Construction History Vol. 20. 2004

Brunel's Lost Bridge: The Rediscovery and Salvage of the Bishops Road Canal Bridge, Paddington

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History

When Isambard Kingdom Brunel (1806-59) was first envisaging the route for the Great Western Railway's main line in 1833, he thought of the Bishop of London's estate at Paddington as a likely site for the London terminus. Here was an as yet undeveloped stretch of land on the edge of town, well connected by roads. It was close to the Paddington branch of the Grand Junction Canal, which had been opened to its own Paddington Basin terminus in 1801, and thus offered a ready means of bringing construction materials and fuel to this end of the line. Many changes and chances were involved in designing the GWR, and the location of its intended terminus shifted to Vauxhall, then to Euston Station, then in the spring of 1836 back to Paddington again. The GWR had to negotiate with the Paddington parish vestry and the Bishop's trustees to acquire the land, and because this route had not been allowed for in their original Act of 1835, they needed a second Act of Parliament, eventually passed on 3 July 1837.

This second Act, at the instance of the parish, carried conditions requiring the GWR to build a number of bridges, most of them to carry existing highways over the line. The easternmost of these, however, represented a new route, along the line of an existing footpath called Bishops Walk, extending the recently-laid-out Bishops Road north-east to join the Harrow Road. The new bridge would cross the GWR's lines, which were sunk in a cutting where they widened out close to their eastern terminus; it would also have to cross the Paddington branch of the canal, referred to above. The bridge's design had to reflect an agreement reached between the GWR and the Paddington vestry in February 1837, specifying its width, and requiring its completion within 18 months of the Act.[1] Brunel accordingly designed a 500 foot long brick viaduct of 25 arches, not counting the canal crossing, to span the shallow cutting, and this seems to have been built in 1837-8. It was always known as the Bishops Road Bridge, despite the rather confusing re-naming in 1937 of the road which passes over it as Bishops Bridge Road.[2]

In the spring of 1836, Brunel made a number of designs for an ambitious terminus on the site of the present station at Paddington, entered from the Conduit (now Praed) Street end. However, the GWR's financial position would not allow this grandiose vision to be realised. Instead, in 1838 Brunel arranged a temporary station of timber platforms and low roofs on iron columns, next to and beneath the new Bishops Road Bridge, and this formed the GWR's Paddington terminus until the 1850s (Fig. 1).[3]

At its north-eastern end the new bridge had to clear the canal and then descend to join the Harrow Road, and this presented a problem to do with levels. The cutting was deep enough for the bridge to span the railway lines with ease. However, the canal was about 21 feet (6.5m) higher than the railway lines, and Brunel was obliged to give the canal company a working clearance of 10 feet (3.0m) above their water-level. Brunel had to clear the canal, and then get the roadway back down to join the Harrow Road at a safe gradient, which was the critical factor. In order to meet all these requirements, Brunel had to keep the canal bridge structure as shallow as possible. Recently-discovered documentary evidence in the

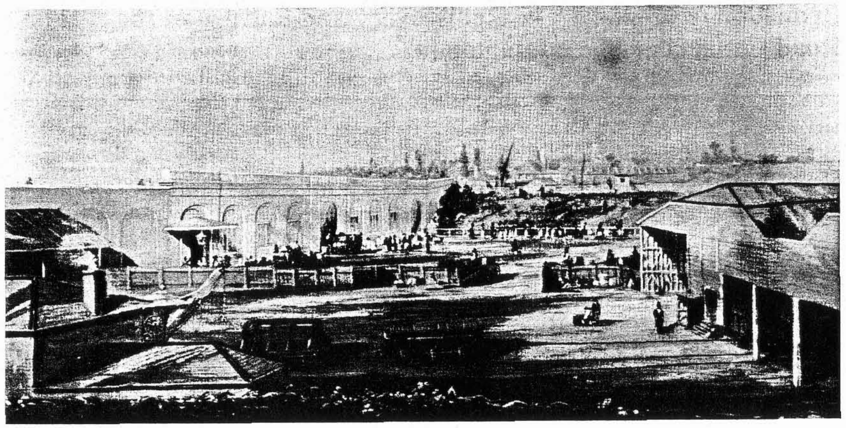

Figure 1. The Bishops Road Bridge and the Great Western Railway's first terminus, Paddington: an anonymous oil painting of c. 1840. (Westminster Archives.)

National Archives shows how he tackled the problem. On 18 May 1838, he wrote to R.C. Sale, at the Grand Junction Canal Office, as follows, (displaying his characteristic impatience with grammar, and economy with punctuation):

> "My dear Sir,
>
> I forward you an elevation of the Bridge we propose to erect over the basin at Paddington in lieu of the present foot bridge by the provision of our Act it is to be a carriage road bridge - 40 ft wide and to communicate with the Harrow road which limits our height. The bridge will therefore be of Cast Iron.
>
> I have made the principal opening as large as I possibly could consistent with safety and have provided a second Arch which is also large enough for barges to pass freely. And the whole is as wide as the present basin.
>
> I propose to get in the foundations during the stoppage of your canal next month and shall therefore feel obliged by an early reply. If Mr Holland wishes to see me on the subject, I shall be happy to meet him, but I must ask him to call on me, as I am still somewhat of an invalid.
> I am dear Sir,
>
> Yours very truly, I. K. Brunel." [4]

Sale evidently discussed the design with Mr Holland, who seems to have been the canal company's engineer. Mr Holland objected. Their reply has not been found, but on 25 May 1838, Brunel wrote to Sale again:

> "My Dear Sir,
>
> I think Mr Holland does not bear in mind that the basin and Towing path at the point of

> crossing is upwards of 60 ft with the head way we have it would be impossible to build such in one opening, perhaps a larger opening than the one I have proposed might be made although really I should not like to try it, but there would not be room to navigate the small arch - by the present proportion.
>
> The large opening is very ample probably the largest on your Canal while the side arch is still quite large enough for all barges - moving about without a tow rope.
>
> With respect to the loss of water, that difficulty also may be removed as it is proposed to drive a stank or dam across the basin and thus save the water south of it, and to drain only that part of it between the stank and the present bridge.
>
> I trust these explanations will be quite satisfactory and that so far as the sanction of your company is necessary we may proceed. A plan shall be sent.
> I am my dear Sir,
>
> Yours very truly, I.K. Brunel."[5]

On 30 May, the directors of the Grand Junction Canal Company considered the design. They do not seem to have viewed it with much enthusiasm:

> "Mr Bouverie reported that Mr Holland had had an interview with the Engineer of the Great Western Railway, for the purpose of considering whether they could devise any less objectionable plan for making a Bridge over the canal at Paddington in lieu of the Wooden footbridge than that of which he had sent a plan, but they agreeing that it would not be safe to carry one flat arch over the whole space,
>
> Resolved - that the plan as proposed be sanctioned."[6]

It is not recorded if Brunel got the foundations in during the summer, as he wished, but the main contract for the canal bridge was let to Messrs Sherwood in the autumn of 1838. They were one of the largest firms of London builders, and they shared most of the contracts for the GWR's extension from Acton to Paddington with Messrs. Grissell & Peto. Brunel, generally a difficult man to please, was impressed by both of them, describing them to the GWR directors as "highly respectable bricklayers and excellent workmen."[7] He recorded the tender prices for various works at the 'London Terminus' from these two firms in a book recording contract tenders for the railway. [8] This includes the following entry:

"Paddington Canal Bridge	B. & N. Sherwood 27 October 1838.		
Brickwork in mortar, per cube yard	£1.	3.	6.
Brick in cement, per cube yard	£1.	9.	6.
Portland Stone dressed, per cube foot	-	7.	6.
Bramley Stone in cutwater, per cube foot	-	8.	-

Casting to Bridge in Ribs, bedplates, bridging pieces, covering plates, railings, including

fitting, chipping, fixing & painting, per ton:	£15	12.	6.
Wrought iron in screwbolts, nuts & ties, per cwt:	£2.	5.	-"

Messrs Sherwood, having taken the contract for the canal bridge on 27 October, subcontracted the manufacture of the ironwork to Gordons & Co. of Deptford. This little-known firm of 'engineers, founders, ship & anchor smiths and export ironmongers', to quote a directory entry of 1840, was based at Deptford Green in a long-established shipbuilding and anchor-forging area. It was linked to the shipbuilders Gordon Brothers and Company, with whom they shared a City office near Fenchurch Street. Both companies disappear from the London directories in 1844.[9]

Happily, copies of the original designs for the bridge have been identified in a group of drawings attributed to Francis Trevithick, son of the more famous Richard, recently acquired by the library of the Institution of Civil Engineers. We do not know whether the drawings of the canal bridge turned up in Trevithick's papers because he was doing some drawing work, including these, for Brunel and the GWR, or because he had simply taken some tracings for his own purposes. The three sheets of drawings, partly illustrated here (in a rearranged layout, Figs. 2, 3 and 4), show the bridge almost exactly as built. They are identified as 'London Terminus, Paddington Canal Bridge', but they are neither signed nor dated.[10] Although the drawings could well be by Trevithick, this does not seem in any way to undermine the attribution of the bridge's design to Brunel, which is clearly established by his correspondence, quoted above.

There is also the evidence of one of Brunel's volumes of research notes. Brunel had his office compile a number of notebooks, all entitled 'Facts', with an amazing miscellany of research notes and information on engineering subjects. There are six of these volumes among a collection of Brunel's private papers, given by his children to the GWR after his death, and now in the National Archives.[11] Two of the volumes, in particular, have a wealth of material relating to the design of cast-iron bridges. On two pages of one of these volumes, one of Brunel's staff recorded (or copied) the results of load-tests carried out in December 1838 on the beams for the 'Canal Bridge at Paddington Depot.'[12]

These tests had been supervised by Joseph Colthurst, one of Brunel's assistant engineers, who had recently been superintending the construction of the Wharncliffe Viaduct over the River Brent at Hanwell, and the adjacent sections of the line to the west where Brunel's first three cast-iron bridges were situated, including the one over the Uxbridge Road noted below. Colthurst's name appears several times in the notebooks, always in connection with the design and testing of cast-iron beams.[13]

The canal bridge beams were certainly tested very thoroughly, all 22 beams being examined. Page 96 of Brunel's notebook (Fig. 5) has sketches of the two types of beam, each seen in half-elevation and in section. Another vignette on the same page shows 'the manner in which the girders for the Canal Bridge at the GWR Terminus were tested.' This shows that the beams were tested in pairs, held heel-to-heel with a wrought-iron frame around their middle, and subjected to point-loading at mid-span by a cylindrical hydraulic jack, the feed-pipe for which is shown leading off to one side.

