of 390 feet, being the largest opening ever spanned by wood.

Coalbrookdale.

Mr Smiles states that the first attempt to build a cast-iron bridge was made in 1755 at Lyons, and that one of the arches was put together in a builder's yard, but that the project was abandoned as too costly. Mr Abraham Darby, the owner of iron-works of Coalbrookdale, was the first person who actually erected a cast-iron arch. This bridge (fig. 120) crosses the Severn by a span of 100 feet, near the town of Ironbridge, which has sprung up in the neighbourhood. Each of the ribs consisted of two pieces. The design is a bold and original one, and has been practically successful. Wearmouth Bridge, completed in 1796, is an arch built of open cast-iron panels, acting as voussoirs; the span is 236 feet, with a rise of 34 feet; the springings begin 95 feet above the bed of the river; and the width of the bridge was 32 feet. It contained 214 tons of cast-iron and 46 tons of wrought iron. The name of Thomas Paine, the well-known author, has been associated with the design of this bridge; but Mr L. D. B. Gordon (first Professor of Engineering in Glasgow) assures the writer that after careful investigation he finds that Rowland Burdon, member for the county, was engineer, architect, and paymaster for this remarkable bridge. It was repaired and widened by Robert Stephenson in 1858. The bridge erected by Telford at Craigellachie (fig. 121), over the Spey, in the beginning of this century, shows a great advance in the conception of what was the safest form in which to apply cast-iron to an arch.

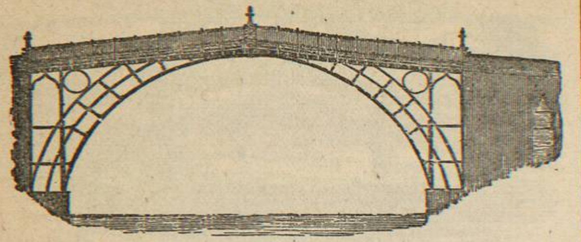

Fig. 120.—Coalbrookdale Bridge.

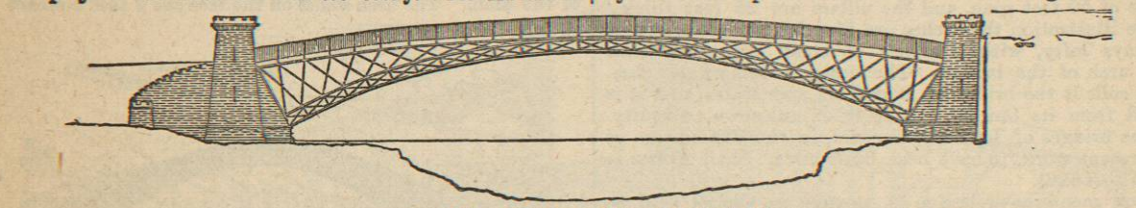

Fig. 121.—Cast-Iron Bridge at Craigellachie.

Craigellachie.

London Bridge.

§ 77. 1817 to 1845.—*London Bridge and Waterloo Bridge.*—London new bridge (fig. 40, *supra,* and Plate XVIII. fig. 2), is as fine an example of the modern stone arch bridge as can be found. The shape of the arches, the variation in their span, the slight curvature of the roadway, and the simple yet bold architectural details, are combined so as to produce a singularly beautiful structure. It is now insufficiently wide for the traffic it has to convey, but all who value beauty must earnestly desire that it may not be disfigured by having overhanging footpaths fitted to it as has been frequently proposed. London can well afford to pay for new bridges, but can by no means afford to part with a single object of real beauty.

The design was made by Mr George Rennie, and the acting engineer was his brother, Sir John Rennie. The centre arch has a span of 152 feet, and rises 29 feet 6 inches above Trinity high water mark; the arches on each side of the centre have a span of 140 feet, and the abutment arches 130 feet. The total length of the bridge is 1005 feet, its width from outside to outside 56 feet, and height above low water 60 feet. The two centre piers are 24 feet thick, the exterior stones are granite, the interior, half Bramley Fall and half from Painshaw, Derbyshire.

