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Thomas Telford's cast-iron bridges

Thomas Telford's innovations using cast iron included a landmark lightweight type of arch bridge with spans of 32–52 m, longer than then practicable in stone and exhibiting an unparalleled combination of strength, economy and intuitive design. This development influenced cast-iron bridge building until the 1830s and the adoption of elegant and effective lozenge-lattice bracing in bridge spandrels until the 1870s. This paper identifies and examines Telford's mastery in cast-iron bridge design, exemplified by a legacy of six bridges which are still operational in varying degrees after nearly two centuries.

Cast iron, when used mainly as by Telford in compression, in the form of arches and columns with firm support, has given satisfactory and long-lasting service. Before the general adoption of steel in structures from around 1890 several thousand cast-iron bridges were erected, including many of arched form.

From 1790 to 1830 the continuing impetus of the Industrial Revolution in Britain required an extension of canal and road making at a time when structural theory and a strength-of-materials design approach were in a primitive

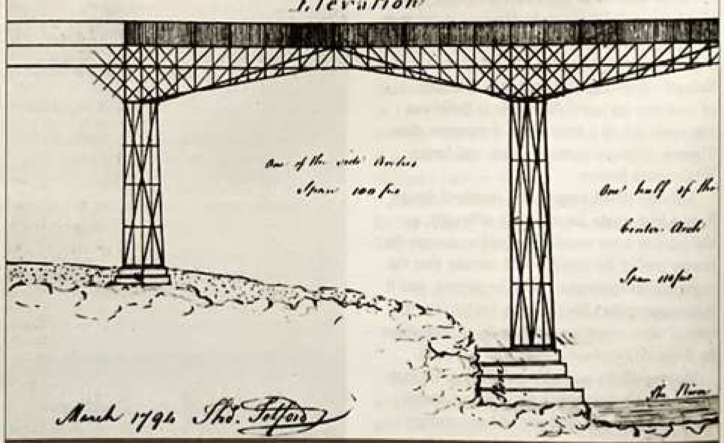

Fig. 1. Telford's preliminary 1794 cast-iron design for Pontcysyllte Aqueduct was based on timber truss design principles and had a main span of 33·5 m (Science Museum Library, London, No. 110, 592/61)

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Fig. 2. Longdon-on-Tern Aqueduct on the Shrewsbury Canal was Telford's first cast-iron aqueduct—completed in 1795, it was operational for 170 years and is now a listed ancient monument

Fig. 3. Pontcysyllte Aqueduct (1805) has 19 cast-iron spans of 13·7 m and is still in use today as part of the Langollen Canal

state. Thomas Telford was at the head of those who rose to this challenge and, by means of practical precepts, bold design and exceptional working relationships, effected outstanding improvements.

Telford developed the use of cast iron, then newly available for sizeable plates and castings to extend the limits of existing practice. His innovations included a landmark lightweight type of arch bridge with spans of 32–52 m, longer than then practicable in stone and exhibiting an unparalleled combination of strength, economy and intuitive design.

Iron aqueducts

A sketch by Telford dated March 1794 (five months after he had been appointed engineer to the Ellesmere Canal) (Fig. 1) is probably the world's earliest-known drawing for a light iron aqueduct, designed to obviate the use of traditional cumbersome, costly and often defective masonry canal aqueducts. This drawing, which was discussed at the time with enterprising iron-master William Reynolds, his close associate on ironwork matters, and the canal company's consulting engineer William Jessop, who either then or soon afterwards approved the concept, shows Telford's preliminary design for a multi-span high-level crossing of the Dee at Pontcysyllte.

Springing from an iron pier framework, the arches comprised a truss arrangement influenced by traditional timber bridge practice. The span was 110 ft (33·5 m). Within a year Telford had refined his design to one with stone piers supporting 60 ft (18·3 m) spans.[1]

Telford's first implemented cast-iron aqueduct, a low-level development of his 1794 concept, designed in consultation with Reynolds and manufactured by him at Ketley Ironworks from March 1795, was erected within a year at Longdon-on-Tern[2] on the Shrewsbury Canal (Fig. 2), for which Telford had been appointed the engineer in October 1794. Its navigable trough of 1 in. (25 mm) thick-flanged plates 5 ft (1·5 m) high by 8 ft (2·4 m) wide was supported by vertical and inclined struts, designed on the results of simple experiments made by Reynolds for Telford in March 1795. Reynolds also determined the crushing strength of grey cast iron at 64 tons/in^3 (1 kN/mm^2).

From another experiment Reynolds found that a 1 in^2 (25 x 25 mm) cross-section cast-iron bar placed horizontally between supports 3 ft (0·9 m) apart broke with a 6·75 cwt (0·34 t) load applied at mid-span, thus providing an indication of the weakness of cast iron in bending.[3] Telford was aware that the strength of a simply supported rectangular beam increased with the square of its depth.

