The evolution of bridge building in Scotland to 1900

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CAST IRON BRIDGES

Cast iron, notwithstanding its tensile and shear stress limitations, made a major contribution to British communications particularly on railways before the development of the wrought iron plate girder from c.1850 in the form of girders, arches, struts and columns. Of the many thousands of cast iron bridges built relatively few survive, a number having been demolished during the past thirty years as a consequence of the contraction of the railway system and modernization. Braid Burn cast iron girder skew bridge (Fig.18) on the former Edinburgh and Dalkeith Railway – although on a modest scale – is of outstanding historical interest as one of the earliest surviving examples of the empirical design practice and technology of the early railway era.

Braid Burn Bridge was one of at least six bridges manufactured and erected by the Shotts Iron Company in 1830 and 1831 under the direction of Jardine. Its main girders, of which there were probably four originally, are 21 ft 7 in long, spanning 17 ft 6 in, with a longitudinally convex top edge, and are of inverted T cross-section. The edge girder which appears shorter (its ends are not visible) has a much greater degree of convexity and is of L cross-section (Fig.19). The convexity of the girders demonstrates an economical approach based on the understandings that the greatest bending strength was required at midspan and that the top flange needed only about one third of the amount of iron in the bottom flange; this latter practice, with some variation of proportion, became almost universal in the following decades. The bridge carried railway traffic until 1968.

Later examples of flat girder bridges exist at Clachnaharry, Inverness (Fig.20) – constructed in c.1861 – and with two spans and parallel top edges at Tanglandford, Aberdeenshire in 1864 (NJ 857375). A frame girder bridge was constructed over the Keltywater near Drymen (NS 535963) in the second quarter of the 19th century and its girders were reused in a footbridge at Gargunnock (NS 706943) in 1975. The girders are about 6 ft deep and unusual in that their upper and lower horizontal members are of tubular form.

The most outstanding achievement of cast iron bridge building in Scotland was undoubtedly the design and construction by Telford of an arch of 150 ft span and 20 ft rise at Bonar Bridge across Dornoch Firth in 1810-12 (Fig.21). The design was of national significance and represented a major improvement in the principles of construction, economy and appearance of iron bridges. By making the elements of the main ribs of equal dimensions cracking was obviated during casting. Telford also avoided the fairly common practice of introducing circles into the spandrels, preferring to transfer the deck loads through the spandrels in the direction of the radii. He introduced roadway deck plates of tray form with 3 in deep edge returns which were cross-bolted to adjoining plates and much stronger than conventional deck plates. The arch was the prototype of at least ten similar arches, mainly of the same dimensions, erected throughout Britain in the following forty years.

The first part of this Paper was published in the June 1983 issue of 'Civil Engineering Technician', on page 8. It deals with masonry bridges and also includes a map showing the locations of all the bridges referred to in both parts of the Paper.

Fig. 18. Braid Burn Bridge (NT 286722)

