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UNION CHAIN BRIDGE'S HISTORICAL ENGINEERING SIGNIFICANCE

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Fig. 1. Union Bridge (Good, 1822) ©Paxton

Introduction

Union Bridge connecting Scotland and England, is jointly owned by Northumberland County and Scottish Borders Councils. When erected in 1819-20 between Paxton in Hutton parish and Horncliffe it was the only road bridge crossing the River Tweed between Berwick and Coldstream. It was commissioned by the Berwick and North Durham Turnpike Trust under the enterprising chairmanship of William Molle. [Fig. 2].

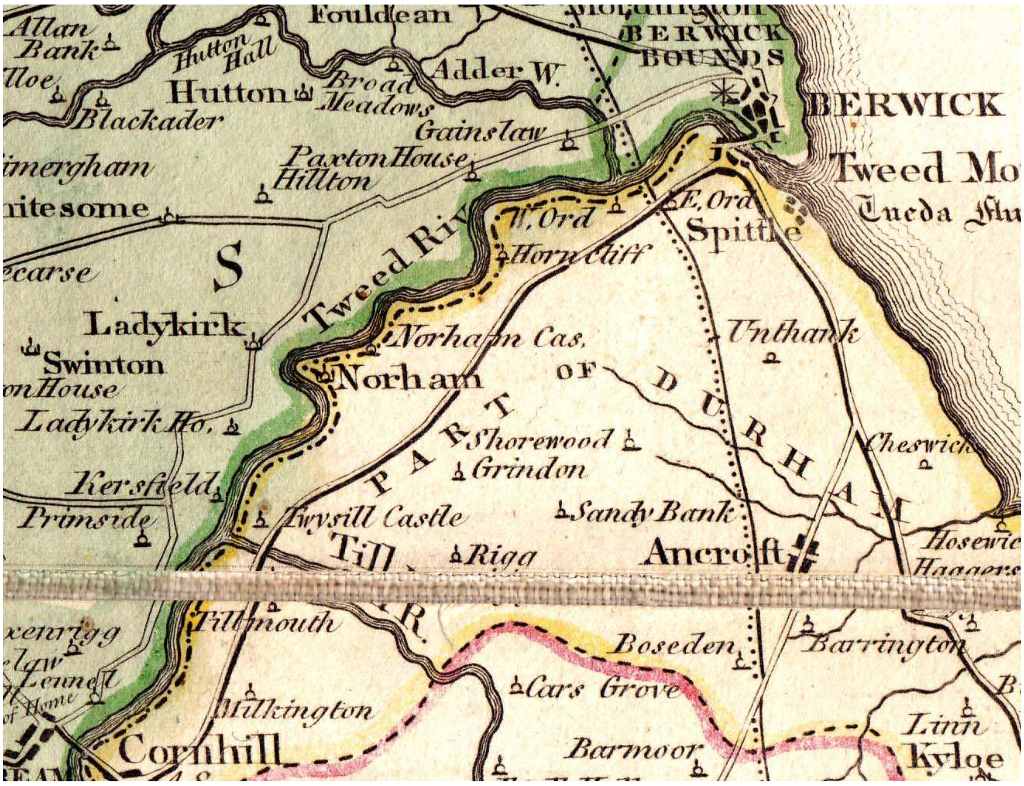

Fig 2. Map – Berwick to Coldstream (Ainslie, 1789) ©Paxton

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When opened, Union chain bridge at 18 feet wide, was almost certainly the world's longest bridge span carrying road traffic and is now also the longest in service at 195 years. So on two counts it is **a landmark in the development of suspension bridges on an international scale**, as can be seen in the table below:

