The evolution of bridge building in Scotland to 1900

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INTRODUCTION

The earliest bridges were constructed of timber or stone. The timber bridges have not survived but were almost certainly of small span. The masonry bridges consisted mainly of small semicircular or pointed arch spans. This situation prevailed in Britain for centuries until the Industrial Revolution began to require a major improvement in the poor inland communications system and from c.1760 bridge building techniques developed and span lengths increased. Improvements in iron manufacture led to the development of cast iron arch bridges and aqueducts from c.1779 and c.1794 respectively and wrought iron suspension bridges from c.1810. At that time wrought iron was manufactured in bars and narrow plates and cast iron in bars, plates, beams and larger castings. These developments created an opportunity for more economical construction and longer spans which was effectively taken up by Thomas Telford (1757-1834), Captain S. Brown (1774-1852) and others. From c.1830 onwards cast iron and wrought iron, often in combination, were used extensively in girder bridges on railways. The advent of Nasmyth's steam hammer enabled wrought iron to be manufactured in larger sections and from c.1850 the use of cast iron diminished except in arches and columns.

Improvements in steel manufacture by Bessemer and Siemens eventually resulted in steel, with its superior tensile and adequate compressive strength qualities, superseding the use of iron in bridge construction and manifesting itself to the world in the huge Forth Bridge spans of 1710 ft in 1889 (see Table 1). The application of iron and steel to

Masonry bridges
1. Stirling Auld
2. Merton
3. Fochabers (part iron)
4. Stow Old
5. Cramond Old
6. Coldstream
7. Perth
8. Banff
9. Pease
10. Drygrange
11. Ayr
12. Ancrum
13. Bridge of Dun, Montrose
14. South Esk, Montrose
15. Hyndford
16. Teviot, Kelso
17. Stenhouse Mills, Edinburgh
18. Kelso
19. Dunkeld
20. Cartland Craigs
21. Dean, Edinburgh
22. Musselburgh New
23. Ken, New Galloway
24. Cree, Newton Stewart
25. Pathhead
26. Warriston Skew Viaduct
27. Ballochmyle Viaduct
28. Falkirk Tunnel
29. St Leonards Tunnel
30. Leaderfoot Viaduct

Iron bridges
31. Braid Burn
32. Bonar (site of)
33. Craigellachie
34. Cambus
35. Langholm
36. Bell Rock (temporary)
37. Union
38. Gattonside Footbridge
39. Portland Street, Glasgow
40. Wellington, Aberdeen
41. Kalemouth
42. Slateford Aqueduct
43. Avon Aqueduct
44. Almond Aqueduct
45. Almond Feeder Aqueduct
46. Roxburgh Footbridge
47. Dalguise Viaduct
48. Tilt Viaduct, Blair Atholl
49. Stirling Viaduct
50. Tay Rail
51. Forth Rail (steel)
52. East Linton
53. Victoria, Haddington (steel)
54. Hutton Mill
55. North Bridge, Edinburgh (steel)
56. Victoria, Aberchalder
57. Ness Islands Footbridges, Inverness
58. Moy Turnbridge
59. Balmoral
60. Leith Turnbridges

bridge building after some initial overoptimism in proposed designs resulted in a progressive and dramatic enhancement of span lengths (Fig. 1).

The various materials were applied in different ways. The early stone bridges were designed by architects or stonemasons using stone in compression in the traditional arch form with the dimensions for foundations, piers, falsework, voussoirs and other parts being derived from practice and experience. This procedure largely continued in the latter part of the eighteenth century although some designers applied a theoretical method to determine a more appropriate curvature for the soffit of an arch by taking into account the increasing spandrel weight towards the springings and thus obtaining an 'elliptical' arch. Sometimes the arch ring was increased in depth towards the springing to accommodate the increased thrust. These measures continued and developed in the nineteenth century and although they arguably improved the appearance of bridge elevations, in strength terms, they were usually an unnecessary refinement because of the great surplus of strength of the voussoirs generally adopted.

