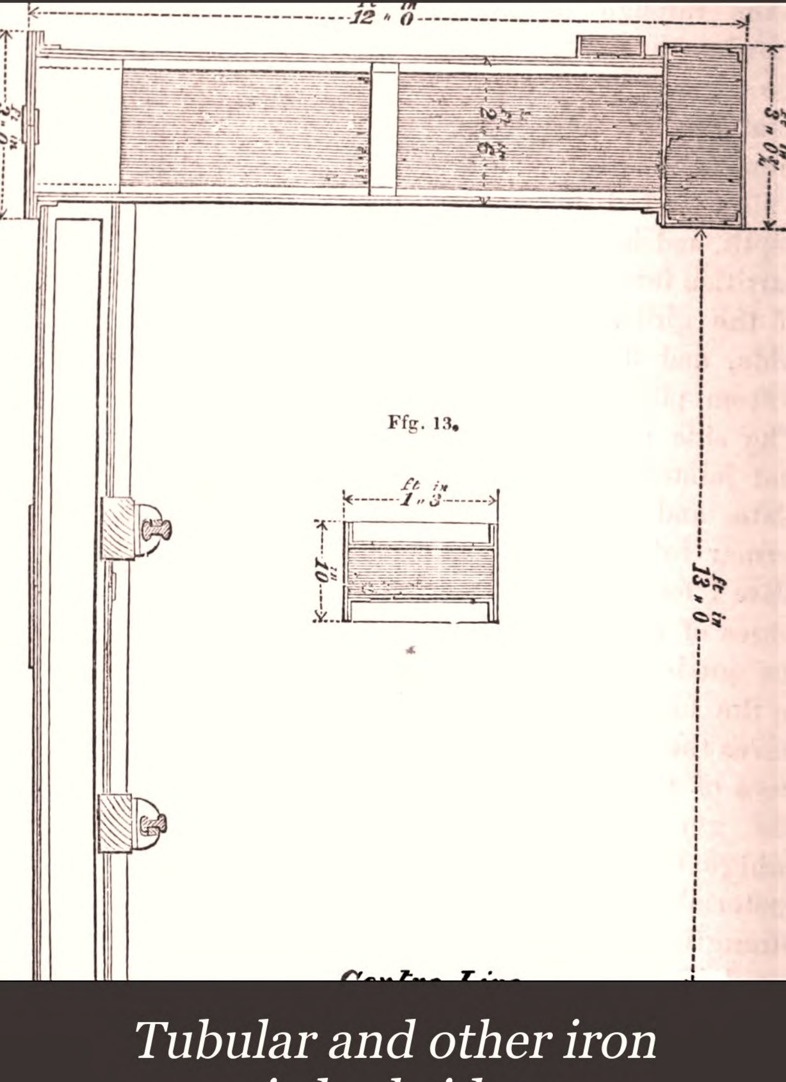

Tubular and other iron girder bridges

George Drysdale Dempsey

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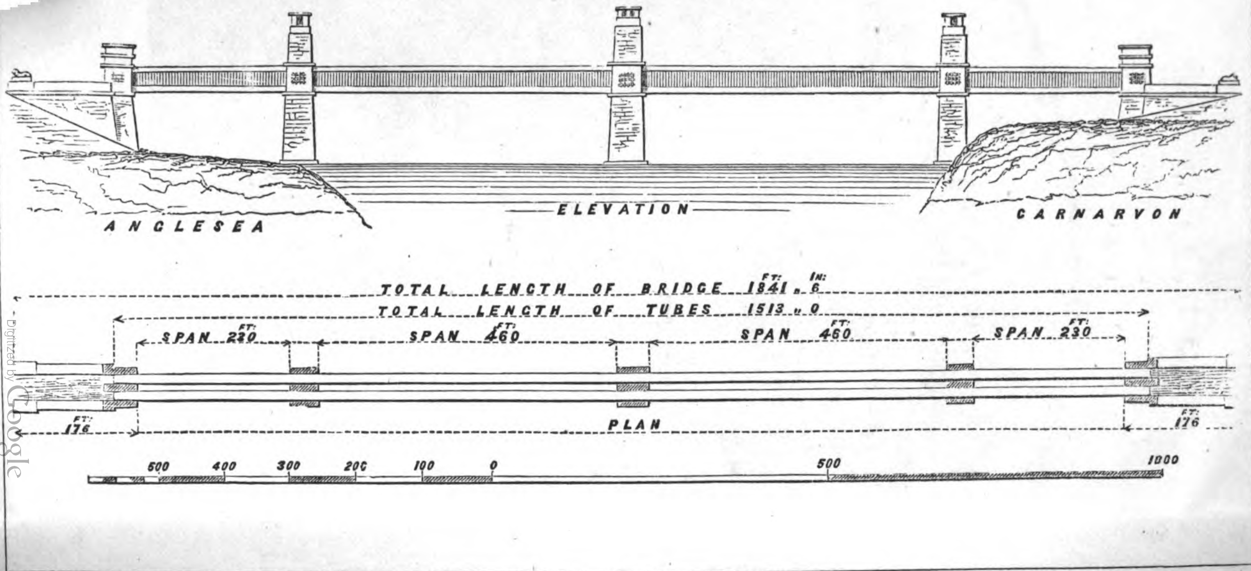
ELEVATION
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CARNARVON
TOTAL LENGTH OF BRIDGE 1841 FT: 6 IN:
TOTAL LENGTH OF TUBES 1513 " 0
SPAN 220 FT:
SPAN 460 FT:
SPAN 460 FT:
SPAN 230 FT:
176 FT:
PLAN
176 FT:
600
400
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100
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RUDIMENTARY TREATISE.

TUBULAR

AND OTHER

IRON GIRDER BRIDGES,

PARTICULARLY DESCRIBING THE

BRITANNIA AND CONWAY TUBULAR BRIDGES;

With a Sketch of Iron Bridges,

AND

ILLUSTRATIONS OF THE APPLICATION OF MALLEABLE IRON TO THE ART OF BRIDGE-BUILDING.

BY G. DRYSDALE DEMPSEY, C.E.,

Author of the "Practical Railway Engineer," "Rudimentary Treatise on the Drainage of Districts and Lands," and on the "Drainage and Sewage of Towns and Buildings," &c.

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CONTENTS.

SECTION I.

Page

Sketch of the History of Iron Bridges—Cast-Iron Arched Bridges—Cast-Iron Girder Bridges — Cast-Iron Compound Girder Bridges, trussed with Malleable-Iron Bars . . . . 1—10

SECTION II.

Malleable Iron—its Manufacture into Plates and Bars of different Sections—The application of Iron Plates in the formation of Steam Boilers — and of Plates and Bars in building Ships, Caissons, &c. . . . . 11—21

SECTION III.

First Constructions of Wrought-Iron Plate Girders—Mr. Fairbairn's Patent Wrought-Iron Tubular Girders—Their application to Bridges-building—Bridge on the line of the Blackburn and Bolton Railway—Bridges of the Liverpool Landing Stage—Great Bridge erected by Messrs. Fairbairn and Sons, on the line of the Manchester, Sheffield and Lincolnshire Railway at Gainsborough . . . . 21—23

SECTION IV.

Malleable-Iron Bridges of different Constructions—Lattice Bridges—Tubular Bow-Bridge—Tubular Girder Bridge, with intervening Arches of Brick-work—Compound Wrought-Iron and Concrete Girders—Combinations of Malleable and Cast Iron in Framed Bridges—Corrugated Wrought-Iron Girders . . . . 33—46

SECTION V.

Chester and Holyhead Railway—General Sketch of the Line—Telford's Holyhead Road—The Menai and Conway Suspension Bridges—Railway Tunnel, Sea-wall, and Viaduct, at Penmaen

Page

Mawr—Parliamentary Proceedings, and Engineers' Reports upon the Communication between London and Dublin—Iron Bridges proposed by Mr. Rennie in 1802—Mr. Robert Stephenson's Design for Cast-Iron Arched Bridges, and selection of Site over the Britannia Rock—Admiralty Opposition, and Mr. Stephenson's consequent Design of the Tube . . . . 46—62

SECTION VI.

General Principles which distinguish Girder Bridges from Arched Bridges—Mr. Fairbairn's Experiments and Report on Tubular Girders—Mr. Hodgkinson's Experiments and Report—Mr. Stephenson's Report . . . . 62—92

SECTION VII.

Description of the Britannia Bridge—The Masonry—Britannia Tower—Anglesea and Carnarvon Towers and Abutments—Arrangements for constructing the Tubes—Main Tubes and Land Tubes—Description of their Construction—Scaffolding and Staging—Arrangements for floating the Tubes—The Pontoons—Raising the Main Tubes—The Hydraulic Press—Connecting the Tubes in the Towers—The Conway Bridge . . . . 92—132

INTRODUCTION.

ENGINEERING Works being usually of a public character, naturally excite a general interest throughout the community, the extent of which feeling is commonly commensurate with the novelty, the magnitude, and the utility of the performance. Thus, a railway, a harbour, a lighthouse, a dock, or a bridge, regarded as subservient to public convenience, is watched with public anxiety, and its completion becomes an occasion of public gratulation. Such a work is therefore a peculiarly suitable subject for one of a series of Rudimentary Volumes, dedicated, in their several features of style, size, and price, to the use of a largely-extended circle of readers and students. And it must be admitted by all that the works which form the main subjects of the following pages have claims of nearly unprecedented amount upon our attention, being new, great, and useful in a pre-eminent degree.

The application of wrought iron to the purpose of bridge-building truly constitutes a new branch of the art, and is, as already proved, susceptible of modifications of form and construction, far more efficient than those of the cast metal. A perfectly horizontal and rigid roadway or railway, 460 feet in length, and having only 3 feet of depth below it, could not be obtained by any other known arrangement of parts than that herein illustrated; and with these successful examples before us, the task of future designing is facilitated to an incalculable extent. For smaller spans the depth of construction may be still further reduced, as shown in the splendid bridge over the Trent, described in this volume; and for the particulars of which we take the pleasure of expressing our obligation to Messrs. Fairbairn and Sons, who have also rendered us much other valuable aid throughout this little work, and thus furnished another proof of their known liberality in acquainting others with the useful and often costly results of their own extended experience.

It is seldom that the invention of works of new design and skilful mechanical arrangement is due entirely to one mind, any more than their construction is due to one pair of hands: hence great difficulty arises in assigning to each contributor his fair share of merit in their production. It must, however, be admitted, that to Mr. Robert Stephenson alone we are in this instance indebted for the original suggestion; and, with this admission, we have endeavoured to avoid any attempt to judge of the precise claims of the two eminent men whose joint labours have produced the Conway and the Britannia Tubular Bridges. That these great works owe their design and construction to these *joint* labours is clearly evident, and, we respectfully submit, amply sufficient to justify the record of the two names of ROBERT STEPHENSON and WILLIAM FAIRBAIRN in an honourable and enduring association.

In order to give a glimpse at the experience which had been had in Iron Bridge-building prior to the use of the malleable material, and to show the defects which this was designed to obviate, a brief sketch of the history of Iron Bridges is prefixed. This is followed by a notice of former applications of malleable iron, with the view of bringing up the sketch to the period at which tubular girders were first used. The description of the works of Telford upon the Holyhead Road is introduced on account of the generally interesting character of those works, and the absence of any account of them within the reach of ordinary readers. While exalting the names and works of our own time, wo can readily afford to acknowledge the claims of those of a preceding age.

TUBULAR, GIRDER, AND OTHER IRON BRIDGES.

SECTION I.

Sketch of the History of Iron Bridges—Cast-Iron Arched Bridges—Cast-Iron Girder Bridges—Cast-Iron Compound Girder Bridges, trussed with Malleable-Iron Bars.

THE employment of iron as a material in the construction of bridges is of comparatively modern date. Seventy years have scarcely elapsed since the first iron bridge was constructed in England over the river Severn, and near to Coalbrook Dale. This bridge was built by Darby, and consisted of five ribs of cast iron, supporting perpendicular spandril pieces of the same material, and upon which the roadway is carried. The arched ribs are nearly semicircular, having a span of 100 feet, and a rise or versed sine of 45 feet. The arches spring at a height of 10 feet above low-water level, and the clear height up to the soffit of the arches is therefore 55 feet. At the time of its construction this bridge must have been duly regarded as a bold and successful work, and its form is well adapted to the high banks of the Severn at the place where it crosses. The design appears to have originated with Mr. Pritchard, an architect, of Eyton Turret, in Shropshire, who, in the year 1773, suggested the practicability of constructing large iron arches, capable of admitting navigation beneath them.

In the year 1787, Thomas Paine, the political writer, presented to the Academy of Sciences at Paris a model of an iron bridge which he had invented; and during the greater part of the following year he resided at Rotherham, in Yorkshire, where a bridge, said to have been *chiefly of wrought iron*, was constructed under his direction by Messrs. Walker, the celebrated iron-founders of that place. This pattern bridge was exhibited in London, and intended for erection in America, but it was subsequently taken to pieces at Rotherham.

In 1790, Mr. Rowland Burdon designed a cast-iron arch for the river Weir at Sunderland, and, in 1792, obtained an Act of Parliament for erecting such a structure. Mr. Burdon's peculiar plan of construction, for which he obtained a patent, September 18, 1795, consisted in "a certain mode or manner of making, uniting, and applying cast-iron blocks, to be substituted in lieu of keystones, in the construction of arches." In this way the patentee proposed to retain the common form and principles of the old stone arch. The Sunderland bridge, as constructed according to this invention, consists of six ribs, 200 feet in span, and having a rise of 30 feet. The total height from low-water level to the soffit of the arch is nearly 100 feet, and the whole structure is distinguished by peculiar elegance and boldness of design. The six ribs forming the arch are placed parallel to each other, and at a distance of 6 feet apart. Each rib consists of 105 separate blocks or castings, 5 feet in depth, connected together with bars and cotters of malleable iron. The ribs are braced together with cast-iron tubular braces and struts. The spandrils are filled in with cast-iron circles, meeting at their peripheries, and supporting the roadway, which is formed upon a strong timber frame, planked over, and covered with a mixture of chalk and tar, upon which a layer of marl-limestone and gravel is laid. The width of the bridge is 30 feet, and the abutments are of stone, founded on rock, and are 24 feet thick, and from 37 to 42 feet wide. The iron-work was executed at the foundry of Messrs. Walker, at Rotherham, and consists of 214 tons of cast and 46 tons of malleable iron. Mr. Thomas Wilson, of Bishop

Wearmouth, designed the architectural features of the bridge, and superintended its erection, which was completed within a period of three years, and at a total cost of £26,000, of which Mr. Burdon, the projector, subscribed £22,000. In October, 1816, the bridge was disposed of for a sum of £30,000 in a lottery, wherein there were 6,000 tickets and 150 prizes, varying in amount from £100 to £5,000 each. The confined situation of the site rendered it necessary to erect the bridge without interrupting the passage of ships with their rigging standing, and this was effected by a perpendicular scaffolding or framing resting upon piles in the middle of the river, and leaving a sufficient passage on each side for the vessels. The centre or transverse framing for supporting the arch was fixed on this scaffolding, and answered its purpose satisfactorily. Some time after the centre was removed, the arch was found to have moved in a horizontal direction eastward, forming a curve of 12 to 18 inches versed sine. This unexpected circumstance, which, if unremedied, would doubtless have led to the destruction of the bridge, was very skilfully counteracted by introducing transverse and diagonal tie-bars and braces, aided by screws and wedges, by which the whole was ultimately restored to its original position, and permanently retained in a substantial state. On July 23, 1802, a patent was granted jointly to Thomas Wilson and Rowland Burdon, of Durham, for "methods of connecting the metallic patent blocks of the said R. Burdon for constructing arches."

Several iron bridges were subsequently erected by Telford, the first of which was that across the river Severn at Buildwas, in Shropshire, consisting of a single arch, 130 feet in span, and having a versed sine or rise of 27 feet. The arch consists of three ribs, placed at a distance of 9 feet apart, or 18 feet wide from out to out. These ribs are 3 feet 10 inches in depth, and connected transversely by tie-bars. The spandrils for supporting the roadway are formed of vertical bars of cast iron, and the abutments are of stone

"The two outer ribs consist of two segments of circles, each struck from different centres, the crown of one terminating immediately below the roadway, the other at the top of the parapet, so that the platform forming the roadway is both suspended and insistent; the object of this being, it is presumed, to increase the depth of the truss supporting the roadway, and thus add to the strength of the bridge: but it was unnecessary, and does not appear to have been adopted in any of Telford's subsequent designs, which are numerous."* Rennie constructed an iron bridge over the Witham, at Boston, in Lincolnshire, which is remarkable for boldness of design and flatness, the rise being only 4 feet, and the span 100 feet. In construction, this bridge resembles the Sunderland bridge, but has an improved arrangement of transverse and diagonal braces, and vertical spandril pieces, instead of circular ones.

The largest iron-arch bridge yet constructed is that over the river Thames at London, and known as the Southwark bridge, which was designed and erected by the eminent Rennie. This splendid bridge, which was opened on March 25, 1819 (the first casting for it having been run on January 1, 1815), consists of three arches, all segments of the same circle, the centre arch being 240 feet in span, with a rise of 24 feet, and the two side arches being each 210 feet in span, with a rise of 18 feet 10 inches. The piers are 24 feet thick; the width of the roadway over the bridge is 28 feet; and the footways on either side are each 7 feet in width. Each arch consists of eight ribs, and each rib is formed of fifteen pieces, which are of such depth that the rib is 6 feet deep at the crown and 8 feet deep at the springing. The metal is 2½ inches thick in the middle, and 4¼ inches at the top and bottom of the ribs. The ribs are connected transversely by cast-iron tie-braces of the same depth as the ribs, but open in the centre of each, and in the diagonal direction the ribs are

* Sir J. Rennie's Address to the Institution of Civil Engineers, Session 1846.

connected by another series of ribs, so that each arch consists of a series of hollow masses or voussoirs, similar to those of stone bridges: the whole of the segmental castings forming each arch, as well as the transverse and diagonal tie-braces, are kept in their places by dovetailed sockets and long cast-iron wedges, by which the necessity for bolts is obviated. The spandrils are composed of cast-iron diagonal framing, and the roadway is formed upon cast-iron plates, resting upon the spandrils, and joined with iron cement.* The abutments and piers of the bridge are of stone, built upon platforms of timber, which rest upon piles, and are surrounded by guard or sheathing piles driven into the bed of the river. In the erection of the bridge, the ribs were commenced in the centre of the span, and continued regularly on both sides towards the piers and abutments. Upon these connecting and bed-plates were secured in the masonry, and when the last segment of each rib was fixed, three wedges of cast iron, each 9 feet long and 9 inches wide, were introduced behind each rib, and nicely fitted and adjusted to them. These wedges are formed with a very slight taper, and were driven simultaneously with heavy hammers, so that the arches were nearly lifted from the centres, which were thus readily removed; and the whole of the iron-work had been so carefully prepared by Messrs. Walker, of Rotherham, and the masonry by Messrs. Jolliffe and Banks, the contractors, that when the work was completed, scarcely any sinking of the arches could be detected. By experiments made during the progress of the works, it was found that the average effect of the expansion caused by the summer increase of temperature was a rise of the arches to the extent of about 1½ inch at the crown, being

* Iron cement, much used in connecting the cast-iron plates of which large tanks or cisterns are often formed, consists of clean iron borings or turnings of cast iron, 16 parts; sal-ammoniac, 2 parts; and flour of sulphur, 1 part. When used, 1 part of this mixture is added to 20 parts of clean borings, and sufficient water to reduce the whole to the consistence of a paste. This cement dries as hard as the iron itself, and forms a joint quite impervious to water.

fixed at the abutments. The weight of metal is recorded as follows: in the centre arch, 1,665 tons; in the two side arches, 2,920 tons; total, 4,585 tons.

The principle of all these iron-arch bridges is identical with that of arch bridges of stone and other materials, which derive their strength and stability by transferring the effect of the loads placed upon them to the abutments. Two requirements are therefore, common and indispensable to all of them, viz. that abutments are obtained of sufficient weight and solidity to withstand the pressure conveyed by the arch, and that sufficient height exists for such an arch-like form to be given to the structure, that the pressure shall be always safely received at the abutments, and the strength of the arch not be in any case wholly dependent upon its depth and section at that part immediately acted upon by the superincumbent load.

When the peculiar properties of cast iron had been studied with a view to its extended application in buildings, and the proportions had been correctly determined for beams of this material, intended to supersede horizontal beams of wood, their employment in the formation of bridges of limited span soon followed; and in the railway works executed during the last twenty years, we have numberless examples of cast-iron girder bridges, as we have also of cast-iron arch bridges, of considerable dimensions and great ingenuity of design and arrangement. The cast-iron girder bridge, depending for its strength upon the sectional area of the girder at that point in its length over which the weight or load acts, requires abutments to resist vertical pressure only, while the abutments of arch bridges have to resist the lateral thrust of the arch. In the cast-iron girder bridge, moreover, the depth of the structure is reduced to that of the section of material due to the maximum load; and hence the peculiar applicability of this form for railway bridges, in which it is desirable to preserve a minimum distance from the under side, or soffit of the girder, to the level of the roadway above. But the limitation of span for which girders are safely applicable has always restricted their employment in bridges, and 40 feet has commonly been considered the maximum length of bearing to which single cast-iron girders can be safely applied, liable to be loaded with railway trains or other heavy weights.

The desire to retain this convenient form of structure, however, and to extend its use to larger spans, induced attempts to combine wrought iron with cast metal in such a manner as should impart to the compound structure the superior power to resist extension, which wrought iron is well known to possess. Malleable-iron bars or rods were, for this purpose, fitted to cast-iron girders, and thus a kind of metal trussing was formed, the depth of the truss being limited to that of the girder. Many railway bridges were erected with these additions, and were considered safely constructed when each girder was cast in two or more separate pieces, making up, when united, the total width of span, and the pieces being secured together by bolts passing through holes in flanges or projecting plates cast on the ends of each piece. One of these cast-iron compound girder bridges, trussed with malleable-iron bars, erected several years since, to carry the Northern and Eastern railway over the river Lea, is formed with girders each 70 feet in length, and composed of two castings, joined at the centre by bolts passing through vertical flanges. An additional security of connection is attained by casting dovetailed projections or bosses upon the meeting ends of the two castings, and by fixing wrought-iron clips over these bosses. Each girder, thus formed of two castings, is perfectly horizontal from end to end, and the top and bottom lines parallel, the uniform depth being 36 inches; the bearings upon the abutments are 2 feet long at each end, and the clear span between bearings is thus reduced to 66 feet. The section of the castings is of the approved form, viz. with vertical rib, and projecting flanges at top and bottom. The truss-bars are arranged in sets, one on each side of the girder, passing obliquely downward from the top of the girder over the bearing at either end, to the under side of the girder, at a distance of about 11 feet short of the centre. This intermediate space of 22 feet has horizontal truss-bars passing beneath, and the horizontal and oblique bars are secured by bolts or pins 3 inches in diameter, passing through projecting saddles beneath the lower flange of the girder. At their upper extremities, these bars pass through sockets cast upon the girders, and are keyed through them. Each set of truss-bars consists of four bars 6 inches wide and 1 inch in thickness. Another bridge of similar construction and dimensions is constructed to carry the York and Scarborough railway over the river Ouse at York.

It is worth while to refer to the great defect of these compound constructions, as it points directly to the superiority of homogeneous fabrics, and, moreover, involves an error in principle which should always be borne in mind in designing works of the kind here referred to. This defect consists in the difficulty, or rather impossibility, of making the two kinds of iron—cast and wrought—act fully together in bearing the load. The strength of cast iron depends upon its rigidity; for although it possesses the property of elasticity, this cannot be tasked with safety, and it is well known that repeated deflections will often destroy a casting which has withstood previous pressures with apparent impunity. Malleable iron, on the other hand, applied in the form of truss-bars to cast-iron girders, is intended to act by the application of its tensile strength, but the effect of this can only be secured when it becomes active *before* the cast girder has suffered any dangerous deflection. It is, therefore, indispensable that the adjustment of the length of the bars during all changes of temperature shall be strictly preserved—a condition which is physically impracticable by any known form of construction or arrangement of parts.