Name of Bridge, Engineer, Main Cables, Dates	**Cable Span** (ft/m)
Newburyport, USA (Finley 1810, bar chain, replaced 1909	244/74
Union, UK (Capt. Brown & Rennie 1820, bar chain, 2t limit	**437/133**
Menai, UK (Telford 1826), bar chain, renewed in steel 1940	580/177
Fribourg, Switzerland (Chaley 1835, iron wire, replaced)	c.870/265
Wheeling, Ohio USA (Ellet 1849 – wire)	1010/308
Queenston-Lewiston, USA (Serrell 1851-64 wrecked, wire)	1040/317
Cincinatti-Covington, USA (Roebling 1867 – wire cable)	1057/322
Niagara-Clifton, USA-Canada (1869-89 wrecked, wire)	1268/387
Brooklyn, USA (Roebling 1883, wire; bar chain anchorages)	1596/486
Forth, UK (Fowler/Baker/Arrol 1890, steel cantilever type)	1710/521
Quebec (Vautelet et al 1917, zenith span steel cantilever type)	1800/549
Ambassador, USA-Canada (McClintic & Co.1929, steel wire)	1850/564
George Washington, USA (Ammann/Gilbert 1931, steel wire)	3500/1067
Golden Gate, USA (Strauss et al 1937, steel wire)	4200/1280
Verrazano Narrows, USA (Ammann/Brumer 1964, steel wire)	4260/1298
Humber, UK (Freeman Fox & Partners 1978, steel wire)	4526/1380
Akashi Straits, Japan (Satoshi Kashima 1998, steel wire)	6532/1991

Chronological list of the world's longest road or railway bridge spans 1810-2016

(All are operational suspension bridges unless otherwise indicated)

The bridge's status and crisis of survival

The historical importance of Union Bridge is recognised in the UK by its highest governmental grades of 'Class 1' by *Historic England* and 'Category A' under the auspices of *Historic Environment Scotland*. It is however more than just an historic monument, being also a useful local crossing facility and an elegant environmental and tourist attraction.

In the past decade the protective paintwork of the bridge has deteriorated and several broken hangers have been temporarily replaced to keep it operational at its low, but much preferable to closure, weight limit of 2 tonnes [Fig. 3]. It is on Historic England's *Heritage at Risk* register. There is significant public concern about its crisis of condition at home and abroad from American, Scandinavian and Japanese engineers (Isohata, 2015).

Fig 3. Prof Isohata from Tokyo viewing temporary hanger, 2014 ©Paxton

Fig. 4. Kalemouth Bridge in 2016 ©Paxton

Successful refurbishment of historic transport works

The authentic refurbishment of the bridge will require funding additional to normal maintenance, a challenge which can and should be met. Successful precedents include, restoration of the Scottish Lowland Canals 1994-2002, refurbishment of the historic railway infrastructure, involving 1,483 *Railway Heritage Trust* grants in the past 30 years; Conwy Bridge, now National Trust; Laigh Milton Viaduct 1811 Kilmarnock, the world's oldest of type on a public railway, which attracted funding from seven sources (Paxton, 2007); bridges at Aberchalder (suspension-stay) by Historic Scotland; Linlathen East (cast iron c.1804) by Dundee Council; and later Capt. Brown bridges at Kalemouth c.1835 by Scottish Borders Council [Fig. 4] and Wellington Bridge 1831 by Aberdeen Council (Paxton & Shipway, 1980).

Apart from its already mentioned attributes, Union Bridge is worthy of refurbishment as a masterpiece of entrepreneur, chain manufacturer and bridge engineer, Capt. Samuel Brown R.N. (1774-1852), introducer of the iron chain cable to the Navy, mercantile marine and suspension bridges and, his consultant on its masonry design, the eminent civil engineer John Rennie (1761-1821). Their achievement is best appreciated on a site visit – an experience with valuable educational and tourist potential.

Early development of the iron suspension bridge concept

The use of wrought iron in chain bridges became practicable following late 18th century improvements in manufacture that made it available at an affordable cost for larger applications. This was not a new concept, the Chinese having erected such bridges, using iron chains, for more than a thousand years. In Europe Verantius designed a bridge using eye-bar rod chains in 1595 (Needham, 1971). But the first significant application of wrought iron to improved chain bridge practice in modern times began in the USA around 1796 (Drewry, 1932) by an ingenious judge, James Finley, who showed a commendable appreciation of chain curvature efficiency and deck stiffening for his time. He erected eight bridges by 1811, the most noteworthy being Merrimack, Newburyport, of 244 feet span with elongated chain links about 10 feet long (Finley, 1811; Stevenson, 1821; Drewry, 1832).

Development of the long wrought iron eye-bar chain

From c.1811, Brown and Telford thought that Finley's practice could be improved on by British skill and technology. It was, but in the event neither provided adequately against severe storm-induced vibration at exposed locations, a phenomenon little understood even as late as 1940 in the USA when Tacoma Narrows Bridge failed in a moderate wind soon after opening.

