

Centres for Large Span Masonry Arch Bridges in Britain to 1833

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The construction of arch bridges requires the provision of temporary works. For structures with piers in water, some means of ensuring adequate bearing under the piers is called for. Where individual stone blocks or other components are beyond the capacity of the workpeople to handle, transport and lifting devices must be provided. Occasionally, more sophisticated items such as diving bells might be used to deal with situations where conventional means are not adequate. However, in all cases centring to support the voussoirs is needed.

A centre is a frame or set of frames, almost invariably in timber, that provides support for the archstones of a bridge before the keystone is set in place and the arch becomes self-supporting. It must be sufficiently strong not only to prevent the premature collapse of the arch but also to ensure that any deformation which occurs before or after striking is kept within acceptable limits. In navigable water, or rivers subject to spate, adequate space must be left for the passage of boats, flood water or large floating objects carried by the current. Finally, it should be capable of being removed easily and safely and in such a way that the materials may be used again.

Falsework, which could rest directly on the ground or be piled in rivers or poor ground conditions, supported frames of either single or multiple trusses. A frame was usually set under each external face of the arch with the other frames dividing equally the space between. The distance between the frames appears typically to have been in the range 4 feet to 7 feet. On top of these were placed rim-pieces or fellies whose top faces, curved to the profile of the intrados of the arch, supported battens or lagging on which the arch stones were placed.

The number of centres required for multi-span bridges changed. In early structures the out-of-balance force on a pier by having an arch built on one side but not the other was absorbed by having piers of adequate width. As piers became more slender, partly for aesthetic reasons and partly to reduce the materials cost of the permanent works, it became necessary to build at least one pier ahead and to provide a centre between that and the arch under construction. At Perth in 1765, where the span: pier thickness ratio was 4.4:1, Smeaton proposed props between the second and third piers while the centre from the first arch was being taken down and transferred to the second. At Pont de Neuilly, Paris in 1768, where the ratio was 9.1:1, Perronet provided centres under all five arches.

Arch bridges have been built in Britain possibly from Roman times, when some significant structures along Hadrian's Wall are suggested (Bidwell & Holbrook 1989). Engineering drawings of

these early structures do not survive though the ten volumes on architecture by Marcus Vitruvius Pollo (translated into French by Fleury and English by Morgan) contain descriptions of bridgeworks. By definition, the temporary works have been removed, so apart from the information given in Vitruvius it is only possible to suggest construction techniques by detailed study of the remaining bridges themselves. For the Roman Empire, O'Connor (1993) lists 330 such structures, with spans up to 35 m, and from them proposes methods of dealing with the superstructure. Many of the types of tool in use then survived almost unaltered until quite recently.

It is not clear why the practice of building stone bridges died out in Europe with the collapse of the Roman Empire, or why they should have reappeared in several countries at more or less the same time. It is not unreasonable to assume that much of the knowledge had remained with the masons responsible for structures such as cathedrals and churches and that a revival of the religious obligations to travellers, new notions of temporal power and the expansion of trade provided the impetus for construction of more permanent structures than the timber bridges of the intervening centuries. In Britain this renaissance dates from at least the late 11th century (Harrison 2004, p. 110). Almost all of the 'vernacular' bridges of the midlands and south of England over the next 600 years are of moderate span, the first one having a span in excess of 50 feet being built at Lewes in 1727. However in the north of England structures of this span appear from the 1350s and in Scotland a century later. By the middle of the 16th century a few spans had reached 100 feet, as much as any remaining Roman bridge. From then to 1738 only the Great Bridge at Blenheim and the Causey Arch in County Durham were of similar span. In the next 110 years only 22 bridges with spans greater than 100 feet were built, but the largest, Grosvenor Bridge at Chester (built in 1827-33), spanned 200 feet and was for thirty years the largest in the world.

Before 1738 most bridges in Britain were constructed for county Quarter Sessions under design-and-build contracts (Chalklin 1998, p.78), in which the surviving records make no reference to the methods to be adopted. More is known about continental practice, from texts such as Leupold (1726) and Gautier (1728). In France, from the time of Hardouin-Mansard, possibly at Pont Royal, Paris (1685-7) but certainly Moulins (1706), flexible centres were used, consisting of framing pieces normal to the intrados, at perhaps 10 ft spacings along the arch, into which the longitudinal members were slotted. The joints at the framing pieces allowed movement and it was therefore necessary to load the crown of the centre to prevent upward movement as the voussoirs were laid on the haunches. Apart from being time-consuming and expensive, it was difficult to predict the resulting movement. The best known example was by Perronet at Neuilly, described by him in his publication of 1783. Sganzin (1839-41, p. 147) suggests that flexible centres were no longer much used. British practice seems always to have favoured a rigid, or 'fixed' centre (Newlands, p. 172), more or less unyielding under the differing load conditions as the masonry is built up from the springing to the crown.