When practicable, Telford adopted an additional security in his designs. Longdon-on-Tern Aqueduct, operational for about 170 years, has three strength elements: the inclined struts which reduce the effective span and provide continuity to the iron trough; the aqueduct sides which act as an equilibrated horizontal or plat-band arch with flanged cross-bolted joints radiating to a common point below mid-span; and the trough acting as an efficiently stressed U-shaped beam.[3] Work on this aqueduct would have been well advanced at Ketley Works by July 1795 when Jessop as chief engineer formally recommended an iron aqueduct at Pontcysyllte to the Ellesmere Canal Company, on the basis of Telford's concept.

For various reasons it was not until 1805 that the as-built version of Telford's Pontcysyllte design (Fig. 3) was realised by William Hazledine and Simpson & Wilson, without any further consultation of Jessop.

Buildwas Bridge

Telford admired the example of the iron arch at Coalbrookdale of 1781, with its span of 100 ft 6 in. (30·6 m), just exceeding that of the masonry central arch of London's Blackfriars Bridge of 1769, but believed that he could improve on its design. Being nearly semicircular, this offered little resistance to the aggressive earth pressure it encountered.

Telford's opportunity came early in 1795 following the destruction by flood of the old stone bridge at Buildwas. As Shropshire's county surveyor, he designed its replacement as an iron bridge, again working closely with Reynolds, who was also a partner of Coalbrookdale Works, the company that cast and erected it.

In his design process Telford was influenced to provide substantial abutments by experiments on curved ribs at Coalbrookdale Works in April 1795. The results showed that the ribs had nearly twice the strength when abutments were provided. Telford also applied the experience which he had gained at Longdon-on-Tern Aqueduct on flanged plates and struts, together with his self-taught knowledge and experience of the properties of the segmental arch and mid-eighteenth century timber construction on the Swiss 'Schaffenhausen' arch principle.[4]

The design basically comprised a low-rise (0·13 rise-to-span ratio) arch of 130 ft (39·6 m) span with three rectangular bearing ribs of 15 x 2·5 in. (381 x 64 mm) cross-section. These consisted of three long pieces secured transversely at each joining a by a grated plate, supplemented by the Schaffenhausen contribution of an outer suspending rib on each side (Fig. 4).[2] The rib scantlings were almost certainly not calculated but experimentally and intuitively derived.[4]

The Schaffenhausen contribution cannot be considered as completely satisfactory in this context as by 1837 rib cracking had occurred. This may have been attributable to differential temperature movement in the partially restrained arcs of differing radii and, or, the aggressive earth pressure movement referred to by Blackwall.[5] According to the author's calculation,[3] the bearing ribs would have been adequate without the suspending ribs. Telford too must have developed doubts about the value of the Schaffenhausen contribution as he never repeated it, always relying in later designs solely on deeper main ribs of similar rise-to-span ratio as the Buildwas bearing ribs.

Other features which contributed to the success of his later designs were the transverse plates with cross-bolted edge flanges to improve lateral stiffness and the cruciform spandrel bracing in elevation.

Although requiring minor repair from time to time Buildwas Bridge was essentially successful and remained in service for 100 years.[5] Telford had achieved a span 30% greater than that of nearby Coalbrookdale Bridge for half the weight of ironwork, demonstrating that the use of cast iron enabled a flatter arch to be achieved. Completed on 24 June 1796,[6] Buildwas briefly became the world's longest-span cast-iron bridge. It was overtaken by Sunderland Bridge, which opened on 9 August 1796 with a span of 236 ft (71·9 m) and of quite different design and construction.[4]

Fig. 4. Buildwas Bridge (1795) featured an experimental Schaffenhausen suspension rib on each side and, at 40 m, was briefly the world's longest cast-iron span

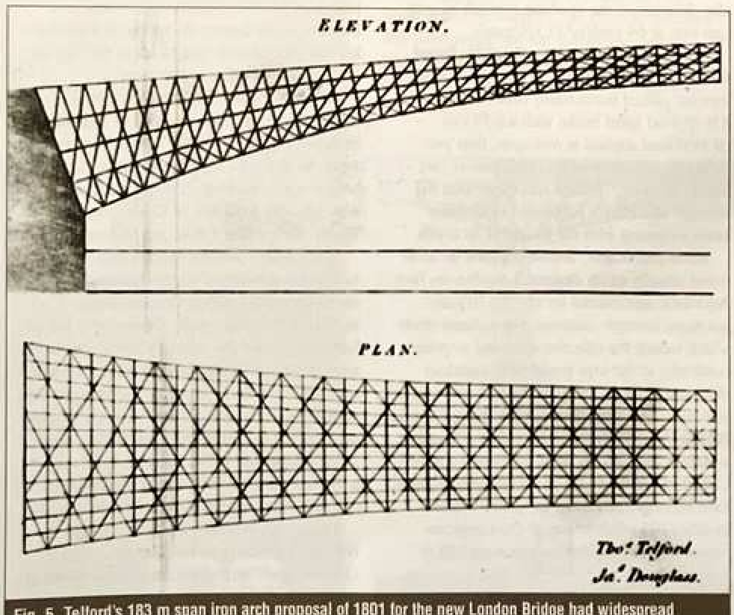

Fig. 5. Telford's 183 m span iron arch proposal of 1801 for the new London Bridge had widespread support but was never built