The important development of the late eighteenth century was the achievement of structures of lighter construction up to the maximum span then practicable of about 100 ft. This span limitation was largely dictated by the inadequacy of contemporary foundation practice in soft or wet ground, although construction had been facilitated considerably by the application of water-wheels and steam engines to pumping. In the nineteenth century, iron piling, steam pile-driving and compressed air working opened up much greater possibilities.

Throughout the nineteenth century masonry bridges continued to be designed in a basically similar way and were constructed in large numbers except where iron or timber structures were more appropriate in design terms or economy. Many timber bridges were also constructed, usually based on traditional designs, but they generally had a short life. For example Fochabers Bridge (NJ 340594), two masonry arches of which were replaced with a single laminated timber arch of 186 ft span following the Moray floods of 1829, lasted only about 20 years and was replaced by the present cast iron ribs and spandrels in 1853.

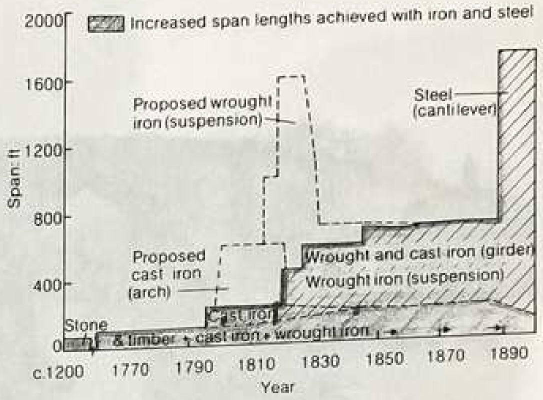


Fig. 1. British bridge span lengths in stone, timber, iron and steel in c.1200-1900

In iron bridge design the method of applying the materials was at first also a practical matter based on traditional designs in masonry or timber combined with the experience and experimental work of individual designers. Knowledge of the strength of materials was in its infancy — often inaccurately quantified and imperfectly applied — although the strength properties of iron were known in broad terms. Wrought iron was used in tension, for example in suspension bridges and for trussing timber beams, and cast iron was used for beams in tension and compression and more appropriately in direct compression.

Between 1817 and 1832 textbooks were published from which bridge designers in iron and timber determined the forms and sectional areas of the various parts of their structures using empirical formulae derived from experimental work and practical experience. However, it was not until the mid-century that a more comprehensive and correct understanding of modern bending theory began to be more generally adopted. In the latter part of the century strength of materials practice improved considerably and theoretical methods were applied in design to a much greater degree, particularly in the analysis of framed structures.

Table 1. Bridge materials, strengths and bridge types in Scotland in c.1200-1900

Material	Breaking stress: ton/in^2			Approximate date used	Bridge type
	Tension	Compression	Shear		
Timber	2-10	*	*	1200-1900	Beam, truss, arch
Stone	1	1-5	*	1200-1900	Arch
Cast iron	6-18	37-65	12	1800-1875	Beam, girder, arch
Wrought iron	13-30	16-18	20-22	1810-1885	Suspension, girder, arch, cantilever
Steel	27-36	26	24	1885-1900	Suspension, girder, arch, cantilever

* No figure available.

Fig. 2 (right). Stirling Auld Brig (NS 797945)

MASONRY BRIDGES

Before c.1760 most masonry bridges in Scotland were built with arch spans up to a maximum of about 55 ft. In the construction of foundations, timber gratings and timber piling were used as necessary in soft or wet ground conditions and foundations were constructed within earth or timber cofferdams. Arch rings were formed on timber centering erected between abutments and piers and on completion of an arch ring the centering was gradually struck, thus allowing the arch to take up a position of permanent stability under its own weight. The spandrel walls were then built up to the required level and the cavity above the arch was infilled with loose stones or earth. Stirling Auld Brig (Fig. 2) with spans of 46 ft, 58 ft, 58 ft, 52 ft and 13 ft 6 in between parapets, although strengthened and reconditioned c.1920, is a good example of a large coursed masonry bridge of an early period. It has triangular cutwaters and rubble masonry protection to the pier foundations.