The results for the larger, 35-foot-span beams are given in a table on p. 97, headed 'Girders for Canal Bridge at Paddington Depot.' Eleven beams are listed: they were tested with loads of 20 tons, 25 tons and 30 tons, and the deflection measured in each case for each beam. The beams deflected by 3/8" to 5/8" at 20 tons, by 4/8" to 7/8" at 25 tons, and by 5/8" to 8/8" at 30 tons. Numbers 6 and 10, which are noted as being 'an outside stronger girder', and an 'outside' girder, showed slightly less deflection: these

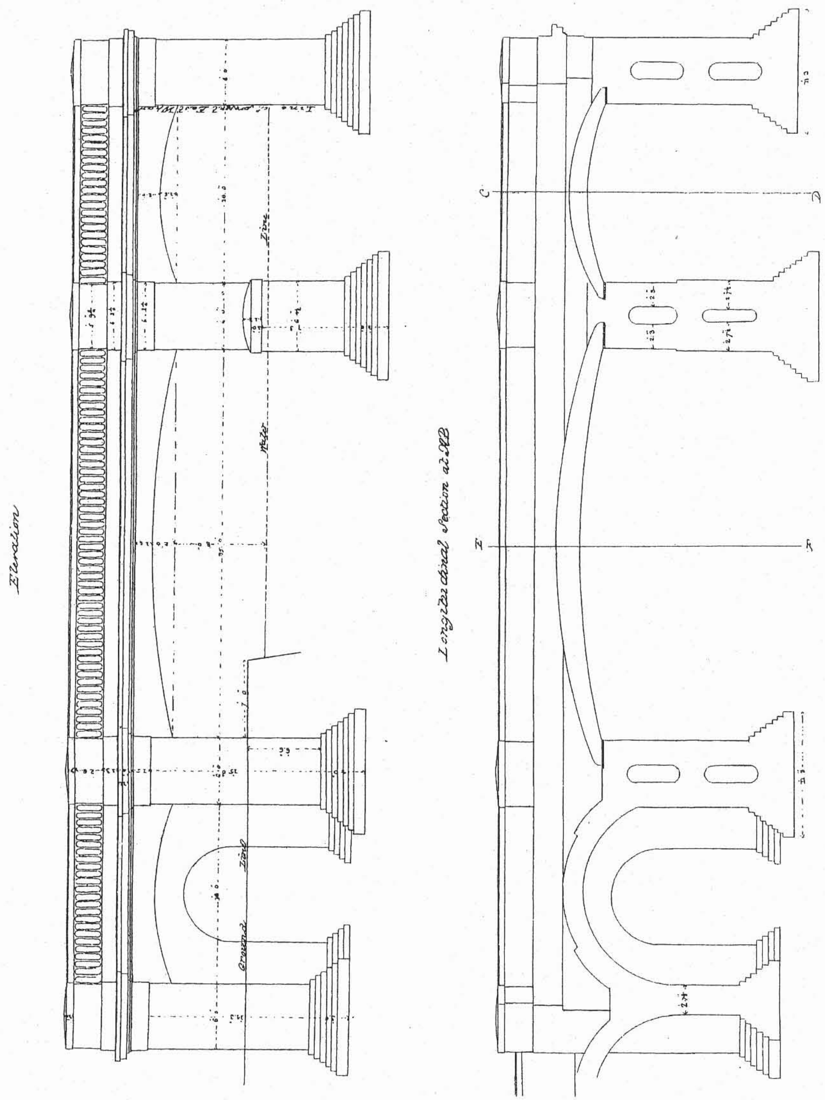

Figure 2. An elevation and longitudinal section of the bridge, c. 1838, from drawings attributed to Francis Trevithick. (Library of the Institution of Civil Enineers.)

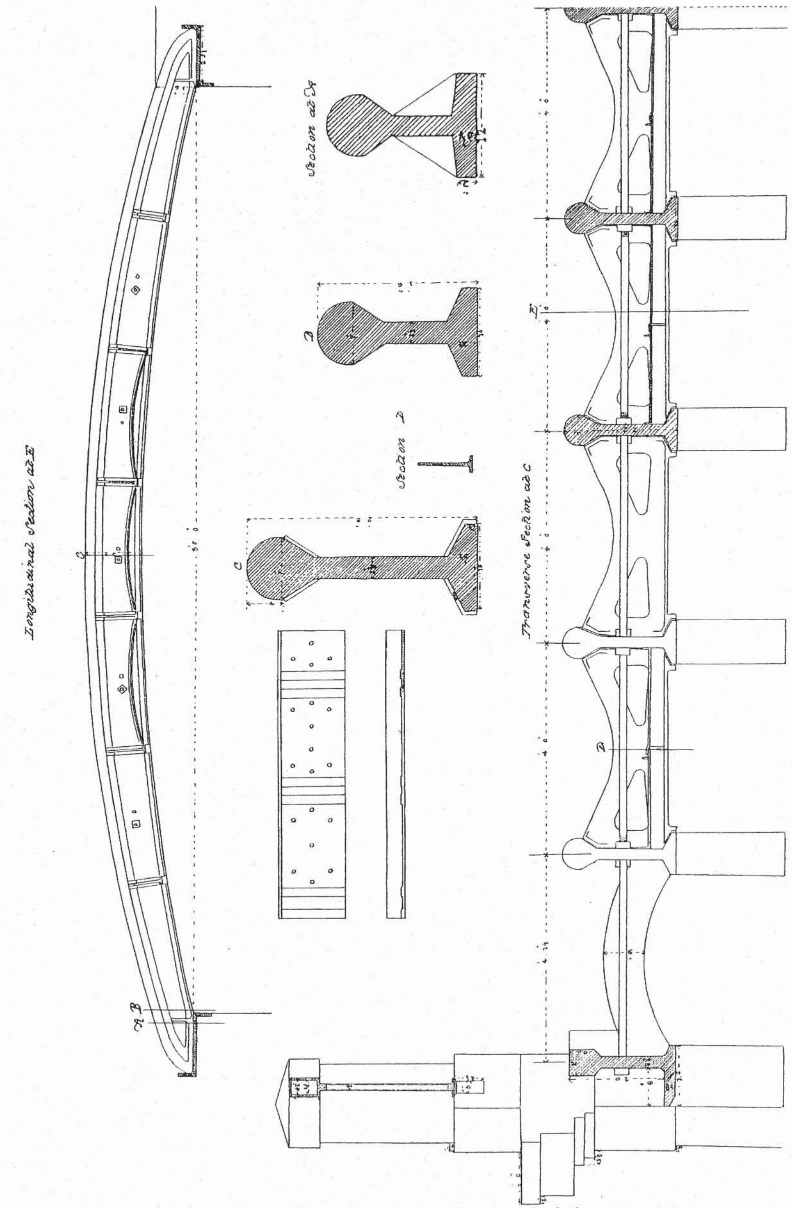

Figure 3. Details of the ironwork of the main span from the Trevithick drawings: (a) elevation and~sections of a main girder; (b) part cross-section, including an edgebay on the left. (Library of the Institution of Civil Engineers.)

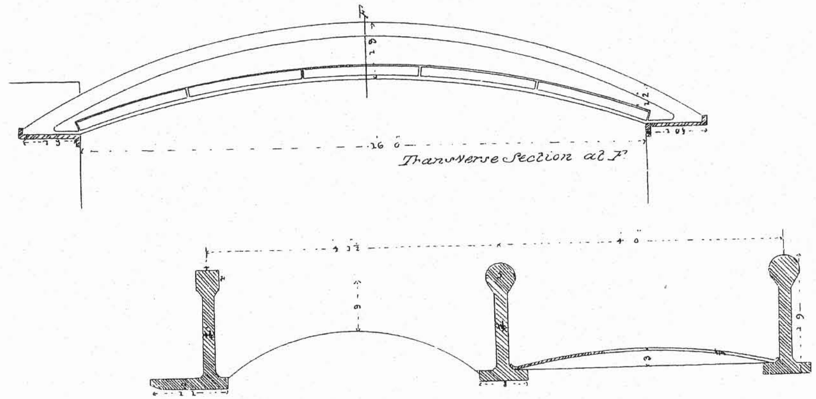

Figure 4. Details of the ironwork of the side span from the Trevithick drawings: (a) elevation of girder; (b) part cross-section, including an edge-bay on the left. (Library of the Institution of Civil Engineers.)

are doubtless the differently-shaped girders made to sit on the sides of the bridge and carry the brick fascias and stone cornices. Beam number 9, however, broke at 28 tons. This, too, is illustrated with a cross-section drawing on page 96, in which areas of the lower flange and one side of the web are stippled with the note "the parts marked with dots composed of nothing but Slag, refuse cinder & Sand."

The beams for the smaller, 16-foot span were all tested as well, to 30 tons of load, but these results are just given in summary on page 97. The nine inner girders deflected by an average of a quarter inch, while the two girders intended to sit on the outside and carry the parapet, 'being of a stronger section', were tested to 35 tons: they also deflected by a quarter of an inch.

The canal bridge, its beams thus proved, was evidently completed by the spring of 1839: indeed, by the agreement of February 1837 with the Paddington Vestry, the road should have been complete by early January. On 18 April, Brunel wrote to Charles Saunders, Secretary to the GWR board, authorising a payment to Messrs Sherlock, and also recommending payment of £1,500 to Messrs Gordon to settle their bill for the ironwork.[14] The Bishops Road Bridge took its place in London's street-map at a time of huge upheaval for the area.