Proposed London Bridge

By 1800 Telford, with a young assistant James Douglass, was making bold iron bridge proposals as replacements for old London Bridge as part of an improvement of the Port of London. His most outstanding proposal was for a single cast-iron arch of 600 ft (183 m) span (Fig. 5), a concept probably based on a long-span timber-arch design by Claude Perrault in 1700.[7] The proposal was so novel that the parliamentary select committee involved considered it necessary to obtain expert opinion on its practicability. Telford formulated 21 queries which were sent to at least 18 eminent people including Reynolds, who was strongly supportive.

The consensus of the experts, including that of Thomas Young 16 years later,[8] was generally favourable to the proposal, but although seriously considered for many years it was never executed. The parliamentary publication in 1801,[9] which included the queries and replies, served as an iron bridge builder's guide for several decades—despite some astonishing differences from several theoreticians. For example, that the thrust on the abutments varied from zero from Maskelyne to 20 550 tons (20 880 t) from Robertson—the author's calculated value is 11 278 t.[3]

In an authoritative modern assessment Professor Skempton concluded that the bridge was not built because of its unprecedented scale coupled with lack of knowledge of and agreement on the technical factors involved. Also, because of its high approaches, it would have presented serious planning problems and significant cost implications. He did not rule out its practicability but thought that the greatest uncertainty was in obtaining unyielding abutments.[10] With Telford's drive and proven track record in eventually arriving at workable designs for unprecedented projects, it is not inconceivable technically that the design could have been achieved using Hazledene's ironwork.

The ironwork arrangement published in 1801[9] contains the embryo of the bracing and rib elevation adopted by Telford in his 1811 designs for proposed bridges at Menai Straits, Conwy, New Galloway and Bonar. For his initial 500 ft (152 m) span Menai Straits cast-iron arch design he proposed suspending the centring from above by means of wrought-iron stays—an ingenious idea which eventually led to his landmark wrought-iron bar suspension bridge.

Cast-iron bridge development

Britain led the world in the development of cast-iron bridges. However, as can be seen in Table 1, which is prepared from the author's and James' researches,[3,11] Wilson's long-span bridges (1796–1804)—which were of Rotherham manufacture with short cast-iron

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rib blocks and wrought-iron connectors developed cracking which may have contributed to the collapses at Staines and Yarm.

Defects had also occurred in Wilson and Rennie's smaller-span Boston Bridge (1804–07), in which many of the connectors between the short two-element rib rings had cracked. In 1807 two 100 ft (30 m) span bridges designed by Jessop for Bristol harbour, cast and erected by the Coalbrookdale Company, were opened after the collapse of one during construction. They represented an improvement by using radially orientated springing plates and long ribs with only one joining without the use of wrought iron, but weak features were the rectangular openings in the ribs and the vertical spandrel supports transmitting point loads to the ribs, often above an opening. These bridges had an average life of only 62 years.

Confidence in iron bridge building, which had been low after the various failures, was restored by the innovation of Telford's landmark lightweight masterpiece at Bonar Bridge in 1812.[10] This proved the first of a genre with 'lozenge-' or diamond-shaped lattice spandrels, of which eight bridges exceeding 32 m were erected by 1830.

Bonar Bridge also encouraged the adoption of iron for other bridges, including James Walker's Regent's Bridge across the Thames in London (on the site of today's Vauxhall Bridge) in 1813, Rennie's old Southwark Bridge in 1814 and James Rendel's Plymouth Laira Bridge in 1827. With its lozenge-lattice spandrels, elliptical arches and innovative iron piers, the latter attracted an Institution of Civil Engineers Telford medal.

The zenith period of development of the long-span cast-iron arch bridge was essentially 1812–27, when the basic parameters of the art were established and the longest span of 73·1 m was achieved. During this era Telford's dominance in the art was such that, of the 19 bridges exceeding 32 m erected by 1830, 18 were in Britain, of which nine were to Telford's design and two more were influenced by it. Three were to Wilson's design and one each to Rennie and others.

Telford also developed an economical smaller-span radially orientated open-frame arch bridge type of which some, such as Engine Arm aqueduct, still exist.

