In recent years pedestrians found crossing the Thames between Charing Cross station and the South Bank Centre neither easy nor pleasant. The walkway attached to the downstream side of Sir John Hawkshaw’s 1864 Hungerford railway bridge was narrow, noisy, frequently wet and somewhat unsafe underfoot. It was not always so. The first bridge on the site, which opened in 1846, was a substantial pedestrian suspension bridge built by Isambard Kingdom Brunel (Figs 1 and 2). It was a toll bridge, providing access to Hungerford market and to boat landings used by people as diverse as Australia-bound convicts and Queen Victoria. Unfortunately both the market and the bridge were in the path of the Charing Cross railway. The market was sold to make way for the station, the masonry piers of the footbridge became supports for the railway bridge and the suspension chains were re-used in Brunel’s 1864 Clifton bridge near Bristol (completed after his death).

The new rail bridge had cantilevered walkways on each side, though the upstream walkway was demolished when the structure was widened in the 1870s. For the Festival of Britain in 1951, the Royal Engineers temporarily recreated an upstream walkway when they erected a Bailey bridge to provide access from the north bank to the festival site on the south. This was supported on timber piles driven into the river bed a few metres upstream of the rail crossing, and provided a wide walkway and a view of the Houses of Parliament.

In the mid-1990s the Cross River Partnership—comprising public and private bodies with a shared interest in promoting links across the Thames—identified Hungerford Bridge as being in need of improvement. Not only was the railway bridge one of the most ‘aesthetically notorious’ bridges in the world, the unpleasant

The £50 million Hungerford Bridge millennium project in London provides two stunning new cable-stayed footbridges across the Thames, one on each side of Charing Cross railway bridge. Effectively it recreates Brunel’s 1846 suspension footbridge to Hungerford market, the piers of which remain in the railway bridge structure. Heightened fears over unexploded bombs in the river bed led to a major redesign just after work started but a switch to the NEC contract helped ensure a smooth completion.
pedestrian route discouraged people north of the river from visiting the South Bank arts complex. With lottery funding, the possibility of improving the crossing became more realistic and a design competition was organised.

From over 40 entrants, the judges invited six finalists (which were paid a small fee) to submit more detailed proposals. The competition was judged following a public consultation exercise and exhibitions around London.

A team comprising engineers WSP Group, architects Lifschutz Davidson and cost consultants Davis Langdon and Everest submitted the winning design (Fig. 3). Twin cable-stayed bridges were proposed, one each side of the railway bridge, with other features including boat landings and low-level link bridges from the South Bank area to Brunel’s south (‘Surrey’) pier. In particular the judges liked the respect shown for the historical context: new spans matched the old and the design emphasised the important parts of the existing structure.

Wide range of funding sources

Westminster City Council took the lead in the project from the start, organising the design competition and committing a substantial share of the funding. Other members of the Cross River Partnership also promised to share the cost, either by providing money or by waiving charges for services.

An application was made for lottery funding from the Millennium Commission, and a grant was made in 1996. The Millennium Commission were particularly concerned that the design quality should remain high and they maintained close involvement throughout the design period.

Other funding came from Railtrack, the London Borough of Lambeth and the Department of the Environment, Transport and the Regions’ single regeneration budget. Although Westminster was relatively prosperous, the same was not true of Lambeth. It was agreed that the bridge would encourage economic development south of the Thames and so regeneration funding was made available. For the same reason the Mayor of London provided a substantial grant when the future of the project was later threatened by heightened fears over rail tunnel safety.

Pre-tender design

The footbridges were to be built across a busy waterway, next to a main line rail-

the Mayor of London provided a substantial grant when the future of the project was later threatened

Fig. 1. The original Hungerford pedestrian suspension bridge completed by Isambard Kingdom Brunel in 1846

Fig. 2. John Hawkshaw converted Brunel’s bridge into a rail crossing in 1864. The suspension chains were used to build the Clifton suspension bridge in Bristol

Fig. 3. Winning concept included low-level link bridges from the south (‘Surrey’) pier
way bridge and above a number of tube tunnels (Figs 4, 5 and 6). They were on established commuter routes to and from Waterloo and Charing Cross and their prominent location required integrated engineering and architecture to achieve a high-quality result.