In Britain, the first bridge to be the subject of a publication was Westminster Bridge (1738-50), built under an Act of 1736 that was only obtained after a prolonged battle in Parliament. The client was a commission of about 175 public men and it was financed by a state lottery and grants. There was intense interest and controversy about the form of the bridge, with economical proposals for a wooden bridge being scorned as unworthy of the capital; it took two years for a decision in favour of stone piers and then a further year and a half to agree on masonry arches. The work was let as a series of more than 90 contracts and bonds, including those with James King for the centres for the arches (Walker 1979, pp. 285-9). In order to defend himself against the criticisms of disappointed rivals, the Engineer of the bridge, Charles Labelye (1705?-53) published two accounts of his work, the earlier of which contains watercolours by Thomas Gayfere the elder, the masonry contractors' foreman on the works (**fig. 1**).

Labelye was Swiss, of French Huguenot parentage and a member of a French masonic lodge in London; he had travelled on the continent, and was familiar with the writings of French engineers such as Beldidor (Skempton 2002, p.389). Although attributed to King, the centres display elements of French practice such as the individual battens beneath each course of voussoirs. Against this, the falsework is supported partly by piles in the riverbed and are thus more widely spread than those used in France, which tended to be carried by the footings of the bridge piers. Although the latter could pose problems in erection, it had the benefit of transferring the load of the arch to the piers as construction proceeded, rather than relatively suddenly as the centres were removed. Also the centre is more rigid, which was thought by later writers to have been traditional British practice. It is interesting to note that the Mathematical Bridge, designed by William Etheridge and built in 1749-50 in the grounds of Queens' College, Cambridge bears a striking similarity to King's centre at Westminster.

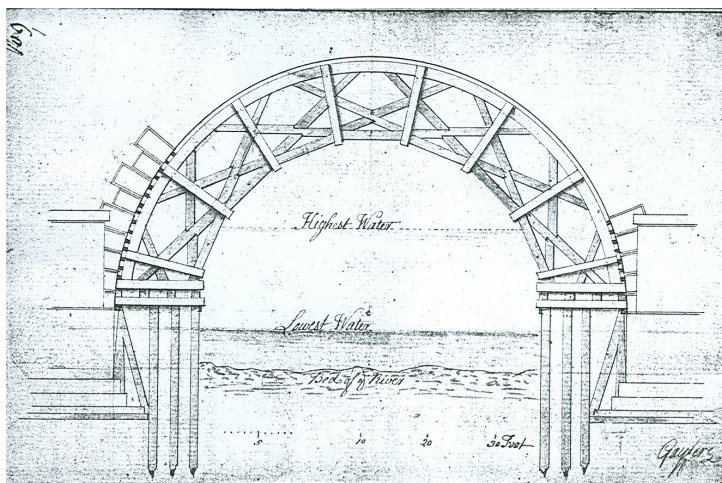


Figure 1. James King's centre for an arch of Westminster Bridge (Labelye 1739)

Unfortunately no drawing by King or Labelye exists to show how the centres were intended to be struck. It appears from the commissioners' records that the centre of the west 68 ft arch was erected in 1742, but that an order for cast iron circular wedges designed by King was not placed until two months later; that is, there were no wedges built into the falsework as it was being erected. It would seem therefore that the wedges were meant to be screwed into the space between the two sills at the head of the piles, forcing them apart and allowing the cross-pieces between them to be withdrawn; the wedges could then be unscrewed and the centres would ease down. It is difficult to see how such wedges could exert enough force between the pre-loaded piles and the weight of the arch to prise the sills apart; perhaps they were meant to gouge out enough of the cross-pieces so that they would collapse when the wedges were withdrawn. Whatever the method, it proved unsatisfactory and Labelye, with advice from William Etheridge, King's foreman, substituted straight wedges in future centres. If a drawing done later by an employee of Etheridge and given to John Smeaton was accurate in this respect (and it shows seven ribs in the centre rather than the correct five), it must have been fabricated *insitu*. The method was so successful that Labelye claimed that decentring took only one hour.

For the next new bridge over the Thames in London, Blackfriars Bridge (1760-9), the architect/engineer Robert Mylne used centres (**fig.2**) that on first impression were similar to Westminster. However, inclined props on a more widely spread base acted as falsework, thus removing the need for temporary piles, although some bracing must have been necessary to prevent the props falling over before the centre was complete above them. On top of the props, and between the tides, were placed folding wedges to support the centres. The drawing in Baldwin (1787) and the well known engraving by Piranesi shows that, as at Westminster, the voussoirs were carried by battens only. Access to the crane mounted at the apex must have been rather precarious.