It was not long before the Paddington vestry began to realise that having a railway company and its terminus in their parish was not going to be entirely a bed of roses. On 13 March 1841, they wrote to Charles Saunders:

> "Many and heavy complaints have been made to the Vestry of the Nuisance which are daily and hourly committed on the bridge over the Canal, and at the corner of North Wharf Road, principally by Passengers to and from the Station, owing, as the Vestry conceive, to the entire want of proper conveniences on the Premises of the GWRC, and I am to suggest the necessity of such convenience being immediately erected, to remedy the evil complained of, the Boards recently stationed on the Bridge by the Vestry proving ineffectual..."

On this decidedly banal note, Brunel's handsome and technically distinctive bridge settled into its

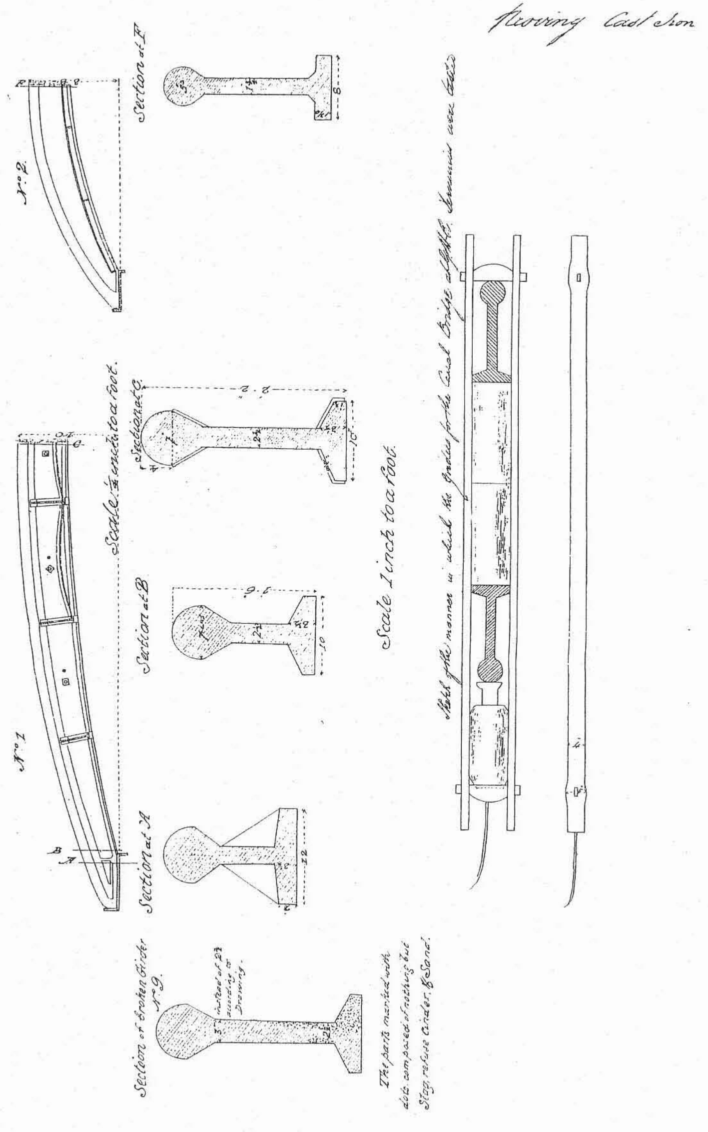

Figure 5. A page from Brunel's research notes, showing girder cross-sections, with the method of proof-testing the girders with a hydraulic jack and (upper left) a section of the girder which broke, with the casting flaws marked. (The National Archives: Public Record Office.)

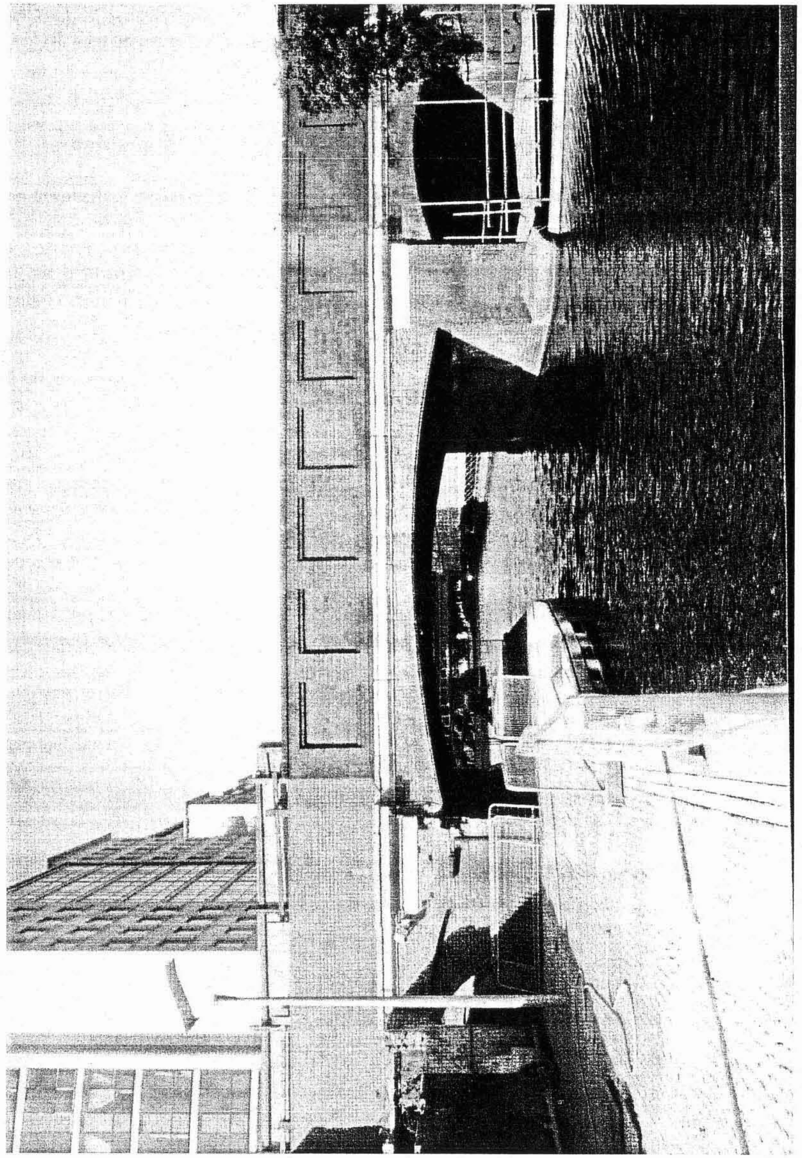

Figure 6. A general view of the bridge from the SE prior to dismantling.(Malcolm Tucker)

place in London's cityscape, and quickly sank from general notice. The canal bridge, as we have noted, formed the northern end of the Bishops Road Bridge, immediately south of its junction with the Harrow Road: it stood until the spring of 2004 at National Grid Reference (NGR)TQ/ 2648 8159 (Fig. 6).

The Design of the Bridge

Brunel arranged the canal bridge into three spans. The two above the navigation employed gently arched cast-iron girders behind a facing of brickwork, while the third, to the south-west beyond the towing path, was a dummy built of arched brickwork to provide architectural symmetry (Figs. 2 and 6). A further, small brick arch beyond the north-eastern abutment completed the viaduct, 29 spans in all. From there the road descended on a brick-retained embankment to the Harrow Road. In the following account, each aspect of the design will be considered in its turn.

First, the navigation was to be affected as little as possible. The width of the channel on the busy approaches to Paddington Basin was 55 feet (16.8m) from bank to bank, but at the bridge it was locally narrowed by 5 feet. This may have been the arrangement of the wooden footbridge previously on the site.[15] The towing path added 7 feet (2.1m), making a crossing of 57 feet (17.4m). Brunel divided this into two unequal openings of 35 feet and 16 feet (10.7m and 4.9m), with a 6-foot (1.8m) pier between that was protected from collision by massive stone-capped cutwaters. The smaller opening, with no towing path, allowed barges to get alongside wharves on the off-side, north-eastern bank. The main opening, 27 feet 9 inches (8.6m) wide at the waterline, was insufficient for two barges 14 feet 3 inches (4.7m) wide to pass each other there, but it was nevertheless wider than that in any other road bridge on the canal and so 'very ample', to quote Brunel, for practical use. In the 20th century the canal company was able to narrow the passage to 20 feet (6m) in order to install stop gates, but doubtless Brunel did not wish to strain relations by haggling on this point. From his recent completion of the railway bridge over the Uxbridge Road, with spans of 34 feet (see below), where there had been difficulties mainly with some specially heavy, non-standard girders, Brunel would have been confident that ordinary cast-iron girders could be satisfactorily manufactured, transported and erected to bridge a 35-foot gap, but making them significantly longer or heavier could have severely tested the foundry's expertise. A conventional arch, assembled in sections, could have spanned the whole canal, but there would have been no headroom at the sides.

For navigation headroom, beneath the critical vertical alignment, Brunel provided a minimum clearance of 8 feet (2.4m) from the nominal water level to the undersides of the girders at the ends of the spans.[16] The girders were not designed or detailed to work as arches structurally, but their soffits were made to rise as shallow circular arcs to achieve a midspan clearance of 10 feet (3m) in the longer span and 6 inches less in the small span. This profile was both elegant and practical, considering the limited space, for it provided the greatest headroom at the centre, where a boat would have its towing-mast. Brunel may also have been aiming to simulate the arguably more elegant and certainly more familiar appearance of a traditional brick arch.

The girders themselves were made sickle-shaped in profile, tapered towards their ends to save weight (Figs. 3 and 4). The midspan depth in the longer span was 2 feet 2 inches (0.66m), or about one sixteenth of the span, a reasonable proportion already adopted in the Uxbridge Road bridge. A filling of lime concrete around the girders and a surfacing probably of water macadam, replaced in modem times by hot-rolled asphalt, completed a total constructional depth of approximately 5 feet (1.5m), from the crown of the roadway to the seatings of the girders. The slightly less deep side-span girders fitted in under the vertical curve over the summit of the bridge.