The pre-tender design was for a multi-span cable-stayed arrangement with relatively short (approximately 50 m) spans supported by Macalloy bar stays. At the time it was felt that the visual qualities of the available end fittings for bars were better than those for strand cables. A large number of stays—28 per pylon—were provided, both for visual interest and to minimise the size of each bar. Pylons were tapered steel cylinders, held at an angle to the vertical by more Macalloy bars and supported on concrete foundations.

At the Surrey pier each deck was suspended from a pair of pylons that were supported on a new island, one upstream and one downstream. The arrangement would help to focus attention on the historic structure and allow a staircase to descend to the
island. From here a walkway would pass through Brunel’s structure, and steel footbridges just above high water level would join the island to the south bank.

Accounting for ship impact

One of the most complex problems addressed at the initial design stage was ship impact. The Port of London Authority advised that ships up to 3000 t displacement could use the river, travelling at 6.2 m/s (12 knots). Impact loads of 30 MN were calculated following the Minorsky method with an angle of impact up to 15° from the line of the river. Producing a substructure that was capable of resisting these forces without being visually obtrusive required substantial design effort.

Other design features include lifts which were provided at the ends of the bridges to allow access by mobility-impaired people. Safety considerations led to straight flights of stairs: pedestrians could see all the way up or down, eliminating fears of unseen attackers. On the bridge deck, handrails were of stainless steel, with horizontal infill bars to afford a better view of the river, but made difficult to climb by inclining the posts inwards by 15°. Stair handrails were glass with plastic coating that could be replaced if scratched by vandals. Lighting was designed to make the bridge a feature of the London skyline and to provide safe levels of illumination on the deck. However, excessive light was avoided to enhance night-time views from the bridge.

The design team also considered introducing canopies and vertical screens to protect pedestrians from wind and rain. These were rejected principally on maintenance grounds as it would have been difficult to design a safe, economical and unobtrusive external access system. Dirty cladding would have spoiled the view from the bridge when the weather was good and covered bridges were generally felt to be unpleasant inside. There was also a view that covering the bridge was unnecessary when the roads and footpaths leading to it were all exposed to the elements.

Bomb fears trigger redesign

In October 1999, only a few weeks after the construction contract was awarded to a joint venture of Costain and Norwest Holst, it became apparent that underground railway operator London Underground was in the process of re-evaluating its criteria for building near tunnels beneath the Thames. The project became embroiled in the development of this new guidance. The new approach took more account of extremely low risks with serious consequences. In this case the risk was that an unrecorded, unexploded World War II bomb could be present, buried deep in the river bed and unaffected by driven piling for the Festival of Britain Bailey bridge. Piling operations could reactivate the timer in such a bomb and, if detonation occurred, it was possible that a path could be opened between the river and the tunnel, causing inundation of the underground railway. Clearly this combination of circumstances was extremely unlikely but the potential human and economic losses were unacceptable.

In order to rule out the risk it would have been necessary to close the railway tunnel floodgates for the duration of piling work and until detonation by time-delay fuses was no longer a possibility. Allowing a suitable margin of error, the tunnels would have to be closed for four days after piling work had ceased, so weekend-only tunnel closures were impossible. It was simply not practical to consider such disruption to London Underground so the client commissioned consultant Halcrow to review whether the project should continue and if so, in what form.

The consultant recommended continuing with a revised design that would eliminate the risk to London Underground. The foundation near the north (‘Middlesex’) bank was moved out of the river. The asymmetric pylon arrangement was not possible in this location and so an A-frame support was introduced (Figs 7 and 8). The next foundation out from the north bank was further from the Bakerloo Line but to eliminate the risk its piles were replaced with a 5 m diameter hand-dug shaft. The two link bridges were omitted from the southern end of the scheme because one had foundations close to the Northern Line and the cost of railway possessions was not justifiable for what were non-essential elements.
Switch to NEC contract

The consultant’s review also recommended a major re-evaluation of the contract. It had been based on the ICE’s Design and Build form that had been amended to incorporate more design detail than was normal for a design-and-build project, the result being called ‘adopt and build’.