The voussoirs of the centre arch (all of granite) are 4 feet 9 inches deep at the crown, and increase to not less than 9 feet at the springing. The general depth at which the foundations are laid is about 29 feet 6 inches below low water. Seven years and a quarter were spent in the construction of London bridge, which was opened in 1831. The total cost was £1,458,311, but the contractor's tender for the bridge alone was £425,081.

Waterloo Bridge, Plate XVIII. fig. 3, is another fine structure of the same character (1817).

Southwark Bridge.

Introduction of Suspension Bridges.—It will be observed that from the earliest ages in which we have records of the construction of permanent bridges until very lately, the stone or brick arch has been the structure principally relied on. Timber bridges more or less permanent have also been employed for great spans, as in the noble bridges erected by the brothers Grubenmann (1757); and after the construction of the bridge at Coalbrookdale (1777) cast-iron was not unfrequently employed in England. The theory of the metal arch was, however, very imperfectly understood, and the great metal arch of Southwark bridge (completed 1819), Plate XVIII. fig. 4 (largest span 240 feet), is little more than a heavy and wasteful imitation of a stone ring. By the use of timber or cast-iron instead of stone, the opening which a bridge could span was, however, somewhat increased. An immense stride in this direction was made when suspension bridges were introduced. A bridge of this kind over the Tees, 70 feet in length, was built in 1741 for the use of miners. Similar bridges are also said to have been used by Mr Finley in America, but the introduction of the modern suspension bridge practically dates from about 1820. (Galashiels bridge, 112 feet in length, was constructed in 1816 also a bridge of similar dimensions at Peebles over the Tweed). In 1819 Telford began the construction of the Menai suspension bridge (Plate XIX. fig. 2), in which the span of the catenary is 570 feet and the dip 43 feet. The success of this structure led to the construction of many other large suspension bridges, as at Fribourg (span 870 feet), Hammersmith (span 422 feet), Pesth (span 666 feet). This form of bridge was not, however, found suitable for railway traffic; and on the introduction of railways engineers were for many years dependent on stone, brick, or cast-iron arches.

Britannia Bridge.

§ 78. *Britannia Bridge,* 1845.—The design by Robert Stephenson of a bridge to carry the Chester and Holyhead Railway across the Menai Straits led to a complete revolution in engineering practice. Mr Stephenson's first conception was that of a tube partly carried by chains. This would have practically been a suspension bridge stiffened by a girder. Under Mr Stephenson's directions, experiments and calculations on the strength and best form of tubes were made by Mr William Fairbairn (Sir William Fairbairn) and Mr Eaton Hodgkinson. In the course of the experiments it was found that the tube could be made self-supporting over the desired span of 460 feet; and in consequence of this discovery the Conway and Menai tubular bridges were built, being the first great examples of properly designed girders. Some disputes arose as to the real inventor of these bridges. Sir William Fairbairn justly claimed the great merit of first perceiving that the girder might be self-supporting. Mr Hodgkinson had, perhaps, the smallest part in the design, but the shares of Fairbairn and Stephenson respectively cannot be very rigorously apportioned; nor is this now of much consequence. Both engineers were men of extraordinary merit, and co-operated in producing the great revolution in practice which has led to the adoption of the wrought iron girder as the most common type of bridge. The first train passed through the Britannia Bridge in 1850. The following description of the structure appeared in the 8th edition of the present work. It will be seen that this description is to some extent a defence of the design against criticisms asserting that the structure was unnecessarily heavy and costly. It is true that a considerably lighter bridge could now be built, but some prudence in introducing so great a novelty was certainly commendable.