Stow Old Bridge (Fig. 3) built in 1654-55 for the Kirk Session has a main arch of fairly typical construction for a smaller bridge of the pre-Turnpike era. The bridge is partly a causeway 6 ft 6 in wide and 125 ft long, including three arches increasing in size from 10 ft to its main span of 47 ft. The main arch ring consists of thin undressed stone about 2 ft deep and is of segmental elevation with a 12 ft rise. The spandrels are of rubble masonry. Many Highland bridges from c.1725 onwards were of similar construction although materials, workmanship and dimensions varied. Town bridges tended to be of better quality masonry work.

Another constructional technique common before the seventeenth century was to build each arch of several separate ribs slabbed across with flat stones to support the superstructure. Cramond Brig (Fig. 4) illustrates this practice.

John Smeaton (1724-92), now known as the father of civil engineering, was one of the first bridge builders to engineer his structures and he built major bridges in Scotland at Coldstream in 1763-67, Perth (NO 122238) in 1766-71 and Banff (NJ 695638) in 1772-79. He increased the span lengths of multi-arch bridges into the 55-100 ft range and achieved lighter more uniform and economical designs.

Fig. 3 (bottom left). Stow Old Bridge (NT 458444)

Fig. 4 (bottom right). Cramond Brig (NT 180755)

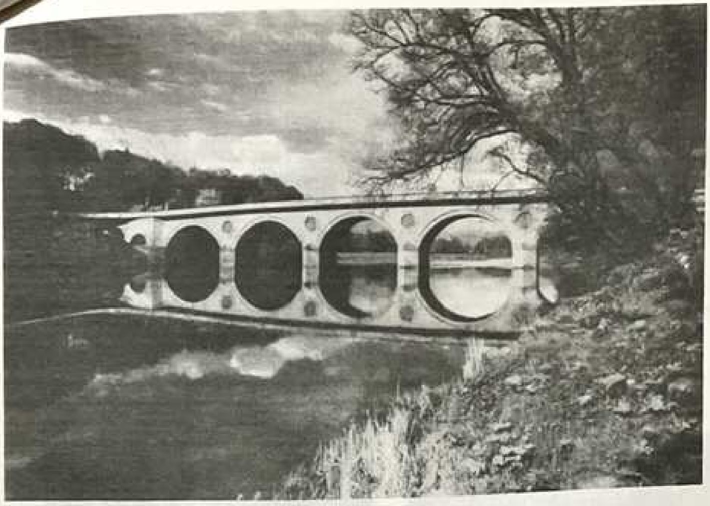


Fig. 5 (left). Coldstream Bridge (NT 848401)
courtesy Ted Ruddock

Coldstream Bridge (Fig. 5) provides a good illustration of Smeaton's practice both in terms of superstructure and foundations. He built all the arches of the same radius so that one set of centres would suffice for all the main arches while a small variation of spans from 58-60 ft 6 in created acceptable gradients down to the river banks. This elevation was the prototype for the seven-arch Perth and Banff Bridges. Ground conditions varied across the river, but rock was nowhere more than 10 ft below the river bed. The foundations of both abutments and the first pier at the south end were placed on rock, but for the two middle piers leakage into the sheet pile cofferdam was too fast and the masonry had to be founded on bearing piles and a grating laid about 3 ft below the bed (Fig. 6). At the position of the northernmost pier the river bottom was bare rock and the pier up to water level was built in an open-topped caisson. However, all these foundations proved insecure in violent spates of the Tweed and it has been necessary to protect them from scour. There has been a cauld (dam) downstream since 1785 and protective 'starlings' round all the piers from an early date, first of rubble stone and now of concrete. The spandrels were originally filled with gravel and earth and by 1828 they were cracked and badly out of plumb and a complete reconstruction with internal longitudinal walls and a clay seal under the road metal was subsequently carried out. At Perth Bridge in 1770 Smeaton introduced longitudinal cavity spandrels thus obviating this problem — a practice that constituted a significant development in the art of bridge building and was often adopted in later structures.