The client and the contractor both agreed that the ‘adopt and build’ contract was no longer suitable because the changes to the design would have to be carried out by the client’s engineer before the contractor’s team could start on them. This would cause additional delay and unnecessary extra cost. Furthermore, it was agreed that a more equitable allocation of cost and risk would be to everyone’s benefit.

A new contract was thus negotiated, based on the NEC Engineering and Construction Contract with main option C (target contract with activity schedule). This allocated all design responsibility (except for dynamics, which remained with the client’s engineer) to the contractor and its designer, and set out a system of open-book payments. A value-engineering exercise was also carried out at this stage to reduce additional costs. This involved close cooperation of the whole project team and identified significant cost savings.

Introducing a new contract part way through the project was an unusual step but it worked well, avoiding what could have been a serious dispute over the allocation and level of extra costs.

Post-tender design development

The contractor’s designer, Gifford and Partners, had been charged with developing the design after tender and producing a set of construction drawings. This was a complex task: the multi-span cable-stay arrangement produced a structure with multiple redundancies in which almost every element had a different loaded length. In addition the changes around the north bank required the whole bridge to be redesigned.

The firm introduced a number of innovations to the original design. For example, unobtrusive spherical bearings were incorporated in the bases of the pylons and in the pylon top fabrications (known as ‘angel wings’ because of their shape—Fig. 9) to relieve global bending effects resulting from temperature, creep and shrinkage. The bearings made it possible to design the pylons as tapered pin-ended struts; they also made erection simpler.

Sections of flat plate, rolled to the required cylindrical or conical shape, were welded together to form the pylons. The plate—generally grade S355J2—was thicker near the ends, where the radius was smaller. The 150 mm thick billets forming the pylon tip were grade S355NL, with enhanced Charpy energy.
absorption requirements and improved through-thickness properties. The plates supporting the top spherical bearings were grade S460NL, again with enhanced Charpy energy absorption requirements.

Sophisticated three dimensional finite-element modelling was also employed to optimise the steel section and minimise complex welding requirements. At the lower end of the stays, fabricated steel deck connections were replaced by castings stressed onto the concrete.

Originally the deck was to have been stressed with tendons at the neutral axis. However when the span adjacent to the new A-frame was lengthened, axial pre-stress was no longer sufficient and the completed bridge required draped tendons in order to deal with the greater sagging moments at mid-span. Also, during the launch this led to undesirable stress reversals and so temporary external stressing was required. The process became very complicated and, because it was possible to design a reinforced concrete deck with the same cross-section, prestressing was not employed.

A new articulation layout was introduced because of the A-frame support at the northern end. The difference in span lengths on each side of the A-frame led to large uplift forces at the northern abutment and it was not feasible to tie the deck down while allowing longitudinal movement. Instead, a simple, maintenance-free stainless steel dowelled expansion joint was introduced to the south of the A-frame to allow longitudinal movement and rotation but resist lateral and vertical movement, with an integral fixed support at the north end. The remainder of the bridge was fixed at the Surrey pier by bracing the pylons and a second expansion joint was provided at the south bank. Lateral restraint was provided by steel struts between the deck and the backstay nodes.

Gaps were provided between the railway bridge and all parts of the new bridge so that under normal circumstances no additional load was applied to older structure, which could also articulate independently of the new. In the event of a major ship impact, however, plastic deformation would occur and the foundations of both bridges would act together to resist the load.

**Innovations in construction**

The contractor and its designer proposed a number of innovative methods for constructing the bridge, the most original of which was for the foundations. In order to resist ship-impact forces the foundations on each side of the rail bridge were to be joined together with concrete beams.