Later long-span examples with half or whole lozenge-lattice spandrel bracing, which can be considered to have stemmed indirectly from Telford's practice, include Nash Mill[12] and Blisworth[13] on the London and Birmingham railway in 1837; Great Ducie Street and Irwell in Manchester[14] around 1839, Defford on the Birmingham and Gloucester railway[15] in 1839, and Water Street on the Manchester South Junction and Altrincham railway in 1848.[16] More northerly examples include Clyde Viaduct

Table 1. A list of cast-iron bridges erected by 1830 with spans exceeding 32 m clearly indicates the dominance and durability of Telford's designs

Bridge	Engineer	Date built	Span: m	Rise-to-span ratio	Iron founder	Life	Cost: £	Weight of ironwork: t	Still existing
Sunderland	Wilson	1793–96	70·7	0·144	Walkers, Rotherham	Perilous 1805 but fixed, lasted 132 years*	27 000 (modified 1859)	264	No
Buildwas	Telford	1795–96	39·6	0·13 & 0·26	Coalbrookdale Co.	Lasted 100 years	6444	176	No
Coalport	Onions	1799 & 1818	33·1		Banks & Onions	Weight limit 3 t	—	—	Yes
Staines	Wilson	1802–03	54·8	0·09	Walkers, Rotherham	Collapsed 1804	5660	274	No
Yarm	Wilson	1803–05	54·8	0·09	Walkers, Rotherham	Lasted 4 months	5660	274	No
Pont d'Austerlitz, Paris	Lamandé	1800–06	32·4	0·16	—	Lasted 48 years	—	—	No
Bonar	Telford	1810–12	45·7	0·13	W Hazledine	Lasted 80 years	9736	183	No
Craigellachie	Telford	1812–14	45·7	0·13	W Hazledine	Strengthened 1964, pedestrian use since 1972	8200	183	Yes
Southwark	Rennie	1814–19	64·0 and 73·1	circa 0·1	Walkers, Rotherham	Lasted 101 years	666 486	5394	No
Chepstow	Rastrick	1815–16	34·1		R Hazledine/ Rastrick & Co.	Strengthened 1889	17 154	—	Yes
Betws-y-Coed	Telford	1815	32·1	0·10	W Hazledine	Strengthened 1923	—	—	Yes
Esk or Garrieston near Longtown	Telford	1820–22	32·1–32·1–45·7	0·10 – 0·10 – 0·13	W Hazledine	Lasted 94 years	12 827+		No
Eaton Hall Estate, near Chester	Crosley (Telford, design)	1824	45·7	0·13	W Hazledine/ W Stuttle (Jnr)	Weight limit 3 t	—	—	Yes
Mythe, Tewkesbury	Telford	1823–26	51·8	0·10	W Hazledine	Strengthened 1923 and 1992, weight limit 17·5 t	14 500	—	Yes
Cleveland, Bath	Goodridge	1827	33·5	0·10	W Hazledine	—	—	—	Yes
Holt Fleet, Ombersley	Telford	1827	45·7	0·13	W Hazledine	Strengthened 1923	—	—	Yes
Bigsweir, Wye	Hollis	1827–28	50·0	0·14	Bough & Smith, Merthyr Tydfil	Weight limit 17v5 t	—	—	Yes
Galton, Birmingham Canal	Telford	1829	45·7	0·10	Horsley Bridge Co.	Pedestrian use	—	345	Yes
High Bridge, Handsacre	Potter	1829–30	42·7	0·10	Coalbrookdale Co.	Rehabilitated 1997	9493	—	Yes

Notes
1. Excludes footbridges and bridges combined with timber or wrought iron (except fastenings).
2. Bridge costs and weights vary with sources and are provided only as an indication.
3. * A prototype of a 33·5 m promotional span to Paine's design was temporarily erected at Paddington Green in 1790.

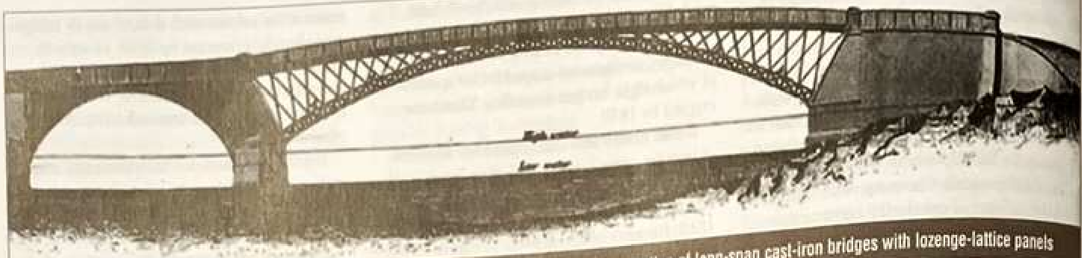

Fig. 6. Bonar Bridge (1812) had a main span of 46 m and was the first of a Telford-inspired generation of long-span cast-iron bridges with lozenge-lattice panels

Fig. 7. Craigellachie Bridge (1814) is identical to the former main span at Bonar and, as the oldest survivor of its genre, is due to become an international historic civil engineering landmark in 2007

at Uddingston[17] in 1848, Robert Stephenson's 1859 reconstruction of the original Sunderland Iron Bridge,[18] Carron over the Spey[19] in 1863, and Balgay Park in Dundee[19] in 1872, currently being modelled for conservation by Gifford.[20]

Bonar Bridge

Telford's Bonar Bridge carried the Great North Road across the Kyle of Sutherland west of Dornoch in Scotland from 1812 to 1892 (Fig. 6). In association with Hazledine, Telford combined elegance with economy and strength to an unparalleled degree in a cast-iron arch span of 150 ft (45·7 m).[21] Improvements over other contemporary cast-iron bridge designs included the following.