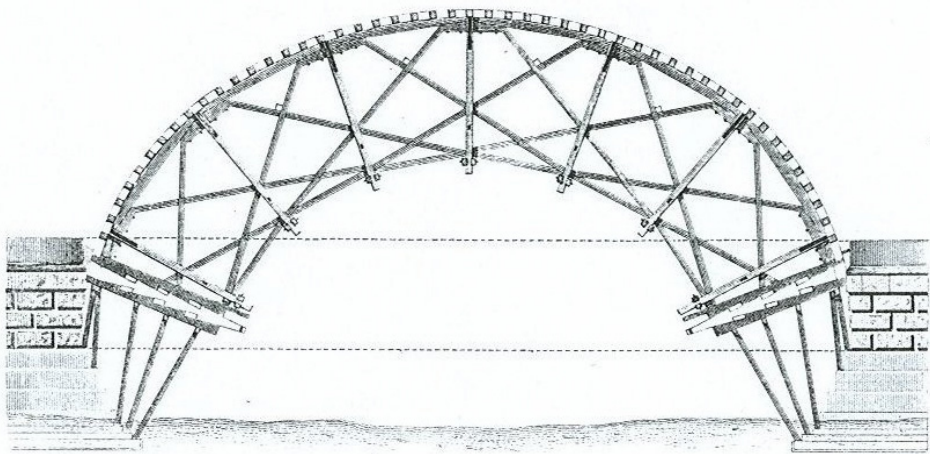


Figure 2. Centre for Blackfriars Bridge, London (Newlands 1869)

Meanwhile in Wales, William Edwards (1719-89) had built the longest span yet attempted in Britain, Pont-y-pridd. The successful structure was his fourth attempt. The first had been undermined by scour after standing for two years but the second had collapsed when the centring failed under it. Robert Mylne's son possessed a model of the centring for the final attempt in 1755-56, from which the sketch in Figure 3 was made. (The plaque with the incorrect date still exists). Because the River Taff was not navigable it was possible to build conventional scaffolding, presumably on piles, though nothing is shown below springing level. Smith (1838, p. 6), in his memoir to the Institution of Civil Engineers, commented that he had not been able to learn how it was struck, or any other particulars relative to the construction. It would certainly have provided a rigid base on which to build, though the radial props immediately below the lagging seem to owe more to the carpenter's art than a knowledge of the disposition of weight.

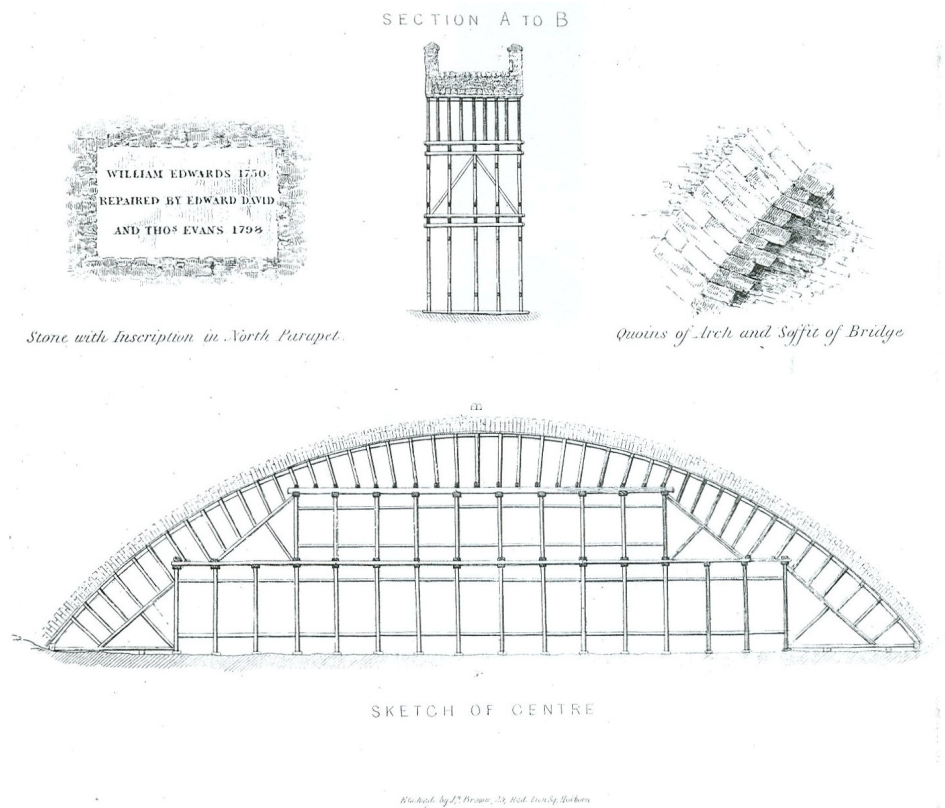


Figure 3. Centre for Pont-y-pridd (Smith 1838)

The leading engineer of the latter part of the 18th century was John Smeaton (1724-92), who built four large bridges over major rivers, as well as some lesser ones. In each of the former cases he was able to pile into the river, though the spacings between the rows could be as much as 17 feet

compared with about 7 feet at Pont-y-pridd. For the first two of these bridges, at Coldstream (1763-7) and Perth (1766-71) (**fig.4**) he designed a king-post truss supporting radial props and rim-pieces, though because at Perth the spans ranged up to 75 feet, compared with just over 60 feet at Coldstream, the alignment of the bracing in the truss and the size of the members differed between the two.