This defect was submitted to a lamentably fatal proof in the failure of the largest bridge of this kind, erected over the river Dee, near Chester, and on the line of the Chester and

Holyhead railway. This bridge, which crosses the Dee at an angle of 48°, consists of three spans or bays, each 98 feet wide in the clear, the three series of girders forming the bridge being supported on two abutments of masonry, one at either end, and two intermediate piers. The width of the bridge is formed by four of these girders, placed parallel to each other, in two pairs, one roadway or railway being supported between each pair of girders, and formed of 4-inch planking laid upon transverse balks of timber, which rest upon the bottom flange of the girders. The girders are secured transversely from moving outward or away from each other by tension-bars, fitted at the ends to dovetailed sockets, cast upon the girders. The entire bridge thus comprises twelve girders, each having a clear span of 98 feet, and a total length of 109 feet; that is, including a bearing at each end of 5 feet 6 inches in length. Each of these girders, 109 feet long, is composed of three castings, or lengths, having an uniform vertical depth of 3 feet 9 inches. The dimensions of the section are as follow: vertical rib, or web, $2\frac{1}{8}$ inches thick; top flange, $7\frac{1}{2}$ inches wide and $1\frac{1}{2}$ inch thick; bottom flange, 2 feet wide and $2\frac{1}{2}$ inches thick. The sectional area of the top flange, including the moulding, is equal to 14 square inches; of the bottom flange, including the moulding, 66 square inches; and of the rib, 80 square inches; making a total uniform sectional area of 160 square inches. The joints of the three castings in each girder, secured by wrought-iron bolts passing through flanges, are strengthened by additional cast-iron joint plates, 3 feet deep at the centre, over the joint, and 13 feet in length, bolted to and scarped over the top flanges of the castings, over a length of 6 feet 6 inches upon each: dovetailed bosses, cast upon the lower flanges, are also secured with clips of wrought iron. The total depth of the girders, at each joint, is thus increased to 6 feet 9 inches. Similar plates, of half the length of those over the joints, are also bolted over the ends of each compound girder; and the vertical inclination of the truss-bars, from the top of the girder at each end to the bottom of it at the joints, is thus increased to about 6 feet. The malleable-iron truss-bars are arranged in sets of four each, one set on each side of the girder, each bar being 6 inches wide and 1¼ inch thick, put together in lengths or long links, similar to those used for suspension bridges, and secured by bolts at the joints of the girders, passing through the cast-iron girder and the eight wrought-iron bars. The upper ends of the bars are secured with wrought-iron keys, driven through the bars and the casting, so as to tighten them well up in their position. By the great length of the girders, and the comparatively small depth thus afforded for the trussing, the action of the bars is reduced to nearly a horizontal direction, and their power to avert deflection in the girders is thus much diminished. Besides this, it must be remarked that the sectional area of the bars is much less when compared with the total length of each girder than in all smaller structures on this principle; and the relative effect of any increase of temperature in extending their length, and thus reducing the effectiveness of their assistance, is similarly augmented. The cause of the failure of one of these girders, which occurred on the 24th of May, 1847, was variously ascribed to a passing train having got off the rails, and to an undue loading of the bridge with additional ballasting; but the inherent weakness of all such combinations of wrought and cast iron in bridges, subjected not only to the action of a dead or merely insistent weight, but to the vastly increased momentum of a rapidly passing and vibrating load, is too apparent to allow of any constant safety in such structures.

We may therefore conclude, that in this last bold experiment, the principle of compound cast-iron girders, trussed with malleable-iron bars, was fully tested to its utmost limits: and the great necessity of seeking a safer construction for bridges, in which the minimum of depth should be equally attained, opened a field for great experiments in engineering construction.

SECTION II.

Malleable Iron—its Manufacture into Plates and Bars of different Sections—The application of Iron Plates in the formation of Steam Boilers—and of Plates and Bars in building Ships, Caissons, &c.

THE duties of the engineer, as imposed in the highest services of his profession, are admitted to involve a constant encounter of difficulties, in order, on the one hand, to surmount natural obstructions of the most formidable character, and, on the other, to adapt such materials of construction as are within his command with economy and success. But the exercise of his genius, thus demanded in bold and discreet design and the skilful application of means, becomes yet more severe when required in the devisal of remedies for failure, by which energy and invention are so liable to have been chilled and prostrated. On this account the name of Robert Stephenson, in its association with the daring experiment described in the first section, and the gigantic design so successfully realised at Conway and the Menai Straits, stands forth as that of one of the greatest among the illustrious of English engineers.

Before proceeding to the description of Tubular Bridges and Tubular Girder Bridges, as composed of malleable-iron plates and frames, we shall find it interesting to refer to other structures formed of these materials, and the previous use of which will help us to understand the history of their application to the purpose of bridge-building.

The manufacture of iron into the forms of plates, and of bars of varied section, is effected by a process of rolling between pairs of rollers, by which any required degree of lamination may be effected in the production of plates, and an infinite variety of sectional forms given to bars of the ductile metal. This invention, in its modern applications, is due to Mr. Henry Cort, of Southampton, who obtained two patents for his improvements in the iron manufacture. The first of these patents is dated January 17, 1783, and the invention is entitled "a method and process of preparing, welding and working various sorts of iron, and of reducing the same into uses by machinery, a furnace, and other apparatus." The second patent is dated February 13, 1784, and is entitled "a new mode and art of shingling, welding, and manufacturing iron and steel into bars, plates, &c., of purer quality, in large quantities, by a more effectual application of fire and machinery, and with greater yield than by any method before attained and put in practice." These inventions are described in the 3rd vol. of the "Repertory of Arts" for the year 1795, and from which the following extract from the patentee's specification is quoted. After describing his process of puddling, Mr. Cort states,—"The whole of the above part of my method and process of preparing, manufacturing, and working of iron, is substituted instead of the use of the finery, and is my invention, and was never before used or put in practice by any other person or persons. The iron so prepared and made may be afterwards stamped into plates, and piled or broke, or worked in an air furnace, either by means of pots or by piling such pieces, in any of the methods ever used in the manufacture of iron from coke fineries without pots. But the method and process invented and brought to perfection by me is to continue the loops in the same furnace, or to put them into another air furnace or furnaces, and to heat them to a white or welding heat, and then to shingle them under a forge-hammer, or by other machinery, into half-blooms, slabe, or other forms; and these may be heated in the chafery, according to the old practice; but my new invention is to put them again into the same or other air furnaces, from which I take the half-blooms, and draw them under the forge-hammer, or otherwise, as last aforesaid, into anconies, bars, half-flats, small square-tilted rods for wire, or such uses as may be required. And the slabe, having been shingled in the foregoing part of the process to the sizes of the grooves in my rollers, through which it is intended to be passed, is worked by me through the grooved rollers, in the manner in which

I use bar or wrought iron, fagoted and heated to a welded heat for that purpose; which manner of working any sort of iron, in a white or welding heat, through grooved rollers, is entirely my own invention." Subsequent improvements have been applied in the rolling and shaping of plates, and the size and power of the machinery employed for these purposes have likewise been considerably extended. As an instance of the great size of which plates are now rolled, we may mention some recently made by the Coalbrook Dale Iron Company, for the bottom plates of steam generators, the dimensions of which were 10 feet 7 inches by 5 feet 1 inch, and $\frac{7}{16}$ inch thick.

Bar-iron is produced by passing bars or strips of the metal between rollers, on the peripheries of which corresponding grooves are cut, so that the space left between the two rollers when brought into contact, or nearly so, is of the form intended for the section of the finished bar. The several forms in which bar iron is thus manufactured are,—the circular section, or round or rod iron; the rectangular section, being square or flat iron; the L-section, or angle iron, which is rolled variously, with sides of equal and unequal length, and with surfaces parallel or tapering towards each other at the edges; the T-section, or tee-iron, having the web and rib of equal or unequal width, and the surfaces parallel or tapering; the double T or ⌶-section, with similar varieties of form.* Besides these general sections, one or more of which is

* The introduction of the double T or ⌶-section appears to belong to Messrs. Kennedy and Vernon, of Liverpool, who obtained a patent, dated April 15, 1844, "for certain improvements in the building or construction of iron and other vessels for navigation on water." The patentees state, that while heretofore iron vessels have usually been framed with L-iron, T-iron, or bar iron, or some modification of these, they claim the introduction of iron rolled in one piece, having a flange on one edge, projecting on one or both sides, for the purpose of strengthening the iron, to be used for the beams of decks and bulk-heads, and for the ribs or frames of the sides of vessels. They also claim the introduction of rolled iron with a rib or flange on one edge, projecting on one or both sides, and a piece or pieces of angle iron or T-iron riveted thereto.

applied in most framed structures of plate iron, there are many other sections prepared for particular purposes, including small bar iron for forming sashes, and the extended variety of sections of larger dimensions, rolled for rails, and used in the formation of railways.

Besides their employment in the manufacture of steam engine boilers, one of the earliest of the modern applications of malleable-iron plates was in the construction of ships,—an art which even yet is still in its infancy, and probably susceptible of improvements that will aid in obviating the objections which have been preferred against it by ignorance and prejudice.

The first iron boat appears to have been constructed by the late Mr. Aaron Manby, in 1820-21, at the Horseley Iron Works, Tipton, near Birmingham. This boat, which was named the 'Aaron Manby,' measured 120 feet in length and 18 feet beam, and when laden drew 3 feet 6 inches water. It was propelled by Oldham's feathering paddle-wheels, worked by an engine of 80-horse power, and, when completed, was navigated across the English Channel by Sir Charles Napier, and continued plying between Paris and Havre for several years. About ten years afterwards four iron vessels were built for the East India Company, by Messrs. Maudslay and Field : these vessels were designed for navigating the Ganges, and each was fitted with oscillating engines of 60-horse power: their dimensions were, 120 feet long, 24 feet beam, and each drew 2 feet water. Wrought-iron boats, besides possessing superior strength and lightness as compared with wooden vessels, are well fitted for the formation of water-tight bulk-heads, which are admitted to give great security in case of accident.

The method according to which iron vessels are now constructed will be best exhibited by describing the construction of one; and for this purpose we select H. M. steam frigate 'Megæra,' just built, and propelled by the screw, for the Government service, by Messrs. W. Fairbairn and Sons

The dimensions of this vessel are as follows:—Length between perpendiculars, 196 feet; extreme breadth, 37 feet 6 inches; depth from under side of deck to top of engine-bearers, 24 feet; tonnage (old measure), 1298 tons; horses' power, 300; (engines by Messrs. Rennie). The keel is 8½ inches deep, and recessed for a depth of 7 inches on each side for the garboard strake. It is 3⅝ inches thick below and 2 inches thick above. The stern is formed by a continuation of the keel, and of the same dimensions as high as the load water-line, above which it is reduced to an uniform bar, 6 inches by 1½ inch. The frames are 12 inches apart midships, reduced to 18 inches apart fore and aft. In midships they are formed of angle iron 5 inches × 3 inches × $\frac{7}{16}$ inch; and fore and aft 5 inches × 3 inches × ⅜ inch. The floors are formed of plate iron 14 inches deep and $\frac{7}{16}$ inch thick, attached to each of the frames. The centre keelson is 18 inches deep and ½ inch thick, and the sister keelsons on each side are 14 inches deep and $\frac{7}{16}$ inch thick. The sheathing or covering plates are as follows:—Two on each side of the keel are $\frac{11}{16}$ inch thick midships, and ⅝ inch fore and aft: bottom plates $\frac{9}{16}$ inch and $\frac{8}{16}$ inch, reduced to $\frac{7}{16}$ inch at the load water-line. The wells are formed of two strakes of ⅝-inch plate. The sides, above the load water-line, are of $\frac{7}{16}$ inch plate, and of ⅜-inch plate midships; and ⅜-inch fore and aft. The riveting is double throughout; the longitudinal joints overlap as high as the load water-line, and above this are worked flush. In the sheathing or covering plates of iron vessels, which are necessarily weakened at the edges by the close rivet-holes, improvements have been designed to compensate for this weakening, by giving an additional thickness to the plates at the edges. Mr. J. G. Bodmer, of Manchester, some years ago patented a mode of doing this, and designed a reversed covering plate to embrace the thickened edges of the two meeting plates, and thus relieve the rivets of part of the lateral strain to which they are exposed. In the 'Grappler,' Mr. Fairbairn adopted she-ing plates rolled with thickened edges, which meet over the centre of the T-iron ribs, and are riveted to them. The importance of these thickened edges may be inferred from the results of experiments on this subject, which showed that the strength of a joint to resist a direct tearing strain is, if single-riveted, only 60 per cent. of the strength of the plate; and, if double-riveted, 75 per cent. In the plates of the 'Grappler,' the edges are thickened in the proportion of about 5 to 3 of the body of the plate; so that the sectional area through the rivet-holes may be nearly equal to that through the body of the plate. This thickening also affords a great advantage in the external evenness of the sheathing, by admitting the heads of the rivets to be countersunk, that is, formed conically, and inserted so as to preserve a flush surface. The sheathing of the 'Grappler' is formed as follows:—In the garboard strake, common plates $\frac{1}{2}$ inch thick, in the longest possible lengths, 15 inches broad, and double-riveted to the keel; the rest of the sheathing of Mr. Fairbairn's thick-edged plates, and of the following thicknesses: bottom plates, $\frac{9}{16}$ inch at edges and $\frac{3}{8}$ inch at centre; lower side plates, $\frac{1}{2}$ inch at edges and $\frac{5}{16}$ inch at centre; upper side plates, $\frac{7}{16}$ inch at edges and $\frac{1}{4}$ inch at centre. The rivets are of the best Low Moor iron, and of the following diameters and distance apart between centres of rivets:—for garboard strake, 1 inch, and 9 rivets per lineal foot, double-riveted; for bottom plates, $\frac{3}{4}$ inch, and 6 per foot; lower side plates, $\frac{3}{4}$ inch, and 6 per foot; and for upper side plates, $\frac{5}{8}$ inch, and 7 per foot, all single-riveted.

Up to the end of the year 1845, upwards of one hundred British vessels are reported to have been constructed of iron, with frames or ribs and sheathing plates; and since that period, many additions have been made in this application of malleable-iron plates and frames.

Another similar purpose for which these materials have been successfully adopted, is the construction of caissons or floating gates for the entrances to wet docks, or basins of large extent. The longitudinal profile of these caissons is that of a truncated pyramid reversed, the bottom horizontal line and the two inclined side lines of the figure forming a continuous keel, which, when the caisson is weighted by the admission of water within it, regulated by sluices, fits into a groove in the sides and bed of the masonry of the entrance, and closes the communication between the outer and inner waters. The ejection of the water within the caisson at the time of low water, and the shutting of the sluices during the rising of the tide, causes the caisson to rise, and become capable of floating out of the groove, so as to open the passage. The central or midship vertical section of the caisson closely resembles that of a ship, and its construction of frames and sheathing plates is also precisely similar to that of iron vessels.

The extended use of plate iron for these and similar purposes has induced several improvements in the machinery for punching and riveting, a few of which are deserving of a brief notice in this place, in order that we may comprehend the state of the art, and the facilities by which its last application to the great objects of bridge-building was promoted.

The operation of connecting iron plates to the ribs or framework of the structure comprises three distinct processes; viz. the making of the rivet, the punching of the holes in the two parts to be connected, and the fixing of the rivet in its place through the two pieces. Iron rivets are now manufactured in large quantities, by improved machinery, by which the proper length of iron is cut off from a rod, and the head accurately formed in a die. Punching the holes was for many years performed with a machine called a "lever-fly," from its construction, one of its principal members being an iron lever of great length and weight,—the raising of the long arm of which had the effect of depressing the shorter arm, and thus forcing down the punch fitted to it with suitable straps, and made to work truly vertically over the boss and bolster, on which the plate to be punched is laid horizontally. Improvements in mechanical engineering have, however, produced several superior machines for punching, by which the work is executed with great rapidity and precision.

In the course of our description of the manufacture of the Conway and Britannia Bridges we shall have to refer to a most ingenious combination of mechanism invented for punching the plates of those bridges by Mr. Roberts, of Manchester; but, in the mean time, we may refer to a clever application of the principle of the hydrostatic press for the purposes of punching, riveting, and shearing metal plates, invented and patented by Mr. Charles May, of Ipswich. The patent is dated April 15, 1846, and entitled, for "improvements in machinery for punching, riveting, and shearing metal plates." The mechanism for the purpose of punching holes in metals consists of a strong frame of iron, shaped like a horse-shoe, one arm of which is fitted to contain a die, having a hole in it of the size of those intended to be punched in the plate. This die is secured in its position in the frame by means of a pinching screw, which also admits of its removal, and the substitution of other dies, according to the size of the intended holes. The extremity of the other arm is cast hollow, and fitted with a ram or solid piston, similar to that of an hydraulic press, and which, in this machine, carries the punch. The ram is truly turned on its cylindrical surface, and fitted to an annular casing bored on its inside to fit the ram, and turned on its outside, to fit the hollow space which is cast in the arm of the frame. Both the casing and the ram have an annular groove cut in their external surfaces, and fitted with cap-leathers, to prevent the escape of the water when the pressure is applied. Attached to the hinder end of the ram is a rod, which passes through a stuffing-box in the frame, and is attached at the other end to a spiral spring, by the action of which the ram and the punch upon it are withdrawn when the pressure ceases. The water is admitted from the pumps to act upon the ram through an aperture in the iron frame of the machine, the form of which admits its suspension from a traversing crane, and thus being moved about at pleasure. In this case the plates to be punched will be applied to the machine vertically, while the action of the punch will be in a horizontal direction. The water is forced in behind the ram by means of two pumps, one of which should be considerably larger than the other, to bring the moving parts to the plates by a rapid action, succeeded by the small pump, which produces the pressure required to force the punch through the metal, and admits only of a slow movement.

The other parts of the invention comprise suitable means for riveting and shearing respectively by rams and pumps. The patentee defines his claim to be, first, the application of the pressure of a fluid, caused by means of pumps, for the punching of metals; secondly, the application of the pressure of a fluid, caused by means of a pump or pumps, for the riveting together plates of metal; and thirdly, the arrangement of a series of hydraulic rams, for the purposes of shearing metal plates. The slowness of movement of this machinery would, it must be feared, neutralise the economy of the power, and render it altogether inapplicable for extended adoption.

The third process involved in the joining of plates or bars of iron, viz. the riveting, is effected by heating the rivet, on which the head is already formed, passing it through the corresponding holes in the two parts to be united, and hammering the projecting end of the rivet into a head of increased diameter. While this is done by one workman, another strikes a hammer firmly against the original head of the rivet. As the rivet cools, its length becomes contracted, and thus tends to bring the two joined parts closely together. The greatest improvements yet effected in the process of and machinery for riveting is that patented by Mr. W. Fairbairn in 1833, by which invention steam is applied in a most effective manner, and the operation made susceptible at once of unexampled rapidity and effectiveness. Subsequent modifications of the apparatus invented by Mr. Fairbairn have been suggested by other persons, among which may be mentioned, one by Messrs.

Schneider and Co., of Creusot, in France; also a later invention patented by Mr. James Garforth, of Dukinfield, Chester, for the direct application of the expansive force of steam to the dies for riveting. Mr. Garforth's patent is dated December 10, 1845, and granted for "certain improvements in machinery, or apparatus for connecting of boilers, and other purposes." The patentee "does not confine himself to the use of steam pressure, as the direct action of water, air, or any other elastic medium may be similarly employed without departing from the principle of his invention. He does not claim as his invention the exclusive use of the several parts of the machine he describes, except it be employed for the purposes of his invention, which consists in riveting metal plates by dies driven by the elastic force of steam, water, or other elastic medium."

The cutting or shearing of iron plates, in order to trim the edges or fit them for the space they are to occupy, is another important operation, for which several forms of apparatus have been produced. Formerly the lever-fly, already referred to as an instrument for punching holes, was adapted also to act as shears; the long arm of the lever being made to pass close to a fixed arm, and each of them fitted with a long cutter of steel. Machines of far greater power and efficiency are, however, now employed for this purpose. To prevent the curling or buckling which long plates are liable to suffer while being sheared, Mr. W. V. Wennington, of Staffordshire, patented a combination of machinery, on July 20, 1846, under the title of "improvements in, or improved methods of cutting plate and sheet iron." This invention consists in the combination of a rotary and continuous horizontal movement. The rotary movement comprises a circular cutter, set in motion by gearing; and the horizontal movement consists of another cutter attached to a traversing table, on which the iron plate is laid. The circular cutter is fixed on one end of a shaft which revolves in bearings fixed between vertical standards, the bearings being provided with regulating screws. The other end of the shaft has a bevelled wheel, which may be alternately geared with each of two bevelled wheels sliding upon keys on the main shaft of an engine worked by steam or other power. By this means an alternate rotary motion is given to the circular cutter, while the table, moving on Λ rails, receives a traversing motion by means of a rack fixed to it, working into a cog-wheel keyed upon the shaft of the circular cutter, and immediately behind it. Each of the bevelled wheels sliding on the main shaft is thrown in and out of gear with the wheel on the cutter-shaft by a forked lever acting on a clutch, which lever is actuated by tappets fixed on the under side of the table, and thus an alternate backward and forward movement is given to the revolving cutter, and the traversing table and cutter.

SECTION III.

First Constructions of Wrought-Iron Plate Girders—Mr. Fairbairn's Patent Wrought-Iron Tubular Girders—Their application to Bridge-building—Bridge on the line of the Blackburn and Bolton Railway—Bridges of the Liverpool Landing Stage—Great Bridge erected by Messrs. Fairbairn and Sons, on the line of the Manchester, Sheffield, and Lincolnshire Railway at Gainsborough.

The first attempts to substitute wrought iron for cast iron, in the construction of girders, were made by joining plates vertically with rivets, and attaching a strip of angle iron on each side, both at top and bottom, so as to form artificial flanges to give the required strength at these parts. Girders thus formed, have been used as deck-beams in ships for fifteen years; indeed, Messrs. Fairbairn applied them in constructing floors in the year 1832. Some of these were constructed to be used in a building erected in 1847, at Portsmouth Dockyard, and were 41 feet 3 inches long, 2 feet deep in the centre, and reduced by a parabolic curve on the upper edge to a depth of 1 foot at the ends. The body of the girder was composed of a double thickness of plates, each $\frac{3}{8}$ inch thick.

Fig. 1.

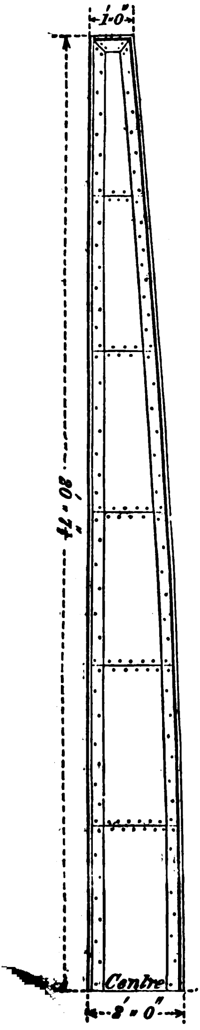
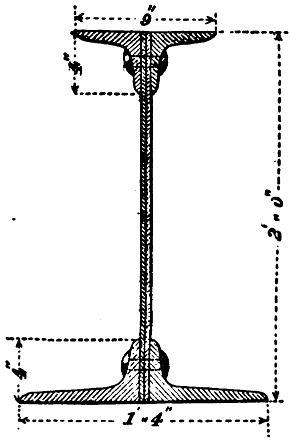


Fig. 2.

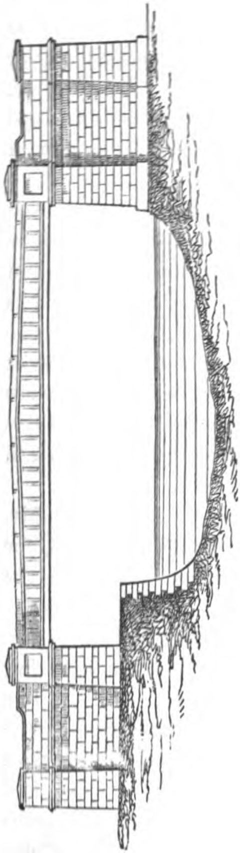


These plates were each about 6 feet 9 inches long, and so arranged as that their joints alternated with each other. An angle-iron was riveted on either side at the top, making the breadth of the girder over the top 9 inches; an angle iron was also riveted on either side at the bottom, but of larger dimensions, making the breadth over the bottom 16 inches; the rivets were $\frac{5}{8}$ inch diameter. Fig. 1 shows the elevation of one of these girders, and Fig. 2 is a section through the centre to an enlarged scale. These girders were evidently formed in imitation of the proportions which have been found desirable in those of cast iron, the less tensile power of which requires additional material at the lower part of the section. Later inquiries, as will be mentioned hereafter, have shown the non-applicability of this law to wrought iron when used in this manner. Experiments tried with these girders, before erection, showed that a load of 15 tons, applied at the centre of each girder with the hydraulic press,—the distance between the bearings being 40 feet 5 inches,—produced a deflection of from 1 inch to 1¼ inch; but on the removal of the pressure, the girders nearly regained their original form, the permanent set or deflection being only $\frac{1}{16}$ of an inch. These girders were, however, found deficient in lateral stiffness, and liable to yield by twisting or bending laterally, before any symptom of vertical fracture or injury was observed.

To obviate this defect, and to obtain the great strength and rigidity required in the employment of wrought-iron girders for railway constructions, the tubular form was designed, and T-iron used in forming vertical ribs, so that the side plates might be arranged vertically. Experiments having also proved that wrought iron thus applied has less power to resist compression than extension, it became desirable to increase the strength of the upper part of girders constructed of this material, and the formation of a separate compartment or cell was adopted to obtain this superior strength.

For these several improvements we are indebted to Mr. W. Fairbairn, who obtained a patent, October 8, 1846, for "improvements in the construction of iron beams for the erection of bridges and other structures." These improvements are described to relate to the construction of iron beams or girders for bridges and other structures, by using plates of metal united by rivets and ribs of rolled iron. The side plates are put together with but-joints covered on the outside with stiles or covering plates, and on the inside with vertical ribs of angle or T-iron, the side plates, stiles, and ribs being riveted together. The top of this hollow beam is formed with two or more rectangular cells, composed of plates arranged vertically, and connected by strips of angle iron and rivets with the top and side plates. The bottom is formed of iron plates connected together by covering plates over the cross-joints, and attached to the side plates by angle iron and rivets. The top may be constructed either of cast or of malleable iron, and cellular-rectangular, or of an elliptical or any other suitable form, to prevent the top puckering from compression; or other methods may be employed, such as thick metallic castings, or lighter iron plates, arranged so as to form hollow cells. The bottom may also be constructed of a series of plates, either of single or double thickness, riveted together. The joints of the plates alternate or break with each other, and are riveted by a peculiar method, which the inventor calls "chain-riveting," as it forms a chain of plates throughout; and the structure so unites the covering plates as not to weaken the plates by rows of transverse rivet-holes, but to form a connecting link to each joint by a series of longitudinal rivets or pins.