From 1813 shallow catenaries were proposed by Brown and Telford, Brown's with a mid-span deflection from the horizontal chord line of 1/25th span for a Runcorn Bridge proposal, believing this curvature and the high chain tension required to achieve it, with side railings, would minimise vibration. But, all considered, it is as well the bridge was not erected. Modern practice would dictate a deflection of about 1/9th span and strong longitudinal and transverse deck stiffening. These early designs were largely based on experiment before a theoretical approach began to be developed by Davies Gilbert at Menai Bridge from 1821 (Provis, 1828).

In 1813, at his Millwall works, Brown erected a working model of a bridge of about 100 feet span, with a view to extending his chain cable enterprise to suspension bridges. This was probably the model inspected by Rennie that bore carts and carriages *'with very little vibration'* (Rennie, 1819). It was the earliest suspension bridge with eye-bar chains, stronger than small link chains of the same weight, and the prototype for Brown's chain and bridge patents (Brown, 1816-17). This innovation attracted visits from leading French engineers one of whom provided posterity with a detailed drawing indicating a mid-span deflection from the horizontal chord line of about $1/30^{th}$ span and links about 5 feet long. [Fig. 5]. (Dutens 1819, Drewry 1832).

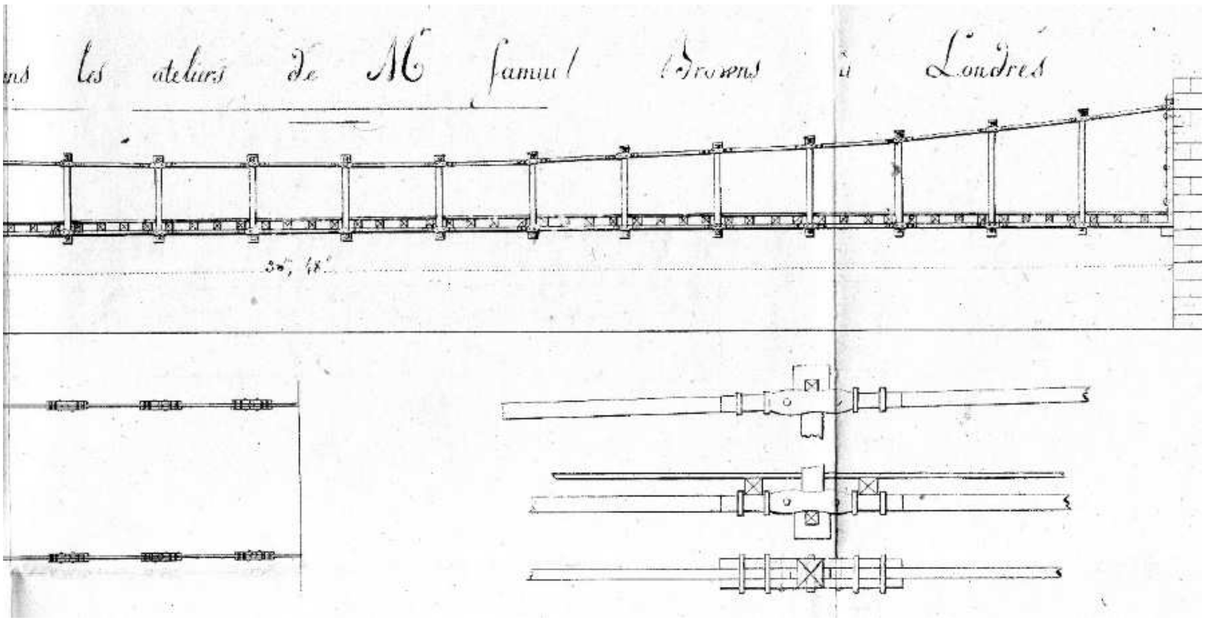

Fig. 5. Dutens's drawing of model chain bridge at Brown's Works ©Paxton

Erection of Union Bridge

The main ironwork comprises single lines of round-bar chain cables weighing about 3 tons, six at each side, formed of 15 feet long by 2 inch diameter, Welsh-made, wrought iron eye-bar links deployed in three pairs, not cross-bolted. They are anchored behind the masonry façade at the English side and into two large cast iron ballast plates 24 feet below ground at the Scottish side, of which a plan signed by Brown has survived (Stevenson, 1821; Paxton, 1999).

