

## APPENDIX 2<sup>1</sup>

### WILLIAM GRAVATT AND THE GWR BRIDGES

Just one month before the first GWR Bill was thrown out of the Lords on 25 July 1834, Gravatt stated that Brunel had been employing him 'for some time ... in making Calculations for the Great Western Railway,' without actually specifying what those 'calculations' related to.<sup>2</sup> Later, in a printed letter to the B&ER shareholders he made the following explicit claim:

I drew up the contracts, and designed all the bridges and culverts, and 'things of that kind,' on the Bristol and Exeter Railway, as I had before done on the greater part of the Great Western.<sup>3</sup>

This Appendix investigates evidence relating to the extent of Gravatt's involvement in the design of the GWR, and the design of GWR bridges in particular, during two phases: firstly, up to the rejection of the first GWR Bill and, secondly, from that time up to July 1836 when Gravatt was appointed Resident Engineer on the B&ER.

Brunel kept two office diaries in 1834, one of which is a sporadic series of brief, disjointed entries – in effect, memoranda of appointments and topics.<sup>4</sup> The other diary is a daily record of his engagements and the projects in which he was occupied, with expences and payments apportioned to each project, no doubt as an aid to invoicing clients.<sup>5</sup> The parliamentary survey for the GWR was deposited on 30 November 1833 and the GWR's London Committee authorised Brunel to 'commence the requisite borings and other examinations required to verify the estimates in Parliament' on 16 January 1834; consequently, his engagement diary entries after mid-January 1834 relate predominantly to GWR matters. On 22 March he recorded in his engagement diary that he was out on GWR business with James Walker, 'on the entrance to London,' whereas in the memo diary there is a cryptic entry: 'Walker at 9 o'clock – Gravatt – Bridges – culverts – Docks.'<sup>6</sup> Six days later his engagement diary records he took a chaise to

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<sup>1</sup> Adapted and expanded from a lecture given by the present writer to the Institution of Structural Engineers' History Study Group on 11 December 2006.

<sup>2</sup> TNA/PRO RAIL 1066/1718, evidence taken before the Lords Committee on the London and Southampton Railway Bill, William Gravatt, 21 Jun 1834, p.297.

<sup>3</sup> Gravatt W., Letter (1841), present writer's emphasis.

<sup>4</sup> BUL DD 1834/1, Brunel's Office Diary.

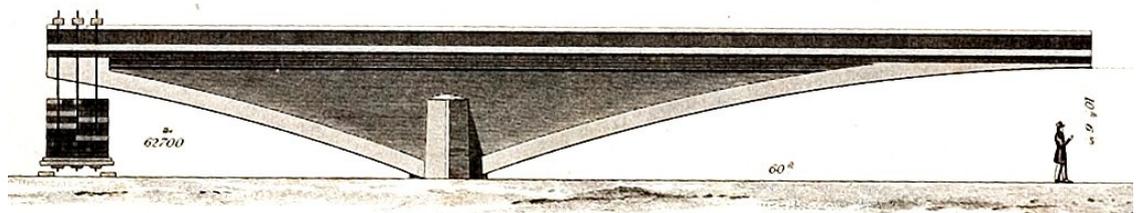
<sup>5</sup> BUL DD 1834/2, Brunel's Office Diary.

<sup>6</sup> BUL DD 1834/1, Brunel's Diary, 22 Mar 1834; BUL DD 1834/2, Brunel's Diary, 22 Mar 1834.

Maidenhead where he was 'engaged on borings &c,' while he noted in his memo diary, 'Jas. Walker – viaduct sections &c – Maidenhead Bridge – List of small bridges.' The following day he recorded in the memo diary, 'Kennet river Bridge – Bath & Bristol sections – Windsor line – Stephenson – Gravatt.'<sup>1</sup> Evidently Gravatt was indeed occupied in GWR matters at that time; James Walker's role has not been established. As the GWR Bill was still going through the parliamentary process at that time, at first sight it seems unlikely that Gravatt, or anybody else, would be involved in the detailed structural design of GWR bridges at such an early stage. Even so, Marc Brunel recorded in his own diary that he was himself engaged on 'the Via-duct across the Brent' for all or part of eleven days between 14 March and 17 April 1834.<sup>2</sup> The Brent viaduct was the nearest major GWR structure to London and hence Brunel had intended that its construction would be the first contract to be let after the Bill was passed.