Fig. 3.



This useful invention, which comprises the best methods yet devised for uniting the several parts of structures of plate and bar iron, contains also the essential principles upon which tubular girders may be, and have been, constructed, of a size adequate to form bridges within themselves, and admit the interior passage of railway trains or other traffic.

The first wrought-iron tubular girder bridge built according to the patent of Mr. Fairbairn was constructed and erected by that gentleman for Mr. Vignoles, for the purpose of carrying the Blackburn and Bolton

Railway over the Leeds and Liverpool Canal. This bridge is represented in Figs. 3 to 6. Fig. 3 is an elevation of the

Fig. 4.

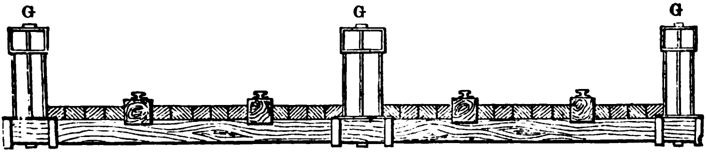


Fig. 5.

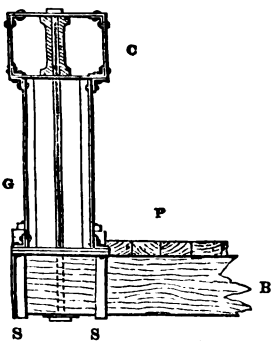
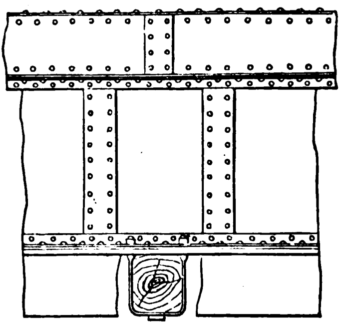


Fig. 6.



bridge; Fig. 4, a transverse section of the bridge to an enlarged scale: Fig. 5 is an enlarged transverse section of one of the outer girders; and Fig. 6, an enlarged longitudinal view of part of one of the girders, showing a section of one of the cross-timbers on which the railway is supported. The span of this bridge is 60 feet, and each girder is 66 feet in total length, the bearings in the masonry being each 3 feet long. The two lines of rails are carried between three parallel girders. Each girder consists of a rectangular top compartment composed of plates $\frac{3}{8}$ inch thick, and riveted at the internal corners to angle iron; of side plates, $\frac{5}{16}$ inch thick, joined vertically by rivets to T-iron ribs, and also riveted to the bottom plate of the top compartment and its internal angle-irons through longitudinal ribs of angle iron placed externally; and of double bottom plates, each $\frac{3}{8}$ inch thick, joined by rivets to external logitudinal strips of angle iron.* The rails are laid upon longitudinal timbers, which, with intermediate planking, are supported upon transverse beams of wood suspended by double straps of wrought iron, which pass upward through the bottom plates of the girders, and are secured by screwed nuts. A vertical bolt of wrought iron also passes through a cast-iron socket in the top compartment of the girder, and downward through each cross-beam, below which it is fixed with a washer plate and screwed nut. Before opened for traffic, this structure was tried by severe tests, and found fully equal to any weight to which it could be subjected. Three locomotive engines, each weighing 20 tons, occupying the entire span of 60 feet, were run together as a train, at rates varying from 5 to 25 miles per hour, and produced a deflection in the centre of the bridge of only ·025 of a foot. Two wedges of the height of 1 inch were then placed on the rails in the middle of the span, and the dropping of the engines from this height, when at a speed of 8 to 10 miles per hour, caused a deflection of only ·035 of a foot, which was increased to ·045 of a foot, or nearly half an inch only, when wedges 1½ inch in thickness were substituted. The comparative weight and cost of a bridge of this construction, with those of a cast-iron girder bridge trussed with malleable-iron bars, have been thus deduced from actual examples:—

CAST-IRON TRUSSED GIRDER BRIDGE, 60 FEET SPAN.

	£	*s.*	*d.*
Cast iron, 76 tons weight, at £12 per ton . .	912	0	0
Wrought iron, 14 tons, at £37 4*s.* ,, . .	520	16	0
	1432	16	0

WROUGHT-IRON TUBULAR GIRDERED BRIDGE, 60 FEET SPAN

	£	*s.*	*d.*
30 tons weight, at £30 per ton	900	0	0

showing a saving of £532 16*s.* in the cost of the iron-work, and insuring far greater strength and security.

* The centre girder, having double duty to perform, is made proportionally stronger.

Another instance of the application of the wrought-iron tubular girder bridge, and upon a much extended scale, is that of the two bridges by which the great landing-stage at Liverpool is connected with the wharf of the docks. This stage, constructed according to the general design of Mr. Cubitt, the engineer, consists of a wooden frame 500 feet long and 80 feet wide, floated upon wrought-iron pontoons fixed beneath and across the platform, and each 80 feet long, 10 feet wide, and 6 feet deep. The communication between the stage and the wharf is afforded by two bridges constructed upon Mr. Fairbairn's patent plan. Each bridge is about 150 feet in length, and is so connected with the shore at one end, and with the stage at the other, as to admit of motion both vertically and horizontally, and thus accommodate itself to the rising, falling, ebbing, and flowing of the tide, and also constantly maintain a passage for carriages and persons. The details of these bridges are represented in Figs. 7, 8, and 9. Fig. 7 is an elevation of one of the bridges;

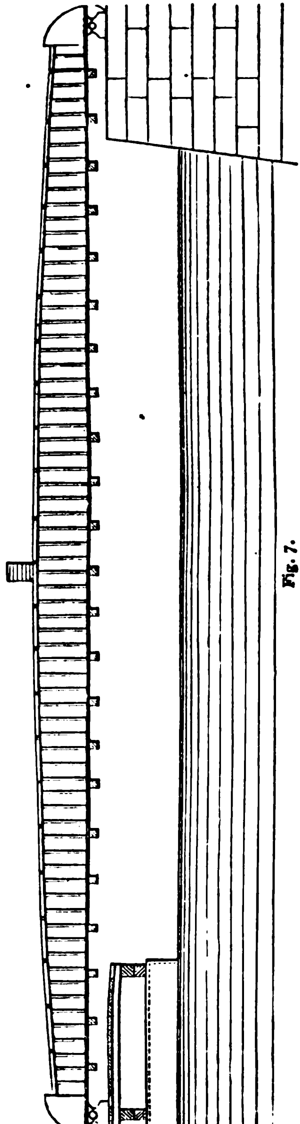


Fig. 7.

Fig. 8, a cross section through the middle of the girders, central road or carriage-way, and two side-ways or galleries

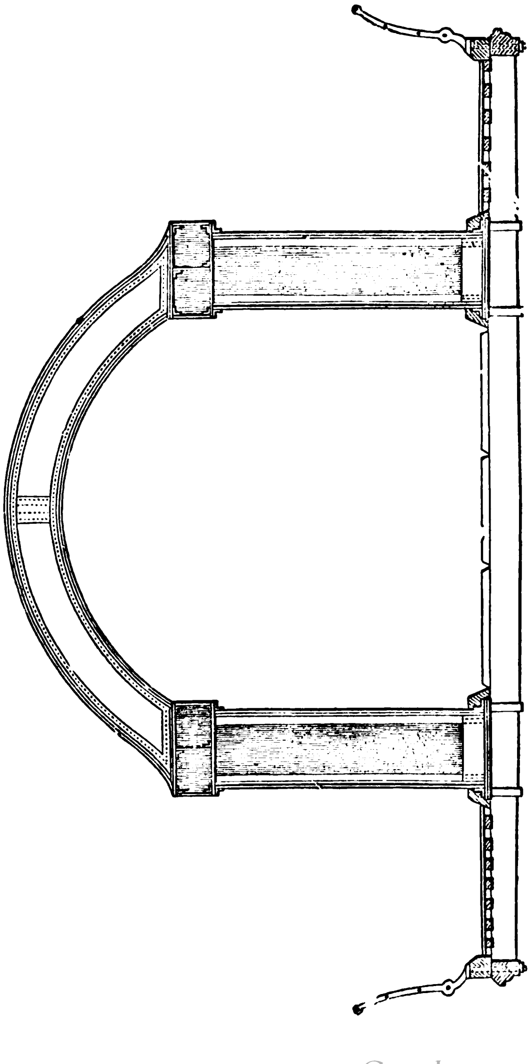
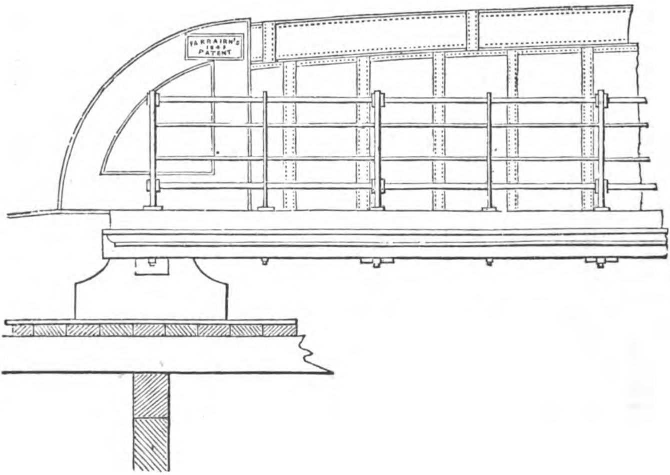


Fig. 8.

for foot passengers; and Fig. 9 is an elevation of the end of one of the girders, drawn to the same scale as Fig. 8. The construction of the girders and mode of suspending the transverse timbers that carry the road and footways are, it will be seen, similar to the bridge constructed by Mr. Fairbairn over

Fig. 9.



the Leeds and Liverpool Canal, and already described. The extreme length of each bridge is 152 feet 4 inches, or 142 feet clear of the cast-iron end casings. The height or depth of the girders is 5 feet 6 inches at the ends, and 8 feet 6 inches in the middle. The upper compartment is 2 feet 6 inches wide, and 1 foot 1 inch deep, and is divided into two cells by a central partition plate, riveted to the top and bottom plates with angle-iron ribs. The body of the girder is 2 feet wide outside, and is composed of plates 2 feet wide, arranged vertically, and the joints covered with joint-plates 4½ inches wide, and fastened with rivets 2¾ inches apart from centre to centre. The plates forming the upper compartment are in 6-feet lengths, with covering-plates over the joints outside. The roadway is

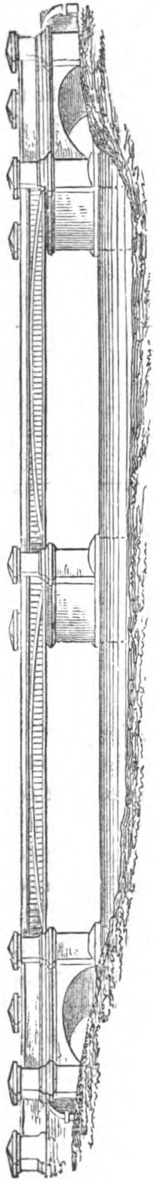


Fig. 10.

11 feet wide between the girders, and each of the footways 6 feet wide. The girders are tied together at the middle of their length by an arched tubular stay of a rectangular section, composed of top, bottom, and side plates, united by rivets and external angle-irons. The dimensions of the section are, 1 foot 9 inches in depth, and 1 foot 6 inches width, from out to out. The cross-beams of timber which carry the road and footways are, 10 × 8 inches at the middle, and 8 × 8 inches at the ends, and are suspended from the girders by wrought-iron straps. Each side gallery or footway is guarded on the outside by a light railing of cast-iron standards and wrought-iron rods.

The largest bridge yet constructed with tubular girders in this form, is represented in Figs. 10, 11, 12, and 13. This excellent specimen of wrought iron-work has been lately erected by Messrs. Fairbairn and Sons, of Manchester, to carry the Manchester, Sheffield, and Lincolnshire Railway, of which Mr. Fowler is the engineer, over the river Trent at Gainsborough, and consists of two spans, each 154 feet wide, with a central pier of masonry and two abutments, each with an end arch of 40 feet span. The courses of the river and of the railway are oblique to each other, and the abutments are therefore placed at an angle of 50° with the longitudinal direction of the girders. The girders are of uniform depth throughout, and are two in number; the entire width of the double line of railway, 26 feet in the clear, being carried between them. Fig. 10 is an elevation, and Fig. 11 a plan, of the entire structure; Fig. 12 is a transverse section of half of the bridge taken through the middle, and showing the construction of one of the girders, which are 12 feet in total depth. The top compartment measures 3 feet ¾ inch in width, and 1 foot 3 inches in depth, and is divided by a central partition into two cells. The body of the girder is 2 feet 6 inches wide, and 3 feet wide over the bottom plates, which are double. The side plates are 2 feet wide, and jointed with outside covering plates and internal ribs, as in the former bridges. A strip of iron plate 1 foot wide, and two rims or edges of angle iron, are fixed on the outside of each of the girders, in the form of an arch, which relieves the flatness of the horizontal lines of the girders, and improves the general appearance of the bridge, but without adding in any material or required degree to its strength or stiffness. The rails are laid in chairs on longitudinal beams of wood, which are supported upon transverse beams of iron plate, put together on the tubular principle, and resting upon the bottom plates of the girders, be-

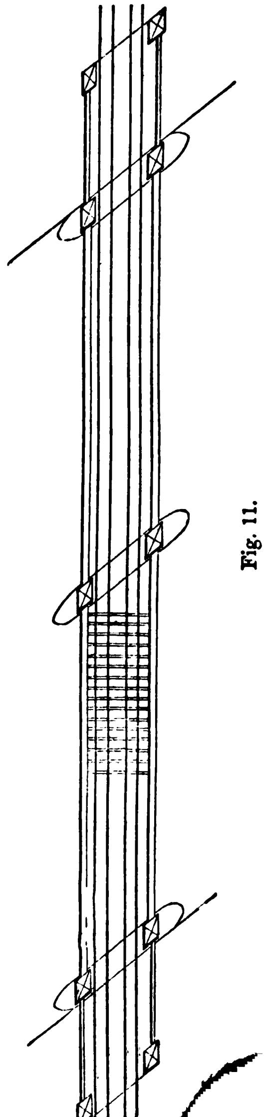


Fig. 11.

sides being riveted through their ends to the side plates of the girders. These transverse beams, which are placed 4 feet apart between their centres and at right angles to the longi-

Fig. 12.

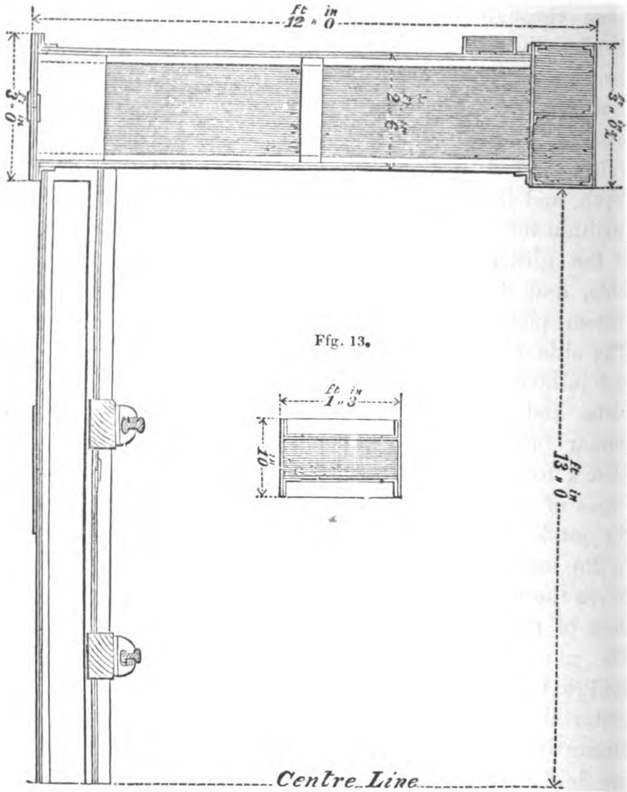


Fig. 13.

tudinal direction of the girders, are composed of top, bottom, and side plates, riveted with external angle-irons at the corners. The section of them, Fig. 13, is uniform throughout, and measures 16 inches in depth, and 10 inches in width over all. The rail-timbers are notched down slightly over these cross-beams, and the intermediate spaces between the timbers are filled in with 3-inch flanking laid longitudinally.

SECTION IV.

Malleable-Iron Bridges of different Constructions—Lattice Bridges—Tubular Bow-Bridge—Tubular Girder Bridge, with intervening Arches of Brick-work—Compound Wrought-Iron and Concrete Girders—Combinations of Malleable and Cast Iron in Framed Bridges—Corrugated Wrought-Iron Girders.

MALLEABLE iron having been applied in several forms of combination—besides that of the tubular girder and tube—to the construction of bridges, we propose, in order to make our historical sketch complete, to devote this section to a succinct description of the principal designs which have been executed or proposed.

To arrive at the earliest of these, we have to go back to the year 1824, when the ingenious Mr. George Smart suggested a combination of wrought-iron bars arranged in a diagonal form, under the title of a "Patent Iron Bridge." This design, which is the parent of the extensive family now known as "lattice bridges," of which our American brethren have erected some gigantic examples, exhibits a vertical framing, perfectly horizontal on its upper and lower lines, and composed of iron bars crossing each other in a diagonal direction, and forming angles of about 18° with the horizon. The framing also comprises vertical or "hanging bars," and "base bars," forming the lower horizontal lines of the framing, and also passing horizontally over each alternate row of intersections of the diagonal bars. The number and dimensions of the several parts are, of course, regulated according to the extent of the structure, and service for which it is destined; but each bar is intended to be forged of enlarged width at the points of intersection, and through which bolts are fixed to connect the whole together. Two of these trussed frames, erected vertically and parallel to each other, would form the supports of the roadway to be formed between them, the two frames being tied together by transverse connecting-rods, the roadway or flooring being situated near the top of the frames, and never on the lower bars, which Mr. Smart considered a common but very erroneous practice in wooden bridges.* Between the frames, cross-braces, consisting of two light bars, are to be fixed, bolted together, and fitted to the connecting-rods. In recommendation of this design, it was urged that it possessed extraordinary simplicity and economy; that the several bars employed being all of different lengths, and the holes all drilled or punched in one uniform manner, none of the parts could be misplaced in erection; and therefore the whole might be put together with great expedition, while, consisting of many small parts, and none of great weight, the bridge might be considered *portable*, easy of transportation by an army, and put up, when required, in a few days. Mr. Smart proposed to construct the piers of a bridge of a diagonal framing of wrought-iron bars, similar to that adopted in the bridge itself, and he showed the applicability of the same system to the formation of wooden bridges, in which he remarked there would be no necessity to limit the length of the pieces forming the framing, as no expansion or contraction takes place in that direction in wood.

Of the numerous examples in which this diagonal form of construction has been adopted in American *wooden* bridges, it does not belong to this sketch of *iron* structures to give any lengthened account, although their remarkable simplicity and strength render them highly interesting studies to the engineer, and will justify a brief notice here, by way of illustrating the value of the principle first suggested as applicable

* To this principle, and its practical value and effects, further inquiry should be devoted; we have here only to record the view entertained by the inventor of the lattice bridge, at a date so long before those experimental inquiries into the forces acting upon loaded beams which have developed the position of the neutral axis and the agency of compressive and extensive forces.

to iron and wooden bridges, by Mr. Smart, twenty-five years ago.

Some of the principal examples of the lattice bridge, in America, are built over the rivers, supporting roads and railways. One of these, erected over the Susquehannah at Columbia, consists of twenty-nine spans or openings, *each two hundred feet wide*, the entire bridge being about a mile and a quarter in length. The principle on which this bridge is constructed has been more properly referred to that of the common roof; the two centre and opposite diagonal bars being considered as two rafters meeting at the centre of the bridge, and abutting at their other end on a tie-beam, which is extended longitudinally on each side to the opposite abutments. A series of rafters, parallel with the centre one, is extended on either side, throughout the whole length of the bridge, being secured at their feet, and also connected at the head with a horizontal upper beam, placed vertically over and parallel with the continuous tie-beam. These rafters are placed at such an angle of obliquity, and at such a distance from each other, that vertical posts or ties between them will unite the head of one rafter with the foot of the contiguous one, towards the centre of the bridge. These ties, which, the bridge being loaded on the lower chord, are subject to a tensile strain, have been recently formed of malleable-iron rods, instead of timber, which rods, fitted with screwed nuts, admit of being regulated in length, so that the whole structure may be brought to a perfect degree of tension, and each joint and each member made to bear its due share of the load: they moreover remedy the mischief of shrinkage of the timber, or other derangement, as the equilibrium and perfect form of the structure can by their means be readily restored and maintained. By screwing up these ties, the bridge tends to assume an arched form, rising with a camber in the middle: this is prevented by the introduction of the counter-braces, which connect the head of one rafter with the foot of the contiguous one, from the centre toward the extremities of the bridge.

In the American bridges of 200 feet span, the following are the dimensions of the members: span, 200 feet; depth of frame throughout, 20 feet; top and bottom chord timbers, 10 × 25 inches; braces, in pairs, $7\frac{1}{2}$ inches square; tie-rods, in pairs, $2\frac{1}{2}$ inches diameter; counter-braces, single, each $7\frac{1}{2}$ inches square. One of these frames is placed on each side of the bridge, connected at the bottom by cross-beams, on which the planking of the roadway is laid.

One distinguishing advantage of this mode of construction is its simplicity; the braces and counter-braces being all cut exactly to the same length, and square on the ends, which simply rest in blocks attached to the top and bottom chords, and are without mortising or jointing in the members: the tie-rods pass through these blocks, and the whole structure is so simple, that it may be readily taken down, removed to another site, and re-erected with the utmost facility and precision.

A lattice bridge of wrought iron, erected across the line of the Dublin and Drogheda Railway, is 84 feet in clear span, and built over an excavation 36 feet in depth. The two lattice beams, set parallel to each other, and resting at each end on plain stone abutments built in the slope, are 10 feet deep, and formed of a series of flat bars of iron $2\frac{1}{2}$ inches wide and $\frac{3}{8}$ inch thick, crossing at an angle of 45°. At a height of 5 feet 6 inches above the bottom edge, transverse bearers of angle iron are fixed, and upon these the planking for the roadway is fixed. To provide for deflection, the beams were constructed with a camber or curve upwards, from the ends to the centre, of 12 inches; but it has been found that the passage of heavy weights does not produce any sensible deflection. The total cost of this structure is said to have been £510.

An important distinction between the simple lattice or diagonal framing and the roof framing must, however, be carefully borne in mind. In the former, the strength is obtained by the connection of the bars at each intersection, while the abutting principle of the roof, which equally belongs to the roof-framed bridges before described, is disregarded. The strain is therefore borne wholly by the rivets or pins which pass through the crossing bars, and the effect of this strain is exhibited in the gradual loosening of the pins. The bars, too, it must be observed, are considerably weakened by the holes through the middle of them; and in wooden lattice bridges, fracture and failing of the material have often resulted. By way of remedying these defects, consequent upon the simple lattice principle, many of the large lattice bridges in use in America have been strengthened by the introduction of strong trussed frames within the lattice frames, or of strong arches of timber-work.

The lattice principle has been considerably improved upon in some bridges designed and built by Mr. R. B. Osborne, C.E., which consist of a top and bottom chord of malleable iron, with intermediate braces of cast iron in the form of rectangular tubes. This form of construction was introduced into the United States of America in the year 1844, since which time about a dozen have been constructed, varying in span from 30 to 90 feet. Girders, formed of diagonal bars of wrought iron, abutting against each other, with cast-iron transoms to support the pressure, while the wrought-iron bars are intended to furnish the tensile power, appear to have been introduced into France before the year 1844. By order of the Minister of Public Works, experiments were tried at Paris upon four girders constructed in this manner, and placed side by side, with a bearing of 74 feet 8 inches. With a load of 62 tons, the deflection of these girders was 1¼ inch; and on the removal of the load, after remaining on them for a month, they resumed their original position without permanent deflection. To try the effect of a sudden shock, a cart loaded with 4½ tons of iron was caused to break down suddenly in the middle of the bridge, without producing any injury, except crushing the flooring planks. The weight of these girders was stated to be 20¼ tons.

A similar combination of cast and malleable iron in the construction of girders for bridges is the subject of a patent granted in the year 1846 to Mr. S. Moulton, the invention being claimed as due to Mr. Rider, of New York. In this combination, the upper chord is described as formed of single T-iron, or two angle-irons connected together, the intermediate framing between the chords being formed of malleable-iron bars arranged diagonally, but not connected with the chords. Cast-iron vertical bars are fixed to the chords, but independent of the diagonal framing. A bridge erected upon this principle for the New York and Haarlem railway, 70 feet in span, and having a double line of rails upon it, is said to contain only 13 tons of metal, and to have cost less than £500.