- Adopting deep, narrow, rectangular ribs pierced between spandrel loading points by triangular cavities to produce a cruciform Palladian timber arch elevation, such that the width of metal was constant to allow equal cooling during manufacture. Although piercing reduced the rib cross-sectional area by about half between spandrel load points, the compressive stress is well within the safe limit. Telford regarded the overall rib depth of 3 ft (0·9 m) as the key factor, similar to the practice he would have adopted for masonry, the additional depth over that strictly required for compressive strength helping to minimise any bending stress, Telford seems to have understood this in his own terms.
- Telford probably designed the ribs as the sole element transmitting the thrust from the dead and live loads to the abutments. On this basis the author's graphical determination of the thrust line within the middle third of the rib throughout[3] is indicative of Telford's use of an 'equilibrated' arch rib. In practice any bending stress induced is likely to have been of a small order. Unlike Rennie, Telford considered varying the rib depth to achieve a thrust line closer to its centre to be an unnecessary refinement.
- Introducing a robust system of flange-bolted open gratings between and on top of the ribs, and dovetailing the roadway bearers into a cast-iron plate at the abutment top secured with bar back-ties into the body of the abutment such that, in Telford's words

  'the whole iron arch and superstructure is connected into one frame'.[21]

  This effect via the lozenge-lattice spandrel bracing, the slight arching of the roadway, and the whole bridge acting as a frame, worked and provided sufficient resilience to accommodate temperature effects, unlike Southwark Bridge with its massive castings where

  'the stone paving was … always out of order over the piers'.[22]

- Reducing weight in members wherever practicable, such as by openings in the ribs and their connecting bracing. The cruciform spandrel member cross-section, rather than circular or square, was much more efficient in strength terms. These measures, commensurate with the required strength, enabled the ironwork to be portable and its cost to be kept below £4000.

The arch, pre-erected and probably load-tested at Hazledine's Plas Kynaston works, became the prototype of a portable economic genre, used to achieve permanent crossings at sites impracticable for constructing stone bridges.

By 1815, the design was being economically modified for a 105 ft (32·1 m) span, by expediently removing one element of rib length from each side of the larger version while retaining the same radius of 150 ft (45·7). The last example known to the author to be closely related in style to Bonar Bridge was erected over the Severn at Abermule, Montgomeryshire in 1852.[23]

Details of the design and construction of the Bonar Bridge genre were promoted in technical publications at home and abroad particularly by Telford[4,21,24-25] and Baron Dupin[26] and, in relation to bridge evolution, as late as the early twentieth century by Gaudard[27] in France and Tyrrell[28] in the USA.

Craigellachie Bridge

The arch at Craigellachie Bridge (Fig. 7), erected under Telford's direction in 1814 on a key road to Elgin which became the A941, crosses the deep and fast-flowing Spey 19 km above Fochabers and is virtually identical to that formerly at Bonar Bridge (Fig. 6). When the latter was destroyed following the collapse of its pier in a flood in January 1892, Craigellachie became the earliest survivor of its genre, and Scotland's earliest surviving iron road bridge.[19]

In July 2007, as a tribute to the achievement of this landmark bridge type, the American Society of Civil Engineers and the Institution of Civil Engineers intend jointly to designate