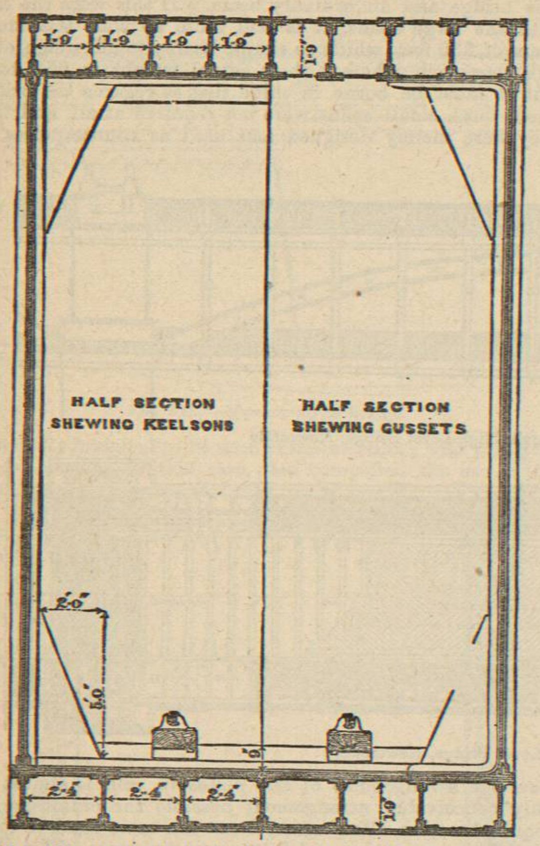

Fig. 122.—Britannia Bridge (Cross Section of Tubular Girder).

"The Britannia Bridge which carries the Chester and Holyhead Railway over the Menai Straits (figs. 122 and 123, and Plate XIX. fig. 1) consists of two independent continuous wrought iron tubular beams, 1511 feet in length, and weighing 4680 tons each, independent of the cast-iron frames inserted at their bearings on the towers. They are 15 feet wide, and vary in depth from 23 feet at the ends to 30 feet at the centre. They rest on two abutments and three towers of masonry at a height of 100 feet above high water. The roadway is laid along the bottom, viz., one line of rails in each tube. The centre or Britannia tower, which is altogether 230 feet high, is built on a rock in the middle of the Straits. The bridge has thus four spans, viz., two spans of 460 feet over the water, and two spans of 230 feet over the land. On each side the weight of a single span of 470 feet is 1587 tons, and of a span of 242 feet 630 tons. These tubes repose solidly on the centre tower, but repose on roller beds on the land towers and abutments. Now, these gigantic dimensions are by no means the only remarkable features in this work. The opponents of the Holyhead Road had imposed conditions on the Chester and Holyhead Railway which were thought insurmountable with respect to this bridge. The navigation was not to be interrupted—no scaffolding could thus be used—and the clear height of 100 feet was to be retained throughout,—arches being objected to unless the springing and not the centre was at this elevation. The tides set through this portion of the Strait with a velocity of 9 miles per hour, and the quiet water at each turn of the tide lasts but for a very short space of time. The tubes were designed to meet all these requirements; they were so constructed at a considerable distance from their permanent site on the shores of the Straits; they were floated upon pontoons upon these rapid tides to the base of the towers; and they were then drawn up by hydraulic presses to their required height. They were here united through the towers by the insertion of shorter lengths, and ultimately brought into the condition of continuous beams as regards strain, by the means employed for their junction. It is evident such structures would be designed specially for such varied circumstances, for example:—

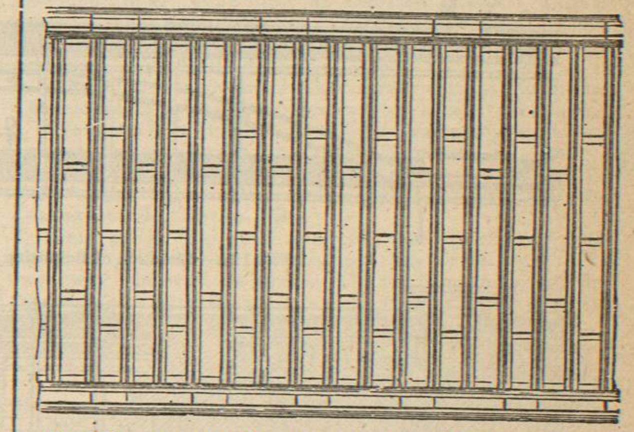

Fig. 123.—Britannia Bridge (Part Elevation of Tubular Girder).