Combinations of cast and wrought iron in trussed girders for bridges have already been referred to, and illustrated by the railway bridge over the river Dee at Chester.* In the official report upon the iron bridges on the Trent Valley Railway, which was prepared by Captain Coddington, it appears that, on that line of railway, there are fifteen simple cast-iron girder bridges, the span of which does not exceed 30 feet; four others varying in span between 35 feet and 37 feet 6 inches; and six bridges composed of cast-iron girders, each in three castings, bolted together at the flanges, clipped underneath, and strengthened with rods of wrought iron. Of these six bridges, there are two over the Trent and Mersey Canal, span 54 feet 3 inches; one over the turnpike-road, span 57 feet; one over the Coventry Canal, span 60 feet; one over the Oxford Canal, span 44 feet; and one over the river Tame, of 70 feet span, for which a double row of piles has been driven into the bed of the river, under each of the joining flanges of the girders, and connected at the heads by capsills extending under the girders. Captain Coddington remarked:—"In the same manner that I consider experience to have proved the sufficiency of a simple girder up to 40 feet (span), I consider it has also proved the sufficiency of the compound girders up to 70 feet."

* A tubular girder bridge was suggested for this work by Mr. Fairbairn, in January, 1846.

Mr. Gibbons, of Corbyn's Hall Iron Works, obtained a patent in 1847 for improvements in iron girders for bridges, the object of which was to provide the required constant adjustment of the length of the cross-bars corresponding with changes of temperature, by the introduction of intermediate springs. Mr. Gibbons proposed to apply his improvement to girders of cast iron, in three castings, bolted together through flanges at the end of each, as before employed. Beneath the middle casting, however, a powerful spring or set of springs is to be introduced, made exactly similar to the bearing springs of railway carriages, with the convex side pressing upwards against the under side of the girder, the wrought-iron truss-rods being fastened to each end of this spring, and bolted up tight to flanges cast upon the extreme ends of the outer castings forming the girder. If the girders are of considerable width, several springs are to be used, ranged side by side, or smaller springs may be applied in pairs, with their concave faces inwards, one under each joint of the castings, and one in the centre, tightly trussed with wrought-iron rods.

A novel combination of wrought with cast iron formed part of a patent granted in 1847 to Mr. Fielder, in conjunction with Messrs. Baker. The wrought-iron plates proposed to be used by the patentees for the purpose of strengthening cast-iron girders were to be fixed with bolts in any of a great variety of positions; thus, on the sides of the rib of the girder to the bottom flange, &c. The value of some of these additions in augmenting the strength of the girders was proved by decisive experiments. Thus a strip of wrought iron, 8 inches by $\frac{5}{8}$ inch, riveted to the bottom flange of a cast-iron girder which had been broken in the middle, enabled it to withstand a proof of $20\frac{1}{4}$ tons without injury to its elasticity, the bearing being 20 feet, and the depth of the broken girder 20 inches. With another piece of wrought iron, 3 feet in length, and 8 inches by $\frac{7}{8}$ inch, added in the centre only, the girder withstood a pressure of $52\frac{1}{2}$ tons. Another experiment was tried upon a cast-iron girder, of which the breaking weight would, by the ordinary rule, be 20½ tons. This was proved to 15 tons, without loss of elasticity; 3¾ tons were then added, and produced a deflection of $\frac{7}{16}$ inch, and a permanent set or deflection of $\frac{1}{16}$ inch after the load was removed. It may be therefore supposed that the metal was in some degree injured. A wrought-iron bottom flange, 6 inches by ¾ inch, was then attached to it, and this compound girder was proved to 30 tons without injury to its elasticity.

Another design for the strengthening of iron beams or girders proposes to employ corrugated sheet iron in their construction. This is the subject of a patent granted December 2nd, 1848, to Mr. J. H. Porter, for an "improved mode of applying corrugated iron in the formation of fire-proof floors, roofs, and other like structures." The value of this invention was tested by experiments upon beams constructed in accordance with it. The following is an account of one of these experiments. Two of the patent beams, each 18 inches in depth, and 22 feet long, were placed at a distance of 9 feet apart, and upon bearers, so that the clear length of each girder between the bearings was 20 feet 6 inches. Each of these beams was formed with top and bottom frames of 4 × 4 inches T-iron, the base being ½ inch thick, and the rib of the girder formed of corrugated sheet iron, No. 16 gauge, with bands 1½ × ½ inch thick. The weight of each girder was 8½ cwt. Across the two girders, two large oak blocks, weighing 1 ton 3 cwt., were laid to support the further load. One of these blocks was 24 inches wide, and the other 19 inches, and they were laid at a distance of 4 feet 3 inches apart from centre to centre; the centre lines of these blocks being equidistant on either side from the middle of the length of the iron girders. The whole of the load was thus confined to a length of 6 feet ½ inch in the centre of each girder, being less than one-third of its length between the bearings. Upon these two timber blocks a weight of 6 tons 17 cwt., in cast-iron blocks, was laid, and remained three days without causing any deflection. An additional load of 7 tons 3 cwt.

16 lbs. (in 121 bundles of plate iron) was then applied, and produced a deflection of $\frac{9}{16}$ inch. This load, remaining twenty-one hours, increased the deflection $\frac{1}{16}$ inch. Another load of 51 bundles of plate iron, weighing 3 tons 9 cwt. 1 qr. 2lbs., was added, and increased the deflection to barely 1 inch. 32 more bundles of plate iron, weighing 1 ton 18 cwt. 12 lbs., were applied, and the deflection became $1\frac{3}{8}$ inch of one girder and $1\frac{3}{16}$ inch of the other, the difference appearing to be occasioned by a settling of the piers, which threw an excess of the load upon one of the girders. A further load of 2 tons 8 cwt. 3 qrs. brought the deflection to $1\frac{5}{8}$ inch and $1\frac{1}{4}$ inch. After this load had remained a short time, a partial dividing of the bottom flange of T-iron in the beam, which hitherto showed least deflection, occurred from a defective "shut," or welding of the bar. This caused a further deflection of $\frac{1}{16}$ inch. An additional load of 2 tons 6 cwt. 2 qrs. 22 lbs. made the deflection 2 inches and $1\frac{3}{4}$ inch; and a final addition of 7 cwt. produced a rapid deflection of the already weakened beam, the corrugated iron giving way at the same time to the longitudinal strain upon the rivets. The other beam was also found to have yielded in several places at the rivets, principally in the lower part of the beam. The breaking weight is therefore considered to be about 25 tons, exclusive of the weight of the beams. The patentee estimates the strength of his patent beams at about double that of cast-iron beams of equal weight, and that they may be supplied for £21 per ton.

Mr. W. C. Harrison appears to have first suggested that application of malleable iron which has obtained the name of the "wrought-iron tubular bow-bridge." The framing of this form of bridge consists of an arched or bow tube, with a horizontal stringer tube or chord carrying the roadway, and deriving its strength from the arched tube, rising above it, through the medium of suspending bars and braces. In a design made by Mr. Harrison for a bridge of this kind, to carry a railway over the river Ouse, the span is 170 feet, and the versed sine, or rise of the arched tube above the chord or horizontal tube, about 15 feet. The arch or bow to be constructed of wrought-iron plates ½ inch thick, and its section throughout to be 4 feet in depth and 3 feet in width; the tie-beam, or stringer tube, 2 feet 6 inches deep and 3 feet wide. For a double line of railway three of these bow-frames are to be used, erected parallel to each other, and at such distance apart that one line of rails may be laid in each of the two spaces included between them. At the extreme ends of the tie-beam and bow, plates of wrought iron are to be firmly riveted over their meeting, and the whole of the tubular work in both of them to be properly put together with rivets. Figs. 14, 15, and 16 represent this design for a wrought-iron tubular bow-bridge; Fig. 14 showing an

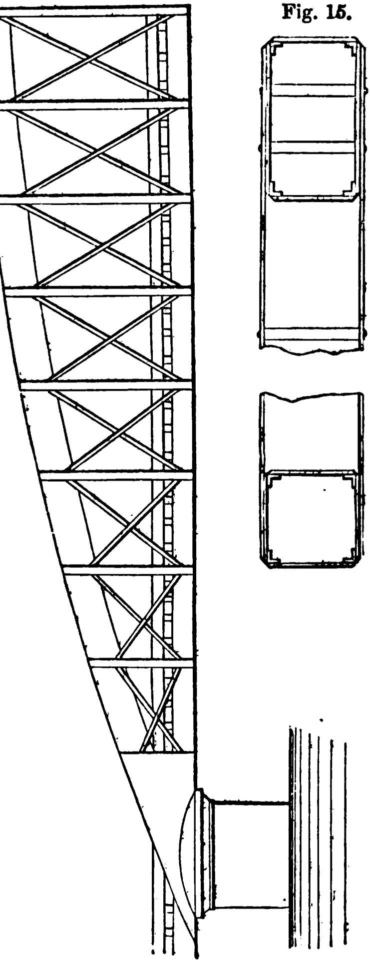


Fig. 14.

Fig. 15.

elevation of half the bridge; Fig. 15, a transverse section through the bow tube above, and stringer or chord tube below; and Fig. 16, a partial section through two of the cross-beams which carry the longitudinal timbers and rails.

Several bridges of similar design to the one last described have been since constructed. Captain Simmonds thus describes two erected upon the extension line of the Blackwall Railway from Stepney to Bow: "These two bridges are of a peculiar form, and the first of their class erected for railway purposes. The roadway upon them is supported on wrought-iron girders, placed transversely between two arches, or ribs, formed entirely of wrought iron. The clear span of one is 120 feet, of the other 116 feet 8 inches. Each arch or rib of the latter bridge, which carries the railway over the Regent's Canal, is formed of a box built with iron boiler plates $\frac{11}{16}$ inch in thickness, and angle iron, firmly riveted together, its breadth being 2 feet 10 inches, its depth about 2 feet, and sectional area 81 square inches, and is connected at the base by a wrought-iron tie-bar, which receives the horizontal thrust of the arch, and is formed of links having a total sectional area of 69 square inches, bolted together with bolts $2\frac{3}{4}$ inches in diameter, aided by eight others at each joint $\frac{3}{4}$ inch in diameter. Between the tie-bars and the arch a system of vertical and diagonal bracing has been introduced, so as in a manner to distribute the weight of passing loads equally over the whole arch. These ribs, so formed, are laid in cast-iron plates, fixed at one end, and free to move at the other over rollers, so as to allow scope for the expansion and contraction of the metal. The clear interval between the bearings is 116 feet 8 inches, and the rise of the arch is 8 feet to the under side of the box of which it is formed, the roadway being beneath the arch, and about 2 feet above the bottom

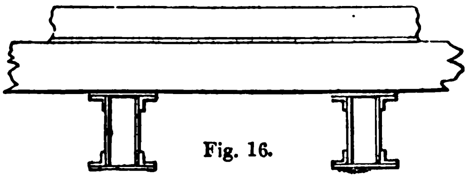


Fig. 16.

of the tie-bar. The structure is exceedingly light, but appears, nevertheless, sufficiently strong to carry the weights which may come upon it in practice, so far as the areas of the arch and bow-string, or tie, are concerned, and has stood the test of a dead weight of 240 tons, in addition to its own weight of 59 tons, distributed in weights of $34\frac{1}{2}$ tons at equal distances over its length, with a deflection of $3\frac{1}{16}$ inches, and recovered entirely its original position upon the removal of the load. As this proof exceeds considerably any weight that can be brought upon it in practice, I am of opinion that it may be used with safety for the passage of trains; but as it is of so novel and light a construction, and the action of the cross-bracing and connection of the tie-bars has not been ascertained by continued experiments of moving weights, I should recommend that it be examined from time to time, so that any defect, if it should exist, might be ascertained, more particularly as the weight of the whole bridge, including the double line of roadway and covering, only amounts to 194 tons, and is very easily set in vibratory motion by any moving power."

Upon a limited scale, tubular girders of wrought iron appear to have been applied to the purpose of bridge building nine years ago, although in a very different manner from their improved construction, as invented by Mr. W. Fairbairn. The instance here alluded to is a bridge which carries the Carmunnock road over the Polloc and Govan railway, near Glasgow. This bridge, which crosses the railway obliquely, was erected by Mr. A. Thompson, and is 31 feet 6 inches in span on the face, or 30 feet square with the railway. The width of the bridge, from outside to outside of parapet, is 25 feet 6 inches, and the roadway is supported upon six girders, each 35 feet 3 inches long, resting upon stone abutments, and at a distance of 5 feet $1\frac{1}{4}$ inch apart between their centres. Each girder stands upon a wrought-iron plate at each end, and is constructed of the best boiler-plate $\frac{3}{8}$ inch thick, in the manner shown in Figs. 17 and 18, of which Fig. 17 is a sectional view through two of the girders, and Fig. 18 a partial plan of the same. The girders are 18 inches deep, 3¼ inches wide in the

Fig. 17.

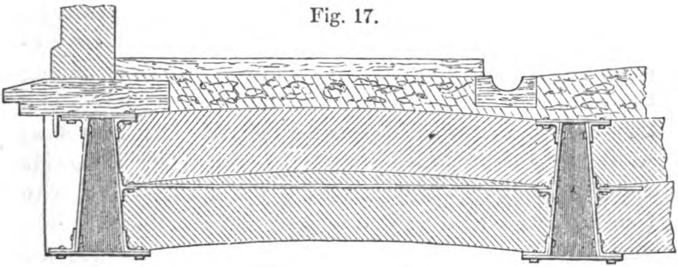
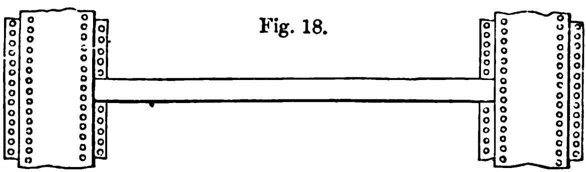


Fig. 18.



clear at the top and 6 inches at bottom. The upper and lower plates are 6 inches wider than the beam, the projection of 3 inches on each side being provided to receive the angle-irons, 3 × 3 × ⅜ inches, which are riveted to the side plates and upper and lower plates respectively with ½-inch rivets placed 1½ inch apart from centre to centre. These girders are filled with concrete, with the view of increasing their resistance against a pressure from the outside, and they are tied together with transverse bars of Low Moor iron, 3 inches by ⅝ inch, attached by bolts to T-irons riveted to the side plates of the girders. The spaces between the beams were filled in with two courses of 9-inch arched brick-work, the rise of the arches being 1½ inch. The crown of these arches was payed over with hot tar, and a layer of clay puddle well rammed down over the tar. Over the puddle a metalling of whinstone was laid to form the roadway, covered with a binding course, 2 inches thick, of engine ashes. The foot pavement on each side of the bridge is 4 feet wide, with a gutter laid between it and the roadway. This bridge was built for W. Dixon, Esq., of the Govan Iron Works, at Glasgow. The communication between the furnaces of these works is by platforms carried upon tubular beams 33 feet in length. The transverse sectional form of these beams is rectangular, instead of having the sides inclined, as described of the bridge girders, and their dimensions are as follows: depth in the clear, 19 inches; width in the clear, 7 inches; plates, ⅜ inch thick. The side and bottom plates are connected by inner angle-irons, with ½-inch rivets, placed 2½ inches apart between their centres. The side plates rise 2½ inches above the top plate, and are connected with it by external angle-irons placed upon the top plate and between the side plates, riveted as the bottom plate is to the sides.

It is scarcely necessary to point out here the many differences between the tubular beams used in this bridge and the patented tubular girders; but the former are probably the earliest application of a tubular plate-iron girder in any form to bridge building, and are therefore historically interesting.

SECTION V.

Chester and Holyhead Railway—General Sketch of the Line—Telford's Holyhead Road—The Menai and Conway Suspension Bridges—Railway Tunnel, Sea-wall, and Viaduct, at Penmaen Mawr—Parliamentary Proceedings, and Engineers' Reports upon the Communication between London and Dublin—Iron Bridges proposed by Mr. Rennie in 1802—Mr. Robert Stephenson's Design for Cast-Iron Arched Bridges, and selection of Site over the Britannia Rock—Admiralty Opposition, and Mr. Stephenson's consequent Design of the Tube.

The railway from Chester to Holyhead, forming an important part of the shortest line of communication between London and Dublin, is highly interesting in its general features, as it is peculiarly so in comprising the two fine structures known as the Conway and Britannia bridges. The length of this railway is 84½ miles; and its several stations, starting from Chester, and their respective distances from that ancient city, are as follows:—

Queen's Ferry . .	Flintshire	7	miles.
Flint	ditto.	12½	"
Bagilt	ditto.	14½	"
Holywell	ditto.	16¾	"
Mostyn	ditto.	20	"
Prestatyn	ditto.	26¼	"
Ryhl	ditto.	30	"
Abergele	Denbighshire . . .	34¼	"
Colwyn	ditto. . . .	40¼	"
Conway	Carnarvonshire . .	45¼	"
Aber	ditto. . .	54¼	"
Bangor	ditto. . .	59½	"
Llanfair	Isle of Anglesea . .	63½	"
Gaerwen	ditto. . .	66½	"
Bodorgan	ditto. . .	72½	"
Ty Croes	ditto. . .	75½	"
Valley	ditto. . .	81	"
Holyhead . . .	Holyhead Island . .	84½	"

The journey between Chester and Holyhead is now usually performed by the mail trains in 3 hours and 5 minutes, of which 35 minutes are occupied between Bangor and Llanfair, a distance of 4 miles, by road carriages. About 25 minutes of this time will be saved when the Britannia Bridge, situated between these two stations, is completed; and the total time of the journey will be thus reduced to about 2 hours and 40 minutes. The royal assent was given to the Bill for this railway on July 4, 1844, and the works have been conducted with considerable vigour since their commencement. The general direction of the line is nearly east and west, but its course is in several parts extremely tortuous, which is rendered necessary by the mountainous character of the country traversed. On this account nearly the whole of the line is constructed on or near to the coast, the first 25 miles from Chester pursuing a direction nearly N.W. At this distance the course is turned towards the south, in the direction W.S.W., and proceeds thus towards Bangor, from which station the direction is nearly W., rising to W.N.W., and N.W. on nearing the terminus at Holyhead; being in some parts of its course nearly parallel with the celebrated Holyhead road, which was so much improved by Telford. Of the several important works executed by that eminent engineer upon this line of road, it would be beyond our province to attempt any detailed description in this place. Nevertheless, since they comprise the two suspension bridges at Conway and over the Strait of Menai, which may now boast of the honourable companionship of the two tubular structures we have to describe, some brief notice of them will serve as a fitting introduction to the details of those modern railway works.

The Commissioners under whose jurisdiction the works for the improvement of the Holyhead road were conducted, were appointed in the year 1815, and in a statement made by their engineer, Telford, to a Select Committee nominated in 1830, "to inquire into the amount of all sums of money received, expended, and repaid" by the Commissioners, these works are classed under eight heads, viz.: 1. Roads made in North Wales, on the London and Holyhead mail line. 2. Roads made in North Wales, on the Chester and Holyhead mail line. 3. Embankments on the Stanley Sands, and at Conway. 4. Bridges over the Menai Straits, and over the river Conway. 5. Roads made between London and North Wales, on the London and Holyhead mail line. 6. The harbours of Holyhead and Howth. 7. The road from Howth to Dublin. 8. The widening and deepening the channel through the Swilly Rocks, in the Menai Straits. Under the first of these heads, Telford describes the reforming of pieces of old road and making new ones, tantamount to the making of a new road from Holyhead pier to Chirk bridge, a point on the river Dee (which here divides Shropshire from Montgomeryshire), and about 6 miles N.W. of Ellesmere. The length of this road is 83 miles and 1320 yards. "The whole of this roadway was constructed with a substantial rubble-stone pavement, carefully hand-set and covered with a 6-inch coating of properly broken stone. There are, in all cases where found necessary, breast and retaining walls of stone, with numerous side and cross drains, all constructed in the most perfect manner. The whole is protected with stone walls; those upon precipices built with lime mortar, most of the others pointed with it. The breast walls on some parts of this road are 9 feet in depth below the surface of the roadway, and 4 feet in height above it, making a total elevation of 13 feet; they are 3 feet 6 inches thick at the base, and 15 inches at top, having a batter or retiring on the outer face of 22½ inches, and on the inner face of 4½ inches. The retaining walls on the other side of the road are 9 feet high, 2 feet thick at the base, and 14 inches at top, having a batter from the road of 18 inches. The clear width of road between the walls is 22 feet." Resuming Telford's account,—"There are several considerable bridges, also numerous cuttings and embankments, in that mountainous country; one, particularly, at the village of Chirk, is 50 feet in height. Four miles of branch-roads have been made."

Under the second head, Telford describes roads formed and improved at Tally Pont Hill, Penmaen Mawr, Penmaen Back, and Rhyalt Hill, of a total length of 9 miles and 1177 yards; and the embankments in North Wales, forming the third divison of the works, are thus particularised: "Near Holyhead there is an inlet of the sea, known by the name of the Stanley Sands: over this estuary an embankment, 1144 yards in length, has been made: the height above the undisturbed surface of the sands, in the middle, is 29 feet; the breadth at the top, including the parapet walls and outer facing, is 34 feet; the slopes on each side are faced with rubble-stone, two feet in thickness; on each side of the road there is a parapet, 4 feet in height, coped with cut stone. The roadway is 24 feet in width; it has a paved bottom, and a coating of broken stone. In order to admit the tide to flow into the space on the west side of the embankment, there is a bridge built upon the only piece of natural rock found in that part of the estuary. This work was executed in two years: 156,271 cubic yards of earth, and 25,754 cubic yards of rubble-stone, were deposited in forming it. It has been completed 7 (now 26) years, and is now in a perfect state.

"The eastern approach to Conway bridge is formed by an embankment upon the sands, over which the tide usually flowed, and rendered it a very difficult and dangerous passage. The distance from the eastern shore to the island is 672 yards: the height of the embankment, on account of the sand being swept away by the violence of the tides during the execution of the work, is 54 feet; its breadth at the base is 300 feet, and 30 feet at the roadway; the side slopes are faced with rubble-stone. 261,381 cubic yards of earth, and 51,066 cubic yards of rubble-stone, were employed in forming it. The whole has been finished 3 (now 22) years, and is now in a perfect state."

The following description of the greatest of his works, classed under the fourth head of his statement, from the pen of Telford, is equally too interesting to admit, and too brief to require, curtailment.

"Besides several stone bridges, three of a novel description were required: over the Menai Straits, which separate the Isle of Anglesea from Carnarvonshire, in order to supersede an inconvenient ferry. It was found, after many years' investigation and discussion, that in a navigable and rapid tide-way a bridge upon the principle of suspension was the most practicable and economical: a bridge of that description, therefore, was begun in 1819, and successfully completed and opened on the 30th of January, 1826. This structure being of very unprecedented novelty and magnitude, considerable apprehensions were entertained concerning its stability: the engineer, therefore, by the advice of his friend, the President of the Royal Society (one of the Commissioners), considerably increased the height of the piers and the dimensions of the masonry and iron-work, beyond the original design; and this unavoidably led to considerable increase of expense; but as all the works were paid for at the prices previously fixed in making the first estimate, and as the quantities have been ascertained by measurements and weights correctly made by the resident engineer, the public has only paid for what was actually found in the work, and the edifice was thereby rendered more substantial. The contractor for the iron-works having made a claim on the Commissioners for alleged loss sustained by him in consequence of the unprecedented rise in the price of iron, the Commissioners felt themselves justified, on inquiry, in representing to the Treasury that the difference between the price paid by him for 2000 tons of iron, employed on this and the Conway bridges, and the price at which the contract had been made, exceeded £5,500; but this claim was not admitted. The distance between the points of suspension, for the middle opening, is 580 feet, and between the pyramids and toll-houses about half as much: to which is to be added what passes down the galleries to the places of fixture in the rocks, making the whole length of each main chain 1750 feet, or one-third of a mile. The height from low-water to the top of the saddles on the pyramids is 181 feet, and between the saddles and the roadway, 60 feet. The breadth of the platform is 30 feet, and consists of two driving-ways and a footpath between them. There are four stone arches on the Anglesea side, and three on the Carnarvonshire side, each 52 feet 6 inches span.

"At the town of Conway, between the before-mentioned island and the rocks in front of the old castle, there is a space through which the tide flows with very considerable velocity: over this space there has been made a bridge on the same principle as the Menai; it is 327 feet between the points of suspension. In this there is only a single roadway. The main chains are fixed in rocks at each extremity; the western approach is by a gateway formed in the old town wall, and by an embrasured terrace around the basement of one of the towers. The masonry of the supporting pyramids, and also the toll-house, is made to correspond with the old castle."

Telford also describes a bridge of one iron arch, 105 feet span, built at the point where the Shrewsbury road crosses the river Conway, above Llanrwst. Under the fifth head, the works comprise new and re-made roads to the extent of 31 miles and 1429 yards; and the Report finally shows the improvements effected in the harbours of Holyhead and Howth since the year 1823 (when they were placed under the management of the Holyhead Road Commissioners), and the improvements of the navigation of the Menai Straits by removing parts of the Swilly Rocks. The total sum expended on these several works during the fifteen years ending at the date of the Report (1830) was £697,637 10*s.* 6*d.*, besides £28,460 4*s.* 1*d.*, for management; £4,583 4*s.* 7*d.* for parliamentary fees in passing Acts, and Exchequer fees, and £2,821 8*s.* 5*d.* for solicitors' bills in passing Acts and other general business.

It has been stated, at the commencement of this section, that the railway now in course of completion between Chester and Holyhead is highly interesting in its general features, apart from the peculiarly novel and striking character of the two great bridges erected, like those designed and just described by Telford, to complete an important highway over the river Conway and the Straits of Menai.