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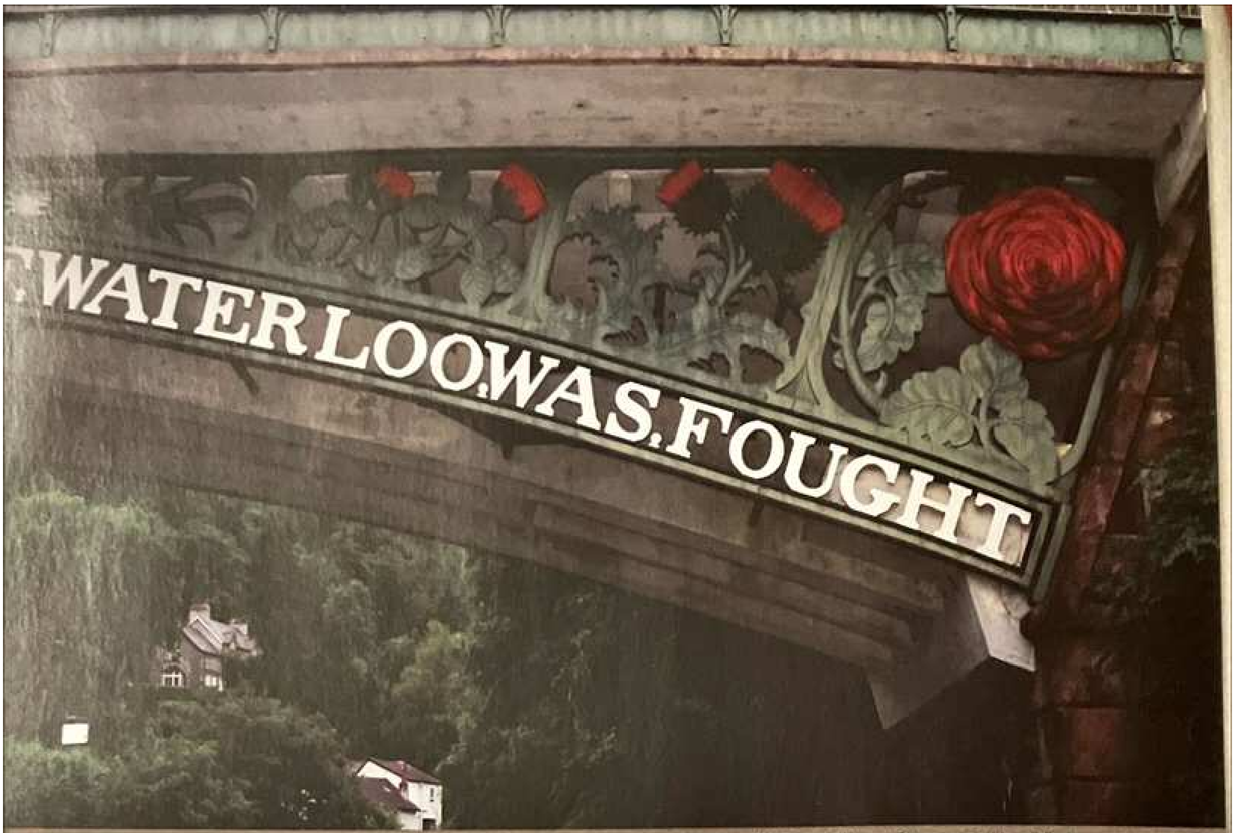

Fig. 8. Telford used a leek, thistle, rose and shamrock design on the outer frames of the 32 m span Waterloo Bridge at Betws-y-coed to celebrate Britain's victory over Napoleon in 1815

Craigellachie Bridge an International Historic Civil Engineering Landmark in the 250th anniversary year of Telford's birth.

The ironwork was transported from Plas Kynaston Works via the Ellesmere Canal and Pontcysyllte Aqueduct, to the Mersey, by sea to Speymouth, and to site by wagon, where it was assembled on pre-erected light centring in August and September 1814 under the direction of Hazledine's foreman William Stuttle. The bridge was opened two months later following completion of the gallery in the rock face at the north approach.

The bridge, with minor modifications, continued in use until 1963–64. It was then reconstructed above the arch ribs, with significant retention of ironwork and character, including the original cast-iron deck, under the direction of W. W. Lowson, of W A Fairhurst & Partners, Aberdeen, whose publication constitutes a valuable case study.[29]

An important finding by Lowson was that Hazledine's fine quality castings were more ductile than common cast-iron with an ultimate tensile strength about 50% greater at 12·5 tons/in.^{2} (194 N/mm^2), nearly half that of modern steel. Knowing that the ironwork was not entirely in compression, Telford would have emphasised the need for the highest practicable tensile strength. This was achieved by the use of high-quality iron with a low level of residual elements and impurities, and blemish-free castings indicative of the use of good clean moulds. The ironwork also had a good start in life from being maintained by Hazledine for its first three years.

Lowson calculated the maximum compressive stress in the rib under the action of two 14 ton (14·2 t) vehicles at 6.85 tons/in.^{2} (106 N/mm^2) and the maximum tensile stress at 1·51 tons/in.^{2} (23·4 N/mm^2), values which agreed fairly closely with 472 strain gauge readings.

The main items of new, matching steelwork were the side railings and spandrel members, all carefully fabricated to the original dimensions by Sir William Arrol & Co. Ltd and fitted into the original rib pockets. Each spandrel cross in elevation consisted of one continuous member supported at the centre by half-length members from above and below. The problem with the bridge was not corrosion but that many half members had become loose, leaving just the member from deck to road carrying the load.[29]

On completion of the reconstruction in 1964, a 14 ton (14·3 t) weight limit was imposed which remained in force until the bridge was bypassed by the new bridge and closed to vehicles in 1972. Craigellachie Bridge remains in the stewardship of Moray Council as an outstanding historical and scenic amenity enjoyed by pedestrians and cyclists.

Betws-y-Coed Bridge

Waterloo Bridge at Betws-y-Coed now carries the A5 on the former London to Holyhead Road, for which Telford was the engineer.