Marc had been experimenting with reinforced brickwork for more than two years, 'to demonstrate the practicability of forming arches with cheap materials and by very economical means,' and it is possible he felt that the Brent viaduct would be a timely opportunity to demonstrate the practicability of his system. He had began building what he called an 'Experimental Arch' at the Thames Tunnel Company's premises at Rotherhithe in May 1832. More accurately, he was building a pair of brickwork balanced-cantilever ribs with arched soffits, reinforced with lengths of hoop iron and timber laths. He ran out of space at one end when the cantilevers reached 36ft. and continued the construction at the other end by balancing the structure with cast-iron

Figure A2.1 Marc Brunel's 'Experimental Arch' in its final form



Source: Steve Hurst collection, undesignated lithograph, 'Elevation of two semi-arches constructed of brick,' undated [c.1835].

<sup>1</sup> BUL DD 1834/1, Brunel's Office Diary, 22,28,29 Mar 1834; BUL DD 1834/2, Brunel's Office Diary, 22,28,29 Mar 1834.

<sup>2</sup> ICE TT/BD/1834, Marc Brunel's Diary, 14 Mar – 17 Apr 1834 passim.

kentledge; in its final form in 1835 it cantilevered 60ft. and had a rise of 10ft. 6ins.<sup>1</sup> John Hammond supervised the work until the spring of 1833, from which time it seems Brunel 'borrowed' him from Marc to assist with the GWR survey.<sup>2</sup>

At various times Marc prepared speculative designs for long-span arch bridges employing his reinforced brickwork system:

... by carrying across the river or road two ribs, similar to the experimental arch, which must be gradually advanced from the piers or abutments until they arrive at the central space left for the key-stone ... when they are properly adjusted, the key stone is to be fixed ... when that is done, the counterbalance weights may be removed. After one rib is carried across, the work is to be extended, by adding a nine-inch rim of brickwork set in cement on each side of the rib, which will, on account of the adhesive qualities of the cement, unite very firmly to the first rib that was carried over. When one rim is thus completed, another rim is added, and so on until the intended width of the bridge is completed ... Centering is wholly dispensed with, and the curvature of the arch is obtained by means of a face-mould or sweep.<sup>3</sup>

He recorded two expressions of interest from the promoters of civil engineering schemes during early 1833 – one for the Greenwich Railway project and another for a bridge across the Wear in County Durham – but neither application came to fruition.<sup>4</sup> No evidence has been found that links Gravatt to Marc's 'arch' experiment or 'engagement' on the Brent viaduct. Under the circumstances it seems most likely that any 'calculations for the Great Western Railway' carried out by Gravatt before the rejection of the first GWR Bill by the Lords Committee on 25 July 1834 related to the general railway alignment and the preparation of estimates, rather than to detailed structural design.

Having assisted with the parliamentary survey for the Merthyr and Cardiff Railway in November 1834 there is a hiatus in the evidence relating to Gravatt's professional activities until Brunel engaged him as the 'Third Resident Engineer' on the GWR in October 1835 to:

... superintend under me the making the designs and drawings which would otherwise have occupied the respective engineers in whose division the works occurred.

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<sup>1</sup> ICE TT/BD/1832-1835, Marc Brunel's Diaries, 1832-1835 passim; BUL DM 1306 I.4, 'General Remarks,' p.140, undated [c.1835]; Beamish R., op.cit., pp.284-287; Steve Hurst collection, undesignated lithograph, 'Elevation of two semi-arches constructed of brick,' undated [c.1835].

<sup>2</sup> ICE TT/BD/1832-1833, Marc Brunel's Diaries, 1832-1833 passim; Vaughan A., Brunel (2006), op.cit., pp.87-90.

<sup>3</sup> Civil Engineer & Architect's Journal Vol.1, No.6 (Jan 1838), pp.119-120.

<sup>4</sup> ICE TT/BD/1833, Marc Brunel's Diary, 15 Feb, 25 Mar 1833.