On leaving Chester, itself one of the most ancient, and in history richly associated, of our English cities, the railway is carried over the river Dee, upon the cast-iron girder bridge which has been before described. For some few miles the traveller passes through an agricultural district, the Welsh mountains forming the back-ground on the left hand; but before arriving at Flint, the broad expanse of the Dee becomes visible on the right, and continues so, with little interruption, till its distant shore recedes from sight, and the river is found to have merged in the open Channel. From Colwyn the line pursues a nearly direct course to Conway, while the land stretches out into the Channel, and terminates in the point known as the Great Orme's Head, which in the distance is easily recognised by its appearance as a long level bank or low headland.

Some of the works involved in the construction of the railway at the intermediate points known as Penman or Penmaen Mawr are of a bold and costly construction. The precipitous face of this mountain descends to the water's edge, forming a cliff of steep and rugged outline; and Telford's work in forming his road at this point consisted of rock-cutting, over a length of 1 mile and 231 yards, and, in some parts, 30 feet in height. This is protected with high breast and retaining walls, having stone parapets laid in lime mortar. The roadway is formed of pavement bottoming and a coating of broken stone; "so that this formerly frightful precipice is now a safe trotting road." (Telford's Report, 1830.) The Chester and Holyhead Railway now passes beneath the foot of the mountain, and about 250 feet below the road thus carved out of its surface by Telford.

The works consist of a sea-wall of masonry, 1¼ mile in length, and in some parts 60 feet high; a viaduct, consisting of vertical piers of masonry, 41 feet high from the foundations, 7 feet thick, 15 feet above Trinity high water on their top surface, and supporting longitudinal girders, 42 feet in span, upon which the rails are carried. This viaduct was substituted for a similar length of sea-wall which was destroyed by a storm in October, 1846. The coffer-dams for the foundations of the piers were commenced in May, 1847, the masonry on the 1st of June following, and the line opened for traffic on the 1st of May, 1848. Through a projecting foot of the hard basaltic rock, the line is carried in a tunnel 235 yards in length, at the east end of which one-half the width of the line is formed by scarfing out the rock, and the other half by an embankment retained by a sea-wall; it is covered with an avalanche roof, of whole timbers, spanning the railway, to prevent injury from loose pieces of rock falling on to it.

The crossing by the railway of the river Conway requires the first of the tubular bridges; and at about 18 miles further on, the separation of the Island of Anglesea from the main land of Carnarvonshire by the Straits of Menai gives occasion for a bolder structure, of which the central pier is skilfully based on a rock named the Britannia Rock, and which thus derives its title of the Britannia Bridge.

The national importance of securing the most direct and rapid communication between London and Dublin, and of selecting, as conducive to this purpose, such a port on the Welsh coast as would reduce the sea voyage to the minimum of time and uncertainty, commanded the anxious attention of Parliament in 1836, a select committee of which, in October of that year, recommended an address to the Crown to procure a "survey of the harbours on the line of coast best calculated for a direct communication between London and Dublin, with a view of ascertaining whether the existing ports of Holyhead and Liverpool, or any other ports on that part of the coast of Great Britain, would, in the judgment of experienced naval surveyors, furnish the greatest facilities for steam communication by packet across the Channel." This recommendation, having been duly adopted by the Lords of the Treasury, was referred by them to the Admiralty authorities, whose hydrographer (Admiral F. Beaufort) reported accordingly on November 4, 1836, in which Report the two following sentences occur. "As long as the Dublin mails are carried by coaches on common roads, the best place of embarkation in every respect will be Holyhead, which is only 62 statute miles from Kingston harbour, and which only requires a little elongation of the pier, in order to admit a larger class of steam vessels at low water. But if a railroad should be constructed for that purpose, it would be probably led to another port, because it is not likely that a steam carriage with a loaded train would be allowed to traverse the present chain bridge at Bangor; and a new bridge there, on arches, would add enormously to the expense of the undertaking; besides the objection that would be raised to such a bridge, from the obstruction it would give to the navigation of the strait."

A bold conception of engineering design, aided by improved skill in metallic construction, is, however, now rearing a new bridge, on which loaded trains of any possible weight may be safely allowed to traverse, and which presents neither arches nor other obstruction to the "navigation of the strait." The dictum of the Admiralty hydrographer appears to have been accepted as conclusive, without further survey, in favour of Holyhead, supposing the bridge difficulty got over, or of Port Dynllaen, on the south-western coast of Carnarvonshire, in order to obviate this difficulty. The communication between this place and London, however, would require a longer line than Holyhead, and was, moreover, at that time associated with a project of equivocal feasibility, for carrying a line of railway through the Merioneth mountains.

Subsequently (June 9, 1843), Captains Back and Fair, in obedience to the commands of the Admiralty, reported on the capabilities of the two ports, Holyhead and Dynllaen, and expressed their "unqualified opinion, that both as to capability and position, Holyhead is unquestionably the most eligible harbour on the coast as a port of communication with Dublin." In the same year, and following one, Sir John Rennie, Mr. James Walker, and Mr. Page, severally reported on the engineering improvements of these harbours as harbours of refuge, and as susceptible of ready communication with the English metropolis by means of a railway.

These Reports of course expressed professional views and opinions upon the several topics of a somewhat conflicting nature, but the practical results of the proceedings then and previously taken have been, as now well known, the adoption of Holyhead as a packet station, and of Mr. Stephenson's line of railway between that port and Chester; while the improvement of the harbour has been intrusted to Mr. Rendel.

Each of the three engineers named as reporters found it incumbent on him to offer some remarks on the best manner of getting over the Menai Straits. A few of these may be properly quoted here. Mr. J. Walker, after expressing his decided opinion of the railway as of the harbour, that "the best line should be selected," and further, that "the railway should be made in a good manner as a great public work," objects to the proposal which had been made of using the suspension bridge for railway purposes, by drawing the trains by horses or a fixed engine up the slope of the present bridge (of which the inclination is at the rate of 1 in 25), and recommends that the line of railway "should be continued direct to the straits, and the straits crossed by an arched bridge built for the railway," which bridge "may cross at the Swilly or Gorred Goch Rocks." Both of these groups of rocks are between the suspension bridge and the Britannia bridge.

Mr. Page observed, with regard to the effect of the passage of railway trains over the Menai suspension bridge, that "the sectional area of the main chains being 260 square inches, and the weight of the bridge (including 130 tons additional weight due to the repairs in 1839 and 1840) 774 tons, the strain upon the main chains, on the principle used by Sir F. Smith and Professor Barlow, amounts to rather more than 5 tons per square inch, *supposing the weight to be borne equally by all the chains, and without any allowance for the momentum produced by undulation*, the effects of which upon the bridge by the gale in January, 1839, are well known. This weight is nearly 1 ton 16 cwt. per square inch more than was calculated upon in the evidence of Mr. Telford and Mr. Rennie, given before a select committee of the House of Commons (April 29, 1819); and as their calculations were made with reference to iron unimpaired in its elastic force, which, after the severe trials to which this structure has been exposed, cannot be said of the chains and rods of the bridge at present, it follows that the limits intended by its engineer have been (perhaps unavoidably) considerably exceeded."— "The weight of railway carriages would be limited to one side or the other, and therefore the strain would be brought upon half the chains and suspending rods; and if a train passes without the engine, taking ten carriages at 5 tons each, the extra strain upon the chains would be 85 tons, which on 130 square inches, being equal to 13 cwt. per square inch, would make the total strain 5 tons 13 cwt. per square inch." Consequently, "the passage of connected railway trains would be injurious to the general stability of the bridge."

The following extract from the Report made by Sir John Rennie will show that nearly half a century ago iron was referred to as the preferable material for constructing a fixed bridge over the Menai Straits:

"In order to conduct the railway traffic in a proper manner, a fixed bridge is absolutely necessary, and ought to be adopted. The late Mr. Rennie was always of opinion, that a permanent fixed bridge was the only fit means of communication across the Menai; and in his Report of the 16th of February, 1802, to the Right Hon. Charles Abbot, he enters into the whole subject with great detail and ability. For the reasons stated in the Report, he says that there are only two situations properly adapted for the construction of a bridge across the straits; viz. the Ynys y Moch and the Swilly Rocks, 800 yards above it; and in this view the late Mr. Telford concurred (see his Report). Upon the former site Mr. Rennie proposed to construct a fixed bridge, having one cast-iron arch of 450 feet opening, so as to span the entire width of the straits at low water, and to spring 100 feet above the high-water mark; and from this main arch he proposed to construct smaller arches of stone, to the extent of 156 yards on the Carnarvonshire side, and similar arches on the Anglesea side, to the extent of 284 yards, making a total length of 640 yards, exclusive of the wing-walls: this design he estimated at £259,140. And the other design, to cross the Swilly Rocks, he proposed to consist of three cast-iron arches, 350 feet span each, and 150 at the crown, above an ordinary spring-tide, and to connect these arches on the Carnarvon side by smaller stone arches to the extent of 200 yards, and on the Anglesea side by land arches to the extent of 434 yards, besides embankments, thus making a total length of 1076 yards: the expense of this design (which he strongly recommended to be adopted in preference to the other) he estimated at £290,417. It is much to be regretted that neither of these designs was adopted, which the expense alone, however, prevented, and the present chain or suspension bridge, by Mr. Telford, was adopted instead, as it was supposed that it could have been completed for £70,000; but if the ultimate costs could have been foreseen, it is more than probable that the fixed cast-iron bridge would have been carried into effect. With reference, however, to carrying the railway across the straits, some similar plan of a bridge ought to be adopted; and, taking into consideration the magnitude of the work and the difficulties of the situation, I do not think that it would be prudent to estimate the cost at a less sum than stated by Mr. Rennie, viz. £290,417. The time also for completing such a work, considering its extent and difficulty, and the numerous contingencies to which it would necessarily be exposed, could not be taken at less than from five to seven years; indeed, the present suspension bridge occupied above seven years, and the late Mr. Telford considered that the site of the Swilly Rocks would be attended with greater difficulties."

In his designs for carrying the Chester and Holyhead Railway over the straits, Mr. Robert Stephenson had thus to determine the two fundamental points of site and construction of his proposed work. The site which, after careful examination, he selected, although not one which had received the approval of former engineers, offers one peculiar advantage, which Mr. Stephenson duly remarked, and determined to [illegible] himself of in the situation of his bridge. This consists in a mass of rock, occupying the centre of the stream, of suitable dimensions to serve as the foundation of a central pier, and standing considerably above the level of low water. The distance of this rock, and of the bridge now being built over it, from the suspension bridge of Telford, is one mile lower down the straits, or in a southern direction. Upon the other great question, viz. the construction of the bridge, Mr. Stephenson brought some of his own experience to bear, which proved far more conclusively than any theoretical inquiries, that the suspension principle is utterly inapplicable for sustaining railway traffic. The following extract from his Report, presented to the Directors of the Railway, in February, 1846, gives the results of this experience:

"The injurious consequences attending the ordinary mode of employing chains in suspension bridges were brought under my observation in a very striking manner, on the Stockton and Darlington Railway, where I was called upon to erect a new bridge for carrying the railway across the river Tees, in lieu of an ordinary suspension bridge, which had proved an entire failure. Immediately on opening the suspension bridge for railway traffic, the undulations into which the roadway was thrown, by the inevitable unequal distribution of the weights of the train upon it, were such as to threaten the instant downfall of the whole structure. These dangerous undulations were most materially aggravated by the chain itself, for this obvious reason,—that the platform or roadway, which was constructed with ordinary trussing, for the purpose of rendering it comparatively rigid, was suspended to the chain, which was perfectly flexible, all the parts of the latter being in equilibrium. The structure was, therefore, composed of two parts, the stability of the one being totally incompatible with that of the other; for example, the moment an unequal distribution of weights upon the roadway took place, by the passage of a train, the curve of the chain altered, one portion descending at the point immediately above the greatest weights, and consequently causing some other portion to ascend in a corresponding degree, which necessarily raised the platform with it, and augmented the undulation. So seriously was this defect found to operate, that immediate steps were taken to support the platform underneath by ordinary trussing; in short, by the erection of a complete wooden bridge, which took off a large portion of the strain upon the chains. If the chains had been wholly removed, the substructure would have been more effective; but as they were allowed to remain, with the view of assisting, they still partake of those changes in the form of the curve consequent upon the unequal distribution of the weight, and eventually destroyed all the connections of the wooden frame-work underneath the platform, and even loosened and suspended many of the piles upon which the frame-work rested, and to which it was attached. The study of these and other circumstances connected with the Stockton bridge leads me to reject all idea of deriving aid from chains employed in the ordinary manner." A fixed and rigid structure being thus indispensable to sustain railway traffic, Mr. Stephenson proposed to cross the straits with a cast-iron arched bridge in two spans of 450 feet each, and prepared his designs accordingly, the height of the arches being 100 feet from the level of the water to the crown of the arch, and the springing 50 feet from the same level. As it was necessary that the water-way should not be interrupted by scaffolding or centering, such as is usually employed in erecting arched bridges, Mr. Stephenson designed to fix the half-arches on each side of the central pier in portions simultaneously, and connect them with tie-rods, so that the weight on either side should balance that on the other.

The Commissioners of the Admiralty, however, who constitute the final authority in these matters, insisted upon one condition which rendered this design inapplicable; viz., that the clear height of water-way under the lowest part of the arches or their springing should not be less than 100 feet. To have retained the same general design, it would therefore have become necessary to elevate the whole structure 50 feet above the proposed position, an alteration involving immense additional cost in the piers and abutments of the bridge, besides being irreconcileable with the adjoining levels of the railway. Under these circumstances the indomitable engineer determined to abandon the arched form altogether, and to seek a horizontal form of construction which should possess all the strength and inflexibility required for the support of its destined loads over spaces of 450 feet, and be at the same time susceptible of erection without obstructing the navigation of the straits.

Here was a problem of nearly unexampled difficulty, demanding for its solution the union of original bold conception, careful scientific experiment, and practical art and skill, rarely required and rarely to be commanded even on the most momentous occasions of engineering expedient. The first of these essentials was early supplied by Mr. Stephenson, who, in the month of February, 1845, announced his suggestion of wrought iron as the best material for the bridge over the straits, and the form of a hollow girder or tube as the shape in which this material should be combined for the purpose. To obviate the difficulty respecting scaffolding, it was determined that each of the tubes should be constructed at some unoccupied place contiguous to its permanent position, and raised and deposited in that position *en masse*. These decisions, which comprised the leading outlines of the plan, were wisely followed up by an elaborate series of experiments to determine, first, the peculiar sectional form which should be given to the tubes, and secondly, the distribution and dimensions of the material which would ensure the required strength and stiffness of the entire structure.

For these detail purposes, it was determined that a high authority in the theoretical and practical departments connected with the strength of the proposed material, and the best methods of its combination, should be enlisted in completing the design; and the authority selected was Mr. William

Fairbairn, who, after conducting a series of experiments to ascertain the strongest form for the tube, called in the aid of Mr. Eaton Hodgkinson in reducing the results and evolving practical formulæ for determining the details of the work. These gentlemen proceeded with their inquiries, and presented Reports embodying the results to Mr. Stephenson, who appended them to his own Report, presented to the Directors of the Railway Company at their meeting in February, 1846. The importance of these summary Reports renders it necessary to quote the results which they exhibit: this we propose to do in the following Section, after stating the general principles which distinguish all beam or girder bridges, whether tubular or solid, from those whose strength depends upon their arched form.

SECTION VI.

General Principles which distinguish Girder Bridges from Arched Bridges —Mr. Fairbairn's Experiments and Report on Tubular Girders—Mr. Hodgkinson's Experiments and Report—Mr. Stephenson's Report.

The earliest philosophers who essayed to develop the laws which regulate the resistance of bodies to transverse strains, viz. Galileo and Leibnitz, assumed a fundamental principle which the celebrated James Bernouilli seems to have been the first to expose. This radical error was, that all the particles of a beam submitted to an excessive transverse pressure are in a state of tension, and that the separation of them by the overcoming of their tensile power is the only action exerted by the weight which breaks the beam. James Bernouilli, however, detected the fallacy of this assumption, and showed that the particles of which a beam so loaded is composed, exert a different kind of force on that side which receives the pressure of the load from that which they exert on the opposite side. The sensible indication of this fact is afforded by the form which the beam assumes, the loaded side or surface becoming *concave*, while the opposite side becomes *convex*. On the concave side the particles are thus *compressed towards each* *other*, while on the convex side they are *distended or drawn from each other.* From this observation, Bernouilli deduced the theoretical existence of a longitudinal line, or rather plane, throughout the beam, which defines the limits equally of the compressive and extensive action; and to this line or limit, which, it follows, is neither reduced nor lengthened by the deflection of the beam, Bernouilli gave the name of the *neutral line.* Now this mutually opposing tendency of the action excited amongst the particles of a beam or girder by a load acting upon it transversely to its length, reduces the pressure which the beam exerts upon its abutments to a simple vertical one, no lateral or oblique force being exerted upon them, unless the form of the girder become so altered that its ends assume an oblique instead of a horizontal direction. An arch, on the contrary, is known to transfer its load to a lateral or an oblique thrust against the abutments, the total material of the arch being in a state of compression, and the abutments receiving the sum of this compression,—minus the elasticity of the material,—in a force which tends to push them outwards or away from each. A suspended structure may be instanced as an illustration of the opposite tendency, the resistance of the fabric to the load being exerted by the tension of the materials, which, transferred to the towers or points of suspension, tends to draw them inwards, or towards each other. The former, thrusting or pushing forces, may be called diverging or opposing forces; and the latter, pulling forces, may be called converging or compressing forces.

In order to produce their maximum strength and stability, the action of an arched, of a suspended, and of a girder bridge, as ultimately transferred to the abutments, is certainly required to be identically the same in *direction*, viz. *vertical.* Thus the maximum strength of the arched form is realised in the semicircular form, which springs vertically from the abutments; and in proportion as this direction of thrust varies from the vertical towards the horizontal through the angles of obliquity,—that is, as the arch becomes flattened and its height reduced,—so, in a determinable ratio, is the strength of the structure diminished. And, in the suspension bridge, the chains would act the most efficiently in carrying a load, if they could be employed in a true vertical direction, while their power is sacrificed the more they are made to diverge from this towards the horizontal direction. The common object of the arrangement of parts in an arch, and of the saddles over which the chains in a suspension bridge pass, is therefore to produce a resulting vertical action upon the abutments and towers.

But in a simple arch with abutments, or a chain with towers, it is necessary, in order to insure the equilibrium of the structure, to introduce other parts, which shall exert counteracting forces. Thus the arch requires an extra weight of materials above it in the spandrils, and the chain requires a counter-chain on either side of each tower, and the precise adjustment of these forces constitutes a problem of great practical importance in designing bridges of either class. Girders or beams, on the contrary, are required to resist their loads by the compound or counteractive power of the tensile and compressing forces exerted by their particles mutually against each other on the opposite sides of the neutral plane or line; so that the pressure imposed by the beam with its load upon the end supports or abutments shall act in a vertical direction only, or as a simply insistent weight. Now, in order to realise this condition of equilibrium of the girder, its dimensions and proportions throughout have to be determined with reference to the amount of force which the material is capable of exerting in resisting the extending and compressing action of the load. This force varies,—1st, according to the vertical distance of the upper and lower sides from the neutral plane, or axis;—and 2ndly, according to the nature of the material employed. Thus, the greater the vertical distance between the upper and lower sides respectively and the neutral plane, the greater will be the resistance exerted by the beam against the power of the load to compress and to extend it. The strength of the girder is hence in proportion to its depth: and the rule for ascertaining the power of bodies of rectangular section to resist the transverse fracture is based upon the principle that this power varies directly with the breadth and square of the depth of the girder, and inversely with its length. To apply one general formula for ascertaining this strength to various materials, it is necessary to introduce one element into the calculation, the value of which varies according to the material, and must be determined by experiments. Using S to denote this variable number; b, the breadth in inches; d, the depth, also in inches; l, the length in feet; and w, the weight in pounds, the general formula is

$$S\, b\, d^2 = l\, w.$$

The value of S has been determined for several materials as applicable to beams or girders, supported at each end and loaded in the middle.

Cast iron	2548
Malleable iron	2050
Teak	820
Ash	675
Canadian oak	588
Pitch pine	544
Red pine	447
Mar Forest fir	415
English oak	400
Riga fir	376
Larch	280

This also represents the order of the strength of the eleven materials enumerated to resist transverse loads. The strengths thus found are the ultimate or extreme strengths, only one-third of which can be safely permitted for a practical load which shall not injure the texture of the beam. On the other hand, the load is here supposed to be collected in one point or line on the centre of the length of the beam; whereas, practically, the maximum load to be provided for will be distributed over its whole length, and the load thus sustained will be double that which can be borne on a central point or line across the beam. The formula for finding the maximum safe load, equally distributed, will therefore be

$$\frac{S\,b\,d^2\,2}{3} = l\,w;$$

or the same result may be found by using 1699 instead of 2548, for the value of S in cast iron.

Subsequent experiments by Mr. Fairbairn and Mr. Hodgkinson have shown that in cast iron the power found by this formula is somewhat too high. These experiments were made upon fifty-two different kinds of cast iron, both hot and cold blast, from the principal Iron Works in the United Kingdom, and also including samples from Elba, and Samakoff in Turkey. The bars upon which the loads were placed in the middle were of various dimensions as to length, breadth, and depth; but the results will be much simplified and rendered more readily applicable by reducing them all to one uniform section and length, and deducing an average from the whole of the varying results. Thus reducing the bars to an uniform breadth and depth of 1 inch, and length of 4 feet 6 inches, or 54 inches, the mean breaking weight of all the trials made upon each kind of iron varied from 581 lbs. to 357 lbs., the average of the fifty-two kinds of iron being 449·36 lbs. To reduce this breaking weight for bars 4 feet 6 inches long to a strength per inch of length, in order to arrive at a rule of general applicability, we may multiply the weight found of 449·36 lbs. by the number (54) of inches in the length of the bars experimented upon, the product of which is 10 tons 16·6 cwt., which we may call 11 tons. This being the strength per inch, the strength of any beam of rectangular figure may be found by multiplying this average unit of 11 tons by the transverse sectional area of the beam and by its depth, and dividing the product by the length. All of these dimensions being taken in inches, the quotient will be in tons, representing the weight which will just break such a beam. To take an example, let it be required to ascertain the breaking weight of a cast-iron beam of average quality of metal and rectangular section, of which the breadth is 2 inches, the depth 5 inches, and the length between the bearings 5 feet, or 60 inches.

$$\frac{11 \times 10 \times 5}{60} = 9{\cdot}16 \text{ tons,}$$

or about 9 tons 3 cwts. 1 qr.; whereas by the rule before quoted ($S\ b\ d^2 = l\ w$), S being for cast iron 2548, the weight would be

$$\frac{2548 \times 2 \times 25}{5} = 25480 \text{ lbs., or 11 tons 7 cwts. 2 qrs.}$$

The rectangular form of transverse section is, however, the strongest for a loaded beam only upon the assumption that the forces by which it resists compression and extension are equal to each other, whereas it has been found by experiment that this is not the case in some (if indeed it is in any) of the materials of which beams are composed. Thus, cast iron has been found capable of resisting compression with six times the force that it exerts in resisting extension; from which it follows, that in order to derive the greatest strength from any given quantity of that material in a beam, that side of it which acts against extension, or the under side —the load being on the top—should have six times as much iron as is necessary in the upper part of it, which resists compression.

Again, as the maximum compressive force acts at the upper limit of the beam, and the maximum extending force acts on its lower limit, both of these forces being reduced to zero at the neutral plane, the distribution of the material should be regulated with a corresponding greater bulk at the limits of the section, and diminished towards the neutral plane.

The form of section determinable by these conditions will therefore assume a resemblance to the outline of two vertical cones, whereof one is inverted over the other so that their apicis meet, and the lower one containing six times the bulk of the upper and inverted one. A more familiar idea of the outline may be derived by comparing it to that of a sand or hour glass, with the difference only of the inequality of the two compartments.

The form of section which has been suggested and practically adopted in the manufacture of cast-iron girders as approaching this theoretical figure, is that of an upper and lower horizontal flange, of which the areas are in the proportion of 1 to 6, with a thin vertical web, or rib, between and connecting them. The selection of this form has been sanctioned by the assumption, which we submit is erroneous, that the greatest strength of the girder is obtained only when the entire material is collected at those points where the compressing and extending forces are acting with the greatest power. Hence it has been inferred that the theoretical, but impracticable, form of section of maximum strength requires that "the material of the extended side and the material of the compressed side be respectively collected into two geometrical lines parallel to the vertical axis;—a distribution manifestly impossible, since it would produce an entire separation of the two sides of the beam." * Now this condition is manifestly as unnecessary, at least, as it is impossible. The equilibrium of the beam simply requires that at the moment when the load begins to surpass its strength, and rupture is about to commence, every particle of the material shall be performing its full duty in resisting this tendency. The assumed occasion for collecting the total material in those limits of the beam at which rupture is commencing, could arise only if the rupture were instantaneous throughout the entire depth of the beam, an "if" which is utterly inconsistent with the existence of compressing and extending forces.