The bridge's erection had begun by 2^{nd} August 1819 (or a week earlier?) when Molle laid its foundation stone. Its chains were probably pulled into place using large, man-powered, capstans. The opening was on 26^{th} July 1820 after a short construction period. It was preceded by a 'bridge proving' recorded by civil engineer George Buchanan whose published drawing shows loaded stone carts, a chaise and gig, in all weighing about 40 tons (Buchanan c.1820).

The weight of the suspended part of the bridge was about 100 tons. At its opening the bridge survived a surprise live loading when **about 700 people broke through barriers and surged on to the platform**. The civil engineer Robert Stevenson, of Bell Rock Lighthouse fame, who was present and published an account of the bridge, estimated their weight at about 47 tons and that the total suspended weight of 147 tons induced about 370 tons of chain tension. A link tested at Brown's works (Barlow, 1817), sustained a force of 92 tons (29 tons sq. in.), Stevenson used this stress to calculate the strength of the bridge at 1104 tons, *'a surplus of say 700 tons'* (Stevenson, 1821). In all the bridge cost £7000-£8,000 (*NSA*, 1845), much less than one in masonry, including a present of 1,000 guineas from the trustees.

Knowledge promotion

Technical details of the bridge are given in numerous other publications (Dupin, 1825; Taylor, 1822; Drewry, 1832; Paxton & Ruddock, 1980; McCreath & Arthur, 1985; Miller, 1999; Paxton & Shipway, 2007). Particularly influential at the time in promoting knowledge of Brown's work were those of Stevenson, published by 1824 in German, French and Polish, Dupin and Drewry, author of the first book in English devoted solely to suspension bridges.

More popularly the bridge's achievement attracted considerable press coverage for example in 1820 in the *Kelso Mail* and *The Scotsman*, the latter commending its '*superiority over a* *stone bridge, that, having no support in the middle of the water, it will not be liable to be swept away by floods. To this quarter the advantages are incalculable; in particular, it will save to an extensive district of country seven or eight miles in going for their coal and lime, and will render these articles accessible to them at all times of the year and in all states of the river…'*

In 1823 *The Mirror* [Fig. 6] refers to the bridge as *'one of those extraordinary results of mechanical science which particularly distinguish the age in which we live … the whole works of the Union-bridge were undertaken by Capt. Brown for about £5,000 – a stone bridge must have cost at least four times that sum'*.

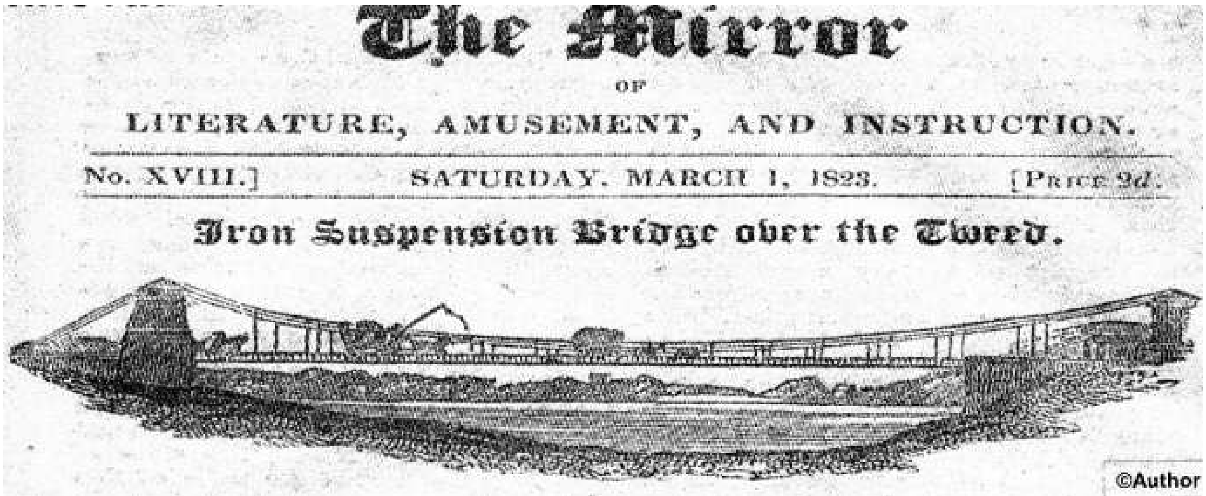
The Mirror
OF
LITERATURE, AMUSEMENT, AND INSTRUCTION.
No. XVIII.] SATURDAY, MARCH 1, 1823. [PRICE 2d.
Iron Suspension Bridge over the Tweed.