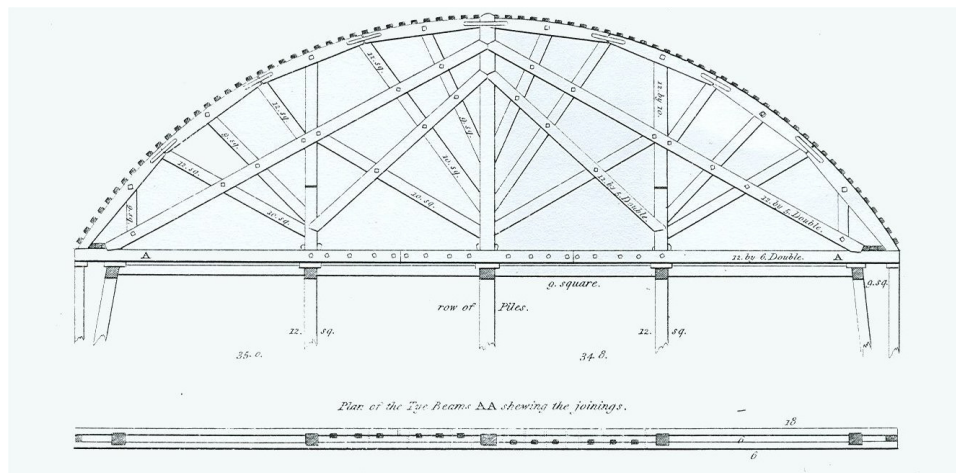


Figure 4. Centre for Perth Bridge (Smeaton 1812)

For the other two, Banff (1772-9) (**fig. 5**) and Hexham (1777-80) Smeaton conceived a much simpler structure, though it required more timber that is shown in his drawing to ensure stability during assembly. He assumed that the carpenter would be able to do this without further instructions. Clearly aware that the voussoirs at the haunches carried part of the weight of the next above but those near the crown were supported almost entirely by the centre, he introduced struts (D in Figure 5) to divert some of the weight of the crown away from the central pile row. Ever mindful of economy, Smeaton specified the timber to be whole Scots fir of their natural taper; it could be worked into ordinary sections after decentering. The arches of the bridge were of constant radius and the road level a gentle curve in elevation, so that the arches increased in span towards the centre of the bridge. To enable re-use of a centre in these circumstances he introduced short rim-pieces (M in Figure 5) supported only by the cap of the pier and the tie-beam; presumably they were different in each span, though it might have been possible to make one set only and have them overlap the rim-piece immediately above for the lesser spans.

Local masons in Scotland would have noted this. James Robertson of Banff, who built the bridges at Inverurie (1789-91) and Ellon (1791-3), is said to have used the same centres, though the spans in each are different. Louis Piccard at Awe Bridge (1779) and Dalmally Bridge (1781), both in Argyllshire, is definitely asserted to have done so (RCAHMS 1975, p. 294).

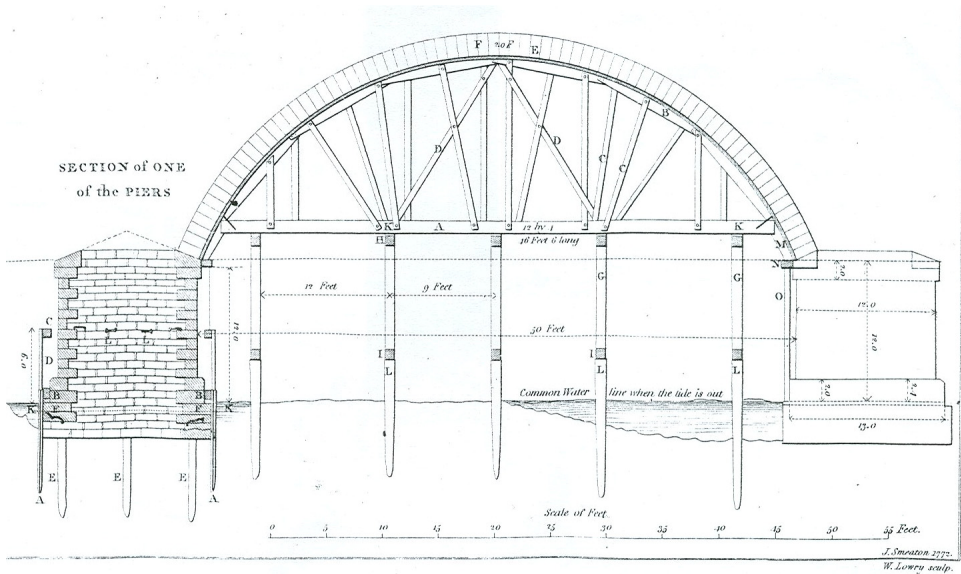


Figure 5. Centre for Banff Bridge (Smeaton 1812)