courtesy Lothian Regional Council

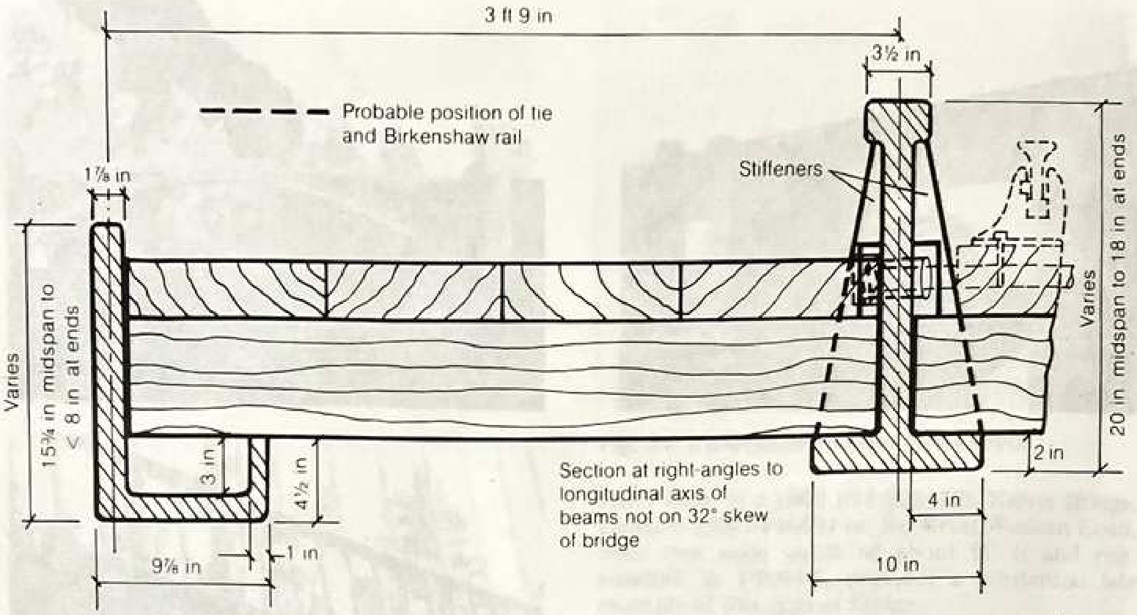


Fig. 19. Braid Burn Bridge — cross-section from edge beam to first main beam

The ironwork consisted of readily transportable parts weighing only 180 tons and it was made and erected by the Salop ironfounder William Hazledine. The four 3 ft deep and 2½ in thick main ribs were assembled first and firmly cross-connected by grated plates in two directions. Cruciform section spandrel connectors were then morticed into the top of the ribs and the deck stringers, followed by fixing of the deck plates and parapet railings (Fig.21). The arch collapsed during the great Highland flood of January 1892, following the fall of the adjoining masonry pier and arch.

The second arch of this type of identical construction and dimensions was constructed at Craigellachie between 1812 and 1815. This outstanding example of Telford's mastery of cast iron with its rustic ashlar and castellated towers still survives, and although it underwent major reconditioning in 1964 its original appearance was carefully preserved (Fig.22). The spandrels, deck stringers and railings were renewed in mild steel but the original main ribs and cross-connecting plates were retained in situ and the original deck plates reused.

The success of Bonar Bridge encouraged the development of iron bridge building generally. An attractively designed and little known example which has survived in its original state is Duchess Bridge on the Buccleugh Estate at Langholm (Figs.22 and 23). This bridge of 104 ft span and 6 ft rise and width was designed by William Keir, Jr, made in Workington and erected in the autumn of 1813. A Telford influence in its gracefully light front elevation is suggested by the combination of cruciform rib type, lozenge spandrels with radial orientation and abutment face and railing treatment. In detail, however, the design differs from Telford's practice and exhibits the independent artistry of its designer. A good example of an industrial use bridge in central Scotland is Cambus Bridge, Clackmannanshire (NS 853940) which is of 65 ft 4 in span, 7 ft rise and 12 ft width.

As the art of bridge-building developed, larger and more intricate castings were used, typical examples being Uddingston Viaduct (Fig.24) constructed in c.1845 with its 3 ft deep plain I section ribs and 95 ft spans, and Carron Bridge, Aberdour, Banffshire which is of about 120 ft

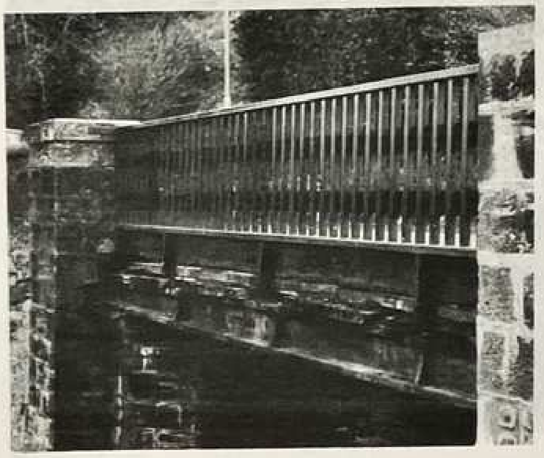


Fig. 20 (left). Clachnaharry Bridge on A9, Inverness (NH 645465); girders cast by the Falcon Foundry, Inverness

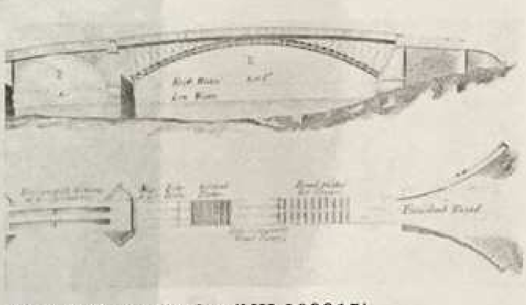


Fig. 21. Bonar Bridge (NH 609915).
9th Report Highland Roads and Bridges 1821

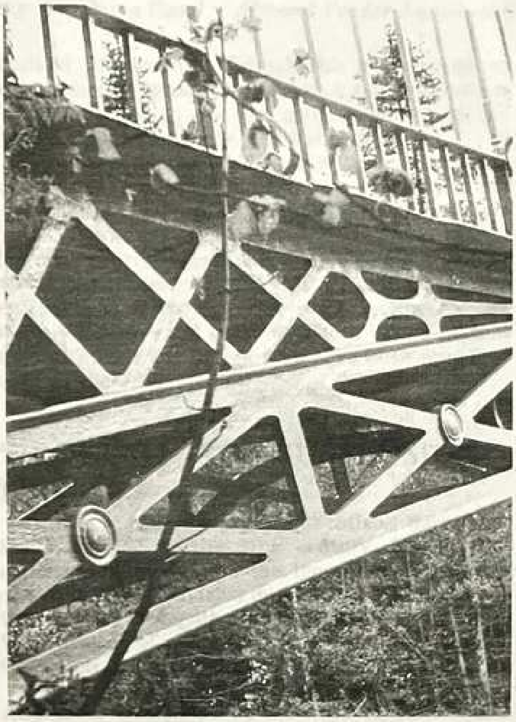


Fig. 22. (Upper) Craigellachie Bridge (NJ 285452); (lower) Duchess Bridge, Langholm rib and spandrel detail