Fig. 6. Popular press coverage in *The Mirror* in 1823

Brown's later bridge work

From 1813 to c.1840, Brown had manufactured and erected at least 22 large iron spans, mostly to his own design, more than any of his contemporaries. These included chain piers at Trinity (Leith 3-span) 1821-1898 and Brighton (4-span) 1823-1896, and bridges at Warden 1826, Welney 1826, Hammersmith 1827, Marlow 1829, Montrose 1829, Stockton (railway) 1830, Fochabers 1831, Forres 1831, Aberdeen 1831, Kalemouth c.1835, Kenmare 1838 and 100 Foot River in the Fens. His many unexecuted bridge designs included three approaching the zenith of practicability for bar chains with spans of 780-1000 feet at Runcorn 1817, North and South Shields 1825 and Clifton 1829. (Drewry, 1832). Brown also erected a bridge at his new home, Netherbyres, Eyemouth in 1834. (*NSA*, 1845).

Netherbyres Bridge over the Eye Water had a span of about 142 feet. It was exceptional in that it avoided the need for towers at its ends by resting a timber deck on, rather than hanging from, a pair of 1½ inch diameter eye-bar chains 12 feet apart anchored into abutments. (These dimensions were measured from its remains by the author and Colonel Simon Furness of Netherbyres, whose father had dismantled the bridge in c.1930 when its deck had become unsafe).

Each chain would have had a breaking strength of about 25 tons and a working load of about 10 tons, much of which would have been used in achieving a shallow mid-catenary deflection to obtain user gradients at each end convenient for pedestrians and light carriages. No image of the bridge has been found but, for an idea of its form and possible deck connection, see Fig. 4.

