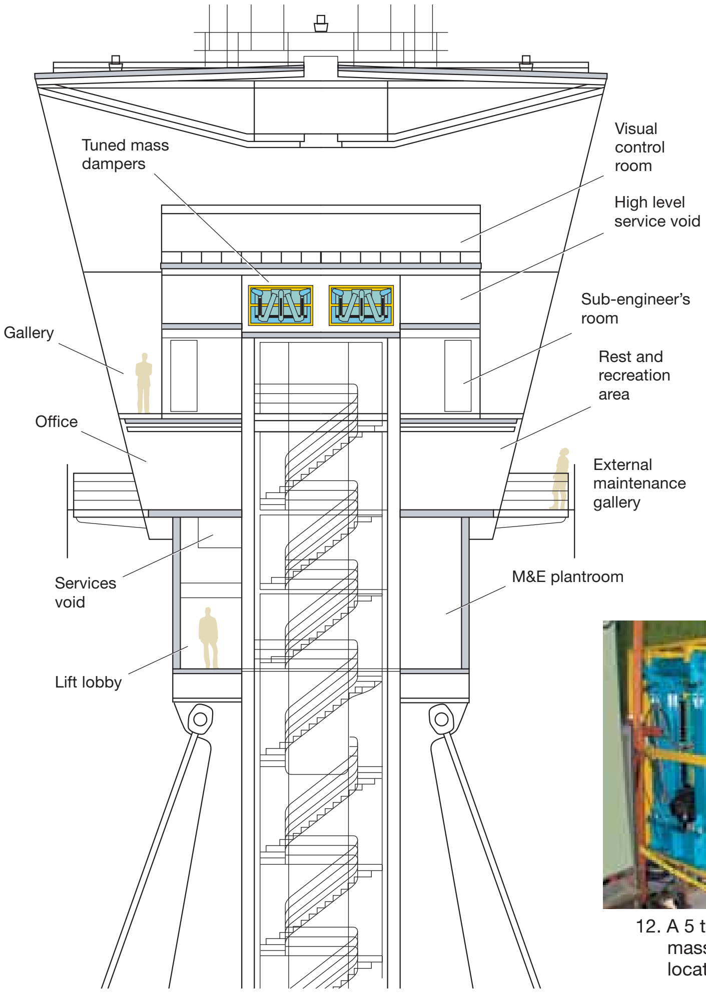
The client, BAA, identified a suitable open site near Terminal 4 that would enable cab construction and fit-out to start early and progress in parallel with installation of the main foundations on the control tower site. These foundations comprise 1050mm and 750mm diameter piles, and pile caps up to 4.1m deep that support the tower, the base building, and permanent guy cables. The site had to be cleared in order to construct the main foundations.

Mast fabrication

As site work progressed, the first 12m long mast sections were fabricated. To achieve satisfactory alignment and force transfer between adjacent mast sections, careful control of tolerances in each was required.

The initial fabrication method used on the two top mast sections did not give adequate steel tolerances, but fortunately they could still be used because the compressive forces at the top of the tower are low, and the lower tolerances

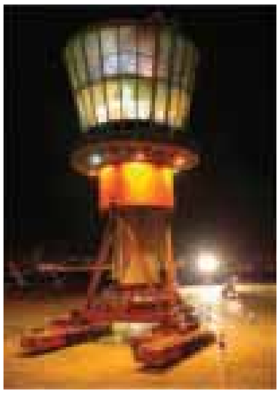
11. Cross-section through top of tower.



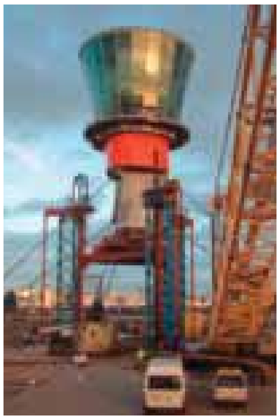

12. A 5 tonne active mass damper located at cab level.

12. Erecting the two top mast sections for cab construction.

13. Locating cab roof onto 24 mullions.



14. Moving 900 tonnes 1.5km across the airport.



15. Jacking the cab to 87m height.

were acceptable. In the revised procedure, precision jigs were used to fabricate 3m long sections of mast tube, which were heavily braced during fabrication to control weld shrinkage effects. Before removal of the bracing, the sections were heat-treated to stress-relieve them and ensure that fabrication accuracy was maintained. The 3m sections were then stacked and welded into the final 12m lengths. Prior to painting, the bolted interface flanges at the ends of the mast sections were milled and CNC (computer numerically controlled) drilled to ensure precise fit and alignment on site. Before transport to site, the mast sections were fitted out with the steel stairs, service risers, and the lift enclosure.

Cab construction

Cab construction on the remote site began with a temporary piled foundation, off which the 32m high cab was built. The top two sections of mast were used as a core from which all the floors were suspended (Fig 12). The main cable anchorages, stressed steel skin, and structural mullion systems were added to create a coronet of 24 mullions to which the roof would connect.

The roof structure, complete with internal acoustic lining, access walkway, decking, and waterproofing was constructed at ground level. The entire 50 tonne roof was craned into place (Fig 13) and connected to the ring of mullions. Before being moved from the temporary site, the cab was fully fitted out with M&E plant, walls, and ceilings.