Fig. 24. Uddingston Viaduct (NS 688608)

span, built in c.1863 (NJ 225412). Kelvin Bridge, Glasgow (NS 574669) on the Great Western Road, with two main spans of about 90 ft and constructed in 1889-91, provides a substantial late example of this type of bridge.

Hugh Baird (1779-1827), the engineer for the Edinburgh and Glasgow Union Canal, used cast iron in the aqueduct troughs and although his work did not have much influence on subsequent design practice, being towards the end of the canal era, it differed from English practice and has stood the test of time. Almond Feeder Aqueduct (Fig.25) of 80 ft span and 6 ft width is an unusual development of the flat arch concept; the main beams consist of voussoir frames extending radially to the circumference of the arch 11 ft 7 in high at midspan and cross-bolted through their radiating joints. Baird constructed major aqueducts on the canal at Slateford (NT 220708), and over the rivers Almond and Avon (Fig.26) – in total 25 masonry arch spans of 50 ft up to 85 ft high. The aqueducts are of unusual design in that the water is carried in an iron trough 12 ft 6 in wide, which rests on longitudinal walls with hollow spandrels; the top of the trough is supported internally by A side-frames (Fig.26). A correspondent reported in the *Carlisle Journal* on 8 July 1820 that the trough, not then enclosed by masonry, 'resembles the hull of a vessel of extraordinary length. The sides are formed of large concave iron plates and the flooring or bed is composed of the same material; these are bolted together and the seams

Fig. 23. Duchess Bridge, Langholm (NY 356853)

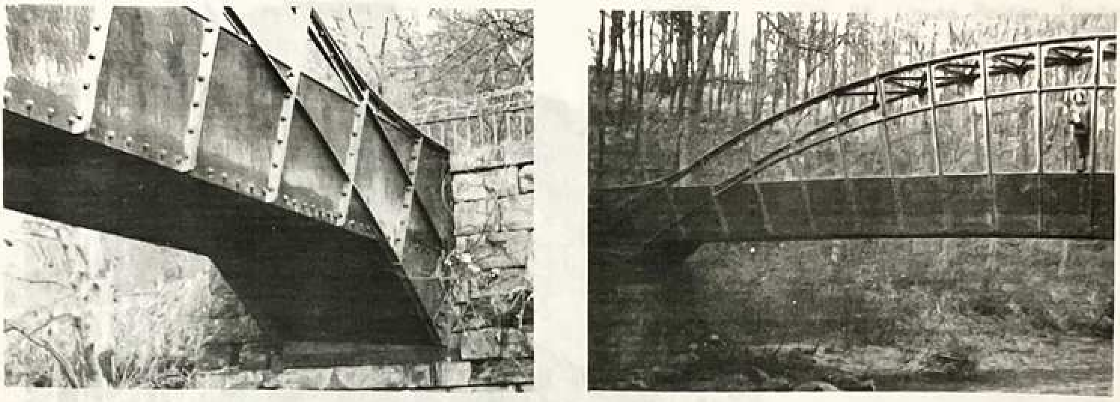


Fig. 25. Union Canal — Almond Feeder Aqueduct (NT 086685)

caulked. On walking through this iron passage an extraordinary sensation is excited and the mind is imperceptibly led to the contemplation of the astonishing improvements of the present age.'

Cast iron superseded timber in the construction of turn bridges. Moy turn bridge (Fig.27) is the last original structure of its type on the Caledonian Canal. It was erected by Hazledine in 1820 and has five parallel rib frames 4 ft 9 in deep and a span of 40 ft. Leith turn bridge (NT 270767) over the entrance lock to the old dock engineered by Rennie and opened in 1806 is to a design of that date although the bridge may have been modified or constructed in c.1853.

WROUGHT IRON SUSPENSION BRIDGES

Iron suspension bridges in Scotland date from the beginning of the 19th century. One of the earliest references is to the temporary footbridge of about 30 ft span used during the construction of the Bell Rock Lighthouse (NO 762270) in 1809. Wire bridges of about 110 ft span were erected at Galashiels in 1816 and Peebles in 1817.