Beyond, north-eastwards, the carriageway descended at a gradient of 1 in 20, so as to reach ground level immediately short of the junction with the Harrow Road, a fall of about 9 feet in 60 yards, while south-westwards the gradient was a more relaxed 1 in 30 for about 200 yards. 1 in 20 was the limiting gradient that Thomas Telford had chosen for his Holyhead road, and it will have been regarded as a maximum for a major new road. The vertical geometry offered little freedom of manoeuvre, and Brunel will have needed to work it out in some detail before the Railway could be committed to agreement with the vestry, back in 1837.

In plan the bridge was straightforward, with a 40 foot (12.2m) clear width between the parapets, as had been agreed with the vestry. The rest of the viaduct and the ramp down to the Harrow Road were required to be 45 feet wide and the narrowing was perhaps an acknowledgment, established in tradition, that an iron bridge would be the costliest part of the road per square yard, but also the grandest, so that 5 feet rather than 7 1/2 feet for each footpath would be no loss. The 30-foot (9.1m) carriageway was respectably wide but not extravagant.

Although, as we shall see, some of Brunel's details were far from ordinary, the structure was laid out conventionally with 11 parallel girders in each span at nominally 4-foot (1.2m) centres (Fig. 7). They were held in place by spacer plates and tie bars, tightened against each other. The soffit was formed by cast-iron plates, supporting the mass-concrete filling. The girder ends, slightly widened for stability, were bedded with iron cement on the horizontal surfaces of Z-section cast-iron seating plates which spread the load onto the brick piers. These bore by corbelled brick footings onto the stiff London Clay subsoil. The piers contained voids, to save on bricks. The bricks were well-burnt 'multicoloured' London Stocks, with a red-to-purple fabric incorporating cinders and a red-to-yellow mottled surface. Hand-made, clamp-fired and sorted for quality, these were the normal choice for robust industrial structures in early- and mid-19th century London. At Paddington, they were laid in Flemish bond on exposed surfaces, for respectability, although in English bond within.

Brickwork covered each fascia so as to hide the cast-iron edge girder, except for the edge of the bottom flange on which the brickwork rested. A shallow brick arch, of three half-brick rings, followed this flange to give the impression of a structural arch. This was laid in strong 'Roman' cement for

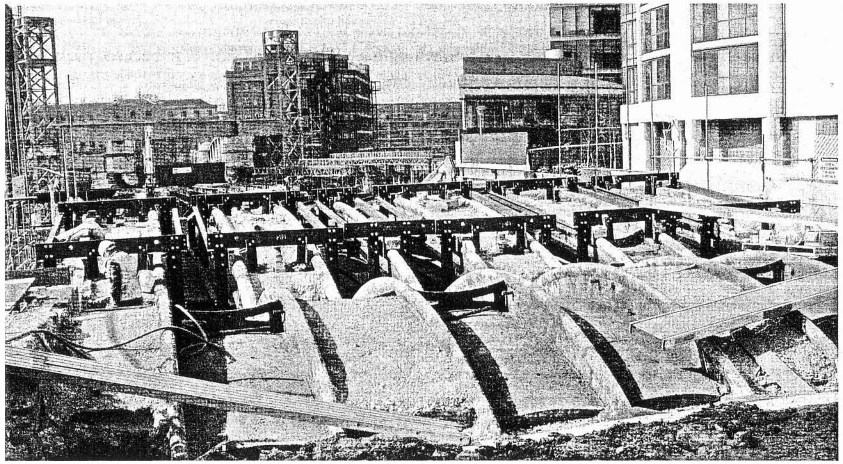

Figure 7. A general view of the structure from the north-east after the removal of the road filling from alternate bays. (English Heritage).

robustness, because there was not the thickness to bond the bricks back conventionally. The third, south-western span was similarly faced with a shallow brick arch, spanning 16 feet to match the north-eastern span. Behind it was not ironwork, but a conventional barrel vault. This sprang from near towpath level, and was hidden from view on each side by a wall recessed beneath the shallow arch, making it blind. This was pierced by a semicircular arch which served as a doorway, and the space within was occupied by two stables.

The facade was topped off with a Portland Stone entablature, of frieze, cornice and blocking course, and a cast-iron railing between stone pedestals. The piers between the spans were extended forward, and the abutment piers further forward, for architectural effect in the best bridge-builders' tradition. With its 1:2:1 modulation, the ultimate model was the Roman triumphal arch, although that would have been lost on the bargemen and wharfingers of the Grand Junction Canal. Unfortunately, the boundary wall between the canal and the railway bisected the south-western arch, so that the composition could have been appreciated fully only on paper. Worse, around 1907-9, the elegant railings were replaced by high walls of harsh red engineering brickwork, and the Portland stonework was removed entirely on the north-western facade.

In the details of the ironwork, the first point to be considered is the cross-section of the girders, which is most unusual (Figs. 3 and 4.). The bottom flange and vertical web were unremarkable, except for a considerable taper on the flange, making the pattern-making more complex. However, instead of a top flange, there was a substantial round bulb, of 7 inches (180mm) nominal diameter in the larger girders. This contained about 40% more metal than the bottom flange (although there was an equivalent reduction of metal in the 'web' compared with an I section). This became a square bulb in the edge girders, where brickwork had to be fitted around it. At the Uxbridge Road bridge, Brunel had followed the pattern advocated by Thomas Tredgold of a symmetrical I section, with equal, somewhat narrow flanges. More up-to-date thinking, following Eaton Hodgkinson, would have made the top flange considerably smaller in section than the bottom, to take advantage of cast-iron's much greater ultimate strength in compression. But here Brunel was moving in the opposite direction, so what was he thinking of ? It was not even as efficient as a Tredgold section, if one subjects it to an elastic analysis. If a broad top flange the mirror-image of the bottom flange had been used at Paddington, the total weight of metal would have been unchanged but the flange would have been further from the centre of the beam, giving a calculated 9% increase in bending strength. Something must have caused Brunel to become concerned, for he rigorously tested every main girder at Paddington, unlike his previous bridges. There had been problems with a particularly heavy girder in the more complex bridge at Uxbridge Road, and evidently he was intent on creating a more robust section or one easier to cast reliably, while perhaps not being able to analyse the matter too deeply.[17] By our calculations, the dead weight of the bridge (roughly 540lb/sq ft or 26kN/m^2) induced a tensile bending stress in the bottom flanges of 2.7 ton/sq in (42N/mm^2), compared with 4.8 ton/sq in (74N/mm^2) under the 30-ton point loading applied in the proof tests, comfortably below Tredgold's supposed elastic limit of about 6.8 ton/sq in (100N/mm^2). These stresses are high compared with later practice, which acknowledged the limitations of cast iron's ultimate tensile strength, as we discuss later.

The ends of the girders were smooth rounded (Fig. 8), unlike the skewback form that would have been used to transmit an arch thrust. Brunel will have appreciated that the shallow and unequal arcs of the girders, perched on top of a relatively flexible viaduct, could not be relied upon to perform as arches. Nevertheless, there will inevitably have been an element of arching action in the completed, solidly embedded structure, to which the chosen rib section was well suited. Whether he saw this as giving a reserve of strength in case of accident we cannot tell but, by reducing tensile stresses, this was probably very helpful when the bridge came to carry modern trunk traffic.

A similar sickle-shaped elevational profile had recently been used for girders of some bridges over the London & Birmingham Railway north of Euston by Brunel's friend and rival Robert Stephenson in 1837. These spanned 26 feet, with Hodgkinson's section.[18] Besides, the architect Charles Barry had erected heavy, sickle-shaped beams of 39-foot (12m) clear span in a roof at the Royal College of Surgeons in 1835: he and his ironfounder, Francis Bramah, had used Tredgold's I section.[19] With this profile, the tops of the Paddington girders were raised well above the bearings, and lateral stability would be important. This is probably why Brunel used vertical spacer plates between the webs, alternating with heavy transverse tie-bars with screwed nuts (the only mechanical fastenings within the bridge), so as to hold everything tightly in position, independently of the rigid concrete filling which could have been an afterthought. Here, he made a rod for the ironfounder's back, because minor variations in the casting of the girder webs gave every spacer plate a different fit. Seating bosses were cast on the girder sides to be individually adjusted by chipping, while each row of plates was individually lettered in the ironwork. Iron cement and occasional wedges completed the fixing operation (Fig. 8).

Between the shorter, less heavily stressed girders of the side span, a single row of spacer plates was provided at mid span. In the main span, however, there was a spacer every 5 feet, and the opportunity was taken to support the soffit plates off these spacer plates, which became cross-beams of inverted-tee section with the soffit plates resting on their flanges. Their webs were pierced to save weight of iron, making them Vierendeel beams, and this resulted in the only significant structural deficiency found in the bridge when it was dismantled. Several of them had not stood up to the pounding of modern trunk-road traffic and their weaker top chords had fractured. The lower chords had then performed as shallow arches, in most cases without further fracture.

Curiously, the soffit plates were not used next to the edge girders in either of the spans. The gap between the girders there was bridged by a one-brick-thick jack arch laid in 'Roman' cement and filled with lime concrete. Tie bars were used, as in the inner bays. The soffit was originally rendered in 'Roman' cement, perhaps to match the smooth surfaces of the cast-iron plates in the soffits of the inner bays. The various plates added 50% to the weight of iron in the bridge (Fig. 9).

Cast-iron deck plates were commonly used to support the road metal in early 19th century cast-iron road bridges, arranged to span transversely from rib to rib. They were nearly always flat, except for stiffening ribs on their concealed upper faces, or sometimes exposed below. For convenience they would usually be placed on the top edges of the ribs, made level for the purpose. But, if placed on the soffit and supported on the lower flanges (so as to reduce the overall depth of the bridge structure or to conceal water and gas mains), then the plates would follow the shape of the bridge's underside, which might be arched as at Magdalene Bridge, Cambridge, of 1823-4. This gentle, barrel-shaped curve was at right-angles to the direction of the span of the plates, not like a jack arch. Alternatively, the plates could be arched to span from girder to girder like jack arches, so avoiding the use of stiffening ribs, but only if they rested on more or less level flanges, without the complications for the foundry pattern matter of having a two-way-curved toroidal shape. An example is the fire-protecting soffit plates in some of the floors of (Sir) Robert Smirke's London Custom House of 1826. Two-way-curved jack arche in brick, following the ribs of a segmental iron arch, may be seen beneath a footbridge, possibly of 1815, across the Regent's Canal in Regent's Park (NGR TQ 273 831), as well as in the edge bays of Brunel's bridge as already noted.