It was of the standard 105 ft (32·1 m) module of the Bonar Bridge genre except for the outer frames in which Telford invoked the leek, thistle, rose and shamrock to commemorate the nation's victory over Napoleon at Waterloo in 1815, the year it was built (Fig. 8).

The bridge was strengthened and widened at deck level in 1923, its inner ribs being encased in reinforced concrete, by the Yorkshire Hennebique Contracting Co. to the design of L G Mouchel & Partners.[21,25]

Fig. 9. Eaton Hall Estate Bridge (1824) has a standard Bonar 46 m span and remains open to 3 t traffic © Phillip Wrightson, Chester

Eaton Hall Estate Bridge

Eaton Hall Estate Bridge of 1824 is a fine surviving example of the basic genre, with its original ironwork including the 150 ft (45·7 m) deck. It has spikey frets in its lozenges, presumably as ornament to please its owner Earl Grosvenor of Eaton Hall (Fig. 9).

William Crosley was the surveyor and William Stuttle, presumably Hazledine's foreman, the founder and erector. The bridge which has been well maintained and is subject to a 3 ton (3·07 t) weight limit and still in everyday use.

From a report of 1964, Laing's calculated stresses for the bridge are of the same general order as those of Lowson at Craigellachie. Their finding was, in general, that the existing

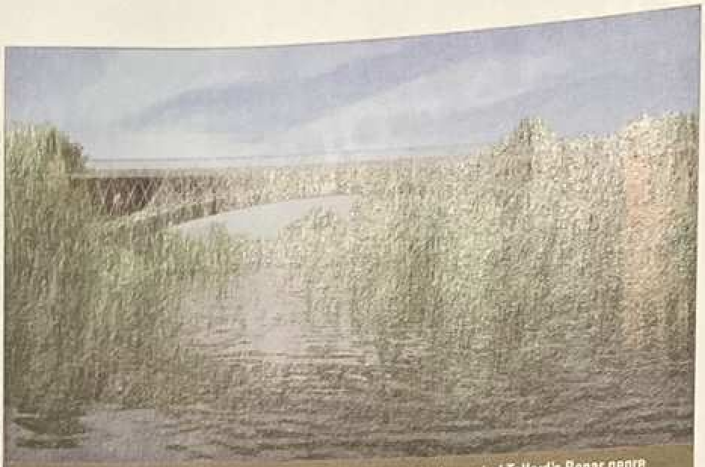

Fig. 10. Mythe Bridge over the Severn at Tewkesbury (1826) is the longest of Telford's Bonar genre bridges with a 52 m span—after strengthening it remains open to traffic but with a 17·5 t weight limit

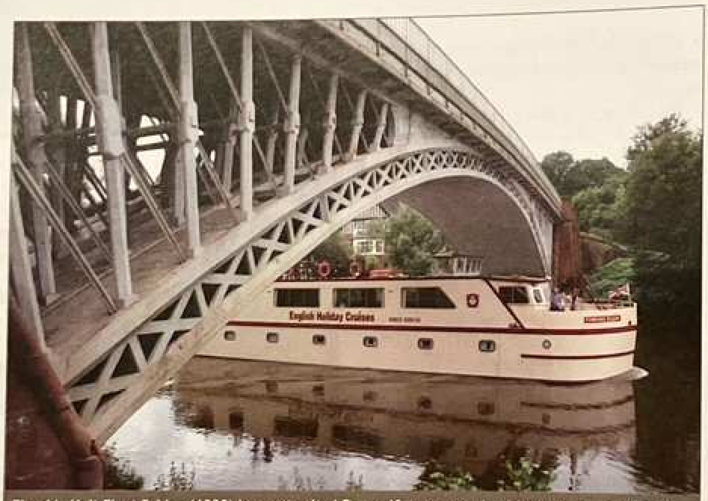

Fig. 11. Holt Fleet Bridge (1829) has a standard Bonar 46 m span and, with the tops and bottoms of its iron ribs now encased in reinforced concrete, remains open to full road traffic

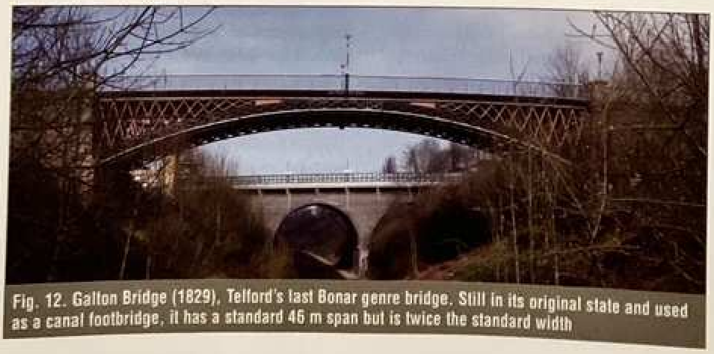

Fig. 12. Galton Bridge (1829), Telford's last Bonar genre bridge. Still in its original state and used as a canal footbridge, it has a standard 46 m span but is twice the standard width