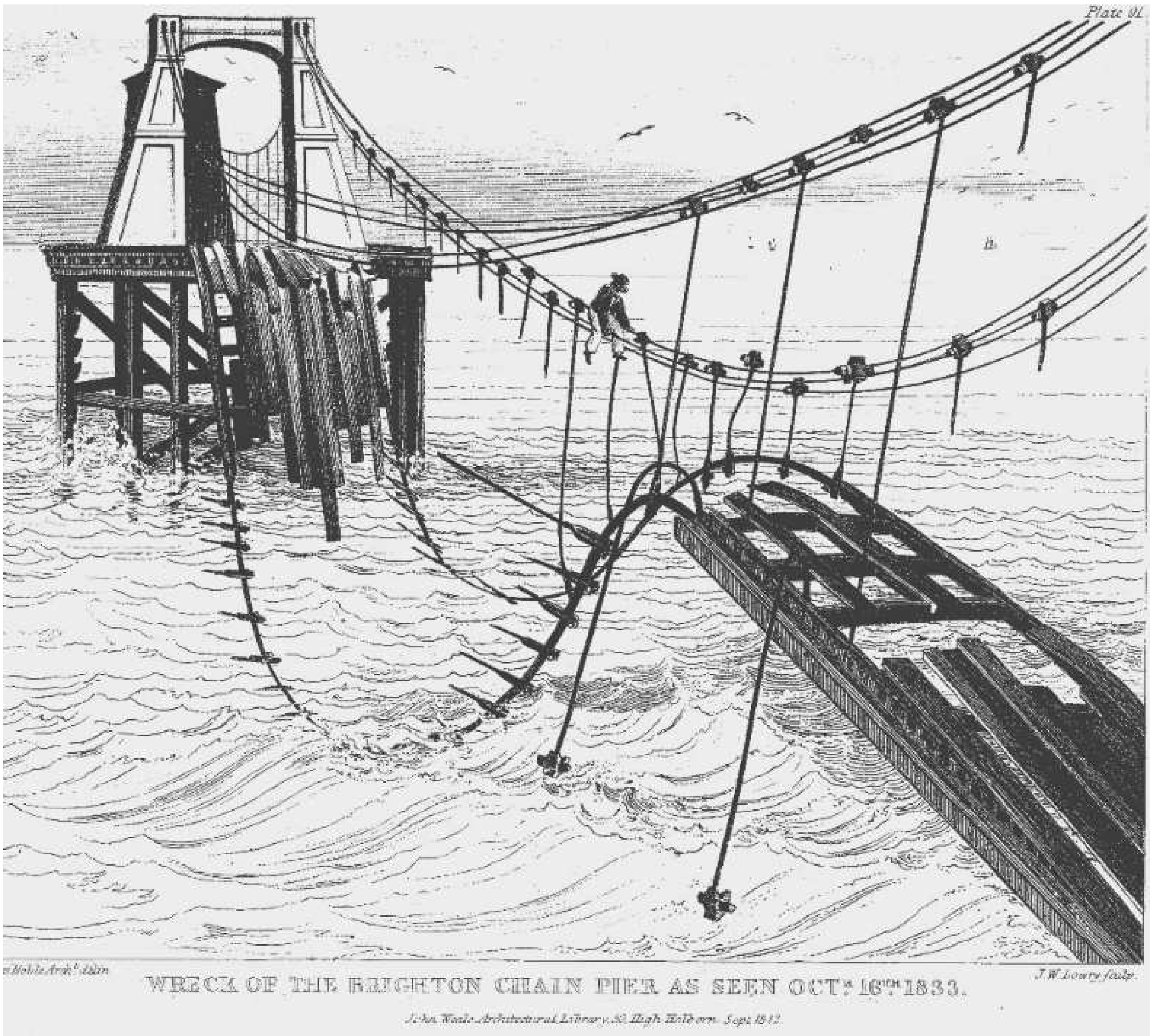

Fig. 7. Brighton Pier. Inspection of storm damage in 1833 ©Paxton

Vibration and oscillation damage

From time to time several of Brown’s coastal structures, for example his prestigious Brighton Pier (Weale, 1843), erected three years after Union Bridge [Fig. 7], also bridges of Telford, Brunel and other engineers, sustained wrecked decks from storm-induced severe vibration and oscillation. Although a relatively minor and resolvable drawback to the advantages of suspension bridges it nevertheless led to a public over-reaction against the bridge type in the UK. This was even though by 1840 Brighton pier had been restored, the deck of Menai Bridge had been strengthened at modest cost and Rendel, at Brown’s Montrose Bridge had introduced longitudinal timber stiffening trusses acting independently of the hangers, a landmark in suspension bridge development (Paxton, 1980 & 1999). Public confidence was partly restored by the completion of Clifton Bridge in 1864 with state-of-the-art iron truss stiffening. But by 1850 the impetus in long span bridge development had already returned to the USA. A smaller version of the Montrose type of timber trussing is still in useful service at Kalemouth Bridge [Fig. 4].

No provision against severe deck vibration was made or, as far as the author is aware, has proved necessary, at Union Bridge which, fortunately, is in a fairly sheltered location. A notable bridge engineer published the canard in 1953 that Union Bridge was blown down six months after erection, probably meaning Dryburgh Abbey footbridge! (Shirley Smith, 1963).

But in 1823 Brown stated of Union Bridge, *'ever since it has been opened the bridge has given entire satisfaction and has been in constant use without any restriction'* (Brown, 1823).

The leading French engineer, Baron Charles Dupin, an earlier visitor to Brown's model bridge at Millwall, when at Union Bridge, noted that the *'oscillations are very inconsiderable and the vibrations, although perceivable produce no inconvenience … the system of masonry is the work of Mr. J. Rennie'* (Dupin, 1825; Paxton & Ruddock, 1980). Other eminent visitors to the bridge included Navier, and the Brunels, both father and son.

Present state

Fig. 8. Union Bridge's 1820 chains with 1903 strengthening cable © Paxton

Some details of the history and maintenance of the bridge over the past 195 years have been published already (Miller, 2006; McCreath & Arthur, 1985; Paxton & Ruddock, 1980), Suffice it to say here that most of the original ironwork is still present and that the bridge's most significant strengthening was made in 1903 by the Tweed Bridges Trust. This was by the addition above the chains of a steel cable and hangers capable of wholly supporting the deck. This arrangement and the present state of the paintwork is shown in Fig. 8.