For the soffit plates of the side span at Paddington, Gordons' were required to follow such a doubly curved shape, but in iron (Figs. 10 and 12). While they achieved this admirably, one wonders at what expense of time and skill. For the main span, perhaps seeking a better approach to the matter, or because of the separate need, already noted, to brace and stabilise the long and deep girders, Brunel chose a

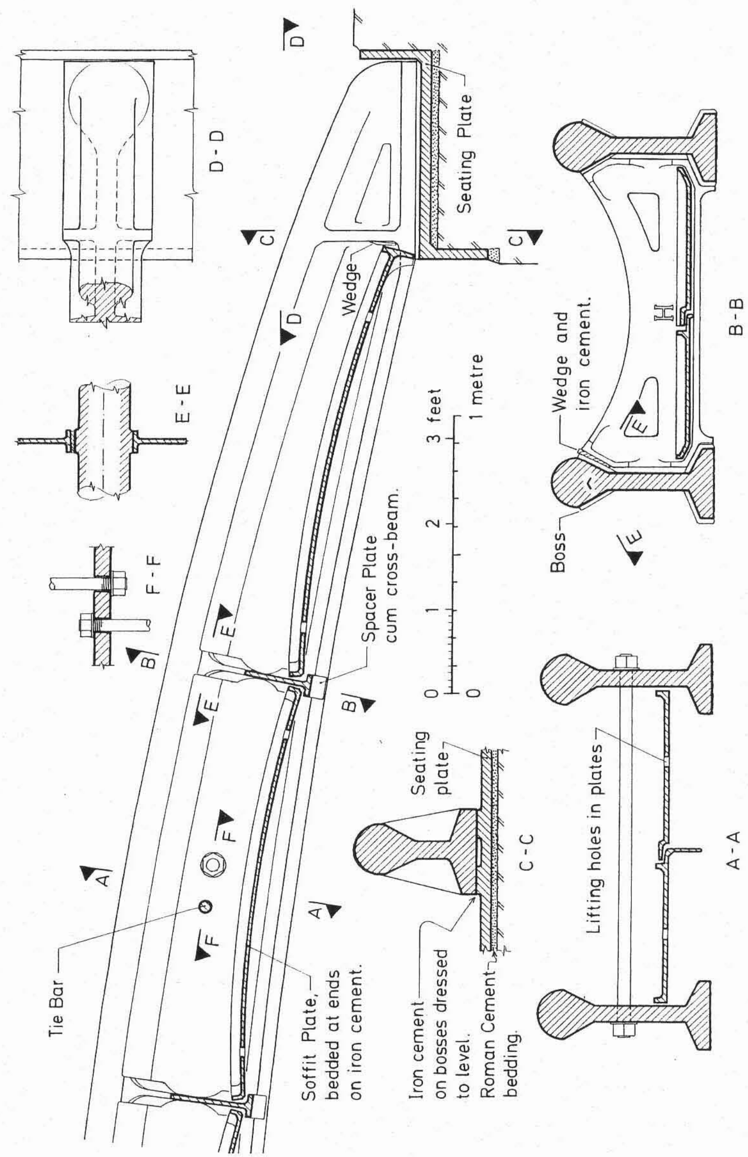

Figure 8. Ironwork of the main span: measured details made from observations on site. (Malcolm Tucker)

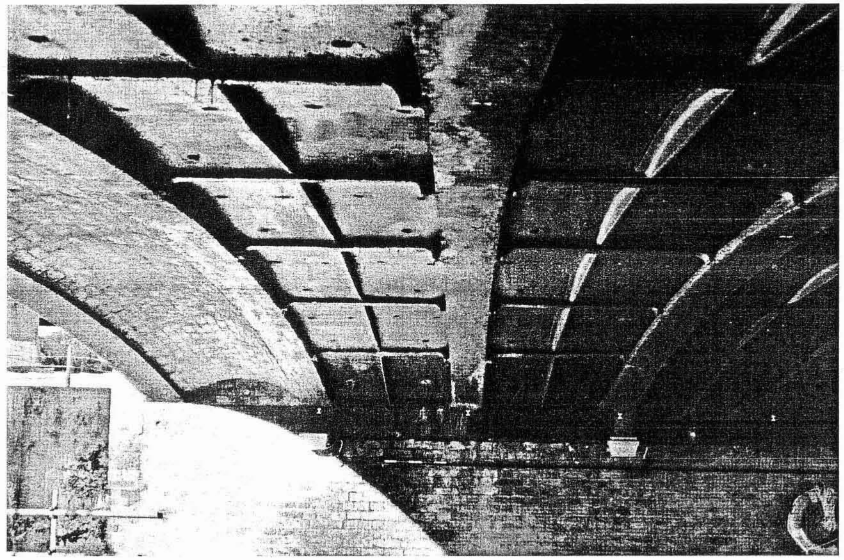

Figure 9. The underside of the main span, showing the longitudinally arched soffit plates supported on the spacer plates as cross-beams, with a brick jack arch in the edge bay on the left. (Malcolm Tucker)

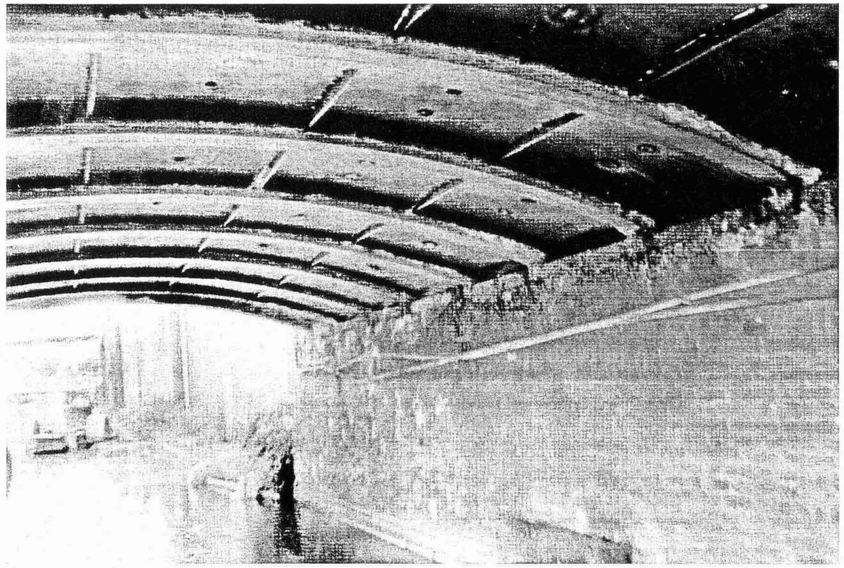

Figure 10. The underside of the side span, showing transversely arched soffit plates, buttjointed with stiffening ribs at the joints (Malcolm Tucker)

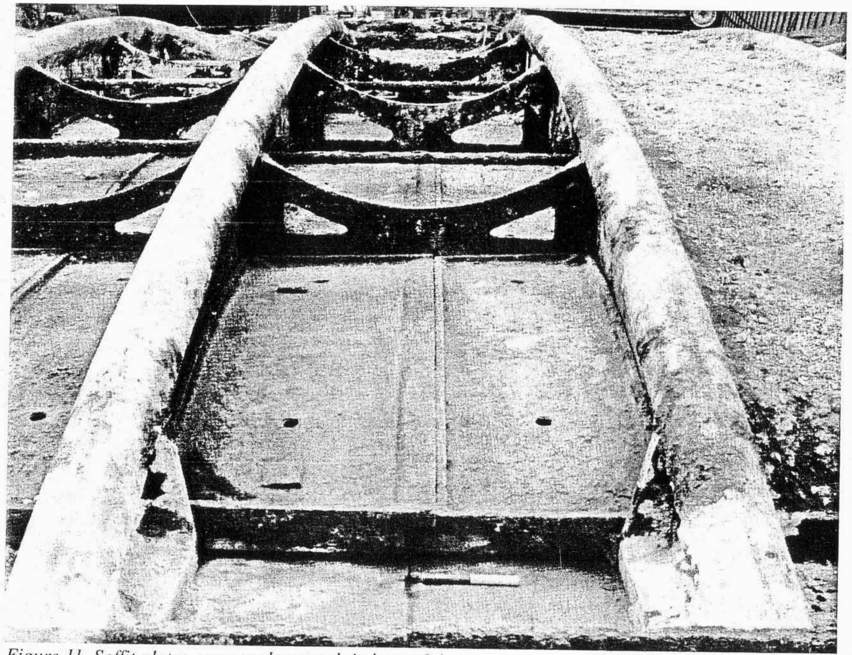

Figure 11. Soffit plates, spacer plates and tie bars of the main span, seen from above (Malcolm Tucker)

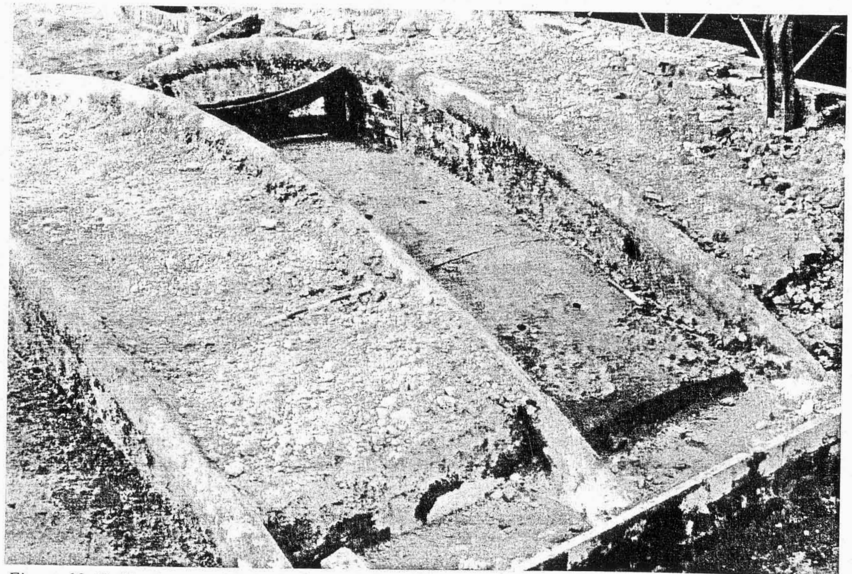

Figure 12. Soffit plates and spacer plate of the side span.(Malcolm Tucker)

'double' system, with the soffit plates arched parallel to the girders to span between spacer plates, which here function as cross-beams (Fig. 11). Thereby the plates kept a single curvature, making it easier to set out the patterns. However, this introduced new difficulties. Firstly, the plates had to be made in halves with a longitudinal joint, to allow them to be manoeuvred into the constricted spaces between the girder webs and the spacer plates. Secondly, the corners of the plates had to be tailored in plan around the end flanges of the cross-beams. Thirdly, the undersides of the plates had to be chamfered at their corners where they landed on the sloping upper surfaces of the girder flanges. So these shapes were just as difficult for the pattern maker (and for the archaeological draughtsman !). Fourthly, stiffening ribs introduced at the longitudinal joint introduced an incompatibility between arching and bending action. This was the probable reason for longitudinal splits observed in some of the plate castings, although without serious consequence.