The accession of strength obtained by adopting a sectional form, designed with reference to the action of the compressive and extending forces at different distances from the neutral plane, has been shown by experiment to be four-elevenths: that is, the unit of strength or cast-iron beams, which, if of

* "Mechanical Principles of Engineering," by Professor Moseley.

a rectangular section, is, as we have shown, 11 tons, is increased to 15 tons when the top and bottom of the beam are formed with greater material in the form of projecting flanges than the middle portion of it, in the section known as the equal flanged or I-section. But by arranging the material of the section with reference to its comparative power of resisting the two forces of compression and extension, which, in cast iron, as we have stated, is as 6 to 1, a still greater strength is derived; and the unit of 11 of the rectangular beam, increased to 15 in the equal-flanged beam, is now increased to 19 in the beam whose section consists of an upper flange and a lower flange of 6 times the area of the upper one, the two being united by a central vertical rib. Using these units respectively instead of 11, the rule given for rectangular sections is equally applicable to those of equal and unequal flanges.

Theory and experiment concur in showing that the uniform transverse strength of a beam throughout its length between the supports or abutments does not require an equality of sectional area in all parts, the strength of the beam being inversely as its length, and the effect of a given load diminishing towards the supports. Hence the *area* of the section may be reduced from the middle of the beam, at which the greatest strength is required, towards the supports, at which the least is sufficient. The diminution of sectional area thus allowable, should, according to the law by which the load operates, be made so that the outline of the longitudinal figure of the beam is an elliptical curve for a passing load, and a parabolic curve for a fixed load.

Being possessed of these few elementary notions of the action of arched, suspension, and girder bridges, and of the principles which determine the form of the latter when constructed of cast iron, we will now turn our attention to the malleable form of the metal, and, from the results of experiments upon it, deduce a comparison of the properties of the two forms of the metal.

In *structure*, malleable iron is essentially different from cast iron, the one being *fibrous* and the other *crystalline*. In *cohesive power*, or that power by which materials resist forces applied to tear them asunder, malleable iron is far superior to cast iron. The results of experiments show that the ultimate cohesive power of English bar iron equals 25 tons per square inch of the cross section of the bar. The power of Russian bar iron is stated at 26·7 tons, and of Swedish bar iron at 29·2 tons; the average of the three kinds is thus 26·96 tons, which may be called 27 tons; while the cohesive power of cast iron is only 7·87 tons; the proportion of the one to the other being thus as 27 to 8. This being the ultimate cohesive power, or representing that force which the bar is just able to resist, must be divided by at least three, to show the maximum strain to which the bar should be exposed. The elastic power of the metal, however, or the power which it has, on the removal of the load, to return its particles to their former condition, is of course much less than the total cohesive power which it is capable of exerting in resisting a force equal to their absolute separation. Thus, while the cohesive force of wrought iron is, as stated, equal to 27 tons per square inch, its elastic power, according to the experiments conducted by Mr. P. Barlow, is about 10 tons per square inch in good iron, and as low as 8 tons in inferior qualities. Taking the average, or 9 tons, we may consider that its elastic power is one-third of its cohesive power.

Upon the transverse strength of bars of malleable iron of rectangular section, as far as their elastic force is preserved, we may quote from Mr. Barlow's experiments, which were very carefully conducted, in the course of his inquiry into the best form for malleable-iron rails. These experiments were made upon bars 1½ inch in breadth, 3 inches in depth, and 33 inches in length between the bearings, the pressure being applied in the middle of them. The deflections produced in two of these bars, and the average, were as follow:—

EXPERIMENTS ON BARS OF MALLEABLE IRON.

Weights.	Deflections.		
	Bar, No. 1.	Bar, No. 2.	Average of the two Bars.
Tons.	Inch.	Inch.	Inch.
·5	·059	·017	·038
1·0	·074	·037 (?)	·055 (?)
1·5	·083	·052	·067
2·0	·095	·061	·078
2·5	·101	·064	·082
3·0	·109	·078	·093
3·5	·120	·089	·104
4·0	·131	·102	·117
4·5	·148	·124	·136

The elasticity of these bars was preserved at a pressure of about 4¼ tons, but injured at 4½ tons. The average maximum deflection which the bars suffered without injury to their elasticity would therefore be between ·117 and ·136 inch. Adopting the medium, or ·126 inch, we may infer that this represents the maximum deflection which such bars can bear within their elastic power. The elastic force of cast iron is less than half of this, being, according to the rule* generally employed and derived from experimental results, ·0504 of an inch for a beam of the same dimensions as these malleable bars. From the experiments conducted upon malleable bars of the double-flanged or I-form, a complicated rule has been derived, which it is not necessary to give in this place, although, by way of showing the increased strength given to the bar by disposing the material in this double-flanged form, we will apply this rule to a bar having the same quantity of material, and length and depth of section, as the two rectangular bars upon which Mr. Barlow's experiments were tried, but with part of the material removed from the sides, and disposed as flanges on both sides of the central rib, in such a manner that the width over the top and bottom flanges

* This rule is, "Multiply the square of the length in feet by ·02, and the product, divided by the depth in inches, will equal the deflection."

is $2\frac{1}{2}$ inches, and their depth $\frac{3}{4}$ inch, the vertical rib being thus reduced to $\frac{1}{2}$ inch in thickness. Such a beam or bar will support 6·18 tons without injury to its elasticity, while the rectangular bars of equal sectional area supported only 4·25 tons. The gain in strength is thus 1 93 tons, or nearly 45 per cent.

In the remaining property of resistance to compressive force we shall find that wrought iron is similarly superior to cast iron. The formulæ which have been deduced from experiments upon the resistance exerted by solid cylinders of the two metals to a compressing force, are as follows:

$$\text{For cast iron} \quad W = \frac{5562\, d^4}{4\, d^2 + \cdot 18\, l^2},$$

$$\text{For malleable iron} \quad W = \frac{11125\, d^4}{4\, d^2 + \cdot 16\, l^2};$$

in which formulæ W is the weight which the cylinder will support in pounds; l, the length in feet; and d, the diameter in inches. Let us apply these to two cylinders 5 inches in diameter and 2 feet in length. In the cast-iron cylinder,

$$\frac{9562 \times 625}{100 + \cdot 18 \times 4} = \left\{ \begin{array}{l} \text{14913 lbs., or 6 tons} \\ \text{13 cwts. 17 lbs.} \end{array} \right.$$

In the malleable-iron cylinder,

$$\frac{11125 \times 625}{100 + \cdot 16 \times 4} = \left\{ \begin{array}{l} \text{17355 lbs., or 7 tons 14 cwts.} \\ \text{3 qrs. 23 lbs.} \end{array} \right.$$

The resistance to compression in the two metals is, therefore, as 14,913 to 17,355, or very nearly as 6 to 7. The properties of the two materials may be thus compared, and the amount possessed by each expressed in figures.

		Cast iron.		Malleable iron.
Cohesive power	as	8	to	27
Elastic power	,,	2	,,	5
Resistance to compression . .	,,	6	,,	7

In these three properties, which compose the practical value of these materials in construction, the malleable metal is thus shown to be greatly superior to the cast metal, although this superiority is by no means of similar amount or extent throughout. But knowing the ratio in which either material possesses two of the properties, that of the other material may be readily deduced. Thus we know that cast iron resists compression with six times the power it exerts in resisting extension, that is, its resistance to compression is 6 times greater than its cohesive power. Hence representing the cohesive power by 8, the resisting power will be 8 × 6 or 48. In malleable iron the cohesive power will be expressed in true ratio to 8 of the cast iron by the number 27. But its resistance to compression being only one-sixth more than that of cast iron, the ratio of this power will be 48 to + 8, or 56. It follows from this, that while the cohesive power of cast iron is to its resistance against compression as 8 to 48, or as 1 to 6, these properties exist in wrought iron in the proportion of 27 to 56, or nearly 1 to 2. This simple comparison, deduced from data which have been long before the public, enables us to understand that the strongest form for a wrought-iron girder will not have a similar proportion of parts to that for a cast-iron girder, and that while the lower flange of the latter should contain six times as much metal as the upper flange, the lower flange of the wrought-iron beam should have only twice as much as the upper one.

These proportions refer to *solid* girders, and of course are applicable only within certain limits; but these limits are sufficiently comprehensive for all practical purposes, and thus the proportions are in effect universally applicable to such girders.

If it came within our purpose to attempt to account for this difference of ratio of powers in the two kinds of iron, we would suggest that it might be traced to the difference of their structural condition. A crystalline and non-fibrous material, such as cast iron, may readily be supposed deficient in that strength to resist pulling asunder, which we find to reside in all fibrous materials whatsoever, the parts of which, beyond their simply molecular structure, appear to be capable of exerting a power of holding each other together by a kind of interlacing in the longitudinal direction. But although devoid of this power, the simply granular formation of cast iron and similar materials requires a total motion of the particles before yielding to compression, which is not so imperative in the fibrous material; and by way of illustrating this, the tendency of fibrous materials, when compressed beyond endurance, to *laminate*, or separate into thin sheets or scales, might perhaps be adduced.

That these rules will not equally apply to hollow or tubular girders might be readily anticipated, and has been proved by the experiments undertaken by Mr. Fairbairn in determining the dimensions and proportions for the Britannia Bridge.

The first point to be determined was the *form* of the tube, and with this view experimental tubes were constructed of several sectional forms, viz. circular, elliptical, and rectangular. The first series of experiments were tried on the first of these, viz. the cylindrical tubes, or those of circular transverse section. The lengths of these, or distance between the supports, varied from 15 feet $7\frac{1}{2}$ inches to 31 feet $3\frac{1}{4}$ inches; their diameters varied from 12 inches to 24·3 inches; the thickness of the plates of which they were constructed varied from ·037, or about $\frac{1}{27}$ of an inch, to ·135, or about $\frac{2}{15}$ of an inch; and the breaking weight varied from 2,704 lbs. to 14,240 lbs. The two smallest, thinnest, and weakest of these tubes failed by being crushed on the top, thus showing a deficiency in their power to resist compression as compared with their power to resist tension. The seven other tubes failed by being torn asunder at the bottom through the line of the rivet-holes, thus showing that neither the ultimate cohesive power of the metal, nor its power to resist compression, was exhausted by the weight which sufficed to break through the parts weakened with the holes for the rivets. These, therefore, were proofs of construction rather than material. The series of nine experiments and their results may be tabulated thus:—

CYLINDRICAL TUBES.

Experiments. Class.	Experiments. No.	Length of Tubes between the Supports. feet.	in.	Diameter.	Area of Transverse Section.	Thickness of Plates.	Ultimate Deflection.	Breaking Weight.	Manner of yielding.
		feet.	in.	in.	in.	in.	in.	lbs.	
A.	1	17	0	12·00	112·1	·0370	·65	2,704	Crushed top.
	2			12·18	116·5	·0408	·39	3,040	ditto.
B.	3	15	7½	12·40	120·8	·1310	1·29	11,440	Torn asunder at the bottom through rivet-holes.
C.	4	23	5	18·26	261·9	·0582	·56	6,400	ditto.
	5			17·68	245·5	·0631	·74	6,400	ditto.
	6			18·18	236·0	·1190	1·19	14,240	ditto.
D.	7	31	3¼	24·00	452·4	·0954	·63	9,760	ditto.
	8			24·20	460·0	·0954	·74	10,880	ditto.
	9			24·30	463·8	·1350	·95	14,240	ditto.

In none of these trials are we to suppose that the test applied reached the ultimate powers of the material. Comparing Classes A and B together, we see that in exp

No. 3 a tube of nearly the same length and diameter as that used in the first experiment, but with 3½ times the thickness, required 4½ times the breaking weight, and then yielded through the lower rivet-holes, while the top effectually resisted the crushing tendency of the weight. Whence we may infer that the greater comparative weakness of the first tube arose from a positive deficiency of material, by which it was prevented from maintaining its form long before the structural strength of the metal was brought into action.

Assuming that the weakness occasioned in experiments 4 to 9, by the holes cut in the plates for the rivets, was in the same ratio as the actual weakness of the material, we may compare the results of these six experiments, as if the tubes had in all cases yielded by the destruction of the full cohesive power due to the thickness of their plates, and we shall find the results vary nearly in the same ratio as the conditions of the several trials. Thus, in experiments 4 and 5, the tubes being the same length, and of nearly equal diameter, the thickness of the plates varying also only in a slight degree (as 58 to 63), the breaking weight was found to be precisely the same; while comparing these with the tube used in the sixth experiment, which was of the same length and similar diameter, but of plates about double the thickness of those used in experiments 4 and 5, the breaking weight was found to be also about double that in those experiments. Again, in Class D, the tubes used being of equal length and nearly equal diameter, the breaking weights are found to vary similarly with the thickness of plates: in the two tubes (experiments 7 and 8) of equal thickness, ·0954, or less than $\frac{1}{10}$ of an inch, the breaking weight varied only from 9,760 to 10,880 lbs., or about 11 per cent. The tube used in the ninth experiment, being of the same length and nearly the same diameter as those used in Nos. 7 and 8, had plates of about 50 per cent. greater thickness, and, accordingly, sustained a weight greater in nearly the same proportion.

In all the seven last experiments we remark the great strength of these tubes, which, from their small dimensions, could scarcely have been anticipated. Thus, in experiment No. 3, we have a tube nearly 16 feet long and 1 foot in diameter, only ·131, or about $\frac{1}{8}$ of an inch in thickness, requiring 11,440 lbs., or 5·1 tons, to break it; and the fracture then occurring in a line where the greatest tensile power was required, and the greatest weakness produced by the holes for the rivets. With such dimensions, we should have expected a total distortion of the tube would have been produced with much less weight. The same may be said of the remaining experiments generally, but between Nos. 3 and 8, and Nos. 3 and 9, an interesting comparison may be drawn. Thus, in the eighth experiment, we have a tube double the length of that used in the third, and of double the diameter, that is, four times the sectional area, and eight times the capacity, formed of plates *thinner* in the proportion of 95 to 131, and yet requiring very nearly an equal weight to break it, the proportion being as 18 to 19. And in the third and ninth experiments, we have results yet more striking. In the latter case the tube was of double the length and diameter, or, as in the 8th, four times the sectional area, and eight times the capacity,—the thickness equal or varying only as 135 to 131,—yet the breaking weight of the longer tube was *considerably more* than that of the shorter tube, being in the proportion of 14,240 to 11,440 lbs., or 6·3 to 5·1 tons. As both tubes yielded at length by the weakness caused by the rivet-holes, without suffering previous crushing on the top, we may suppose that neither the power to resist crushing, nor the cohesive power of this small quantity of material thus disposed, was exhausted even by this great weight. Let those who did not witness the experiments imagine a tube 31 feet in length, 2 feet in diameter, and only $\frac{1}{8}$ of an inch in thickness, loaded with 6 tons and 7 cwt. before it can be made to yield; and to form a notion of the amount of this weight, we should try that of a single half-hundred weight by lifting it, and then survey an array of 274 of these, required to make up the weight of 6 tons and 7 cwt.

Another series of experiments were tried upon tubes of an elliptical form. The results of these are shown in the following Table :—

EXPERIMENTS UPON ELLIPTICAL TUBES.

Experiments. Class.	No.	Length of Tubes between the Supports.	Diameter.	Area of Transverse Section.	Thickness of Plates.	Ultimate Deflection.	Breaking Weight.	Manner of yielding.
		feet. in.	in.	in.	in.	in.	lbs.	
E.	10	17 0	14·62 / 9·25	106·2	·0416	·62	2,100	Crushed on top.
	11	17 6	15·00 / 9·75	114·9	·1430	1·30	15,000	Ruptured on both sides.
F.	12	24 0	21·25 / 14·12	235·7	·0688	·45	7,270	By compression.
	13		21·66 / 13·60	229·7	·1320	1·80	17,070	By extension.
G.	14	18 6	12·00 / 7·50	70·7	·0775	·95	6,867	By compression.*

* This tube had a fin on the top.

These experiments are grouped together in three classes, and numbered consecutively from the last, the numbers having no reference whatever to the order in which the experiments were conducted.

Upon these results Mr. Fairbairn remarks, "It will be observed that the whole of these experiments indicated weakness on the top side of the tube, which, in almost every case, was greatly distorted by the force of compression acting in that direction. It is probable that those of the cylindrical form would have yielded in like manner, had the riveting at the joints been equally perfect on the lower side of the tube. This was not, however, the case, and hence arise the causes of rupture at that part."

The results of the two experiments in Class E are somewhat striking: the tubes were of nearly equal length, diameters, and area; the thickness of plates in the proportion of about 1 to 3·5, while the relative strengths were found to be as 21 to 150, or nearly 1 to 7·5. As the thinner of these tubes yielded by being crushed on the top, it would appear that the extreme thinness of the plates (about $\frac{1}{25}$ of an inch) caused the distortion of the tube before the virtual strength of the metal was called into action. In Class F we have two experiments which fairly show the value of the increased thickness of the plates. The tubes used were of equal length, and of similar diameter and sectional area, but of different thicknesses; and the increased thickness, in the proportion of 132 to 69, augmented the strength in the proportion of 171 to 73, and caused the tube to yield by extension instead of compression. The tube used in the single experiment in Class G was 1 foot more in length than that in No. 11, of much less sectional area,—in the proportion of 70 to 114,—about half the thickness of metal, and bore less than half the weight. Although this tube had a fin on the top, it yielded by compression, while that in the eleventh experiment was ruptured on both sides. This result seems to favour the supposition already suggested, that the yielding by compres-

[illegible] similar [illegible] considerable power [illegible]

[illegible] experiments were made with rectangular [illegible] importance [illegible] Mr. [illegible] rectangular [illegible] experiments, and probably the more important, were [illegible] rectangular [illegible] the many advantages [illegible] over every other yet experimented [illegible] I am inclined to think [illegible] not only the strongest, but the best adapted [illegible] lightness or economy [illegible]." These experiments may be arranged as follows.—

EXPERIMENTS UPON RECTANGULAR TUBES.

Experiments. Class	Experiments. No.	Length of Tubes between the Supports. feet.	Length of Tubes between the Supports. in.	Depth. in.	Width. in.	Area of Transverse Section. in.	Thickness of Plates. Top. in.	Thickness of Plates. Bottom. in.	Ultimate Deflection. in.	Breaking Weight. lbs.	Manner of yielding.
H	15	17	6	9·6	9·6	92·16	·075	·075	1·10	6,788	By compression.
	16						·272	·075	1·18	8,273	By extension.
	17						·075	·142	0·94	3,788	By compression.
	18						·142	·075	1·88	7,148	By extension.
I	19	17	6	18·25	9·25	168·81	·050	·149	0·93	6,812	By compression.
	20						·149	·050	1·73	12,188	ditto.
	21	18	0	13·25	7·50	99·37	·142	·142	1·71	13,680	ditto.
	22	24	0	15·00	9·25	138·75	·100	·100	2·06	17,000	ditto.
K.	23	18	6	13·00	8·00	104·00	·066	·066	1·10	8,812	ditto.*
	24	19	0	15·40	7·75	119·35	·230	·180	1·50	22,400	Sides distorted.†

* This tube was formed with a fin on the top and a circular bottom.
† This tube was formed with a corrugated top.

The four experiments in Class H were with square tubes—the remainder were performed upon tubes whose depth more or less exceeded their width, and the strength of which varied generally with the depth. The value of the increase of depth is evident by comparing No. 18 with No. 20. These tubes were of equal length, and similar width and thickness of plates; the former having the advantage, however, in the bottom plates, in the proportion of 75 to 59, and a very slight inferiority in the top plates, viz. as 142 to 149. But the tube in experiment No. 20, being nearly twice the depth of that in No. 18, required nearly double the weight to make it yield, the proportion being 12,188 to 7,148, or nearly as 29 to 17. The difference in the manner of yielding must be also remarked, as the deeper tube yielded by compression, showing that its tensile power was not exhausted, while the square tube gave way by extension.

The striking and highly important fact to be deduced from these four experiments in Class H, however, is the great accession of strength obtained by increasing the thickness of the top plate only, the other parts remaining the same. Thus the tube used in experiment No. 15 had its strength more than doubled by giving an additional thickness of ·197, or about $\frac{1}{5}$ of an inch, to its top plate; and while, in its former state, the tube yielded by compression, its power of resistance was so much increased by the thickened top plate that it then yielded by extension. Comparing Nos. 15 and 17 together, it is seen that no additional power was derived from doubling the bottom plate; the tube still yielded by compression to about the same weight. But when reversed so that the thickened plate was at the top, the tube being identically the same in all respects, its strength was doubled, and yielded at length by extension.

These results, as Mr. Stephenson has remarked, show "that in *such tubes* the power of wrought iron to resist compression is much less than its power to resist tension," it having "invariably been observed," as Mr. Fairbairn states, "that in almost every experiment the tubes gave evidence of weakness in their powers of resistance, on the top side, to the forces tending to crush them." But we are not to accept these results, true as they undoubtedly are, of wrought-iron fabrics of limited dimensions, as proofs of the *ultimate strength of wrought iron.* We have already shown (page 72) that upon the best and admitted data, the cohesive powers of cast and wrought iron are as 8 to 27, and that their resistance to compression is as 6 to 7. Now, adopting these proportions, and the equally acknowledged fact that the cohesive power of cast iron is to its resistance to compression as 1 to 6, or as 8 to 48, it follows indubitably that the resistance to compression exerted by malleable iron (being to that of cast iron as 7 to 6, or as 56 to 48) must, compared with its cohesive power, be as 56 to 27; or, in other words, if a cubic inch of wrought iron may be broken by extension with a force of 27 tons, it will not yield to a compressing or crushing force of less than 56 tons.

Practically, however, the results of these experiments are of the highest value, as bearing upon the limits of strength of girders of wrought iron built up or constructed of plates in the manner proposed and adopted for the tubular bridges. In cast-iron girders, formed, as they are, solid throughout, the ultimate strength of the material may be applied; but in those formed of wrought-iron plates connected with rivets, ribs, &c., the *constructive* strength of the work, rather than the absolute strength of the material, is the point of practical importance in the design. In these cases the term "compression" is scarcely properly applied; the effect produced being really, as described by Mr. Fairbairn, a "crippling or doubling up." The power to resist compression thus becomes a power to resist bending, and this is, of course, comparatively small in thin sheets or plates even of wrought iron. In like manner, the cohesive or tensile power is practically reduced to that of the rivets, to withstand the strain upon them, or of the plates at the longitudinal joints.

The effects produced by thickening the tops of the tubes, and reversing them in position, are thus described by Mr. Fairbairn: "With tubes of a rectangular shape, having the top side about double the thickness of the bottom, and the sides only half the thickness of the bottom, or one-fourth the thickness of the top, nearly double the strength was obtained. In experiment 15, a tube of the rectangular form, 9½ inches square, with top and bottom plates of equal thickness, the breaking weight was 3738 lbs.

Riveting a stronger plate on the top side, (experiment No. 16), the strength was increased to . . . . . 8273 lbs.

The difference being 4535 lbs.;

considerably more than double the strength sustained by the tube when the top and bottom sides were equal. The experiments given in Nos. 17 and 18 are of the same character, where the top plate is as near as possible double the thickness of the bottom. In these experiments the tube was first *crippled by doubling up the thin plate* on the top side, which was done with a weight of 3788 lbs.

It was then reversed with the thick side upwards (experiment No. 18), and by this change the breaking weight was increased to 7148 lbs.

Making a difference of 3360 lbs.;

or an increase of nearly double the strength, by the simple operation of reversing the tube, and turning it upside down.

"The same degree of importance is attached to a similar form, when the depth in the middle is double the width of tube. From the experiments (Nos. 19 and 20) we deduce the same results in a tube where the depth is 18¼, and the breadth 9¼ inches. Loading this tube with 6,812 lbs. (the thin plate being uppermost), it follows precisely the same law as before, and becomes wrinkled with a hummock rising on the top side, so as to render it no longer safe to sustain the load. Take, however, the same tube, and reverse it with the thick plate upwards, and you not only straighten the part previously injured, but you increase the resisting powers from 6,812 lbs. to 12,181 lbs. Let us now examine the tube in the 24th experiment, where the top is composed of corrugated iron, forming two tubular cavities extending longitudinally along its upper side. This, it will be observed, presents the best form for resisting the "*puckering*," or crushing *force, which, on almost every occasion, was present in the previous experiments.* Having loaded the tube with increasing weights, it ultimately gave way by tearing the sides from the top and bottom plates, at nearly one and the same instant after the last weight, 22,469 lbs., was laid on. The greatly increased strength indicated by this form of tube is highly satisfactory; and provided these facts be duly appreciated in the construction of the bridge, they will, I have no doubt, lead to the balance of the two resisting forces of tension and compression.*

"The results here obtained are so essential to this inquiry, and to our knowledge of the strength of materials in general, that I have deemed it essential, in this abridged statement, to direct attention to facts of immense value in the proper and judicious application, as well as distribution, of the material in the proposed structure. Strength and lightness are desiderata of great importance, and the circumstances above stated are well worthy the attention of the mathematician and engineer.

"For the present we shall have to consider not only the due and perfect proportion of the top and bottom sides of the tube, but also the stiffening of the sides with those parts, in order to effect the required rigidity for retaining the whole in shape. These are considerations which require attention; and till further experiments are made, and probably some of them upon a larger scale, it would be hazardous to pronounce any-

* These experiments on tubes with fins on the top and with the corrugated top, first led Mr. Fairbairn to propose the cellular distribution of the material on the tops of the great tubes.

thing definite as to the proportion of the parts, and the equalisation of the forces tending to the derangement of the structure. So far as our knowledge extends,—and judging from the experiments already completed,—I would venture to state that a tubular bridge can be constructed, of such powers and dimensions as will meet, with perfect security, the requirements of railway traffic across the straits,"—"and although suspension chains may be useful in the construction in the first instance, they would nevertheless be highly improper to depend upon as the principal support of the bridge. Under every circumstance, I am of opinion that the tubes should be made sufficiently strong to sustain not only their own weight, but, in addition to that load, 2000 tons, equally distributed over the surface of the platform,—a load ten times greater than they will ever be called upon to support. In fact, it should be a huge, sheet-iron, hollow girder, of sufficient strength and stiffness to sustain those weights; and provided the parts are well-proportioned, and the plates properly riveted, you may strip off the chains, and leave it as a useful monument of the enterprise and energy of the age in which it was constructed."