John Rennie (1761-1821) was one of the earliest civil engineers in Britain to have attended university. Although a mechanical engineer by training, he showed an early interest in bridge construction and regularly took the opportunity to visit other sites when travelling around the country in the course of his profession. He is known to have owned an extensive library, including works by continental engineers, and kept in contact with French engineers such as Prony despite the war that raged between their countries for much of his career. His works were marked by a degree of solidity and his design (**fig. 6**) for the centre for Waterloo Bridge (1811-17) is no different. On much the same structural arrangement as Blackfriars, but adapted for a span of 120 feet, the timbers are socketed into cast iron nodes instead of being spliced into each other to give long straight pieces.

It can also be seen that there is no support to the vault for the first seen courses above the springing. Voussoirs could be corbelled out until their angle of inclination rose to about 30° . Tredgold (1853) refers to experiments having been made to ascertain the point at which support becomes necessary, but does not state when they were carried out. It is clear that Rennie had a good feeling for this, and provided only as much centring as was required.

Rennie's son George (1791-1866) prepared a design for London Bridge but it was not until 1824, three years after the father's death that work started, with (Sir) John Rennie (1794-1874), the younger son as Engineer. The spans here were 150 feet and the centre (**fig. 7**) an X truss with the tie beam more than halfway up the rise of the arch, rather higher than usual.

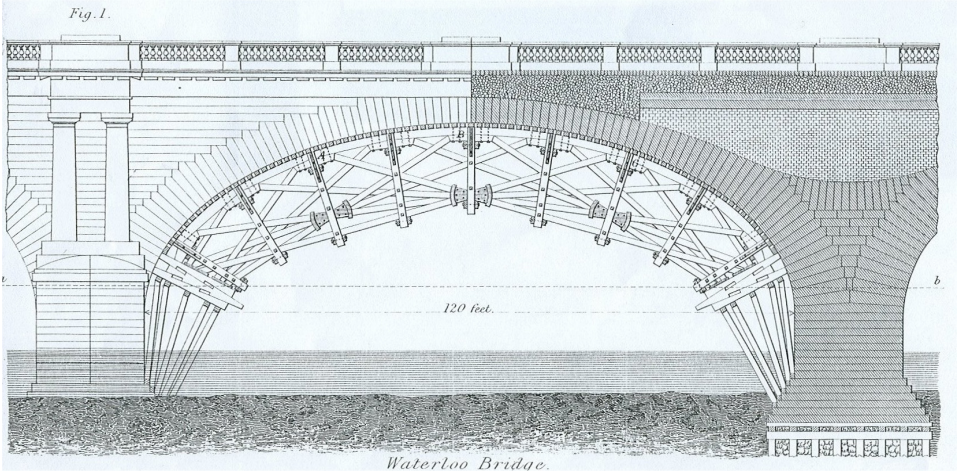


Figure 6. Centre for Waterloo Bridge, London (Newlands 1869)

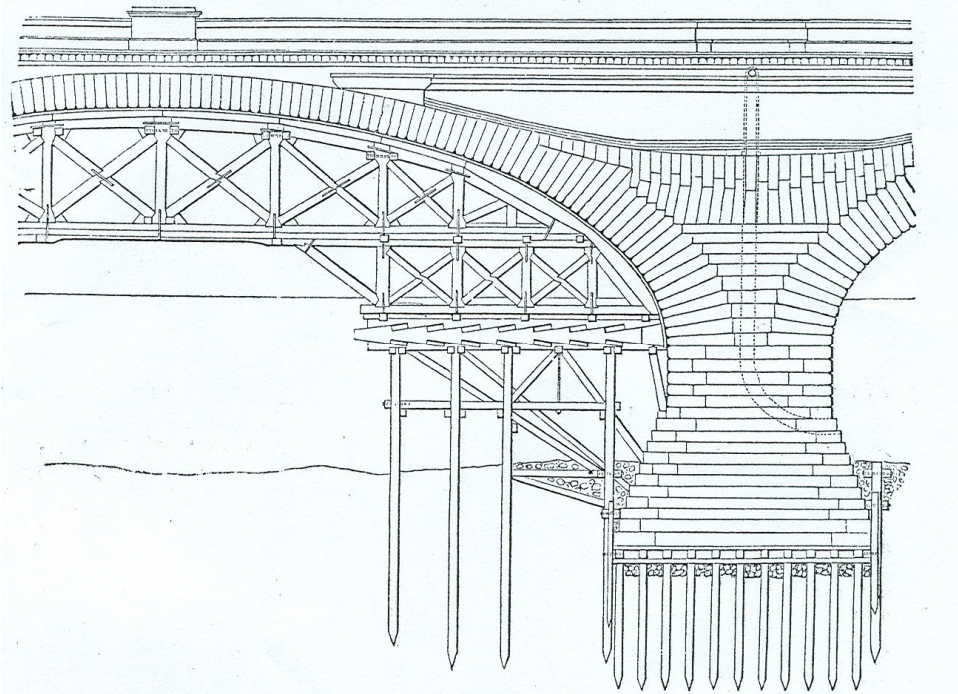


Figure 7. Centre for London Bridge (Cresy 1847)