Brunel could have benefited from the system of soffit plates used in 1866 at the canal bridge which carries the Harrow Road at Westbourne Green, one kilometre west of the Bishops Road site (at NGR TQ 254 819). They are square in plan with a flat, straight rim along all four edges, but domed up in the middle like a very shallow pyramid, by the intersection of two shallow-arched surfaces each of a single curvature. This shape became known as a buckle plate when, later, it was pressed hydraulically from wrought-iron or steel sheet metal.

Having looked at most aspects of the design, we should consider how the contractors performed, and from the evidence revealed in the dismantling, we can say that Sherwood's and particularly Gordons' did a pretty good job. Since Trevithick's drawings show the cross-beams (or spacer plates) and the two types of soffit plates in their final form at 1 inch to 1 foot (1:12) and girder sections at 2 inches to 1 foot, while also showing the general arrangement identically to the GWR's drawing in Network Rail's archive, they must represent the designs prepared under Brunel's direction. But working up the details to full size, setting them out and modelling them in three dimensions and getting the pieces to fit together will have been the pattern maker's achievement. Few of the members, from girders to soffit plates, had a straight edge or a right angle for setting out.

The main girders, each weighing about $5^{1/2}$ tons, may have been cast on their sides, as was normal practice, since some local cold-joint flaws were seen on the north-west-facing edge of some of the bottom flanges, presumed to have been uppermost in the casting pit. Their sectional dimensions were within 5 to 10mm of those specified. The asymmetrical edge-girder castings had a slight sideways warp. Some of the soffit plates had gas holes in their undersides, evidently cast upside down. They were within ±3mm of their nominal 19mm (3/4 inch) thickness. The ironfounders cast their name, 'GORDONS & Co/ DEPTFORD' proudly on one side of each beam, but where inevitably no one could see it once the bridge was complete (Fig. 13).

Water had penetrated the deck over the years, especially at the road edges, washing lime out of the concrete and redepositing it as dripstone on the soffit. Nevertheless, British Waterways, the recent owners, had been able to chip and blast much of this away and keep the underside neatly painted. Internally, rust had built up to 5 or 10mm in thickness in low-lying areas, and it was feared that this, in conjunction with the original iron-cement joint-filling compound, would impede the sliding and lifting out of the plates during dismantling. However, deft use of pneumatic chisels readily loosened them up. Most of the upper parts of the ironwork, protected in their lime-rich environment, were pristine, and some of the painted component numbering was still to be seen. The bridge's good condition and ingenious design made its dismantling in 2004 a particularly memorable, if sad, operation.

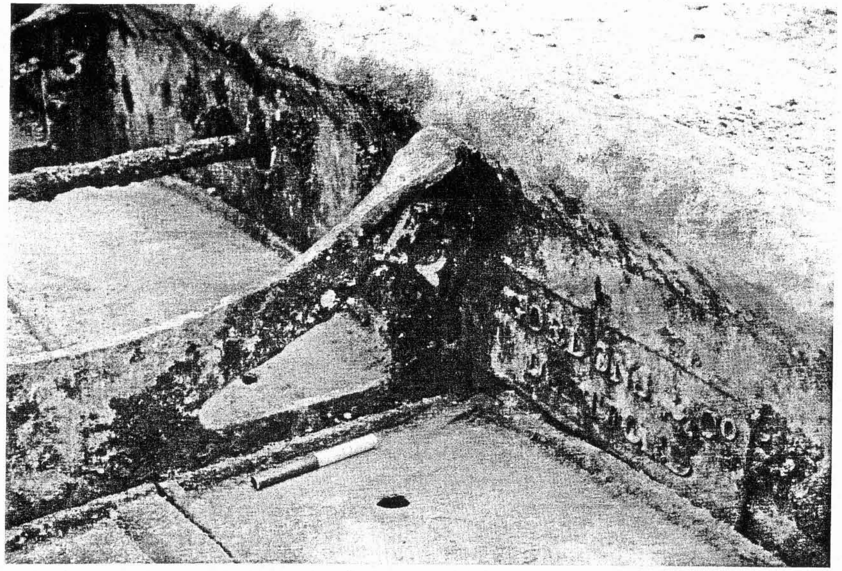

Figure 13. The ironfounder's name cast on a main girder, with location numbering painted on a spacer plate.(Malcolm Tucker)

The Bridge in its Historic Context

The Bishops Road canal bridge at Paddington is highly distinctive: indeed, it appears to be unique, as no other bridge with beams of this section and possibly none with deck plates of such complicated patterns seem to have been built. The reason would seem to be that from 1836 into the 1840s Brunel was experimenting in this area, and this bridge represents a stage in this progress. A good deal of new evidence for Brunel's cast-iron bridges and his experiments with the material has recently been found by the present authors: we intend to make this the subject of a further article, and for present purposes can only attempt a summary, to set the Paddington bridge in its context.

We need briefly to consider the understanding and use of cast-iron, in particular as a bridging material, in the 1830s.[20] In the early 1820s the engineer and writer Thomas Tredgold carried out experiments to ascertain the strength of cast-iron beams, publishing his findings in 1822 in a widely-disseminated textbook.[21] It would seem that he was misled by his use of small specimens about one inch square, which generally show a much higher ultimate strength in bending than do full-sized beams: this phenomenon, which had not then been perceived, can partly be explained by modern fracture mechanics. Tredgold took the limiting state for the design of a beam in service as the elastic limit, beyond which a permanent deformation would be imparted to the metal. Mistakenly believing that there was an ample reserve of strength beyond that point, before the beam would fracture, he was not concerned that, under increasing loads, his beams would ultimately break on the tensile side well before the compressive side would crush. In the elastic range, cast iron behaves the same in tension as in compression, and accordingly he judged that the optimum shape for a cast-iron beam was an I-section, with top and bottom flanges of equal size (Fig. 14a). I-shaped beams, occasionally used before Tredgold's publication, were

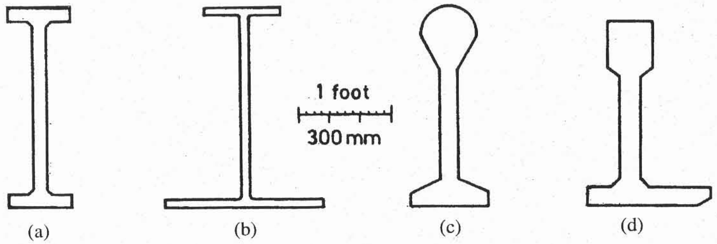

Figure 14. Different approaches to the design of cast-iron beams (Malcolm Tucker):
(a) Brunel's bridge carrying the GWR over the Uxbridge Road, 1836, based on Tredgold.
(b) Stephenson's bridge carrying the Hampstead Road over the London & Birmingham Railway, 1836, based on Hodgkinson.
(c) Brunel's Bishops Road canal bridge, main span beam, 1838 - sui generis.
(d) Brunel's Bishops Road canal bridge, main span edge beam, with an asymmetrical bottom flange, designed to carry a ring of brickwork on the outer (RH) side, and a jack arch on the inner (LH) side.

thereafter used on a large scale in some prominent buildings, until cast iron itself went out of use for such purposes. [22]

However, the scientist Eaton Hodgkinson looked into the matter more deeply. He showed that cast iron in full-sized girders was typically about six times as strong in compression as in tension. The bottom flange of a loaded beam must bear the tensile force, and therefore needed to be much larger in section than the top flange, if the material was to be used in the most efficient way. Iron beams made according to his principles were probably first used by George Stephenson on the Water Street bridge of the Liverpool and Manchester Railway in 1830.[23] Hodgkinson published his work in Manchester the following year, recommending that the bottom flange of a beam should be six times the size of the top one, but this was not republished in London until 1846, after a brief mention in 1842.[24]

In the 1830s Robert Stephenson and his assistant engineers, Charles Fox in particular, made use of Hodgkinson's findings in designing numerous cast-iron girder bridges for the London & Birmingham Railway: about thirty were built c. 1835-8, including a group of four over the extension from Chalk Farm to Euston Square.[25] In practice, for ease of casting and construction, the beams tended to have a ratio of bottom flange to top flange that was more like 2:1 or 3:1 than 6:1, but nevertheless, the designs were usually based on Hodgkinson's findings (Fig. 14b). Very few of these bridges are thought to have survived, because of track-widening operations and the inadequacy of cast-iron girders for increasing traffic loads, but many similar girders remain *in situ* elsewhere, where circumstances were less critical.