In 1818 an Edinburgh civil engineer James Anderson, influenced by the work of Telford and Captain Brown on the Runcorn Bridge project, made an over-ambitious proposal for a Forth Bridge at Queensferry with 1600 ft spans. It was not erected and the first major suspension bridge

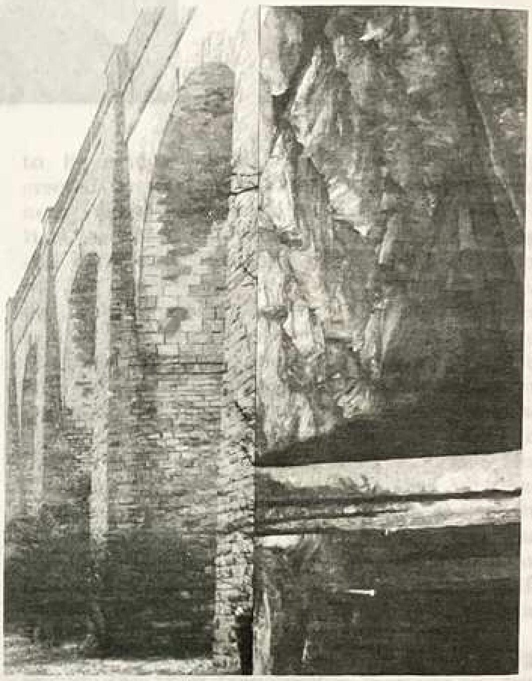


Fig. 26. Union Canal: (left) Avon Aqueduct (NS 966758); (right) Almond Aqueduct — inside hollow spandrel, side of iron trough on right (NT 105707) courtesy Ted Ruddock

Fig. 27. Caledonian Canal — Moy turn bridge and Ben Nevis (NN 162826)

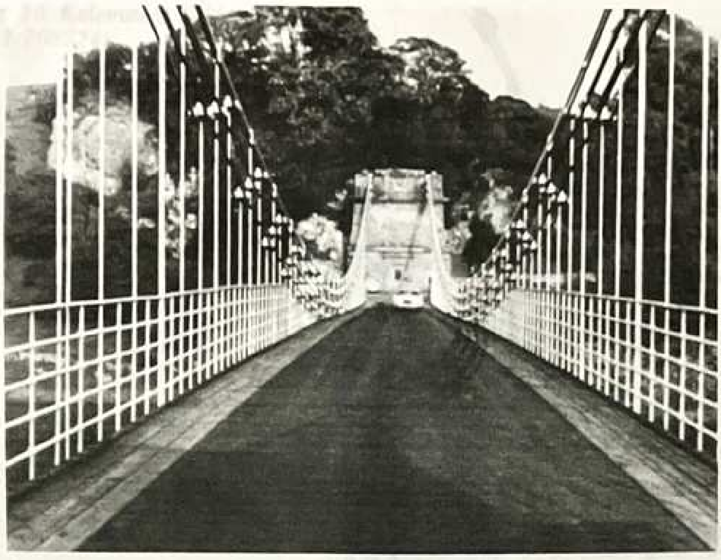
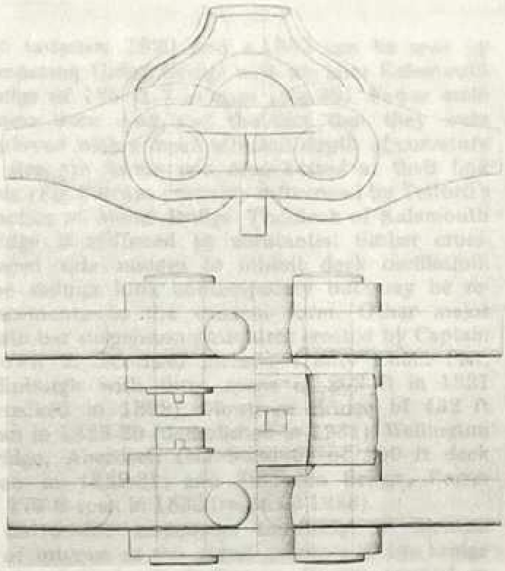


Fig. 28. Union Bridge, Paxton, Berwickshire (NT 934510)