International significance of the bridge

Union Bridge, the most important of the enterprising Capt. Brown's many creations, when erected, was almost certainly the world's longest bridge span carrying road traffic. It is now also the longest serving in this capacity at 195 years. By example and through widespread promotion, by word of mouth and in publications, it encouraged the erection of suspension bridges for the economical crossing of wide water. It also acted as a catalyst in establishing the UK at the forefront of a new era in bridge-building, overtaking the USA for several decades in providing the main impetus in this activity [see Table]. The table also shows that the UK bridges holding the world's longest span record in the past 206 years were Union, Menai, Forth Rail, and Humber, and universally, with 13 other great bridges.

The prime movers in this impetus in the UK, which began with Brown's introduction into the genre in 1813 of the long iron eye-bar chain, were Telford and himself, acting independently. It was the successful use of this chain at Union Bridge that almost certainly influenced Telford, then finalising the design of Menai Bridge (Paxton, 1980), to adopt eye-bars for its main chains in preference to cables of bundled iron wire or small cross-section bars unproven in use by road traffic and more susceptible to corrosion. Today Union Bridge exemplifies the high quality and longevity of Brown's ironwork. Also, Telford was aware of the high quality and strength of Brown's iron from published strength tests that helped to establish 27 tons sq. in. as the average ultimate tensile strength of wrought iron (Barlow, 1817).

But at Menai, Telford did not apply the chains in single lines using round bar links with suspender caps resting on them as at Union Bridge, or as on Brown's patent drawing, but in a stronger form using five parallel, rectangular-section, plate links nearly 10 feet long cross-bolted to short interconnecting links into which the suspender tops were bolted (Provis, 1828; Telford, 1838).

It was this Menai basic form of chain that was used in many large bridges at home and abroad for the next 70 years. For example by I.K. Brunel (Hungerford), Von Mitis (Danube Canal Vienna), Navier (Paris Bridge), Clark (Budapest), Barlow & Hawkshaw (Clifton, Bristol, 1864), Bouch (Forth Bridge 1877, abandoned 1880), Roebling (Brooklyn, New York, anchorages, 1883) and Wolfe Barry's (Tower Bridge London, side spans, 1894), although by then the use of wire cables had for some time become the norm for long spans.

The success of Union Bridge encouraged Brown to extend the concept to railway use which he did at Stockton Bridge in 1830. Although the bridge proved inadequate for its applied loadings, required deck propping and lasted only just over a decade, it did provide an instructive example at the start of the railway era that suspension bridges were then inappropriate for railway use.

Roebling, Brooklyn Bridge's celebrated engineer wrote in 1867, *'Telford's successful accomplishment of the old Menai suspension bridge was the great feat of those days … his great achievement was mistakenly left unappreciated and greatly undervalued'*. Union Bridge's key role in this feat deserves some appreciation too, which is why it is so important to preserve this precious piece of international heritage.

Fig. 9. Union Bridge in 2015 **©Paxton**

International Recognition

The Institution of Civil Engineers (ICE) through its Panel for Historical Engineering Works and publications (Paxton & Ruddock 1980; Paxton & Shipway 2007) encourages the conservation of outstanding historical engineering works and is supportive of an authentic refurbishment of this bridge. It also supports the *Friends of the Union Chain Bridge* and the aims of Northumberland County Council, stated in a letter to the author of 27 January 2014, *'that together with our colleagues from Scottish Borders Council we remain committed to securing the future of the structure with the ultimate goal of completing its refurbishment prior to the bicentennial celebration in 2020'*.

This process has begun and for the celebration the ICE plans, together with the American Society of Civil Engineers and the support of Northumberland County and Scottish Borders Councils, to recognise the bridge's significance more widely by designating it an ***International Historic Civil Engineering Landmark*** at a joint presidential plaque unveiling.

Readers interested in the bridge's preservation are encouraged to join the *Friends of the Union Chain Bridge*, and to do everything within their power to support the Councils towards its successful and appropriate refurbishment.

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