Brunel is not known as a designer of cast iron bridges. Indeed, the modern studies of him hardly mention the subject.[26] Brunel does not seem to have built a cast-iron bridge prior to his work on the Great Western Railway in 1836, though he had, of course, produced his winning design for the Clifton suspension bridge in wrought iron, 1829-31. When planning the GWR main line, Brunel kept the use of structural iron to a minimum, but he does seem to have designed at least six cast-iron bridges to carry the railway, in addition to the Bishops Road canal bridge. With the exception of the latter, and of a simple arched cast-iron footbridge over the line in Bath, they all seem to have been destroyed.[27]

Immediately after the pages in the book of 'Facts' which record the tests for the Bishops Road canal bridge, there are notes on a number of other load-tests.[28] These refer to another three bridges: the Uxbridge Road Bridge, the 'Grand Junction Canal Bridge,' and the 'Paddington Canal Bridge.' No further clue as to their location is given, but it has become clear that these refer to three separate briges, all on the GWR main line between Hanwell and Hayes in West London. The first of these is reasonably well-known, primarily on account of its having been illustrated in J.C. Bourne's 'History of the Great Western Railway.' This large bridge carried the GWR main line, at a severe 60° skew, over the turnpike road from London to Uxbridge, just where it was intersected by the north-south road from Greenford to Brentford (NGR TQ 142 802). Its beams were of 34 (10.4m) foot clear span, arranged to span at right angles to heavier beams placed on pillars parallel to the highway, with subsidiary beams running diagonally at the fascias. All the main beams had I-shaped sections of, 2'2" (0.66m) deep with equal top and bottom flanges, thus following Tredgold's principles, not Hodgkinson's. Brunel noted that 'only three of the girders were tested by weight' and tabulated their deflections under 18 tons load, adding in a further note that:

> "The weight of 30 tons was suspended from the centre of the Bridge & the deflection of the main Girders with that weight was 1/16". The rest of the Girders were tested by blows of a Sledge Hammer & listening to the sound produced by the impact. The Grand Junction Canal Bridge was also proved by the Sledge Hammer."

On the 'Grand Junction Canal Bridge' there is no other data given. However, it seems certain that this refers to the bridge which carries the GWR over the Grand Junction Canal near Hayes (NGR TQ 101 794). The railway crosses the canal at a considerable skew (56°), with limited clearance over the water. The bridge deck has been replaced with modern steelwork, and it has been widened on both sides. Nevertheless, the original abutments can be plainly discerned, 30 feet apart, and it is clear from these that the bridge was built with iron beams resting on continuous gritstone seatings, at 10 feet above the water level.

This leaves the third, rather delphic reference, on page 99, to the 'Paddington Canal Bridge Girders.' One might well take this to refer to the Bishops Road canal bridge - the main subject of this article. The difficulty is that page 99 has a section drawing of an I-shaped beam of the Tredgold type, 1'9" deep, with a note to the effect that the beams were 'subjected to a strain of 27 tons each,' but no beams of this design were found in the Bishops Road bridge when it was dismantled. The answer is that this refers, not to the bridge at Paddington, but to a bridge carrying the GWR main line over the Paddington branch of the Grand Junction canal, popularly known at the time as the 'Paddington Canal' and so named on the first edition Ordnance Survey map.[29] This branches off from the main canal at Bull's Bridge in Southall, and the railway bridge referred to is about 200 yards up from this, so these two iron bridges were no great distance from each other. Hére Brunel had to design a 34° skew bridge with a similarly tight vertical clearance over the canal. The bridge has been trebled in width, and the original span replaced in prestressed concrete. Nevertheless, it is clear from an examination of the abutments that it was built with cast-iron beams: seven padstones can be seen on either side for beams to bear at 10 feet above the water.

So, the first stretch of the Great Western main line from Paddington to Maidenhead, which opened in May 1838, had three cast-iron bridges, all built by the contractors Grissell & Peto.[30] Construction of the line had started nearby, at the Wharncliffe viaduct over the Brent valley, and these three bridges must have been among the first parts of the work for which detailed drawings were required. It is striking that Brunel designed beams with equal top-and-bottom flanges of the Tredgold type for them: was he unaware of Hodgkinson's research, or was he simply discounting it ? The first proof-tests, as recorded on pages 98-9 of the volume of 'Facts', are not dated, and they have a rough and ready quality to them.

We have not found any more material relating to the two canal bridges in the GWR material held by the National Archives, but we do know that the Uxbridge Road bridge gave serious trouble, with a beam breaking in June 1837 during construction, requiring elaborate temporary works, and major repairs.[31]

This was the immediate background to the design of the Bishops Road canal bridge. Brunel, having experienced difficulties with I-section beams at the Uxbridge Road, seems to been looking for a better design. However, instead of simply developing a Hodgkinson-type design for beams with a big bottom flange, along the lines of Stephenson and Fox's bridges on the London & Birmingham Railway, he produced his own. The Bishops Road canal bridge beams, as we have seen, deliberately went in the other direction, by making the bulb-shaped upper flange about 40% bigger in section than the lower flange. See figure 14 for a comparison of the different sections. We do not yet really understand Brunel's thinking here.

The Bishops Road canal bridge, and the rigorous tests that Brunel ordered, were followed by a whole series of experiments with materials which Brunel was conducting and recording in these notebooks. The same volume, for example, records a series of tests on iron castings from 49 different, named foundries, to examine their elasticity, deflection, breaking weight, specific gravity and power to resist impact.[32] Brunel was evidently not satisfied with the design he had arrived at for the Bishops Road canal bridge: the following years, c. 1839-40, saw him commission a great series of tests of experimental beams, all run by Mr Colthurst, and recorded in a later volume of 'Facts'[33], and there is reason to believe that Brunel's experiments with the material went on into the mid 1840s. A great deal more evidence on this subject has been found, far more than can be covered here, and we hope to do justice to this in a future article.

None of the modern studies of Brunel has paid serious attention to this aspect of his career: oddly enough, the only biography to devote a significant amount of space to his work in cast-iron is that by his son Isambard Junior. This quotes an interesting letter to one of the GWR directors, dated 18 April 1849:

> "Cast-iron girder bridges are always giving trouble - from such cases as the Chester Bridge, and our Great Western road bridge at Hanwell [i.e., the Uxbridge Road Bridge], which, since 1838, has always been under repair, and has cost its first cost three times over, down to petty little ones, which, either in frosty weather or from other causes, are frequent failing. I never use cast iron if I can help it; but, in some cases it is necessary, and to meet these I have had girders cast of a particular mixture of iron carefully attended to, and I have taught them at the Bridgewater foundry to cast them with the flange downwards instead of sideways. By these means, and having somebody always there, I ensure better castings, and have much lighter girders than I should otherwise be obliged to have. The number I have is few, because, as I before said, I dislike them, and I pay a price somewhat above ordinary castings, believing it to be economy to do so.[34]

So the Bishops Road canal bridge at Paddington was apparently a one-off design, representing a second phase in Brunel's work with this material. His earlier iron bridges, which seem to have had beams following Tredgold's thinking, have apparently all been destroyed. The Bishops Road Bridge is thus doubly unique, both in terms of its design, and as the earliest iron bridge by Brunel to survive. Its rediscovery has unlocked a previously unknown chapter in Brunel's career, though much about this remains obscure and requires further study.

Oblivion, Rediscovery, and Rescue

The canal bridge was such an inconspicuous thing that by the end of the 19th century, despite its proximity to Paddington Station, it had disappeared from memory as one of Brunel's works. It probably had a narrow escape when, in 1906-7, most of the Bishops Road Bridge was demolished as part of a major campaign of track re-alignment, and replaced in part with a 200 foot steel truss, made by Messrs Westwood of Millwall.[35] Four of the brick arches to the north of the tracks were retained, but widened with piers of engineering brick and steel beams. Four other arches adjacent to the canal bridge were replaced soon afterwards with two steel-girder spans. It is reasonable to suppose that Messrs Grierson and Armstrong, the GWR's chief civil engineers, examined the iron canal bridge and gave it a clean bill of health, though no documentary evidence for this has yet been found.

Unfortunately, the canal bridge's original railings were removed, together with the cornice on the north-west side, and replaced with much higher parapets of red brick. These were of a piece with the construction of a large new building, to house the GWR's goods offices, which was being built flanking the north-west side of the Bishops Road Bridge, immediately west of the canal bridge. A small oblong one-storey building, rebuilt at about this time on the opposite, south-east side of the Bridge, had a fine stone property-marker with the initials of the GWR and the GJCC set in its front wall. Other than this, the works marred the canal bridge's appearance, partly obscuring it from the towpath, and completely blocking any views of the canal from the roadway. This was undoubtedly a major factor contributing to the oblivion into which the bridge now fell: from road level its separate identity was blotted out, while from the canal its elevations were partly concealed and its design marred. In any case, this section of the towpath was not open to the public. So the canal bridge remained, unrecognised as a work by Brunel, until 2003.

By the 1990s, the Bishops Road Bridge, a two-lane road linking Westbourne Grove and the Bayswater area to the major arteries of the Harrow Road and the Westway, had long been a serious traffic bottleneck. The situation was becoming worse owing to a steady rise in both road and rail traffic, in and around Paddington Station, in particular after the introduction of the Heathrow Express services in 1997-8. With major redevelopments in prospect on the Paddington Goods Yard site and around Paddington Basin, and redevelopment of the northern flank of the station itself under discussion, it was clear that major infrastructure improvements were becoming an urgent necessity. A consortium of Westminster City Council, Britsh Rail, the British Airports Authority and British Waterways was formed, to address the situation, c. 1989: however, funding could not be found, and it was not until 1999 that serious planning for a new road bridge at Paddington began.[36] The existing bridge was surveyed and the canal bridge was identified as being of cast iron, and thus presenting a safety issue.[37]

Planning and designing the new bridge proved to be extremely complex: it involved demolishing and replacing a bridge over a main railway line next to one of the busiest stations in Britain; closing an important highway for two years; building over a waterway; building directly above the Bakerloo line tunnels; and diverting numerous sewers, water and gas mains and other services. As complex as this was, assembling the very large budget required proved to be yet more difficult, ultimately requiring a contribution from central government. Given these complications, it was not until 2003 that the planning works were complete, and the Paddington Bridge consortium was ready to go out to tender.[38] By May 2003 the consortium was about to sign a contract for demolition and replacement of the Bishops Road bridge, and the project timetable was fixed.