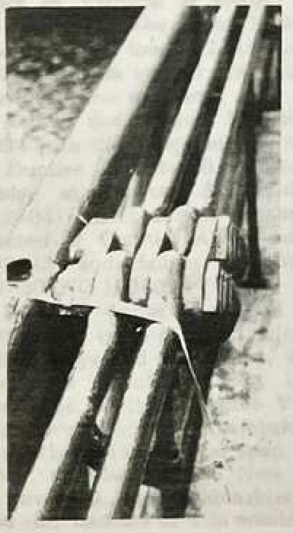


Fig. 29. (Above) Union Bridge — interconnecting link and hanger saddle detail (cross-pins do not connect the two main chains); (left) Kalemouth Bridge — cross-pins connect the main chains

to be completed in Britain was Union Bridge erected by Captain Brown over the River Tweed near Paxton, Berwickshire in 1819-20 (Fig.28). It is the oldest surviving British suspension bridge still carrying vehicular traffic and was a triumph of the newly emerging bridge technology of its day, achieving a span between points of suspension of 437 ft — several times greater than that of the largest masonry span and greater than that of any timber or cast iron bridge. Its success encouraged the building of suspension bridges and influenced the use of bars rather than cables for main chains and suspenders. The bridge was erected in the remarkably short time of about one year and cost approximately £7700 — at the time a masonry bridge would have cost at least £20,000. The ironwork was designed and manufactured by Captain Brown with advice and modifications to the bridge design by John Rennie, particularly in respect of the masonry work.

Features of particular interest at Union Bridge include the 15 ft long by 2 in diameter eye bars which were made in South Wales, the manner in which the chains are carried over the towers and anchored, and the hanger connections. Captain Brown used individual lines of chains in three pairs, one above the other at each side of the bridge. The tops of the hangers are secured into capping clips each saddling a pair of chains (Fig. 29). The chains are anchored to four large cast iron ballast plates, two of which on the Scottish side are 24 ft below the level of the roadway; on the English side they are just above the foundations of the pillar and set nearly perpendicular to the direction of the strain and connected with a horizontal arch of masonry which is dovetailed into the rock. The chains are stopped into the ballast plates by a 3 x 3½ in oval bolt. The steel wire cable on each side above the main chain was added in 1903. The timber deck was last renewed in 1974 and during the past few years defective main chain interconnecting links have been replaced with spheroidal graphite cast iron links.

Developments in Captain Brown's design prac-

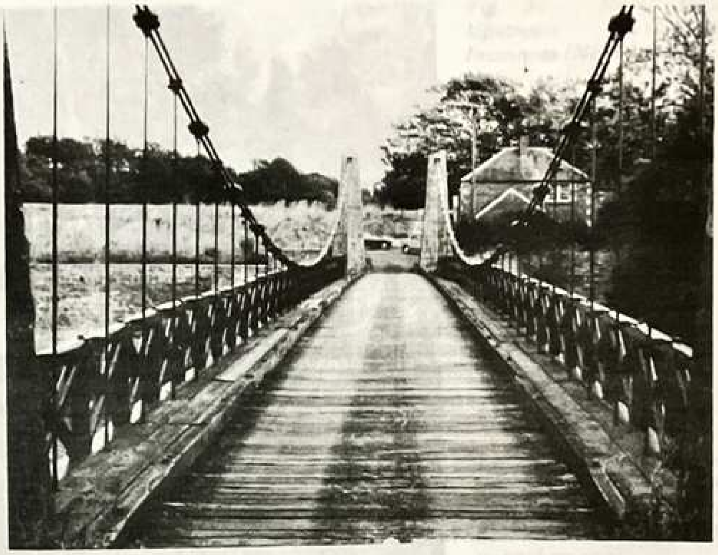


Fig. 30. Kalemouth Bridge (NT 708274)

tice between 1820 and c.1835 can be seen by comparing Union Bridge with his later Kalemouth Bridge of 186 ft 7 in span (Fig.30). Fewer main chains were used and the fact that they were deployed with a more efficient depth of curvature in strength terms and cross-bolted at their link ends (Fig.29) was probably influenced by Telford's practice at Menai Bridge. The deck of Kalemouth Bridge is stiffened by substantial timber cross-braced side railings to inhibit deck oscillation. The railings look contemporary but may be replacements in the original form. Other major chain-bar suspension structures erected by Captain Brown in Scotland include Trinity Chain Pier, Edinburgh with three spans of 209 ft in 1821 (wrecked in 1898); Montrose Bridge of 432 ft span in 1828-29 (demolished in 1931); Wellington Bridge, Aberdeen (NJ 943049) of 200 ft deck span in 1829-31; and Findhorn Bridge, Forres of 270 ft span in 1832 (replaced 1938).

Gattonside suspension footbridge at Melrose is of interest as the oldest example of the bridge work of Redpath & Brown. It was erected in 1826 (Fig.31). The chains consist of 1¾ in diameter eye bars 10 ft long and the main span is 296 ft. In 1928 the firm carried out repairs and refurbished the bridge free of charge.

A local development further north occurred in 1824 with the design and erection by John Justice of Dundee of a stayed cantilever suspension footbridge at Glenisla, Angus of 62 ft span (NO 213603). Later Justice suspension bridges were erected at Crathie, Aberdeenshire in 1834 (NO 267943) and Haughs of Drimmie, Perthshire in c.1830 (NO 170502).