Gravatt continued in this post up to July 1836, and his later claim to have drawn up the contracts, and designed all the bridges and culverts 'on the greater part of the Great Western,' clearly relates to this nine month period.

Brunel's report to the GWR Directors on 26 May 1836 gives a good indication of progress to date on the contracts that were then underway at the London end. Six contracts had been let, including those for the Brent viaduct and the Maidenhead bridge. One abutment and several piers of the viaduct were in a 'forward state'; the contractor for the Maidenhead bridge was just about to start work. Brunel noted that:

The preparations for the Contacts beyond Maidenhead are very forward and I have reason to hope that the necessary Drawings and Specifications for the whole of the Line to Reading will be completed by the end of June.

In a subsequent report he stated that three contracts were under way between Bristol and Bath which included three tunnels and two large bridges.

William Bell, who wrote the chapter on railway bridges and viaducts in I. Brunel's biography of I.K. Brunel, had this to say about the 'early days' of the GWR:

Special designs were made for every one of the ordinary bridges over and under the railway; but when, in consequence of the rapid extension of the Great Western system, the number of bridges to be designed became very large, Mr. Brunel had a set of 'standard drawings' prepared and engraved, which embodied the experience gained, and contained designs suitable for various situations ... The standard drawings being based upon the results arrived at in an extensive practice, the proper structural arrangements and dimensions were indicated with far greater accuracy than could be attained in a reasonable time by an independent calculation in each individual case.<sup>1</sup>

The term 'ordinary bridges' almost certainly referred to the great preponderance of unremarkable bridges such as those over and under turnpike roads, parish roads, accommodation roads and the like. There is evidence to suggest that Brunel settled the basic form of these bridges, in terms of aesthetics, the arch intrados profile and the span, but notably not arch thickness, by early January 1836: his early sketch elevations of the road bridges at the London and Bristol ends of the line are dated between 24 December 1835 and 1 January 1836.<sup>2</sup> It therefore appears highly probable that Gravatt superintended the structural design of these 'ordinary' bridges from that time.

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<sup>1</sup> Brunel I., op.cit., p.172n, present writer's emphasis.

<sup>2</sup> BUL SB 1835, Brunel's GWR Sketchbook, 24 Dec 1835 - 1 Jan 1836, pp.78-90 passim.

There is much less certainty in the case of the major, or 'extra-ordinary,' bridges. It is clear from Brunel's parliamentary evidence during the second GWR Bill proceedings in June 1835 that the final form and dimensions of the major bridges had not been settled by that time. For example, when he tabled drawings for the Brent viaduct and the bridges over the Colne, the Slade, the Thames at Maidenhead and the Avon at Bath, he commented:

... none of those drawings were made for show; they were mere outlines and working drawings to form my estimates upon and not for appearance ... sufficient to give all the information but not to produce any effect.<sup>1</sup>

Moreover, he noted differences between the span arrangements as shown on the tabled drawings and as he now proposed. The Brent viaduct (alias Wharncliffe Viaduct) and Maidenhead Bridge will be examined in detail, as more evidence has been found concerning the development of their designs than for the other major bridges.

In June 1835 Brunel stated that the Brent viaduct would have nine arches of 60ft. span.<sup>2</sup> His earliest sketches of the viaduct to have been found are dated 14 July 1835. They comprise two elevations of semi-elliptical arches of 60ft. span and 18ft. rise, and one unfinished sketch of two circular segmental arches of 60ft. span and 10ft. rise.<sup>3</sup> The next tentative sketches and some accompanying calculations, dated 2 August, relate to the foundations of a viaduct with spans of 70ft.<sup>4</sup> Two more pages of sketches, dated 9 and 11 August, show various arrangements for the centering of a semi-elliptical arch of span 70ft. and 18ft. rise.<sup>5</sup> As with the sketches of the 'ordinary' road bridges, the aesthetic form rather than the structural form was Brunel's main interest – the arch barrel is never shown in longitudinal profile and there is no mention of the arch thickness. On 27 August Brunel sketched the details of an unusual lightweight cellular brickwork pier foundation.<sup>6</sup> Less than one month later, on 22 September Marc recorded in his diary, 'Gave directions for the construction of the Experimental Pier required by Isambard for his high viaducts.'<sup>7</sup> The experiment was the test-to-destruction of a reinforced brickwork structure which Marc called 'the Experimental Pier' or 'the Experimental Foundation.' The 'pier' was in fact a 25ft. long brick wall, 4ft. high and 2ft. 7ins. wide at the base

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<sup>1</sup> TPA HL/PO/JO/10/8/1116, evidence taken before the Lords Committee on the GWR Bill, I.K. Brunel, 26 Jun 1835, p.9.