Thomas Telford (1757-1834) was a stonemason by training, during which he worked on the construction of Langholm Bridge over the River Esk. His library which, as its first President, he bequeathed to the Institution of Civil Engineers, contained works by Leupold and Gauthey, but not Gautier, Labeyle or Perronet. He built over 1100 bridges in the Highlands of Scotland alone and towards the end of his life devoted considerable time to writing his autobiography. It was accompanied by an ‘Atlas’ of plates of many of his works. Of his masonry arches, the only two for which he showed the centres were Cartland Crag and Over (1838, plates 56 and 63).

For Cartland Crag Bridge (1821-2), where the 52-foot arches are 122 feet above a ravine north of Lanark, Telford used inclined trestles springing from corbels on the piers (**fig. 8**), the latter a technique known from Roman times.

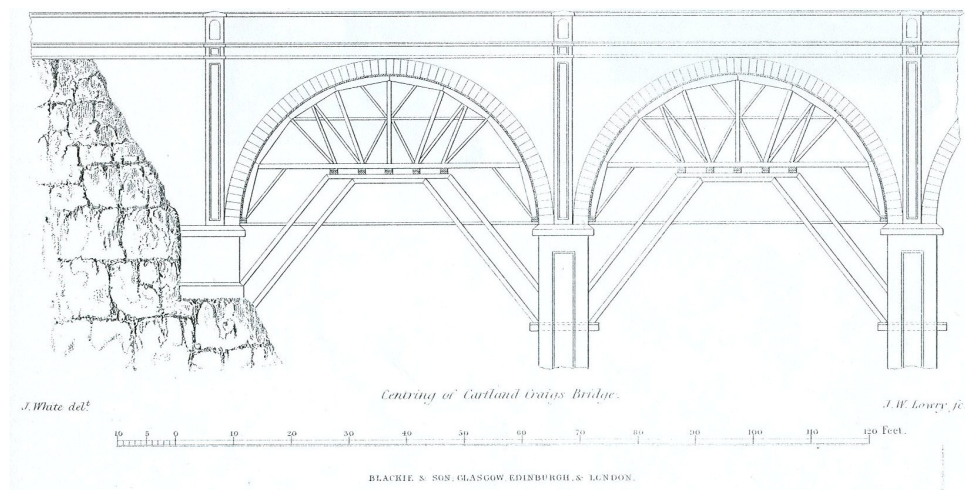


Figure 8. Centre for Cartland Crag Bridge, near Lanark (Newlands 1869)

The centre for the 150 ft span of Over Bridge at Gloucester (1826-8), (**fig.9**), was designed by the contractor, John Cargill, the son of a house-carpenter. It comprised two different structural forms: fans of props rising from piles over the central two-thirds of the arch, and tied arches spanning from the outside row of piles to the footing of the abutments. Cargill built a platform on top of the falsework on which to assemble the centre, which was then lifted into place by four cranes, one on each abutment and two on barges. The River Severn is liable to severe floods – many of the bridges over it had been destroyed in 1795 – and Cargill extended his platform upstream to provide working space but also to provide a fender against objects in the river. In the event it was a wise decision; although he had allowed a 16 ft opening for the passage of barges, two from the Herefordshire & Gloucestershire Canal were swept against it and sank. The platform extension was badly damaged and but for it the centre would have failed (Newlands 1869, p.173).

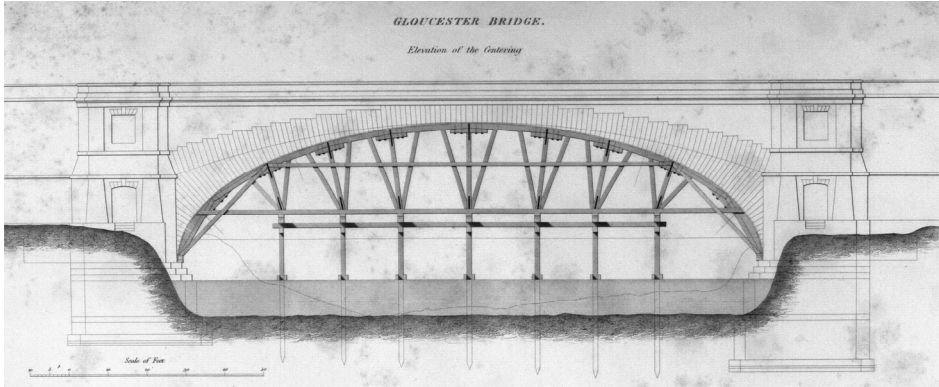


Figure 9. Centre for Over Bridge, Gloucester (Telford, 1838)