"As soon as they were completed on temporary platforms, these platforms were removed, and they became isolated beams; the ends were accordingly strengthened with cast and wrought iron framing for this special object, and had they always remained there the sides might have been throughout considerably lighter than they are; they now weigh nearly 40 per cent. of the whole weight. But in the next operation, that of floating, the tubes were liable to be supported at *any point* of their length, besides being subjected to chances of considerable distortion, and to disasters which on more than one occasion did actually threaten their entire destruction. The stiffening frames and gussets, which in an ordinary girder would have only been necessary at the ends, became therefore necessary throughout the whole length, and even the top and bottom were considerably modified, as it is evident that while overhanging the pontoons on each end to the extent of 70 feet, the top, instead of being in compression was thrown into extension; the weight of the tubes was consequently much increased by these arrangements. Again, they had to be raised by being suspended freely from four chains. Provision for this suspension from such limited attachment had also to be made of a totally opposite character from that made for their vertical support when on their bed; and, ultimately, when raised to their place, they remained no longer independent beams, but were converted into continuous beams, parts before in tension being now thrown into compression, and *vice versa;* while the ends which were before subject to no horizontal strain were now exposed to greater strain than even the centre of the span. And, last of all, during the act of raising one of these enormous masses, the press from which it was suspended burst, and one end of the beam fell through a space of no less than 9 inches on to a loose uneven heap of planks beneath it, bulging in the bottom plates, breaking all the castings, distorting seriously the sides and stiffening frames; while the broken press itself, which descended from a height of about 100 feet above, broke through the top plates and completed the crippling of the whole section of support. It may surely be doubted whether anything but a tube could have stood such unexampled violence; and in proportioning the parts of a structure destined for such usage, the mere consideration of the strain to which as an ordinary beam it would be subjected, formed but a part of the problem; no direct comparison can therefore be made between the weight of this bridge and an ordinary beam. If this were the case with the large spans, it is still more so with the small spans of 230 feet, which as simple beams would weigh only 230 tons each, whereas their actual weight is 650 tons. But it must be borne in mind that as regards the bridge itself these small spans were not required at all, and that they were merely designed and used as counterpoises for the large tubes, for the important purpose of converting them into continuous beams by their overhanging weight. By examining their detail, it will be found they are designed solely for this special purpose, their use as beams being made entirely subsidiary.

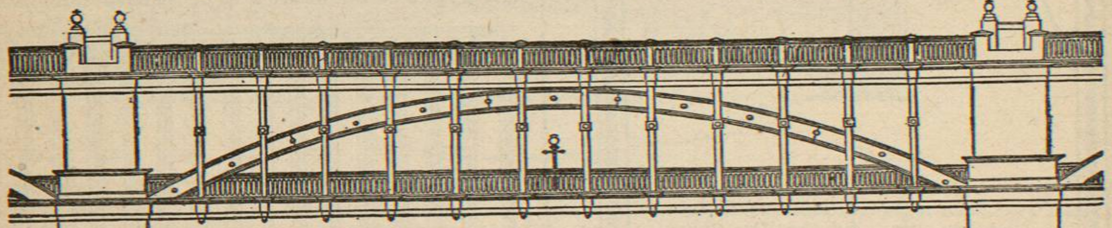

FIG. 124.—Elevation of Bowstring Arch, High-Level Bridge, Newcastle

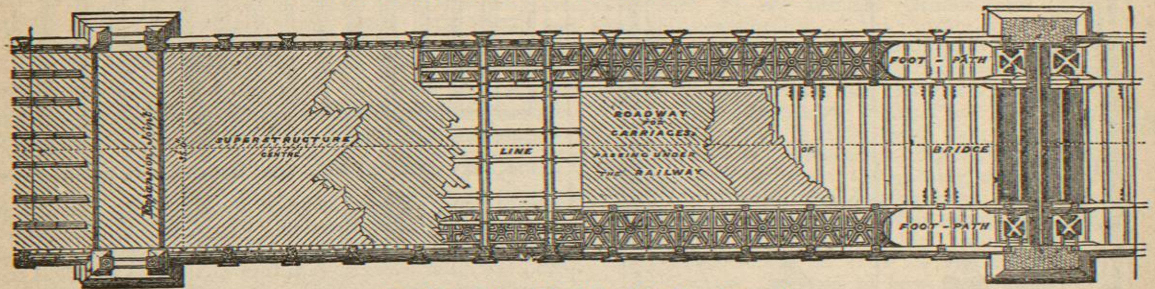

FIG. 125.—Plan of High-Level Bridge, Newcastle.