By coincidence, one of the present authors was completing a new history of Paddington Station for English Heritage, in 2002-3. At a late stage of the research the books of 'Facts' came to light in the Public

Record Office, and thus the pages relating to the canal bridge at the 'GWR Depot - Paddington' were found. Initially, it seemed unlikely that this survived, since everything that was visible from street level seemed to date from c. 1907-8, and the body of the bridge could not be viewed as the towpath was inaccessible. Nevertheless it seemed worth investigating further, and Westminster City Council were contacted in April 2003. Thus two simultaneous discoveries were made, firstly that there was a previously unrecognised iron bridge by Brunel here, and secondly that it was due to be demolished in less than a year's time. It was plain from the outset that the canal bridge could not be left *in situ*: for fundamental engineering reasons it was impossible for it to be preserved within or beneath the proposed new structure.

From Westminster City Council's side it was clear that the discovery was of real historic value and importance, the difficulty being that they had entered into a major contract with an inflexible timetable, which depended on the canal bridge being removed by May 2004. From English Heritage's point of view, it seemed unthinkable that something of this historic significance should be destroyed, but equally it was felt that to obstruct an infrastructure project of this importance would be contrary to the public interest, and might well present political difficulties. The only way forward seemed to be by confidential negotiation.

From May to December of 2003, English Heritage engaged in discussions and investigative works, with Westminster City Council, their project managers (Symonds), the main contractors (Hochtief PLC), and their consulting engineers (Cass Hayward). The bridge's structure was recorded by drawn survey and photogrammetry. Two test pits were dug in the road surface, so that the ironwork could be seen from above as well as below and its construction properly understood. The idea of sliding the bridge sideways was assessed, costed, and rejected. By September we had established that the bridge could be dismantled and had an outline cost estimate, and in October, thankfully, Westminster City Council were able to approve this. By December, a detailed method statement by Cass Hayward had been agreed, and we were ready to go. The method statement depended, in essence, on stripping the bridge to the ironwork in alternate bays, removing the iron soffit-plates, spacer plates and ties from there, and constructing steel cradles around the bays which remained *in situ*, so they could be lifted out bodily. This method allowed for a relatively swift dismantling, while leaving as much of the historic structure together as possible: it thus managed, to a remarkable degree, to reconcile the interests of all the parties concerned.

The Bishops Road Bridge closed to road traffic, as planned, on 10 January 2004. The main contractors, with Gilpin Demolition as the subcontractors, demolished the bridge parapets, broke out the road surface, and uncovered the ironwork of the two spans. In March, a public announcement was made, attracting national interest and media coverage. Public interest remained high through the following two months, with a steady stream of visitors to the site. The sections of the main 35-foot span were lifted on 31 March and 1 April, and the 16-foot span sections on 15 April (Fig. 15). The bridge came apart very cleanly: the only elements which had to be cut were the tie-rods. As is noted above, the transverse beams seem to have been the weak point of the design, and a number of them were found to be broken when uncovered: they should, however, all be repairable. Indeed, every single piece of the original ironwork should be re-useable. The Portland Stone cornice sections have also been salvaged, as have over 15,000 stock bricks. All this material, at the time of writing, is being stored by English Heritage at Fort Cumberland, near Portsmouth, as one of their contributions to the project.

At the time of writing, a site for reconstruction of the bridge has been identified about 200m along the canal from the original site, next to a bridge carrying the Harrow Road. British Waterways and Westminster City Council are developing a project for Brunel's iron bridge to be rebuilt, as close to its original design as possible, as a pedestrian footbridge, housing a shop or a cafe, and facilities for canal-

Figure 15. Lifting out the first pair of girders, 31 March 2004. (Malcolm Tucker)

boat users, in the abutments. Work is in progress to raise funds for this.

For Brunel, the Paddington canal bridge was a one-off challenge, where severe site constraints pushed him towards the use of cast iron. Despite the bridge's modest size, its unique design, and the documentary evidence for Brunel's design and testing of it give it great historic interest and value. We very much hope that the partnership between Westminster, British Waterways, and English Heritage, which has saved the bridge from destruction, will succeed in reconstructing it, and restoring this 'lost' work by Brunel to the public.

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3. Ibid. Chapter 2.

4. The National Archives, Public Record Office (henceforth PRO), RAIL 1149/4, I.K. Brunel, letter book iii.1838 - xi.1838, pp. 82-3.
5. Ibid., pp. 95-6.
6. PRO, RAIL 830/6, Board Minutes of the Grand Junction Canal Company, 1835-8, pp. 293-4.
7. PRO, RAIL 250/82, GWR Board Minutes, 6.vii.1837.
8. PRO, RAIL 1149/44, GWR Tenders, p. 35.
9. London Post Office Directory, Commercial Section; Pigot's Directory; N. Dews, *History of Deptford,* (2nd edition, 1884), pp. 234-7, 250, 271, 274.
10. Institution of Civil Engineers Library, Trevithick Collection. We are very grateful to Mr Mike Chrimes for telling us of the drawings' existence.
11. PRO, RAIL 1149/8-13, books of 'Facts'.
12. PRO, RAIL 1149/9, pp. 96-7.
13. Obituary memoir of Joseph Colthurst, *Minutes of Proceedings of the Institution of Civil Engineers,* Vol. 73 (1883), pp. 356-8.
14. PRO, RAIL 1008/35. We are very grateful to Mr David Greenfield for passing this reference on to us.
15. The narrowing was already shown on Brunel's sketch layout plans for the terminus made around 1837, see Tutton, op. cit., figures 14 and 15.
16. The dimensions are quoted from Trevithick's set of drawings and ignore slight as-built variations due to constructional tolerances. Recent measurements found the water level now 0.1m higher.
17. It must be largely a coincidence that the cross-sectional form superficially resembled the tubular-flanged wrought-iron girders that Brunel developed ten years later, as in the Cumberland Basin swing bridge at Bristol of 1849, since the mechanical principles and materials involved were so different. See R. Cragg (ed.), *Civil Engineering Heritage, Wales and West Central England,* (2nd edition, 1997), p. 123.
18. S.C. Brees, *Railway Practice* (first series, 1837), plates 4,5, 38. They were also sketched while under construction by G. Scharf, as reproduced in P. Jackson, *George Scharf's London,* (1987), pp. 134-5.
19. Sketched by George Scharf, reproduced in Jackson, op. cit., p. 138.
20. We are very grateful to Mr R.J.M. Sutherland for his help and advice in this area.
21. T. Tredgold, *Practical Essay on the Strength of Cast Iron,* (1822) and second edition (1824).
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25. R.J.M. Sutherland, 'Iron Railway Bridges', in M. R. Bailey, ed., *Robert Stephenson - The Eminent Engineer* (Aldershot, 2003); and see above, n. 18.
26. The one major exception is that by his son: I. Brunel, *The Life of Isambard Kingdom Brunel,* (1870), pp. 190-2.
27. The iron bridges on the GWR have never received serious study, and we are not yet sure how many there were. We have documentary evidence for under-line bridges over the Uxbridge Road and two over the Grand Junction Canal in West London, discussed below, and others subsequently over the Wilts & Berks Canal at Ardington and Woolstone in Berkshire, and at Swindon in Wiltshire: PRO, RAIL, 1149/13. The cast-iron footbridge which still spans the main line, at Sydney Gardens in Bath, can now be confidently attributed to Brunel and dated to 1840-41: PRO, RAIL 1149/6, I.K. Brunel,

letter book iii 1840-x1841, pp. 209-10.Ongoing research has identified several former bricle-arched underbridges of circa 1840 that had cast-iron "trough girders" built into them, on the GWR main line, and a considerable number of cast-iron girder bridges and aqreducts, mostly over-line, that were built for some of Brunel's later railways.

28. PRO, RAIL 1149/9, pp. 98-9.
29. The Grand Junction Canal, later the Grand Union Canal, was begun in 1793, and its first section, from the Thames at Brentford to Uxbridge, opened in 1794. The canal was opened for its full lengt (to Braunston, Warwickshire) in 1805, but by that time the Paddington branch had been built from Bull's Bridge to Paddington Basin, c. 1795-1801. A.H. Faulkner, *The Grand Junction Canal* (Newton Abbot, 1972); Ordnance Survey, 1 inch to 1 mile, 1st edition, sheet 7 (1822).
30. PRO, RAIL 1149/44, GWR Tenders. This volume contains summaries of the tender prices for contracts for the GWR main line: it covers much of the work from Paddington to Bristol. The contract for the Uxbridge Road bridge (2L), and that for the line from 'Paddington canal to Field Number 1, Iver', which would seem to include these two canal bridges, were both awarded to Grissell & Peto, and both include unit prices for cast-iron work. PRO, MT 8/1, Returns of Iron Railway Bridges, 1847, gives details of the canal bridges but has no entry for the Uxbridge Road Bridge, which had been damaged by fire in May of that year: Brunel made his return in September, and in due course he rebuilt it with wrought iron box girders. Given the reason for the 'Returns' being compiled in the first place, for Brunel to have omitted the bridge on these grounds seems singularly disingenuous, not to say unhelpful !
31. PRO, RAIL 1149/2, I.K. Brunel, letter book vii 1835-viii1838, pp. 241, 278.
32. Ibid., pp. 192-7.
33. PRO, RAIL 1149/13, pp. 62-87, 90-95, 98-107.
34. I. Brunel, 1870, op. cit., p. 190.
35. S. Brindle, op. cit., p. 140; Anonymous article, 'The engineering department - Bishop's Road Bridge,' in *GWR Magazine*, February 1908, pp. 39-40.
36. Information from Mr Graham King, Department of Planning and Environment, Westminster City Council: pers. comm.
37. Hyder Consulting Ltd., Bishops Bridge Detailed Assessment, 1997. At this point, a 10-ton weight restriction was placed on vehicle traffic using the bridge.
38. Personal communications from Mr Graham King and Mr David Ferrett, Westminster City Council.