Pease Bridge (Fig. 7) near Cockburnspath, built in 1783 to the design of David Henderson, is a notable early example of a very tall bridge of the Turnpike era of road improvement. Even Telford was impressed by its boldness. It is 19 ft wide and the parapet is 117 ft above the burn. The four arches are approximately semi-circular with spans varying from 41 ft 8 in to 55 ft 6 in. Each spandrel contains an arched cylindrical void 9 ft in diameter to reduce the weight of the superstructure on the foundations — a practice influenced by Henderson's experience of inadequate foundations at Forteviot and North Bridge, Edinburgh in 1769.

Another daring design of this period was Alex-

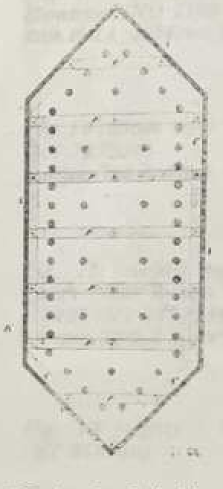
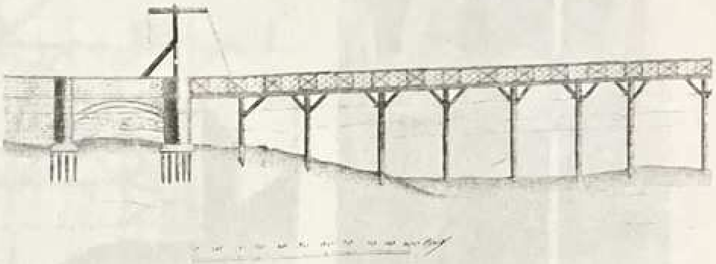


Fig. 6 (bottom left). Coldstream Bridge: cofferdam, pile foundations and grating to pier
Smeaton's Reports: 1812

Fig. 7 (bottom right). Pease Bridge (NT 791699)
courtesy Borders Regional Council



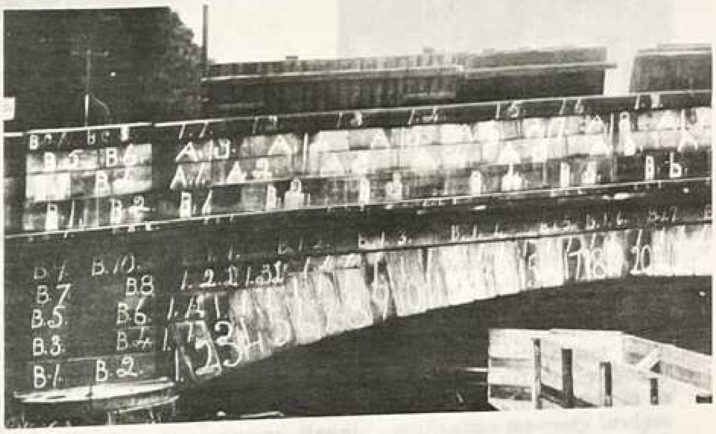


Fig. 8 (top left). Drygrange Bridge (NT 575346) and Leaderfoot Viaduct (NT 574347)
courtesy Ted Ruddock

Fig. 9 (top right). South Esk Montrose (NO 710570)
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Fig. 10 (above left). Kelso Bridge (NT 727336)
courtesy Ted Ruddock

Fig. 11 (middle right). Musselburgh New Bridge widening in c.1925 (NT 342727)
courtesy Blyth & Blyth