"Some misapprehension exists on the object and importance of the cells of which the top and bottom of these tubes is composed. These cells are rectangular, there being eight of them in the top and six of them in the bottom, and they run throughout the bridge. With respect to their importance, it must be observed that the whole section of the top of the Britannia tube at the centre is 648·25 square inches, and of the bottom 585·43 square inches, and that the tube is 15 feet wide; the thickness of a single plate to ensure this section would therefore have been 2·7 inches for the top, and 2·3 inches for the bottom; and had such a plate been procurable, nothing better could have been desired, and the cells would be unnecessary. Such a thing, however, is evidently impossible, and the engineer in this, as in numberless other details, had to adopt what he could obtain; now the arrangement of the plates in cells is almost the only conceivable arrangement possible for obtaining the required section, allowing access, at the same time, to every part for construction and future maintenance. This alone led to their use in the bottom of the tube, where their form was totally unimportant. With respect to the top, however, it was of great importance, since thick plates could not be had, to ascertain the best form of cell for resistance to compression that could be devised with thin plates. A series of valuable experiments by Mr Eaton Hodgkinson led to the use of the rectangular cells as actually used, not because such form presented any peculiar advantage over any other form, as some have imagined, but because these experiments demonstrated that cells of that magnitude and thickness were independent of form, and are crushed only by the actual crushing of the iron itself; under these circumstances, the square cells were used as the best practical method of obtaining the sectional area required.

"Similar misapprehension also exists as to the considerations which led to the rectangular form of the tubes

themselves. Now, the result of direct experiments made with round, oval, and rectangular tubes—there being precisely the same section and weight in all three, and, consequently, different depths—was, that the circular tube was the weakest, and the oval tube the strongest, the rectangular form being intermediate. The oval tube was, indeed, first studied with a view to its use. Its form, however, was not favourable —neither for its actual construction, nor for its connection with the suspension chains which were originally intended to be used in the erection; and practical considerations, in this case, also compelled the use of the rectangular tube. It must also be remarked, that the result of experiments made on round, oval, and rectangular wrought iron tubes, when reduced to the same depth and compared, was in favour of the rectangular form, although within ordinary limits the form was not proved to be a matter of very great importance. It may be added, that this bridge has now been in use six years, that the deflection has been carefully tested, from time to time, with the utmost precision, and that not the slightest perceptible increase has taken place during that period. The care with which the painting has been attended, and the protection afforded by the roof, have also entirely preserved it from the slightest damage by oxidation; and it is difficult to conceive that even the lapse of centuries can in any way affect such a structure, or to doubt that it will remain one of the most durable, as it certainly is one of the most remarkable monuments of the enterprise of the present century."

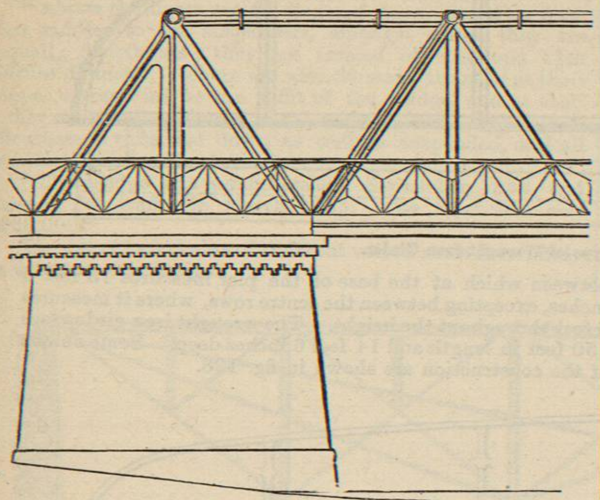

FIG. 126.—Newark Dyke Bridge.