It would thus appear, that at that early period Mr. Fairbairn had already determined that the proposed auxiliary chains should be dispensed with.

In the following Table the results of some of the experiments upon each of the three forms of tubes, viz. cylindrical, elliptical, and rectangular, are selected from the preceding Tables, and arranged in corresponding columns, for the purpose of showing the proportion between the transverse sectional area, the quantity of metal or material, and the breaking weight of each tube. The tubes are selected on account of their similarity of length; those tried in experiments 1, 2, and 10, being each 17 feet in length, and the remainder 17 feet 6 inches. The relative quantity of metal is obtained by simply multiplying the perimeter of each sectional area by the thickness of plates used, both in inches and decimal parts.

	Nos. of Experiments.	Diameters.		Area.	Metal.	Breaking Weight.	Proportion of Metal to Breaking Weight.
		Depth.	Width.				
		in.	in.	in.	in.	lbs.	
Cylindrical Tubes.	1	12·00		112·1	1·02	2,704	1 to 265
	2	12·18		116·5	1·57	3,040	1 ,, 194
Elliptical Tubes.	10	14·62	9·25	106·2	1·61	2,100	1 ,, 130
	11	15·00	9·75	114·9	5·68	15,000	1 ,, 264
Square Tubes.	15	.	.	.	2·88	3,738	1 ,, 130
	16	9·6	9·6	92·16	4·77	8,273	1 ,, 173
	17				3·52	3,788	1 ,, 108
	18	.	.	.	3·52	7,148	1 ,, 203
Rectangular Tubes.	19	18·25	9·25	168·81	4·14	6,812	1 ,, 164
	20				4·14	12,188	1 ,, 294

Mr. Fairbairn's experiments were thus reduced by Mr. Hodgkinson:—

Cylindrical Tubes.—The strength of a cylindrical tube supported at the ends, and loaded in the middle, is expressed by the formula

$$w = \frac{\pi f}{a l} (a^4 - a' 4),$$

where l is the distance between the supports, $a\ a'$ the external and internal radii, w the breaking weight, f the strain upon a unity of section as a square inch at the top and bottom of the tube in consequence of the weight w, $\pi = 3{\cdot}14159$.

From this formula we obtain

$$f = \frac{w\,l\,a}{\pi\,(a^4 - a'^4)}.$$

As it will be convenient to know the strain f per square inch which the metal at the top and bottom of the tube is bearing when rupture takes place, this value will be obtained from each of Mr. Fairbairn's experiments; the value w being made to include, besides the weight laid on at the time of fracture, the pressure from the weight of the tube between the supports, this last being equal to half that weight. Computing the results, we have, from

Experiment	1.	$f = 33426$	
„	2.	$f = 33456$	
„	3.	$f = 35462$	
„	4.	$f = 32415$	
„	5.	$f = 30078$	Mean 29887 lbs. = 13·34 tons.
„	6.	$f = 33869$	
„	7.	$f = 22528$	
„	8.	$f = 25095$	
„	9.	$f = 22655$	

Fracture in all cases took place either by the tube failing at the top, or tearing across at the rivet holes: this happened on the average, as appears from above, when the metal was strained 13⅓ tons per square inch, or little more than half its full tensile strength.

Elliptical Tubes.—The value of f in an elliptical tube broken as before (the transverse axis being vertical), is expressed by the formula

$$f = \frac{w\,l\,a}{\pi\,(b\,a^3 - b'\,a'\,3)},$$

where $a\ a'$ are the semi-transverse external and internal diameters, $b\ b'$ the semi-conjugate external and internal diameters, and the rest as before, w including in all cases the pressure from the weight of the beam. Computing the results from Mr. Fairbairn's experiments, we have, from

$$\left.\begin{array}{lll} \text{Experiment } 13. & f = & 36938 \\ \quad ,, \quad 12. & f = & 29144 \\ \quad ,, \quad 17. & f = & 45185 \end{array}\right\} \text{Mean } 37089 \text{ lbs.} = 16{\cdot}55 \text{ tons.}$$

Rectangular Tubes.—If in a rectangular tube employed as a beam, the thickness of the top and bottom be equal, and the sides are of any thickness at pleasure, then we have

$$f = \frac{3\,w\,l\,d}{2\,(b\,d^3 - b'\,d'\,3)},$$

in which d d' are the external and internal depths respectively, b b' the external and internal breadths, and the rest as before. Mr. Fairbairn's experiment No. 15 gives by reduction

$$f = 18495 \text{ lbs.} = 8{\cdot}2566 \text{ tons.}$$

This is, however, much below the value which some of my own experiments give, as will be seen further on.

The value of f, which represents the strain upon the top or bottom of the tube when it gives way, is the quantity per square inch which the material will bear either before it becomes crushed at the top side, or torn asunder at the bottom. But thin sheets of iron take a corrugated form with a much less pressure than would be required to tear them asunder; and therefore the value of f, as obtained from the preceding experiments, is generally the resistance of the material to crushing, and would have been so in every instance if the plates on the bottom side (subject to tension) had not been rendered weaker by riveting. The experiments made by myself were directed principally to two objects:—

1. To ascertain how far this value of f would be affected by changing the thickness of the metal, the other dimensions of the tube being the same.

2. To obtain the strength of tubes, precisely similar to other tubes fixed on,—but proportionately less than the former in all their dimensions, as length, breadth, depth, and

thickness,—in order to enable us to reason as to strength from one size to another, with more certainty than hitherto.

EXPERIMENTS UPON RECTANGULAR TUBES.

Length.		Depth.	Breadth.	Distance between Supports.		Weights.		Thickness of Plates.	Last observed Deflection.	Corresponding Weight.	Breaking Weight.	Value of f for crushing Strain.
feet.	in.	in.	in.	feet.	in.	cwt.	qr.	in.	in.	tons.	tons.	tons.
31	6	24	16	30	0	44	3	·525	3·03	56·3	57·5	19·17
31	6	24	16	30	0	24	1	·272	1·53	20·3	22·75	14·47
31	6	24	16	30	0	10	1	·124	1·20	5·04	5·53	7·74
						lb.	oz.			lb.	lb.	
8	2	6	4	7	6	78	13	·132	·66	9416	9976	23·1
8	2	6	4	7	6	38	11	·065	·32	2696	3156	15·31
8	2	6	4	7	6							
4	$2\frac{1}{8}$	3	2	3	9	10	12	·061	·435	2464	2464	24·56
4	$3\frac{1}{4}$	3	2	3	9	4	15	·030	·130	560	672	13·42

Another object, not far pursued, was to seek for the proper proportion of metal in the top and bottom of the tube. Much more is required in this direction. In the three series of experiments made, the tubes were *rectangular*, and the dimensions and other values are given in the preceding page.

"The tube placed first in each series is intended to be proportional in every leading dimension, as distance between supports, breadth, depth, and thickness of metal,—and any variations are allowed for in the computation. Thus the three first tubes of each series are intended to be similar, and in the same manner of the other tubes, &c.

"Looking at the breaking weight of the tubes varying only in thickness, we find a great falling off in the strength of the thinner ones; and the values of f show that in these—the thickness of the plates being ·525, ·272, ·124 inch—the resistance, per square inch, will be 19·17, 14·47, and 7·74 tons respectively. The breaking weights here employed do not include the pressure from the weight of the beam.

"The value of f is usually constant in questions on the strength of bodies of the same nature, and represents the tensile strength of the material; but it appears from these experiments that it is variable in tubes, and represents their power to resist crippling. It depends upon the thickness of the matter in the tubes when the depth or diameter is the same; or upon the thickness divided by the depth when that varies. The determination of the value of f, which can only be obtained by experiments, forms the chief obstacle to obtaining a formula for the strength of tubes of every form.

"In the last Table of experiments the tubes were devised to lessen or avoid the anomalies which riveting introduces, in order to render the properties sought for more obvious. Hence the results are somewhat higher than those which would be obtained by riveting as generally applied.

"The tube 31 feet 6 inches long, 24 cwts. 1 qr. weight, and ·272 inch in thickness of plates, was broken by crushing at the top with 22·75 tons. This tube was afterwards rendered straight, and had its weak top replaced by one of a given thickness, which I had obtained from computation; and the result was, that by a small addition of metal, applied in its proper proportion to the weakest part, the tube was increased in strength from 22·75 tons to 32·53 tons; and the top and the bottom gave way together."

For the details of these and the subsequent experiments, which are too extended to be introduced in this place, we must refer to the elaborate work of Mr. Fairbairn upon the "Conway and Britannia Tubular Bridges," where they are given with a mass of highly interesting correspondence, in which the entire history of the proceedings is narrated, and reductions of the experiments furnished.

SECTION VII.

Description of the BRITANNIA BRIDGE—The Masonry—Britannia Tower—Anglesea and Carnarvon Towers and Abutments—Arrangements for constructing the Tubes—Main Tubes and Land Tubes—Description of their Construction—Scaffolding and Staging—Arrangements for floating the Tubes—the Pontoons—Raising the Main Tubes—The Hydraulic Press—Connecting the Tubes in the Towers—The CONWAY BRIDGE.

HAVING in the preceding section given an abstract of the preliminary experiments upon wrought-iron tubes, we have now to describe the structures erected over the Conway River and the Menai Straits, and to show the admirable manner in which the material has been disposed to obtain the necessary strength for rigidity for bridges of such vast extent, designed to sustain the heavy weight and momentum of railway trains.

Of these bridges, that over the Conway was the first constructed, and was in itself an instance of triumphant success in design and execution; but as the Britannia Bridge far surpasses it in dimensions, and embraces similar works upon [illegible] extended scale, besides others not required in the Conway

Bridge, it will be advisable to devote our detailed notice to the former structure, and then point out the differences between it and the smaller one.

The shores of the Menai Straits, opposite the Britannia rock, and at the point which Mr. Stephenson selected for his passage, are somewhat different in their character and outline. On the Carnarvon side the shore rises abruptly from the water's edge, and shelves upward with a gentle inclination, so that a horizontal line which passes at an elevation of 100 feet over the water is, when extended about 400 feet inland from the water-line, only a few feet above the natural surface of the ground. On the Anglesea side the rocky surface extends for a considerable distance, and at a length of about 250 feet from the water-line the surface is from 80 to 90 feet below such a horizontal line as that just described. The consequence is, that the embankment required to continue the railway from the Anglesea end of the bridge is much higher, and more extended, than that needed at the Carnarvon end of the bridge.

The Britannia rock, which rises from the bed of the strait, near the middle of its width, is at high water covered to a depth of 10 feet, and stands at low water about 10 feet above it, the tide commonly rising 20 feet. On this rock a noble tower of masonry is erected, and at the clear distance of 460 feet from it, at the limit of the water-way, another tower is built on either side of it. At the distance of 230 feet from each of these towers, a continuous abutment of masonry, 176 feet in length, is erected, and the further extremities of these abutments constitute the two ends of *the bridge*. The masonry of the edifice thus consists of—

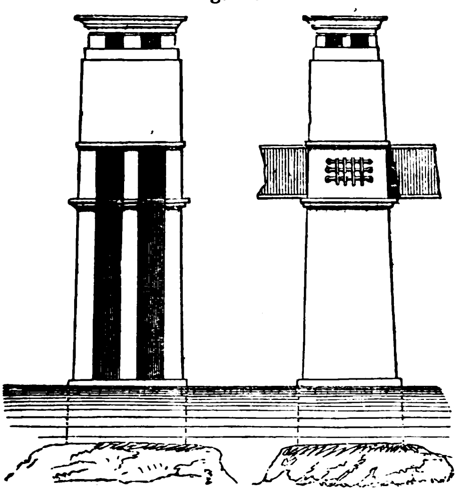
The Anglesea Abutment.	The Anglesea Tower.	THE BRITANNIA TOWER.	The Carnarvon Tower.	The Carnarvon Abutment.

The sides of these five stupendous masses of masonry are tapered or formed with a straight batter, by which the size of the upper parts is reduced, and greater firmness given to the mass, with a corresponding boldness in the character of the design. These works are of the following general dimensions.

Britannia Tower—62 feet by 52 feet 5 inches at the base, and reduced by the batter to 55 feet by 45 feet 5 inches at the height of 102 feet above high-water line, at which level the tubes pass through it. A plinth extends round the base of this and the other towers; and the height of this tower above high-water level is 200 feet, or nearly 230 feet from the bottom of the foundation on the rock. The stone used for the external parts of this, and the other towers and abutments, is a limestone of hard and durable quality, known as "Anglesea marble." It is quarried at Penmaen, on the shore and near the north-eastern extremity of the island, and is "got" in stones of great size, some of them weighing 10 to 14 tons. The interior of this and the other masonry is constructed of red sandstone, which is a soft stone, and therefore readily worked. It is quarried at Runcorn, in Cheshire, and is durable for inside work. The solid contents of this tower, if solid, would exceed 575,000 cubic feet, but it is constructed with hollow spaces or chambers within it, and the quantity of stone said to be actually used in it is 148,625 cubic feet of the limestone, and 144,625 cubic feet of the sandstone. The total weight of the masonry in this tower is about 20,000 tons, and about 387 tons of cast iron in beams and girders are built in it. The two views in Fig. 19 will give a good idea of its general proportions and appearance—the first of them being an elevation transverse to the direction of the railway, and showing the openings for the two tubes, while the other shows the elevation on the face of the bridge, with a portion of the tube projecting on each side.

The foundations were laid, and the work up to the level of high-water was constructed, during the intervals of the tide, no coffer-dam being employed, and thus some months were occupied in laying the first course, which was commenced in May, 1846. The scaffolding used for this and the other

Fig. 19.



parts of the work was of whole timbers or balks, put together with iron straps and bolts where required, and braced with diagonal half-balks connecting the upright posts. Parallel timbers were laid horizontally on the tops of the posts, and rails fixed upon them; and upon these rails, travelling crabs or "jennies" were enabled to pass in both directions to pick up the stones from the ships, raise them to the required height, and deposit them exactly in their intended places. The stones in the whole of the masonry are left with the quarry or rough face, except at the angles, where they are dressed to a square arris, and in the recesses and top entablature, where they are dressed to a fair face all over.

Anglesea and Carnarvon Towers.—The same dimensions at the base as the Britannia tower, viz.—62 feet by 52 feet 5 inches, reduced by the batter to 55 feet by 32 feet at the level of the bottom of the tubes; height from level of high water 190 feet, or 10 feet less than the Britannia tower. In architectural design and general appearance these towers exactly

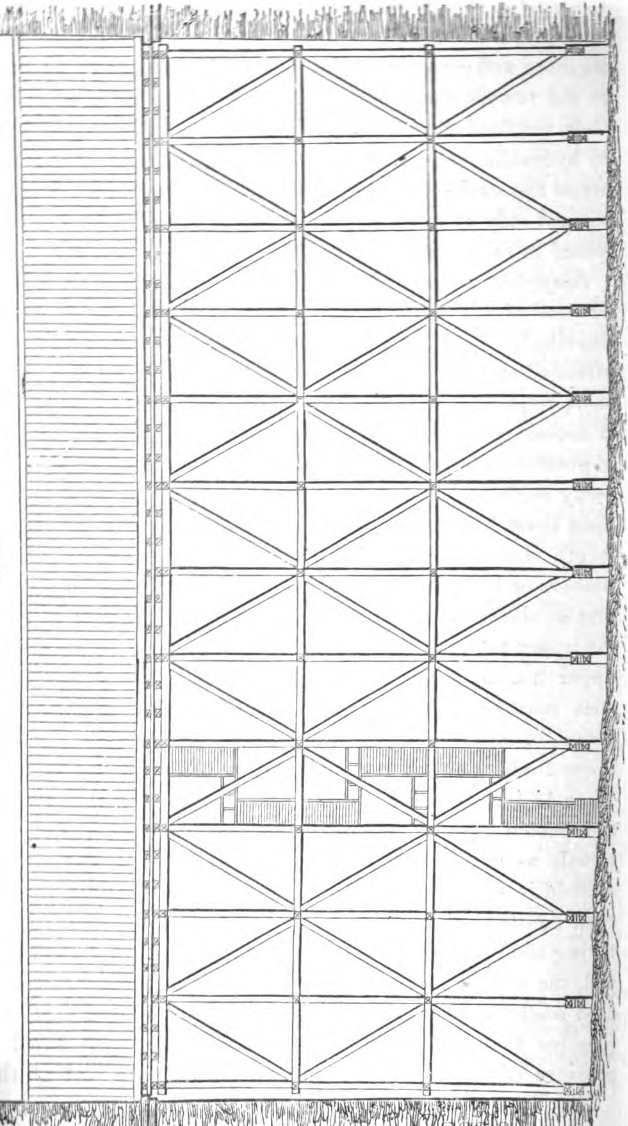


Fig. 20.

platform. The upright posts are connected at intervals with horizontal beams of similar dimensions, from 12 to 15 inches square, and strengthened with inclined struts, besides diagonal

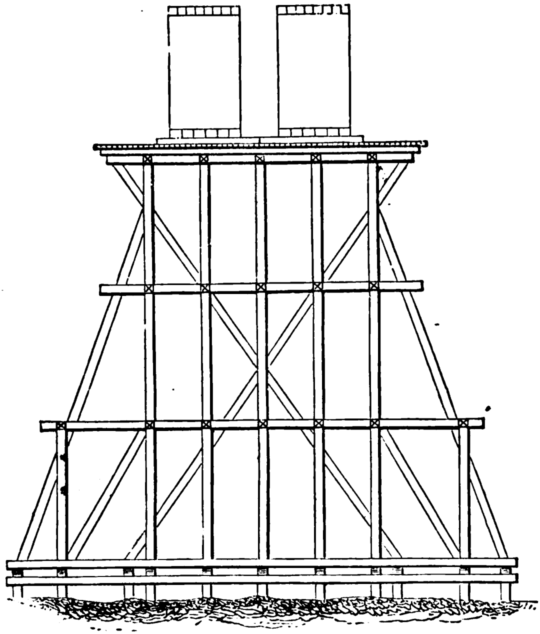


Fig. 21.

braces and longitudinal ties of half-timber. Longitudinal sills are laid on the posts with cross beams, and upon these strong planking is laid, forming a continuous platform upon which transverse balks are arranged, and carefully adjusted as the bearings upon which the foundation plates of the tubes are laid out, and the whole of the work erected.

Staging and Platforms for building the Main Tubes, Workshops, &c.—The site selected for the construction of the four main tubes, each of which is 472 feet in length, being an allowance of 6 feet at each end beyond the net span of [illegible] feet, was on the margin of the shore on the Carnarvon

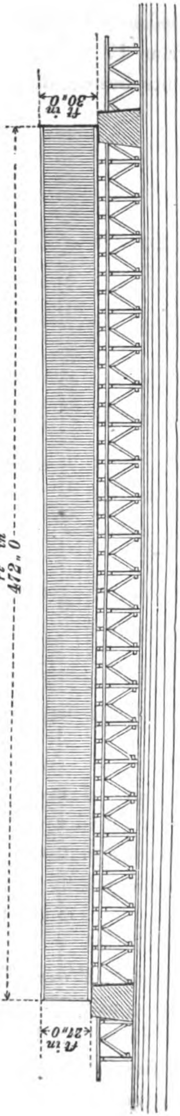


Fig. 22.

and to the south of the bridge. An intermediate space was occupied with offices and workshops; and on the higher part of the ground, wooden cottages, for about 500 workmen, were built. In order that the building of the four tubes might proceed simultaneously, a series of four strong stages were erected upon piles, and a continuous platform laid from end to end of the site. The staging was also extended inland, so as to provide space for several workshops, steam engine, stores for cordage, &c. &c.

In these workshops, machinery for punching and shearing the plates, and preparing the several parts of the tubes, was erected, besides vices, lathes, &c. &c., and all necessary tools provided for the workmen. Fig. 22 will convey an idea of the kind of staging and platform for each of the large tubes, consisting of timber-posts and struts, with top stringers and beams, and covered with stout planking. At each end a pier of masonry was built, extending under each end of the tube for a length of 6 feet. When each tube is completed, the platform is removed, and the tube is entirely supported upon these end piers, by which means the deflection of the tube, caused by its own weight, can be immediately ascertained, and its variation (if any), from day to day, noted. Parallel with the line of each tube, and just outside its boundaries, two lines of rails are laid, upon which a traversing stage is moved with winches. This stage is sufficiently wide and high in the transverse opening to stride the tube, and along the top of it a little crab, moving upon wheels, may be made to traverse the width of the work, and thus applied to raise the plates and materials in every part of it. Similar stages and gearing are also used in building the land tubes, and portable furnaces accompany the men employed in riveting, as the building of the tubes progresses.

The Tubes, —their dimensions and construction.—The four separate tubes, which make up each line of way through the bridge, will be, when the work is completed, united together; so that instead of eight separate tubes, there will then be only two parallel tubes, each of the length of 1,513 feet, or about $\frac{2}{7}$ths of a mile. For this purpose short lengths of tube are constructed within the towers, and the ultimate union of these with the main lengths will make up each complete and continuous tube of the length here stated. The portions of tube which will eventually occupy the Anglesea and Carnarvon towers are constructed on the scaffolding at either end, and after the main tubes are raised to their places these portions are launched forward to meet them, and properly connected together. The spaces thus left vacant between the portions thus advanced and the land tubes, are then filled up by building intermediate portions of tubing, and the whole connected together. To provide for the changes in length of these extended lengths of iron-work, produced by variations of temperature,* each tube is fixed in the middle of its length, that is, in the centre of the Britannia tower, but left perfectly free to contract or expand in its total length, by being simply supported upon rollers of cast iron, where it passes through

* It appears from the experiments of the late Professor Daniell, as reported in the "Philosophical Transactions" for 1831, that a variation of 76° Fahr. produces a change in a bar of malleable iron equal to $\frac{1}{2000}$th of its length.

each of the towers and abutments. With the ordinary range of the thermometer, the change of length thus produced will probably equal 12 inches, representing a movement of 6 inches in each half of the tube. The transverse sectional form of the tube is rectangular throughout, and its sides are perfectly parallel, that is, its width is uniform from end to end, but the height is slightly varied. The height externally is 30 feet at the centre in the Britannia tower, reduced to 22 feet 9 inches at the extremities in the abutments, the bottom line being horizontal, but the top line forming a parabolic curve, the rise of which thus equals the difference in height, or 7 feet 3 inches. The clear height inside is reduced by the construction, as will be presently described, to 26 feet at the centre, and 18 feet 9 inches at the ends. The width externally is 14 feet 8 inches, reduced by the construction to 14 feet inside the plates, and from this width another deduction is made by the ribs of 7 inches, leaving a clear width of 13 feet 5 inches for the railway inside.

Fig. 23.

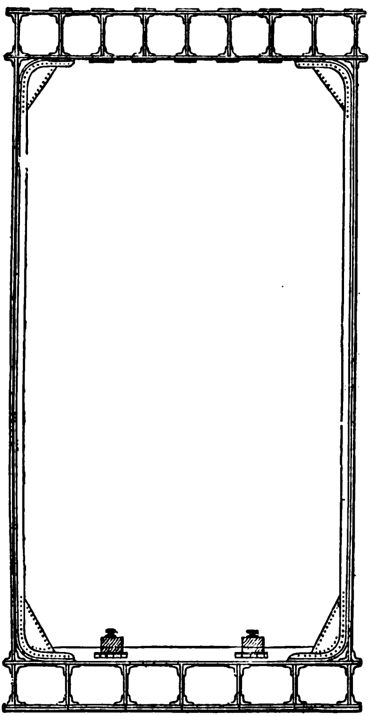


Fig. 23, which represents a cross section of one of the tubes, shows the general form of their construction. The covering of the tubes consists of malleable-iron plates connected together by rivets with ribs of T and

L iron, besides strips of flat bar iron over the joints. The top and bottom portions of the tubes are strengthened with internal longitudinal tubes or cells, of which there are eight in the upper part, and six in the lower. The greater number of these cells, and correspondingly increased quantity of metal in the top of the tube, gives greater stiffness and power to resist the crippling or bending, which the experiments showed the weight has a tendency to produce.