Tender drawings envisaged the impact beams being constructed *in situ* but the contractor proposed precast construction instead. This avoided the need to construct sheet-piled caissons beneath the railway bridge, which would have required large amounts of time-consuming and difficult low headroom working.

The beams were precast in the contractor’s yard at Erith and delivered to site in pairs by barge (Fig. 10). They were then transferred to temporary works, joined together and lowered into place. Reinforcement comprised a large universal column section cast into the bottom of the beam. The connections to the pilecaps were made initially using large steel pins that passed through carefully set-out holes and the final connection was made with *in situ* concrete.

The main bridge decks were constructed using the incremental-launch technique. A casting bed was built on a steel framework in the non-navigable span adjacent to the south bank and a section of deck approximately 50 m long was cast. A temporary stiffening truss was bolted to the top of the deck section and hydraulic strand jacks were used to pull it northwards (Fig. 11). The whole process was repeated until the full length of deck was complete. A temporary support, comprising rectangular concrete ‘biscuits’ stressed to the pilecap beneath, was provided at each pier position. Steel supports would have been easier to construct, but they would have been vulnerable to a major failure in the event of ship or floating plant impact.

The *TakLift 5/400 t* floating crane was used to lift the pylons into place (Fig. 12). Each pylon was erected with its backstays attached and the stays were kept straight during lifting by attaching them to steel strong-backs. On completion of the launch, the deck was jacked up. Deck stays were fabricated to preset lengths, temporarily supported by strong-backs and installed...
with a preset sag to help connection of the fork-and-spade pin anchorages at each end. Following installation of all deck stays the deck was slowly lowered in a controlled sequence until it was supported entirely by the stays. The temporary truss and tower supports were then removed (Fig. 13).

Stay tensions were monitored simply and effectively by measuring their natural frequency, this procedure being checked and calibrated by a limited number of strain gauges and hydraulic stressing jacks. A small number of the stays required adjustment in order to rectify either high or low tensions resulting from fabrication tolerances or to optimise the final deck profile.

**Ensuring a wobble-free design**

The dynamic behaviour of the bridge was studied in detail, using computer models, wind tunnel tests and measurements on site. Because the deck was relatively wide, restrained at reasonably close centres and made of concrete, the analysis results predicted a lateral natural frequency of 1.6 Hz, above the normal range of concern for pedestrian footfalls. In the vertical direction, the fundamental frequency was around 0.7 Hz—too low for pedestrians to excite. There was some concern that higher frequencies...
could be excited deliberately, so sockets were cast into the deck soffit to allow dampers to be attached at a later date.

The physical tests involved a machine with a rotating eccentric weight, supplied by the Building Research Establishment, and 160 pedestrians, supplied by Westminster City Council. The tests showed that the calculated frequencies were accurate and there was no danger that the bridge would bounce or wobble under normal pedestrian loads. Damping measurements gave a lower than expected value (0.4% of critical).

Conclusion

The upstream bridge opened in May 2002 (Fig. 14), with its downstream counterpart following in September 2002. It has proved popular—pedestrian flows have increased compared to the old walkway and it has already become a favourite spot for tourist photographs (Fig. 15).

A summary of the principal dimensions and quantities are shown in Table 1.

Acknowledgements

The project team was as follows: client—City of Westminster; funding bodies—Cross River Partnership as recipients of government single regeneration budget, Department of the Environment, Transport and the Regions, London Borough of Lambeth, Mayor of London, Millennium Commission, Railtrack, Railway Heritage Trust, Transport for London and Westminster City Council; concept engineers and dynamics—WSP; concept architect—Lifschutz Davidson; lighting architect—Speirs and Major; client’s advisor—Halcrow; cost consultant—Davis Langdon and Everest; contractor—Costain Norwest Holst joint venture; contractor’s designer—Gifford and Partners.

The authors also thank the various members of the project team for supplying the photographs in this paper.

Fig. 15: London Eye viewed from the upstream footbridge at night (Photo: Cross River Partnership)

References


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