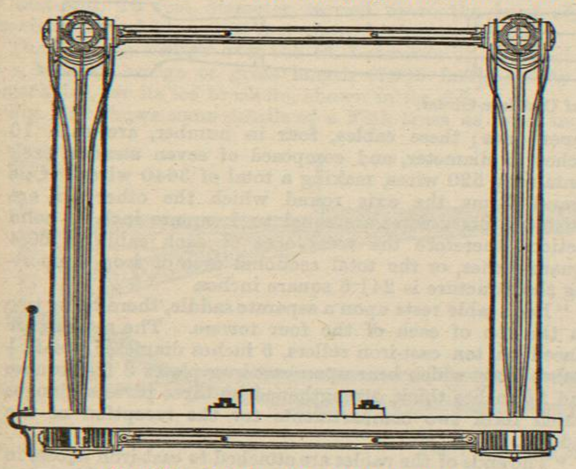

FIG. 127.—Section of Newark Dyke Bridge.

§ 79. *Newcastle High-Level Bridge. Newark Dyke Bridge. Crumlin Viaduct.*—The High-Level Bridge at Newcastle (figs. 124 and 125, also Plate XIX. fig. 3) is a fine example of the true bowstring arch, in which there is no cross bracing. This bridge is also described at great length in the 8th edition; but the type cannot be recommended for imitation, being essentially more expensive and heavier than a true girder. The bridge was opened by the Queen in 1849. The design was therefore made almost at the same time as that for the Britannia Bridge, and is chiefly interesting as showing a transitional form intermediate between the arch and beam. The bridge has six spans, each of 125 feet, and the superstructure is supported on stone piers and abutments, the height to the soffit above high water being 83 feet. The arched ribs are cast-iron, and the ties wrought iron. 4728 tons of cast-iron and 321 tons of wrought iron were employed in the superstructure. There are two roadways, the carriage roadway passing under the railway. The bridge cost £243,000.

The solid or continuous plate girder soon led to the introduction of open frames, designed on similar principles.

Newark Dyke Bridge.

Newark Dyke Bridge (the earliest example of a Warren girder bridge) carries the Great Northern line over a branch of the Trent near Newark. It was erected (1851–53) under the direction of Mr Joseph Cubitt from the designs of Mr Charles Wild.

This bridge (figs. 126 and 127) consists of four independent girders, viz., two for each line of railway. The roadway is beneath the girder. The top flange of each girder consists of a series of cast-iron pipes butting end to end; the lower flange consists of wrought iron links, and the flanges are connected by diagonals forming a series of equilateral triangles, and these diagonals are alternately struts and ties. The ties are formed of wrought iron; and the struts of cast-iron: the length of each side of these triangles is 18 feet 6 inches.

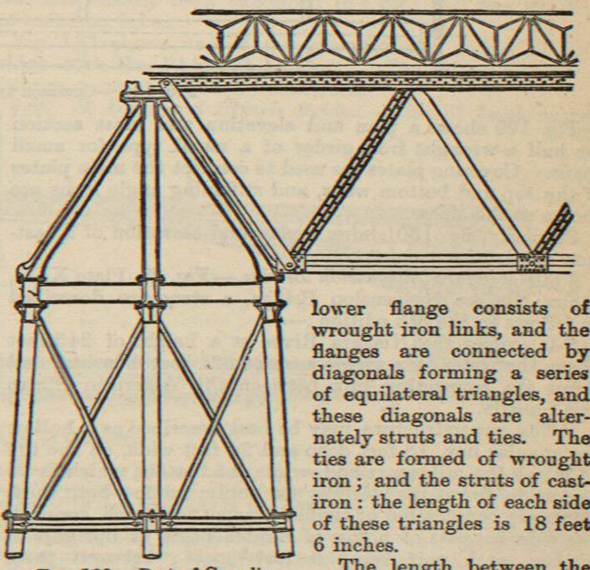

FIG. 128.—Part of Crumlin Viaduct.

The length between the supports is 259 feet, and the depth from centre to centre of the joint pins is 16 feet. The clear span between the abutments is 240 feet 6 inches.

The weight of iron is 244 tons 10 cwt., of which 106 tons 5 cwt. is wrought iron, and 138 tons 5 cwt. cast-