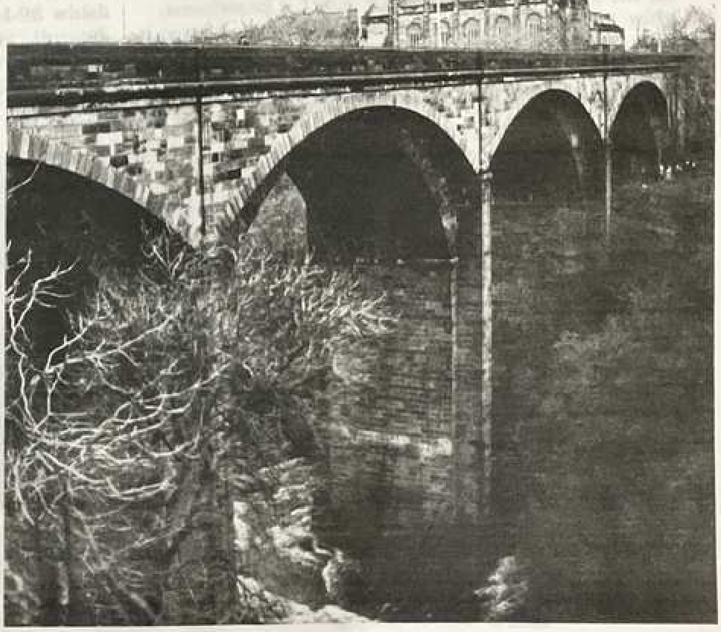
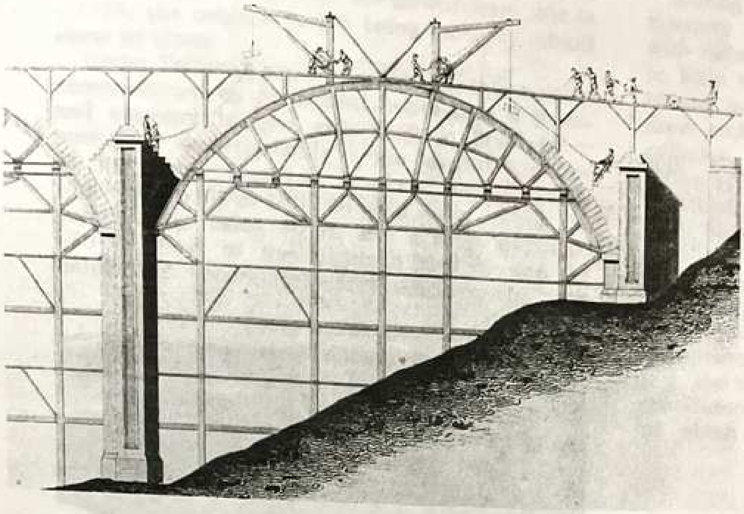


Fig. 12 (right). Dean Bridge (NT 243740)



ander Stevens' (d.1796) three-span Drygrange Bridge (Fig. 8) built in 1779-80 with a middle arch of 105 ft and 34 ft rise. The thickness of the large arch is only 2 ft 6 in at the crown, increasing to 4 ft at the springings — both dimensions being remarkably small for such a large span. Three longitudinal voids were formed in each spandrel. The pier foundations are of large hewn stones all joined by cramps and laid directly on rock; the cutwaters are of the curved and pointed shape preferred by French engineers but still very new to Britain in 1780. The roadway is 16 ft wide between parapets. Strengthening and pointing work has been carried out this century, but little or none of the old masonry has been removed. Stevens built numerous other bridges including Ayr (NS 337223) in 1786-89, Ancrum (NT 638237) in 1784, the Bridge of Dun at Montrose (NO 663585) in 1785-87 and a remarkable 700 ft long masonry and timber crossing of the river South Esk at Montrose (Fig. 9) in 1794-96 which involved driving the timber supports through water. It was replaced by a suspension bridge in 1829 which was in turn replaced by the present Owen Williams' reinforced concrete structure (NO 710570) in 1930. Stevens also designed Hyndford Bridge (NS 914414) in c.1773 and probably the Teviot Bridge at Kelso (NT 720336) in 1794-95.