In 1837 James Dredge of Bath developed a distinctive type of economical bridge with inclined stays and suspenders, of which nearly 50 had been manufactured by 1850. Surviving examples in Scotland include Victoria Bridge over the River Oich at Aberchalder, Inverness-shire which is of 146 ft clear span and was erected in 1850, and two of the Ness Islands footbridges at Inverness. The Aberchalder bridge main chain and stay bars are of 1 in nominal diameter varying

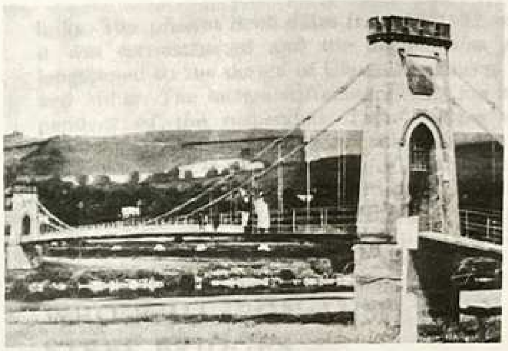


Fig. 31. Gattonside Footbridge (NT 545347)

Fig. 32. Victoria Bridge, Aberchalder (NH 337036)

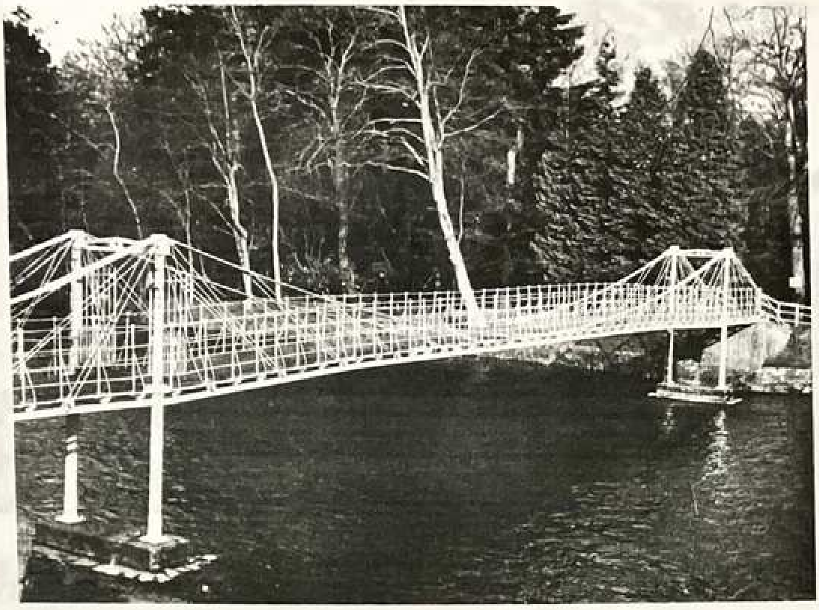


Fig. 33. Ness Islands Upstream Footbridge, Inverness (NH 661436)

Fig. 34 (below). Inverness Suspension Bridge c.1890, demolished c.1960; Greig St Bridge (NH 663454) in background

in length from 6 ft to 7 ft 6 in and increasing in number towards the supports (Fig.32). The iron-work which weighed only about 20 tons was forged and fitted on site. The bridge — one of the largest and most interesting of its type — is now disused and deteriorating. The Ness Islands bridges have spans of 97 ft 3 in (Fig.33) and 83 ft and were erected in 1854.

Following several failures in the 1830s, mainly through the effects of deck oscillation, a period of public disenchantment with suspension bridges set in, but confidence returned towards the mid-century as the matter became better understood as a result of the efforts of J.M. Rendel (1799-1856) and others. Substantial chain bar suspension bridges were erected across the River Clyde at Portland Street, Glasgow in 1851-53 and at Inverness to an unusual design by Rendel in 1850-55 (Fig.34). Portland Street footbridge is of about 414 ft span and 16 ft width with four-bar and five-bar parallel chains of 10 ft x 4 in x 1.125 in links. The present deck dates from 1870-71 when it was reconstructed and the main chains were lengthened to the design of Glasgow engineers Bell and Millar. The lattice stiffening girders are independent of the suspenders. Later bridges were generally constructed with wire cables and wrought iron or were of steel tower and deck construction, with spans in Britain tending to diminish rather than increase. Greig Street Bridge, Inverness erected in 1881 is a good example (Fig. 34).