'deck is satisfactory if vehicles can be made to cross the bridge with their wheels as near as possible to the central pair of ribs, and that although the ribs are capable of taking a greater load, the spandrel struts are only capable of carrying the 6½ ton Bedford Horse Box or the 7 ton F.W.D. crane'.[30]

This understandably seems to discount any effect of the whole spandrel acting as a frame and the high strength of Hazledine's iron. The author from calculation found the roadway bearers to be one of the least strong elements compatible with Telford's 10 ton (10·3 t) design wagon loading for the genre. The weight limit is undoubtedly a prudent precaution.[3]

Mythe Bridge

Mythe Bridge of 1826, with a 17·5 t weight limit carrying the A438 road over the Severn at Tewkesbury, constitutes the largest span and the ultimate development of the Bonar Bridge genre (Fig. 10). At Mythe Telford incorporated more structurally efficient vertically orientated lozenges into the spandrels.[25,31]

The bridge, which is of 170 ft (51·8 m) span, was strengthened in 1923 by substituting a ferro-concrete deck for the earlier construction which included a clay waterproofing layer below Telford's classic road construction.[32] The author uncovered a similar feature below a weak lime concrete layer during an investigation of the carriageway construction of Telford's Dean Bridge, Edinburgh, in 1973.[33]

In 1992, Mythe Bridge was strengthened more substantially by discreet internal plate additions and spandrel strut thickening measures to inhibit buckling using splints under the direction of John Wallace,[34] which tastefully achieved the 17·5 t weight limit without detriment to the bridge's appearance.

Holt Fleet Bridge

Holt Fleet Bridge of 1827 is about 30 km to the north of Mythe and carries the A4133 road over the Severn (Fig. 11). With an arch seemingly identical to that at Craigellachie, it was ingeniously strengthened in 1928 by the Yorkshire Hennibique Construction Co. Ltd, but with some loss of character.

The tops and bottoms of the ribs were encased in concrete across the full width of the bridge and much of the ironwork above encased within a thin layer of concrete after steel reinforcement had been electrically welded on to it.[35] These measures preserved the original ironwork and the bridge is still in use without weight restriction.

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Galton Bridge

Galton Bridge was erected in 1829 to carry the road to Sandwell across the Smethwick cutting on the Birmingham Canal (Fig. 12).[36] It was the last of the Bonar genre for which Telford was the engineer, but wider with six ribs and with vertically orientated spandrel lozenges as at Mythe Bridge. The ironfounders were the Horseley Bridge Company.

This fine bridge, which appears to be in its original state and now restricted to pedestrian and cycle use is, according to Cragg,

'rightly described as one of the seven wonders of the Birmingham canals'.[37]

Conclusions

From 1812 Bonar Bridge restored confidence in the art of long-span cast-iron arch bridge construction from a low ebb, a development which influenced cast-iron bridge building until the 1830s and the adoption of elegant and effective lozenge-lattice bracing in bridge spandrels until at least the 1870s.

Before inter-city railway travel developed from 1830, Telford had designed nearly a half of all cast-iron bridges erected with spans exceeding 32 m. These were on main roads in England, Scotland and Wales, at sites impracticable or uneconomic for building masonry bridges.

Telford's achievement of the portable, lozenge-lattice, standard, economical bridge of the Bonar type was based on a combination of his practical experience of masonry and ironwork, self-taught wide-ranging knowledge of architectural practice, exceptional working relationships with contractors, particularly Hazledine, and bold intuitive design.

Attractive visual features of Telford's Bonar genre are, in general, the Palladian cruciform elevation of the slender ribs, the gently curved parapet line and the gossamer-like slenderness of the lozenge spandrels. Significant in this slenderness was Telford's design concept of the whole of the bridge ironwork acting as a huge frame in addition to its parts being designed to act separately. Examples leavened with his fondness for the gothic style are at Craigellachie in scenic grandeur and in the Mythe approaches.

Of eight bridges of the Bonar genre erected from 1812–29, six are still operational in varying degrees. Strengthening to meet modern traffic requirements has been undertaken at four still carrying main roads with varying degrees of ingenuity and sensitivity. Lowson's calculations and findings[29] are of great value in demonstrating the efficiency of Telford's mastery at Craigellachie Bridge, after 150 years of often heavy usage, and the continuing high quality and strength of Hazledine's ironwork.

In the context of Telford's immense and diverse overall workload, his remarkable achievement in iron bridge engineering generally is even more so for taking up only a small proportion of his working time, probably less than 10%, during the period 1794–1831. There were of course periods of greater intensity at some of the dates indicated above and during his pioneering development of the wrought-iron suspension bridge at Runcorn and Menai in 1814–25.[38]

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