The next generation of masonry bridge builders in Scotland was headed by Telford and John Rennie (1761-1821). Their period of activity was characterized more by solid achievement in improving the national road network rather than further design innovation, the art of masonry bridge building having reached a zenith point in its development. Rennie's multi-span masonry bridges included Stenhouse Mills in Edinburgh (NT 217716), of which only the parapets now survive, Kelso (Fig. 10) in 1801-04 — one of his finest designs with five elliptical arches of 72 ft span — Musselburgh (Fig. 11) in 1806-08, Ken at New Galloway (NX 640783) in 1811 (rebuilt 1822), Cree at Newton Stewart (NX 412656) in 1812-14, and Cramond (NT 179753) in c.1820 which was demolished c.1962. Kelso Bridge is notable for its correct and bold architectural details — the wide projecting cornice, the perfectly proportioned entablatures and columns, the V jointed arches and the semi-circular rusticated cutwaters. Mussel-

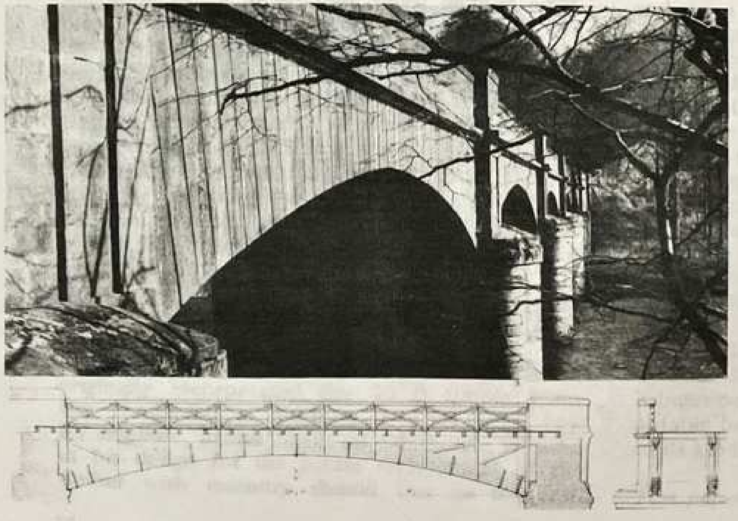


Fig. 13 (top left). Dean Bridge under construction in 1831
from Telford Atlas 1838

Fig. 14 (top right). Dean Bridge spandrel interior at arch extrados

Fig. 15 (left). Mertoun Bridge (NT 610321) with one of its original timber arches burgh Bridge is remarkable for its five low-rise arches. It was widened on the downstream side in c.1923, the original facade being carefully rebuilt stone by stone.

Under Telford's superintendence as the engineer commissioned by parliament, more than a thousand masonry bridges were built in Scotland — mostly in the Highlands — the longest and one of the finest being at Dunkeld (NO 027424) which was built in 1806-08 with seven arches, the middle span being 90 ft, and a total length of 685 ft. Most of the Highland bridges were of simple and economical construction to standardized designs with spans of 4-50 ft. Telford also engineered the Glasgow and Carlisle and Lanarkshire Roads, which were the equivalent of motorways in their day. One of the most dramatic surviving structures on the latter road is the 122 ft tall three-span Cartland Craigs Bridge (NS 869444) with slender piers, built in 1822.

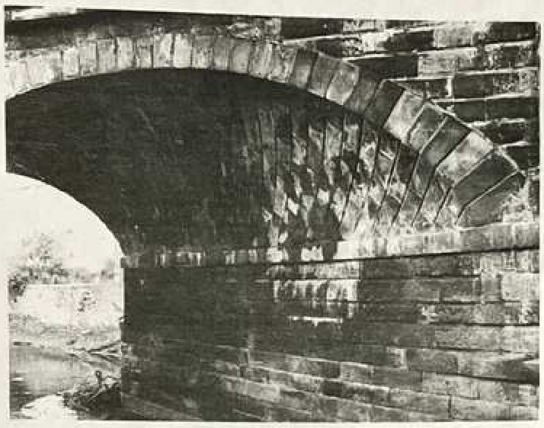


Fig. 16. Warriston Viaduct skew arch, Edinburgh (NT 252754)