Moving the cab

Preplanning the cab's 1.5km journey across the airport took considerable effort. The route crossed over the southern runway and involved using the main taxiways to get to the final site. The entire route had to be meticulously assessed for its load-carrying capacity because at close to 900 tonnes, the transported load greatly exceeded the 400 tonnes of a fully-loaded Boeing 747 for which the pavement was designed. Damage to the runway or breakdown of the transporter en route could cause effective closure of the airport - with resultant damages likely to exceed half the value of the entire control tower project. Detailed contingency plans were put in place to cover all eventualities.

After a 24-hour delay due to thunderstorms, the overnight move (Fig 14) was achieved without incident in less than two hours amidst a sea of press and TV cameras. At the control tower site, the 32m high, 750 tonne cab was manoeuvred and placed onto its foundation to within 10mm of dead centre.

Mast erection

Once the cab was successfully moved, the mast jacking towers were installed and the first of five mast lifts commenced, each mast section being successively added to the underside of the tower (Fig 15). Software developed by the jacking contractor was used to ensure that the lift was always level by controlling the strand jacks and guy cables. Prior to its use on site, the control logic of this custom-written jacking software had been tested and refined using a small-scale test rig.

To ensure verticality of the tower during the lift, both optical and GPS surveying were used to monitor the plumb of the mast. In general the top of the tower was maintained within 25mm of plumb throughout erection (Fig 16).

During the jacking cycles a procedure linking regional weather forecasting and local wind measurement was put into place to predict and monitor the weather conditions during each lift. The erection procedure had various wind limits placed on it but in the case of the most severe predicted weather, the tower was to be lowered onto its foundation and supported on multiple interconnected jacks forming a hydraulic pin at the base. In this situation, a second set of guy cables (Fig 5) were to be tensioned to give the mast additional strength and stiffness. Fortunately no weather severe enough to need these precautions was experienced. As well as eliminating non-uniform compression stresses in the mast, the hydraulic pin also served as a damper to absorb energy from wind-induced oscillations and remove the risk of aerodynamic instability during all stages of erection.

As the lifts progressed, a cycle of mast jacking during the day was followed by preparation of the next mast section during a night shift. Although the rig could raise the mast to the required height for each lift in a day, the process demanded so much preparation that it took about three weeks in all. However, all five mast lifts were completed without incident while airport operations continued uninterrupted around the site (Fig 17).

Completion

With mast erection complete, the project immediately progressed to the erection and fit-out of the base building and the connection of services between it and the cab. Once this was complete, the temporary guy cables were removed and the permanent 150mm diameter locked coil cables installed from a crane and tensioned during a further series of night-time operations.

The final installations and commissioning in the tower included tuning the hybrid mass dampers to suit the tower's final as-built natural frequency. Also installed was a 100m pedestrian bridge link from the control tower base building to the end of Terminal 3's Pier 7. Each section of the glazed bridge, designed by Thyssen, was prefabricated in 30m lengths, brought directly to the tower site, and rapidly craned into place during night time operations.

16. Jacks controlling guy cables during the lift.

Conclusion

The new tower went "live" in February 2007 when full airport operations transferred and the old tower was closed after 52 years of service.

Building a new air-traffic control tower in the centre of Heathrow's airside operations involved unique construction and operational requirements that largely dictated its architectural and engineering form (a more detailed description of the project has been published elsewhere[3]). This tower satisfies the air-traffic controllers' requirements, yet was constructed with no disruption to the airport's daily operations and no accidents. Its successful completion demonstrates the value of T5's integrated design and construction philosophy.

17. Tower and base building under construction.

Jeremy Edwards is an Associate of Arup with the Building London 4 group. He is a structural engineer and has had several roles on T5, including assistant structural engineer for the air-traffic control tower.

Richard Matthews is a Director of Arup with the Building London 9 group. He leads the structural engineering team for T5, and acted as Project Leader for BAA on the air-traffic control tower.

Sean McGinn is a Senior Associate of Arup with the Buildings Melbourne, Australia, group. He was lead structural engineer of the air-traffic control tower.

Credits

Client: BAA (building owner, airport operator, overall project manager) **Building operator:** NATS **Architect:** Richard Rogers Partnership **Project manager, structural engineer (superstructures), acoustics, façade, wind and dynamics engineer:** Arup - Andrew Allsop, Mike Banfi, Francesco Biancelli, Nick Boulter, Anita Bramfitt, Simon Cardwell, Jeremy Edwards, Rob Embury, Matteo Farina, Graham Gedge, James Hargreaves, Richard Henderson, Roger Howkins, Angus Low, Richard Matthews, Chris Murgatoyd, Daniel Powell, Sean McGinn, Nils Svensson, Ian Wilson, Peter Young, Andrea Zelco **Engineer (substructure):** Mott Macdonald **Temporary works designer:** Dorman Long Technology **Infrastructure engineer:** TPS **M&E engineer: DSSR** **Cost manager:** Turner & Townsend/EC Harris **Construction integrator:** Mace **Steelwork supplier:** Watson Steel **Substructure contractor:** Laing O'Rourke **Jacking and cab transportation:** Faggiolli **M&E and infrastructure contractor:** AMEC **Façade supplier:** Schmidlin **Lift supplier:** Schindler **Fit-out supplier:** Warings **Logistics:** Amalga **Illustrations:** 1-10, 12-17 BAA/HATCT project team; 11 Nigel Whale.

References

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