<sup>2</sup> Ibid, p.114.

<sup>3</sup> BUL SB 1835, Brunel's GWR Sketchbook, 14 Jul 1835, pp.54, 55.

<sup>4</sup> Ibid, 2 Aug 1835, p.56.

<sup>5</sup> Ibid, 9,11 Aug 1835, pp.57, 58.

<sup>6</sup> Ibid, 27 Aug 1835, pp.63, 64.

<sup>7</sup> ICE TT/BD/1835, Marc Brunel's Diary, 22 Sep 1835, emphasis as in the original.

narrowing to 1ft. 7ins., supported at its ends and loaded at the centre; the bottom six courses were reinforced with hoop-iron strips.<sup>1</sup> The loading test was still in progress during the tender period for the construction of the Brent viaduct – one of the tender drawings<sup>2</sup> shows the foundation arrangement to be generally as sketched by Brunel on 27 August and that it was structurally similar to the 'pier' tested by Marc. In late November several contractors refused to submit unqualified tenders for the foundation as-drawn, and it appears that Brunel did not use this foundation system either here or elsewhere.<sup>3</sup> No mention of Gravatt by name has been found in the records of Brunel or his father during this period, but it is perhaps significant that Brunel had re-engaged him in early October, very shortly after he had settled the form of the Brent viaduct.

In the case of the Maidenhead bridge, Brunel was reported to have stated on 25 June 1835 that the bridge was to have two main arches of 80ft. span over the Thames and two spans of 40ft. on each approach over the meadows. The following day he tabled a drawing of the bridge and told the Committee:

I should wish to correct an answer I find in the short hand notes of yesterday. I perceive with respect to Maidenhead Bridge my answer is that there were two arches of 80 feet – whether I said two or not I do not remember – it ought to be three.<sup>4</sup>

The earliest drawings of the bridge found during this study are six sketches dated 24 February 1836 which show the elevation of a two-span bridge. The elevations are little more than tentative outlines of circular segmental and semi-elliptical arches with spans between 130ft. and 150ft.<sup>5</sup> A week later Brunel started on a more purposeful approach.

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<sup>1</sup> Brunel M.I., 'Particulars of Some Experiments on the Mode of Binding Brick Construction' Transactions Institute of British Architects of London Vol.1, Part 1, (1836), pp.61-65.

<sup>2</sup> Reproduced in: Brindle S., Brunel: The Man Who Built the World (2005), pp.116-117.

<sup>3</sup> On 25 November 1835, the day before tenders for the viaduct were due to be opened, Brunel was told that several of the contractors who would otherwise tender for the contract objected to:

... your System of preparing or forming the Foundations of the Viaduct, & decline to become responsible for the soundness of the Work. One Builder of great eminence will put in a qualified Tender - he will execute the Work according to your Plan for a certain Sum, not guaranteeing the work, but he will do it, on his own Plan for so much less, guaranteeing it for 24 instead of 12 months:

Charles Saunders to Brunel, 25 Nov 1835: BUL DM 1758.

<sup>4</sup> TPA HL/PO/JO/10/8/1116, evidence taken before the Lords Committee on the GWR Bill, I.K. Brunel, 25 Jun 1835, pp.118-119; *ibid*, 26 Jun 1835, p.3.