Of Telford's town bridges, Dean Bridge in Edinburgh (Fig. 12 and 13) has survived as an outstanding example of the best of his practice. The bridge is about 106 ft high, of strong hollow-box construction, both in its four-cavity piers and its spandrels which incorporate seven parallel longitudinal cavities with masonry cross-ties (Fig. 14). Its external appearance exhibits a lightness of elevation achieved by slender pier pilasters and four shallow external arches of 96 ft span. The method of construction of these arches was unprecedented in that all four arches were supported at the same time solely on their 5 ft square pilasters after the centering was struck, thus allowing any differential settlement in the arches to take place before the main arch spandrels were built up behind. Pathhead Bridge (NT 391645) with five arches of 50 ft span and built to Telford's design in 1827-31 can be considered the prototype for the Dean Bridge elevation.

An interesting masonry road bridge which originally incorporated five 70 ft timber spans was completed at Mertoun in 1841 (Fig. 15). Its engineer, James Slight of Edinburgh, allowed in his design for the future replacement of the timber with masonry should this be required.

During the nineteenth century considerable masonry feats were accomplished in connection with railway development. The skew arch — hitherto little known — came into almost universal use by the mid-century. The beds of the courses of a skew arch consist of spiral lines wound round a cylinder, every part of which cuts the axis at a different angle, the angle being greatest at the keystone and least at the springing. When viewed from beneath the courses appear as straight lines. Warriston Viaduct in Edinburgh (Fig. 16), built in 1841, is an early example. Every stone on the face of the arch is cut to a different angle, thus presenting a neat termination.

Numerous tunnels were built, first on canals (e.g. the 696 yd Falkirk Tunnel (NS 883786) on the Union Canal in c.1820) and then on railways, of which one of the earliest (1827-29) was at St Leonards in Edinburgh (NT 274725) on the former Edinburgh and Dalkeith Railway. The civil engineers for these structures were respectively Hugh Baird (1770-1827) and James Jardine (1776-1858). The St Leonards tunnel is 566 yd long and on a gradient of 1 in 30. It is 20 ft wide with a semi-circular soffit 15 ft high at the centre and is constructed in Craigleith ashlar masonry. The south end can be inspected from Lothian Regional Council's new cycleway/footpath.

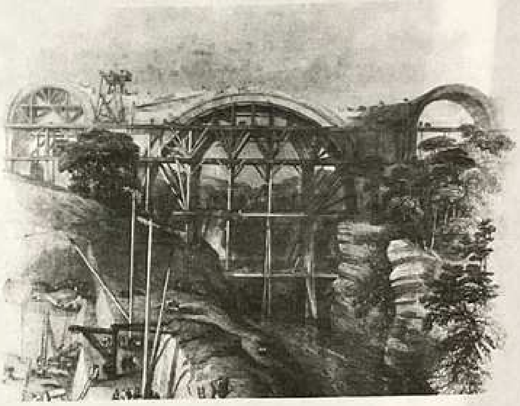


Fig. 17. Constructing Ballochmyle Viaduct in c.1840 (NS 509253) from The Carpenter and Joiner's Assistant by J. Newlands, 1860

Of the many masonry railway viaducts constructed, two outstanding examples which survive are Leaderfoot (Fig. 8) and Ballochmyle (Fig. 17). Leaderfoot Viaduct, with its 19 arches of 43 ft span, is notable for its slenderness and great height from the water level of the Tweed to soffit of the arches (123 ft). It was the major structure on the Berwickshire Railway which was opened in 1865; the engineers were Jopp, Wylie and Peddie. Ballochmyle Viaduct at Mauchline, built by John Miller (1805-83) for the Glasgow, Paisley, Kilmarnock and Ayr Railway in 1846-48, is notable for its central span of 181 ft — the largest of its kind in Scotland.

This paper will be continued in the August issue