WROUGHT IRON AND EARLY STEEL BRIDGES

Wrought iron was rarely used in the compression components of early iron bridges — cast iron was preferred on account of its economy and greater strength — although its use was advocated by a Mr Hislop of Fountainhall in 1819 in arch bridges of light construction for country districts. A model

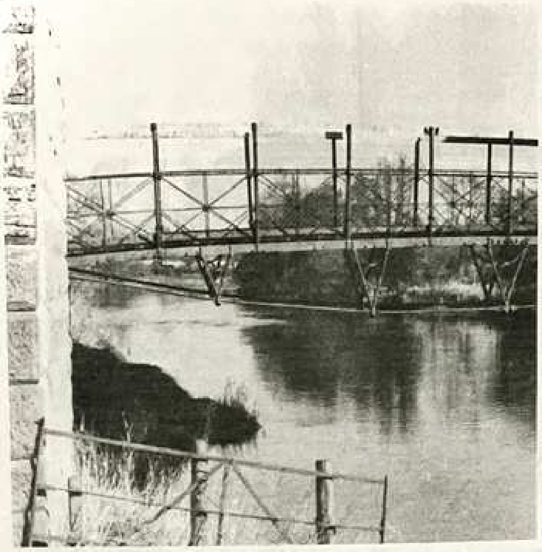


Fig. 35. Roxburgh Viaduct Footbridge (NT 702304)

of his proposed bridge exists in the Royal Scottish Museum, Edinburgh but it is not known if any bridges were erected. Arched or flat beams sometimes also of timber or cast iron were occasionally trussed with wrought iron rods to provide tensile strength, a rare survivor being Roxburgh Viaduct Footbridge erected over the River Teviot in c.1850 which has three spans varying between 49 ft and 52 ft (Fig.35). Its fish trusses, which are simply supported on the cutwaters of the railway viaduct piers, are 4 ft deep at midspan and kept in position vertically by ornamental spacers.

At the approach to the mid-century wrought iron plate girder design and technology was developed by William Fairbairn (1789-1874) and Robert Stephenson (1803-1859) to achieve the

Fig. 37. Tilt Viaduct, Blair Atholl (NN 874652)

Fig. 36. Balmoral Bridge (NO 262949)
courtesy S.K. Jones

Fig. 38. Tay Bridge, Dundee under construction c.1883 — girders being transferred from the 1878 bridge for in situ strengthening and reuse

bridges in the Lothian Region being North Bridge, Edinburgh (NT 258739), designed by Cunningham, Blyth and Westland and constructed in 1894-97 and Victoria Bridge, Haddington (NT 517740). North Bridge, which replaced a 125 year old masonry bridge, has three segmental arches of 175 ft span and 22 ft rise and 4 ft deep plate girder ribs. The facades are of cast iron to a traditional elevation. Victoria Bridge, Haddington, constructed from 1898 to 1900 with 3 ft deep plate girder ribs, is on a much smaller scale and superseded a proposal for reusing some of the girders from the ill-fated Tay Bridge. The slender curvature of its twin 60 ft span arches of only 6 ft rise imparts a pleasing appearance to the elevation.

TIMBER AND CONCRETE BRIDGES

Although timber bridges played a useful part in Scottish communications, particularly before c.1860, their contribution was relatively short-lived in comparison with masonry and iron bridges. Several of the more important timber bridges have been replaced by iron structures.

The construction of concrete bridges was in its infancy at the end of the 19th century. The earliest structures include Glenfinnan and Borrowdale Viaducts (NM 910810 and NM 698855), both of which were constructed in c.1898 in mass concrete. Glenfinnan Viaduct is remarkable for its length and size, consisting of 21 spans of 50 ft, and Borrowdale Viaduct for its 127 ft 6 in central span, believed to be the largest in the world at that time.

Acknowledgements

The Author wishes to thank the contributors of photographs and in particular his co-author Ted Ruddock of 'A heritage of bridges between Edinburgh, Kelso and Berwick' (ICE, Edinburgh; 1981) for the use of material on Coldstream, Kelso and Drygrange Bridges. He also thanks Aonghus Mackechnie of the Historical Buildings Council for Scotland and Mr A.C. Findlay, Factor of the Buccleugh Estates, for information on Duchess Bridge. Peter Mason, Director of Highways, Lothian Region and members of his staff gave much appreciated interest and support; in particular thanks are due to Alan Laughlin for photography and Margaret Young for diagram preparation.

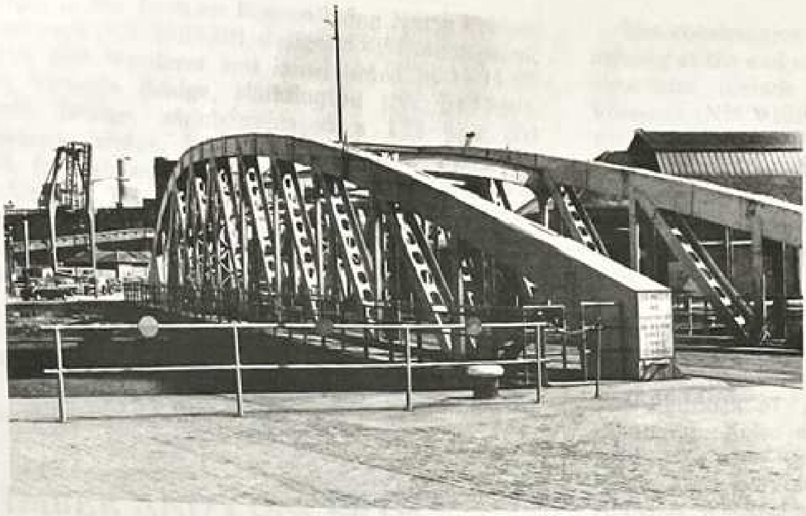


Fig. 39. Victoria Swing Bridge, Leith (NT 271768)