Almost contemporary with Over, but with a span at 200 feet one-third as large again, Grosvenor Bridge at Chester (1827-33) was then the largest in the world. The centre (**fig. 10**) was designed by the contractor, James Trubshaw junior (1777-1853). It attracted considerable notice at the Institution of Civil Engineers "for the novelty of the principle on which it was formed, the efficiency with which it did its work and the economy that attended its use" (Borthwick 1835-6). As at Over, the formers were supported by fans of props, but in this case they arose from temporary masonry piers. Although he was at least the fourth generation of a family of stonemasons, it is not clear why Trubshaw chose to use masonry. As there were only three piers across the span, clearly the loads to be carried were that much greater than at Over, but there would have been difficulty in ensuring adequate bearing for the bases of the piers in the river, which piled scaffold towers, similar to those for the 236-foot cast iron span at Sunderland, might have avoided.

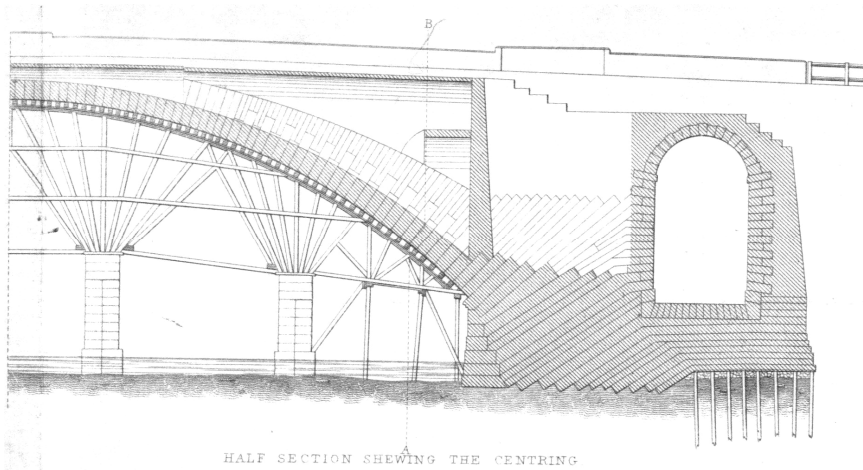


Figure 10. Centre for Grosvenor Bridge, Chester (Trans. ICE 1836)

An even more striking innovation was the disposition of the wedges. On top of the fans of props were laid two thicknesses of 4 inch planking bent to the shape of the arch, then, to support the lagging there was a pair of folding wedges at each course of voussoirs. As there were six ribs in the centre, there were 600 pairs of wedges to ease (Combe 1830, p. 149). This arrangement did allow great control over the striking of the centres; any part could be raised or lowered independently. After working from the springing upwards, and leaving the crown tight for some time, it sank by only 2½ inches.

Probably the most complete depiction of the construction of a bridge is that in Weale (1856) (**figs. 11 & 12**). Hutchesontown Bridge, Glasgow (1829-33) was the seventh, and arguably the finest bridge designed by Robert Stevenson. It had 5 arches up to 79 ft span and, if the title of the plate is to be believed, the centring of the 'left-hand' arch was being erected and that for the 'right-hand' arch struck, both in 1832.