<sup>5</sup> BUL GWR SB 1836, Brunel's GWR Sketchbook, 24 Feb 1836, pp.10-11. He gave his reasons for the change from three to two spans in a peevish letter to the Thames

To begin with he set out his design parameters – the height of the rails above tow-path and river level, and the width of the waterway which he had measured as 436 Gunter links (287ft. 9ins.) and rounded down to 280ft. He next sketched two-span arrangements with spans between 122ft. and 130ft. and with varying central pier widths, all based on a waterway width of 280ft. He then tinkered with various intrados profiles – circular segmental, slightly pointed and semi-elliptical – and various architectural effects and ornamentation, before settling on a semi-elliptical profile.<sup>1</sup> Again, the arches in these eight sketches were always shown in elevation, never in longitudinal or transverse section. None of the arches has exactly the dimensions usually quoted for the finished bridge, namely 128ft. spans and 24ft. 3ins. rise, nor its architectural features; the final sketch dated 4 March 1836 showed spans of 125ft. with a rise of 25ft.<sup>2</sup> Construction of the bridge was just about to commence in late May 1836, while Gravatt was still in post as 'Third Resident Engineer.'

Professor Owen has stated that the underlying principles and assumptions made by Brunel in his designs for arch bridges can be largely inferred from a series of undated strength calculations relating to the Brent viaduct, the Maidenhead bridge, Thorney Broad Bridge and the Avon bridge upstream of Netham weir in Bristol, which are contained in Brunel's 'general calculation book.'<sup>3</sup> However, those calculations are not in Brunel's hand, they do not appear to be works-in-progress, and they must have been entered into the book after all the structural details had been settled, as the outline drawings of the arches, on which thrust lines have been constructed, are identical to the outlines as they appear on the contract drawings, even to the extent of showing details that would not have been determined at the time that calculations aimed at designing and refining the arch profile and thickness would need to be carried out. That the

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Commissioners in August 1836, in which he listed the several measures he had taken to 'ensure the security of the navigation during the construction of the bridge – and at considerable expense':

I have done that which I suspect I will be severely criticised for, namely, made a two-arch bridge for the purpose of throwing the only pier required on an existing island:

Quoted in: Clifford D., *op.cit.*, p.137. I. Brunel noted that, 'in the middle of the stream there is a small shoal, of which Mr. Brunel took advantage of building the centre pier': Brunel I., *op.cit.*, p.173.

<sup>1</sup> BUL GWR SB 1836, Brunel's GWR Sketchbook, 4 Mar 1836, pp.14-16.

<sup>2</sup> TNA/PRO RAIL 252/180, contract documents for GWR Contract 6L, 'Maidenhead Bridge over the Thames,' undated [circa May 1836].

<sup>3</sup> BUL DM 162, Brunel's 'General Calculation Book,' pp.1-18 *passim*, undated [circa Dec 1835]; Owen J.B.B., 'Arch Bridges,' in: Pugsley A. (ed.), *op.cit.*, p.96.

calculations are not in Brunel's hand does not of itself prove that the original calculations were not carried out by Brunel, of course; they could well be fair copies of original calculations that had been made by Brunel himself or an assistant, and show merely the final stage of the calculations, omitting earlier trials. On the other hand, they could just as well be calculations that were made after all the details of the structure had been determined, in other words as part of an analysis of the structure as-drawn for the contract. Brunel would have directed the making of the calculations even if he did not actually carry them out himself, and in that capacity he would have made certain that his policy of maintaining equilibrium by ensuring that 'all forces should pass exactly through the centre of any surfaces of resistance' would be adhered to.<sup>1</sup>

To summarise, despite no evidence having been found that directly links Gravatt to any of the GWR bridges, be they large or small, there can be no reason to doubt his claim in respect of the design of the 'ordinary' bridges on the GWR. It is highly probable that he also carried out the routine calculations for long-span bridges, at least up until mid-July 1836: he was in the right position at the right time, and he certainly had the necessary skills.

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<sup>1</sup> Brunel to unnamed assistant, 30 Dec 1854, quoted in Brunel I., op.cit., p.178. In 1852 Brunel wrote to a Swiss correspondent that the curve of the arch of Maidenhead Bridge was:

... intended to be such that with the superstructure and a certain adjusted weight of railway ballast and with the weight of trains, it should be in perfect equilibrium; and should you build a large brick arch I should recommend your satisfying yourself on that point by your own calculations ... as the result of my experience is to attach great importance to the perfect equilibrium of all the parts of such works:

Brunel to N. Stehlin, 7 Jan 1852: BUL PLB 8, emphasis as in the original.