solid-sided tubular bridges at Menai and Conway. Important contributions were made by others including I.K. Brunel (1806-1859). An excellent example of Brunel's work exists at Balmoral. Balmoral Bridge (Fig.36) — a slightly cambered road bridge of 125 ft span and part-lattice girders 6 ft 6 in deep with flanges curved in cross-section — was made and erected by R. Brotherhood of Chippenham in 1856 and completed in 1858. The solid-sided box girder developed into the more economical lattice box girder and frame girder for substantial spans. Dalguise Viaduct (NN 990480) with spans of 250 ft and 150 ft opened in 1862, and Tilt Viaduct, Blair Atholl (Fig.37) of similar construction — both on the Perth to Inverness

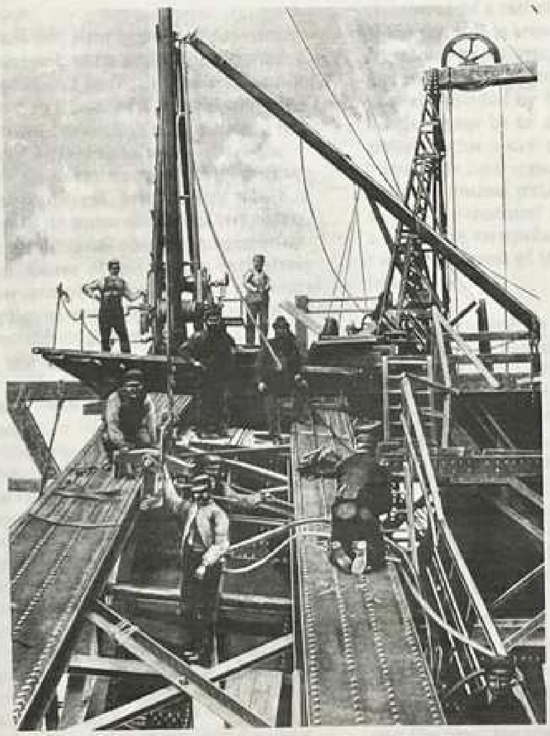


Fig. 40. Forth Bridge — rivetting Queensferry south-west top member in June 1888.
The Engineer 9 November 1888

Railway — were built to the design of Telford's former pupil Joseph Mitchell (1803-83) and are typical examples of lattice girders, as are Stirling Viaduct (NS 798944) and East Linton Viaduct (NT 592771) which replaced a 90 ft timber span strapped with wrought iron and erected in c.1846. Timber spans were not uncommon before c.1850 but rarely lasted longer than 20-30 years. A slender example of a lattice truss road bridge exists at Hutton Mill (NT 921546). It has two spans, one of 54 ft and one of 55 ft, and was erected in 1878 by D and T Stevenson, Engineers, Edinburgh. Economical frame girders were adopted for the first Tay Bridge at Dundee in c.1876 with spans of 129 ft, 145 ft and 245 ft (Fig.38). Victoria Swing Bridge, Leith of 120 ft span was constructed in 1871-74 and was originally hydraulically operated; it is a good example of a different type of girder bridge (Fig.39). For bridges of up to 50 ft span plain plate girders were often used.

From 1885 the use of steel rapidly began to supersede iron in bridge building, the first major British steel structure being the Forth Bridge which was constructed from 1883 to 1890 (see cover photograph and Fig.40). This outstanding bridge was constructed with an ample safety margin on the cantilever and suspended span principle. Its spans exceeded that of Brooklyn Bridge, New York and held the world record for nearly three decades. The principal details of the Forth Bridge are shown in Table 2.

Between 1890 and 1900 numerous steel bridges were built, good examples of large and small arch

Table 2. Principal details of the Forth Bridge

Labour: 5000 men day and night for 7 years
Engineers: Sir John Fowler and Sir Benjamin Baker
Contractor: Sir William Arrol
Cost: over £3500,000
Length: over 1½ miles; two clear spans of 1710 ft and two of 680 ft
Height: 361 ft above high water level to highest point
Depth: deepest foundation 91 ft below high water level
Weight of steel: 51,000 tons
Number of rivets: 5000,000

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