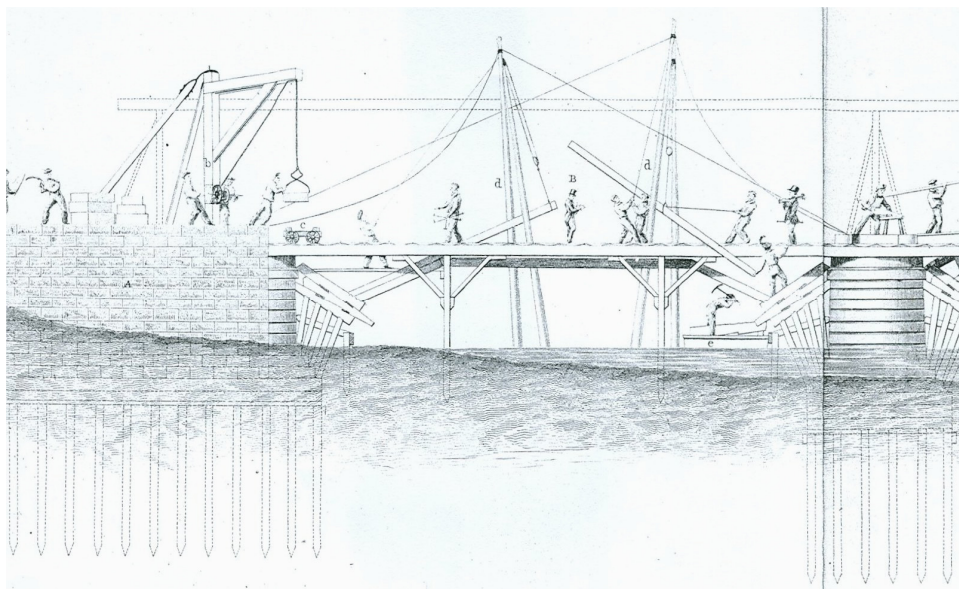


Figure 11. Building the centre for Hutchesontown Bridge, Glasgow (Weale 1856)

Under the 'right-hand' arch, two men in a pontoon at each side are swinging a ram suspended from the centre. This would drive the central wedges upwards; the upper wedges would move towards the abutment, allowing the centre to move downwards. As it required eight men to swing the ram backwards and two forwards at Over (**fig. 9**) where the wedges were set perfectly level, (Newlands 1869) and the men there could work on a stable platform, there is presumably some artistic licence here.

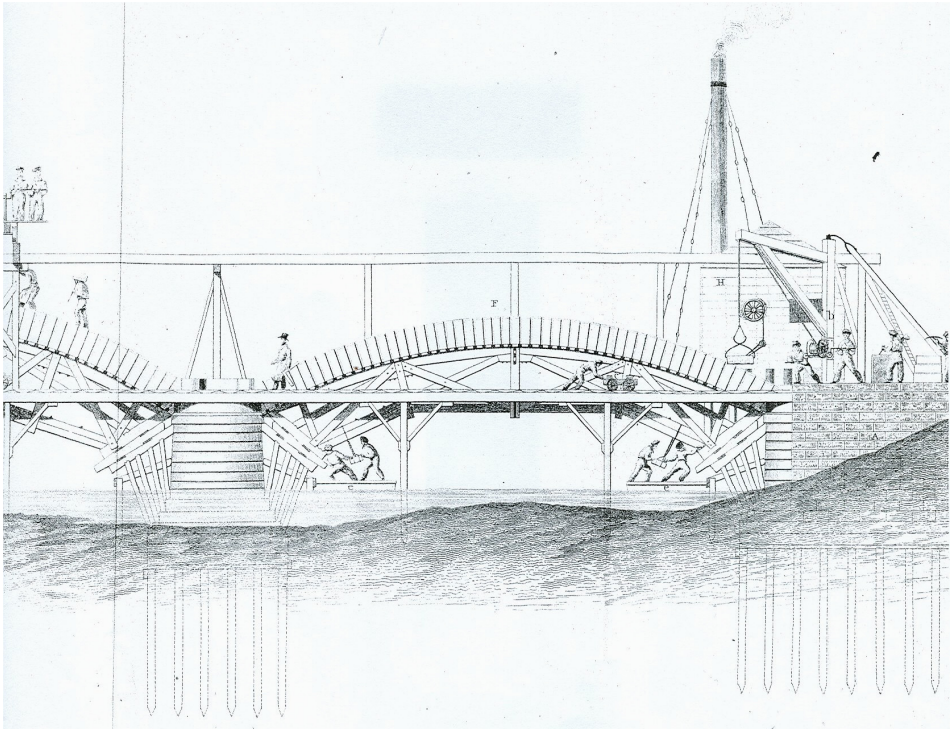


Figure 12. Decentring Hutchesontown Bridge, Glasgow (Weale 1856)

Stevenson was an early advocate of railways, and although Hutchesontown Bridge was built well into the era of steam railways, it was left to others to undertake this work. I K Brunel with his 128-foot brick arch at Maidenhead (1839) and John Miller for the 181-foot span of Ballochmyle Viaduct near Mauchline (1846-48) both opted for a fan of struts radiating from the top of substantial timber uprights, though this form was by no means universal. Perhaps Brunel's experience helped to form his ideas for the timber viaducts he provided later in Cornwall and South Wales.

Several of the examples illustrated above are highly redundant structurally and would have been impossible to calculate, even if reasonable assumptions could have been made about the actions of the joints. Gauthey (1809) gave equations for estimating the proportions of the weight of the masonry that would transfer to the centre and it may be that the fan design developed as being more susceptible to estimation of the loads in and sizes of members, though even Smeaton, for Banff (**fig. 5**), gave only approximate sizes to be used (1812, p. 353).

Throughout the period under review, there appears to have been little agreement about the best form of centres for large masonry bridges. From the 1770s at least, British engineers possessed

publications by their continental colleagues that included chapters on the subject, but there is little evidence that they were influenced by them. Indeed, continental authors included many British examples as models of good practice. Even at the end of the period, the design of centres was something of an art.

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