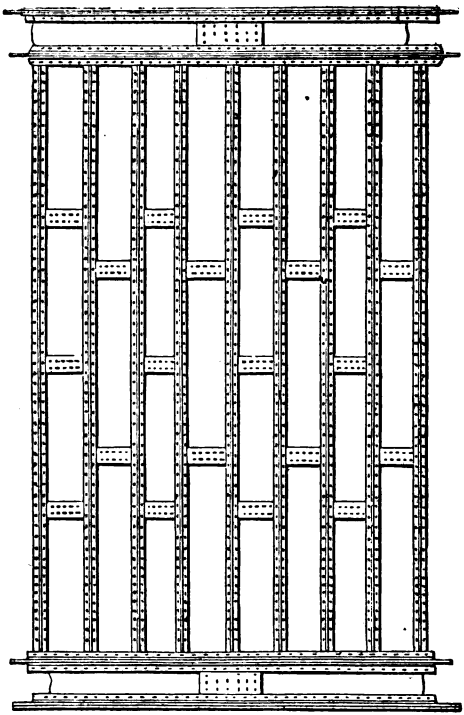
The plates are of various dimensions and thicknesses. Those forming the sides are reduced in thickness from the ends towards the middle of the tube, and those forming the top and bottom are increased in the same direction according to a scale carefully worked out for the several successive portions of the length of the tube.* The side plates are alternately 6 feet 6 inches and 8 feet 8 inches long, and all 2 feet wide. They are arranged vertically, so that the joints occur at every 2 feet; they are $\frac{1}{2}$ inch thick in the middle of the length of the tube, and $\frac{5}{8}$ inch thick at the ends. The top plates are all 6 feet in length, 1 foot 9 inches in width, and in thickness varying from $\frac{5}{8}$ inch at the ends of the tube to $\frac{3}{4}$ inch in the middle. The bottom plates are of much larger dimensions, being 12 feet long, and 2 feet 4 inches wide; they are laid in two layers, and the plates in each are $\frac{7}{16}$ inch thick at the ends of the tube, and $\frac{9}{16}$ inch thick in the middle of the main tubes. The difference in width of the top and bottom plates is occasioned by the difference in the number of cells in the top and bottom of the tube, 1 foot 9 inches being the width of each of the eight top cells, and 2 feet 4 inches the width of each of the six bottom cells. All the joints of the plates are "but-joints," that is, they meet each other at the edges, without overlapping. The horizontal joints at the ends of the plates are covered with plates of iron

* For the particulars of this scale we must refer to Mr. Fairbairn's work already mentioned, "Conway and Britannia Tubular Bridges," by Wm. Fairbairn, C.E. Weale, 1849.

on both sides, and firmly riveted through them, and this mode of joining and strengthening is adopted throughout.

Fig. 24 shows a side elevation of part of the tube and the

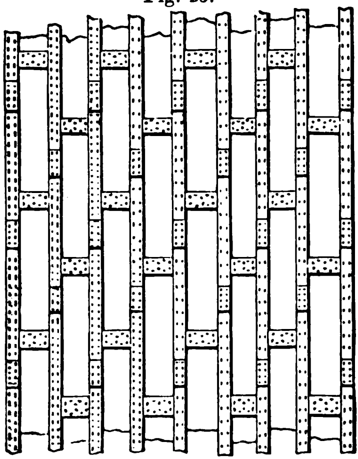
Fig. 24.



arrangement of the plates, with the covering plates over the end or horizontal joints of the side plates, and the large covering plates over the joints of the upper and lower plates forming the sides of the cells.

Fig. 25 shows a plan of part of the top of the tube with the joints in the plates alternating with each other, and strengthened with covering plates. The joints in the longitudinal joint plates are similarly strengthened with plates.

Fig. 25.



The internal vertical *frames* upon which the plates are fixed are chiefly of T-iron. These ribs are bent at right angles at the ends, and extend for about 2 feet along the top and bottom plates of the principal compartments of the tube. The plates forming the sides of the tube meet with a "butjoint" over the centre of the rib, and a similar rib being placed outside in reversed position, the whole are firmly riveted together. At those parts of the tube which pass through the towers, its extreme width is reduced by substituting flat bar iron for the outside T-iron ribs. The vertical joints of the main tubes are strengthened for about 60 feet at each of the ends by a strong plate 9 inches wide, which passes at right angles between the edges of the plates, and the connection of the plates is effected by rivets through four ribs of L-iron, fitted into the angles. Every sixth rib throughout the entire length is strengthened with an additional plate, inside, meeting the edge of the T-iron rib, and firmly connected by means of rivets and side plates, or flitches. Figs. 26 to 30 show the sections of rib-iron employed, and the several modes of forming the frames.

Fig. 26 represents the sections of T-iron and L-iron used for the ribs. The former, T, is 5 inches wide over the table,

Fig. 26.

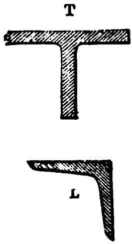
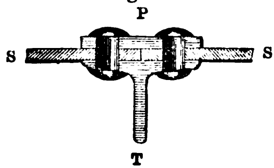


Fig. 27.



and 3½ inches deep; the latter, L, is 3½ inches wide each way.

Fig. 27 shows the kind of joint used in connecting the side plates within the towers; S S are the side plates of the tube, P is the outside covering plate; and T, the inside rib of T-iron.

Fig. 28 shows the ordinary framing of the ribs and side

Fig. 28.

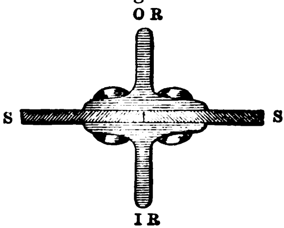
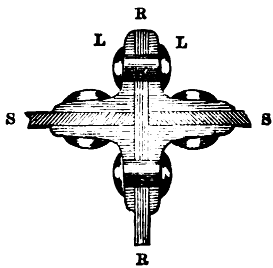


Fig. 29.



plates; S S are the side plates of the tube; O R, the outside, and I R, the inside ribs of T-iron.

Fig. 29 represents the framing of 30 of the vertical joints at each end of the main tubes, showing the central plate, against which the ends of the side plates are fitted, with the four L-iron ribs in the angles, the whole of which are firmly riveted together.

Fig. 30.

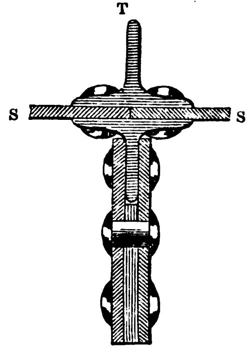


Fig. 30 shows the framing adopted at every sixth of the vertical ribs, or every 12 feet distance throughout the main tubes; S S are the side plates of the tube; T, the outside rib of T-iron; A A, the flitches of plate iron; and B, the filling-in plate, riveted between them.

Fig. 31.

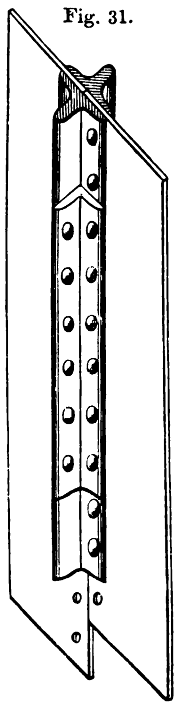


Fig. 31 is a perspective sketch of a part of one of the ordinary vertical joints, showing a portion of two side plates, meeting at the centre of the inside and outside ribs. This figure also shows the manner in which the joints of the T-iron ribs are strengthened with side pieces of L-iron, and riveted through them.

The angles of the principal compartment of each tube are strengthened with triangular plates of iron, technically called "gussets," riveted through the ribs of T-iron, and shown in Fig. 23. The gussets at every sixth rib are of larger dimensions, being about 5 feet in height and 1 foot 9 inches in width.

The Cells are formed with vertical partitions of plate iron connected at the angles with the upper and lower plates by horizontal ribs of L-iron, fitted to the angles, and firmly riveted. The L-iron used for this purpose in the top cells weighs 45 lbs. per yard, and that in the bottom cells 27 lbs. per yard. The top and bottom edges of the side plates of the tube are in like manner riveted to the horizontal plates, forming the cells through ribs of L-iron in the angles.

The rails for the railway are supported in chairs upon continuous longitudinal timbers, which are supported upon pieces of L-iron, reversed so as to form brackets, and riveted through plates of iron 9 inches wide, set on edge, and fixed across the tube at intervals, and secured to the vertical T-iron ribs, and the plates forming the top of the lower cells.

Riveting.—The rivets are a full inch in diameter, and arranged in rows. The spaces between the centres of the rivets are 3 inches in the vertical joints, and 4 inches in the horizontal joints. The rivets are heated in portable furnaces, which are moved from place to place as the work proceeds; from these furnaces they are taken up with tongs and placed in the holes punched for them, and the ends firmly clenched or riveted before cooling, with heavy hammers. The rivet-head thus formed is then finished by hammering a steel cup-shaped tool upon it, and the contraction of the length of the rivet in cooling draws the plates closely together with a considerable force. The number of rivets is said to be 327,000 in each of the main tubes, and about 2,000,000 in the entire bridge. A very beautiful machine, upon the principle of the Jacquard loom, was invented by Mr. Roberts, for the purpose of punching the holes in the plates. By this machine, which is nearly self-acting, the precise distances and intended positions for the holes are very truly observed, and the design displays a most skilful arrangement of parts, being in this respect similar to many other contrivances which have emanated from the same clever machinist.*

It is almost needless to observe that in the preparation of the plates, and execution of the whole work, judicious means and practical contrivances have been adopted in facilitating the construction, and rendering it uniform and correct in all its details. Thus, templates were prepared for the plates and

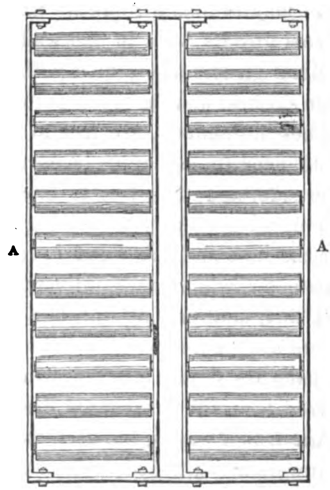
* An elaborate and well illustrated account of this machine will be found in the "Civil Engineer and Architect's Journal" for 1848.

ribs, &c., and all the holes truly marked with unerring precision and certainty, so that all the parts, when presented to their intended positions, should be found to "fit." Large portions of the plating for the tubes were thus put together partially on the platform, and being raised to their places with the stages and tackling described, were speedily fixed in their true positions, and required the straightforward work of riveting only to complete their connections.

Bearing Rollers and Frames, Bed-plates, &c.—The tubes, in passing through the towers and abutments, are, as we have described, supported upon rollers. These rollers, with the frames in which their axes revolve, and the cast-iron plates between which they work, are shown in Figs. 32 and 33.

Fig. 32 is a plan of one set of rollers with their frame. One of these frames is placed under each side of each end of each tube, so that thirty-two sets of rollers and frames are employed altogether. Each set comprises twenty-two rollers, arranged in two parallel rows, and 6 inches diameter, turned over the surface and formed with axes projecting at the ends. These axes revolve freely in holes drilled in a parallel frame of wrought iron, formed in pieces bolted together, as shown in the figure, and the

Fig. 32.



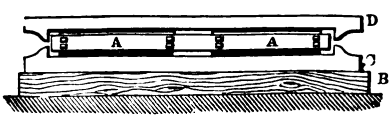


Fig. 33.

depth of which is less than the diameter of the rollers, so that it is perfectly free from the cast-iron plates with which the rollers are in contact.

Fig. 33 shows a front view of the cast-iron plates and of the intermediate rollers and frame. In these figures, A A is the wrought-iron frame for the cast-iron rollers; B, a bed of wood for the under roller-plate of cast-iron, C; and D is the upper roller-plate on which the tube simply stands, and is, therefore, free to move according to the contraction or expansion which it undergoes. The dimensions of these plates and frames are varied, being somewhat less towards the ends of the tubes than in the middle.

The ends of the tubes are also supported by an apparatus of cast-iron girders and gun-metal balls, which are thus applied: longitudinal girders are fixed upon the projecting ends of cross girders built in the walls of the towers; these longitudinal girders are formed with a groove or channel in the upper surface, and in these grooves the gun-metal spheres, 6 inches in diameter, are free to move. Similar girders are placed over these, having a corresponding groove on their under side, and thus free to move over the spheres. Upon these upper girders, transverse girders are fixed, which pass over the tube and are fixed to it with strong bolts, 3 inches in diameter, which stand up vertically above the tube, bolted to its side, and, passing through holes cast in the transverse girders, are secured to them with screwed nuts. These girders and balls are shown in Figs. 40 and 41, and will be further referred to in the subsequent description of those figures.

Cast-iron Frames, Girders, &c.—The ends of the tubes in the towers are stiffened with cast-iron frames of considerable dimensions. These frames, which are composed of horizontal and vertical girders, strongly bolted together and notched into each other at the joints, are represented in Figs. 38 and 39, which will be hereafter referred to. Three of these frames, or sets of girders, are built in at each end of each tube, being placed in the spaces between the T-iron ribs, and those portions of the tube which pass through the towers have these cast-iron frames throughout them.

Under each end of each of the four main tubes, three cast-iron girders, or key-beams are provided, and which, as soon as the tube reaches its intended elevation, are put into their permanent places beneath it. Each of these beams is 24 feet in length and 4 feet in depth, and weighs 11 tons.

Fig. 34.

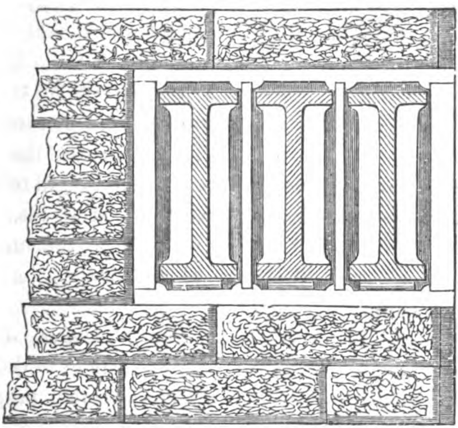


Fig. 34 represents a section of one set of these beams, and an elevation of the cast-iron frame or box built in the masonry within which they are placed. During the raising of the tubes, these beams are drawn back from their final position, and their projecting ends are supported upon scaffolds borne upon wooden struts, and held up with wrought-iron ties, as shown in the perspective sketch, Fig. 37, which will be presently described.

Weight of the Tubes.—The weight of each of the main tubes is said to be 1,600 tons, besides cast iron in the fixed frames, probably 150 tons in weight. Of these 1,600 tons of malleable iron, 500 are calculated to be disposed in the bottom, 500 in the top, and 600 in the sides. The weight of each of the small tubes, when quite complete, is 660 tons, so that the total weight of iron in the two completed tubes, each 1,513 feet in length, will probably be about 9,640 tons. Now it may be interesting to calculate the average thickness of metal throughout the tube to which its weight is equal. For this purpose we will take one of the main tubes, and consider it as a rectangular body of the uniform width of 14 feet, depth 29 feet, and length 472 feet, and excluding the cast iron, we will take its weight at 1,600 tons. Then

$$\begin{array}{l} 29 \times 2 = 58 \\ 14 \times 2 = \underline{28} \\ \qquad\qquad\; 86 \times 472 = 40{,}592 \text{ superficial feet;} \end{array}$$

and dividing the number of pounds, 3,584,000, contained in 1,600 tons, we get a quotient of 88·3 lbs. as the average weight per superficial foot; and taking the weight of a superficial foot of wrought iron, one inch thick, at 40 lbs., we have a total weight of malleable iron in each of the main tubes equal to an average thickness of 2·2 inches in the top, bottom, and sides.

Floating the Main Tubes. The Pontoons, &c.—The floating of the tubes from the building stage to the base of the towers was a work involving considerable preparatory arrangement. Each tube being completed was, as we have said, left to bear upon the piers of masonry at its ends; and the intermediate length of the tube, 460 feet, is left free, the staging below being wholly removed. For the purpose of transporting the tube, eight floating vessels or pontoons were provided. Six of these are of wood, and were used in floating the Conway tubes; the other two are of iron. They are flat-bottomed, and the sides inclined outward towards the top, like an ordinary washing trough, and are made of iron plates and ribs, in the ordinary method of iron ship-building. Each of these iron pontoons is 98 feet long, 25 feet wide, and 11 feet deep, and is capable of supporting 400 tons. When bearing the tube, they draw 5 feet of water. In the bottom of each pontoon, large valves are fitted, which, being kept usually open, admit the tide, and thus prevent them from rising. The first operation for floating the tube is bringing these pontoons under it, at low water, and arranging them in two groups of four each, one group near each end of the tube. The valves are then closed, and the rising of the pontoons with the tide lifts the tube from its bearings, and the whole becomes a connected floating body.

The next operation,—that of towing and guiding this mass, 472 feet in length and 98 in greatest width, covering an area *three times* that of the leviathan 'Great Britain,'—was one which called for skill and experience in the highest degree, in maturing all the required arrangements, calculating the time likely to be occupied in the removal, and "bringing her up alongside," in handsome style, and with all the nicety, moreover, needed for the exact position in which alone the tube could be ready for lifting. Calculating that the towing would occupy one hour and a half, it was arranged that the start should take place thus much before high water, and with a current of three miles an hour. This towing into the middle of the stream was performed with large capstans, each worked by fifty men on the opposite shore, the hawsers being made fast to the pontoons at each end. For the purpose of guiding it, two large hawsers were laid down the stream, one on either side, one end of them being secured to the towers between which the tube was intended to be raised, and the other to fixed points upon the shore, about half a mile from the bridge. These hawsers passed over the pontoons, and through fixed sockets, in an apparatus called a "cable stopper," by which either hawser could be instantly gripped, if necessary, so as to arrest the motion of the tube. The action of these "cable stoppers," the invention of Mr. C. H. Wild, who was engaged with Mr. E. Clarke, under Mr. Stephenson, in superintending the construction of the tubes, is simple and effective. The socket through which the cable passes is in two parts longitudinally, and the upper part, which works vertically between two strong cheeks or frames, is pressed down on the top by a

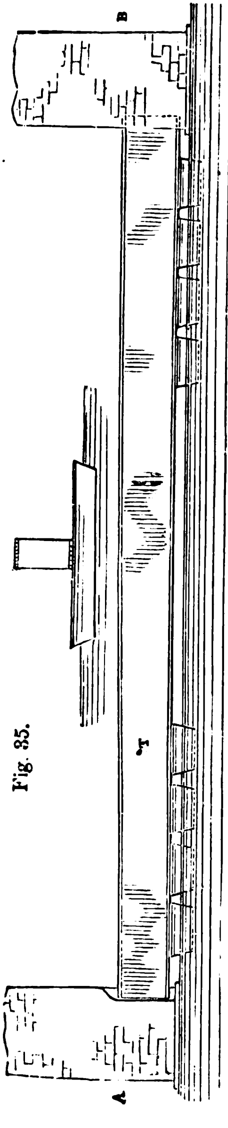


Fig. 35.

powerful screw, similar to that of a common screw-press, worked by means of handspikes fitted into the capstan-head of the screw. By these means any required force can be applied in gripping the cable, and thus stopping the progress of the floating mass. Besides these towing and guiding cables, several smaller ropes were secured to the pontoons, and capable of being taken in or given out by capstans at various convenient points on the shore.

The tube having arrived at the feet of the towers at high water, the next work, that of depositing it on the projecting plinths of the towers, which form shelves, as it were, for that purpose, had to be accomplished during the fifteen minutes whilst the tide ceases before the return. Figs. 35, 36, and 37 will show the manner in which the tubes were received upon the towers, and the latter formed for the purpose. Of these figures, 35 represents the lower part of the Anglesea and Britannia towers, A and B; T is the tube supported upon the eight pontoons, and ready to be deposited upon the projecting plinths of the towers. In this figure the tube is shown in dotted lines as inserted within the recess left in the Britannia tower, and in the Anglesea a portion of the masonry is left out, forming the side of the recess, and of a height sufficient to admit the tube.

Fig. 36 shows a sectional plan of the two towers, A and B. The former has two recesses on one side for receiving the main tubes, and the latter similar recesses on both sides for the same purpose. One tube, T, is shown as in its place, and the side of the recess at R built up; the other, T′, is represented as still on the pontoons, one end being in the recess of the Britannia tower, and the other end approaching its place in the Anglesea tower, the side of the recess in which, shown in dotted lines, is still unbuilt to receive it.

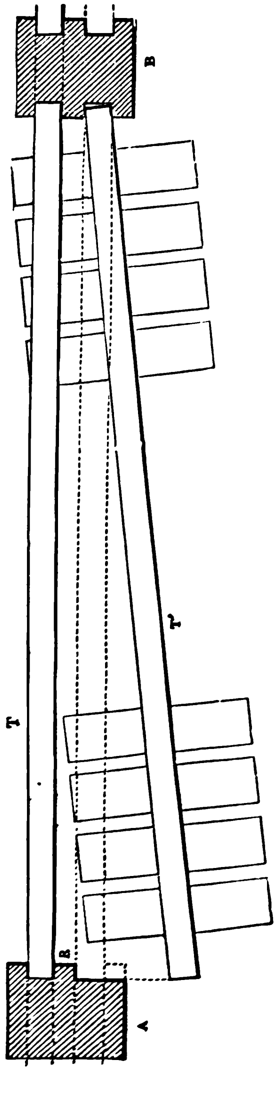
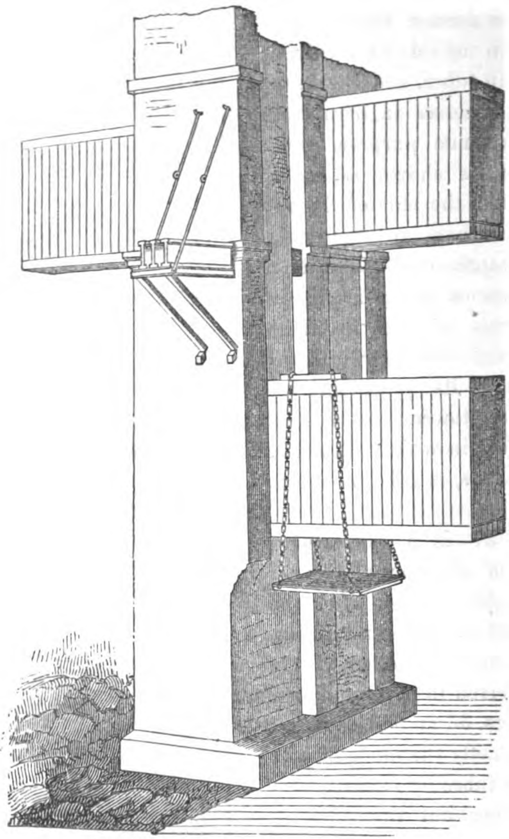


Fig. 36.

Fig. 37 is a perspective sketch of the lower part of the Anglesea tower after the raising of one tube and during the raising of the other. It is now referred to in conjunction with Figs. 35 and 36, as showing distinctly the mode of getting the tubes into the recesses by leaving out the sides of them at the lower part; but the other points illustrated in this figure will claim our notice and proper description presently.

Of the two lines of railway which will eventually be per-

Fig. 37.



fected through the bridge, one—the northern—will be first completed, requiring the erection of two of the four main tubes. And the first of these two tubes erected has been that at the west end of the bridge, or between the Anglesea and Britannia towers. At this time (Nov. 1849), this one only of the tubes has been erected and completed; and the following sketch of the proceedings connected with the floating of the tube on the 27th of June last, written by an eye-witness, is sufficiently interesting and authentic to be quoted. After the preliminary arrangements for letting go had been completed, Mr. Stephenson and other engineers got on the tube, as also Captain Claxton, R.N., famed for releasing the 'Great Britain' from her dangerous imprisonment in Dundrum Bay, to whom the management of the floating was intrusted. "Captain Claxton was easily distinguished by his speaking-trumpet, and there were also men to hold the letters which indicated the different capstans, so that no mistake could occur as to which capstan should be worked; and flags, red, blue, or white, signalled what particular movement should be made with each. About half-past seven o'clock in the evening, the first perceptible motion, which indicated that the tide was lifting the mass, was observed, and, at Mr. Stephenson's desire, the depth of water was ascertained, and the exact time noted. In a few minutes the motion was plainly visible, the tube being fairly moved forwards some inches. This moment was one of intense interest; the huge bulk gliding as gently and easily forwards as if she had been but a small boat. The spectators seemed spell-bound; for no shouts or exclamations were heard, as all watched silently the silent course of the heavily-freighted pontoons. The only sounds heard were the shouts from Captain Claxton, as he gave directions to 'let go ropes,' to 'haul in faster,' &c., and 'broadside on:' the tube floated majestically into the centre of the stream. I then left my station and ran to the entrance of the works, where I got into a boat, and bade the men pull out as far as they could into the middle of the straits. This was no easy task, the tide running strong; but it afforded me several splendid views of the floating mass, and one was especially fine; the tube coming direct on down the stream,—the distant hills covered with trees,—two or three small vessels, and a steamer, its smoke blending well with the scene,—forming a capital background; whilst on one side, in long stretching perspective stood the three unfinished tubes, destined ere long to form, with the one then speeding on its journey, one grand and unique roadway. It was impossible to see this imposing sight and not feel its singleness, if we may so speak. Anything so mighty of its kind had *never* been *before; again* it would assuredly be; but it was like the first voyage made by the first steam vessel,—something till then unique. At twenty-five minutes to nine o'clock the tube was nearing the Anglesea pier, and at this moment the expectation of the spectators was greatly increased, as the tube was so near its destination; and soon all fears were dispelled as the Anglesea end of the tube passed beyond the pier, and then the Britannia pier end neared its appointed spot, and was instantly drawn back close to the pier, so as to rest on the bearing intended for it. There was then a pause for a few minutes while waiting for the tide to turn; and when that took place the huge bulk floated gently into its place on the Anglesea pier, rested on the bearing there, and was instantly made fast, so that it could not move again. The cheering, till now subdued, was loud and hearty, and some pieces of cannon on the shore gave token, by their loud booming, that the great task of the day was done."* When in its position, the tube is made to settle down upon a bed of timber on its bearings at the feet of the towers, by opening the valves in the pontoons, and thus sinking them sufficiently to free them from the tube.

Lifting the Tubes with the Hydraulic Presses.—If there is one part in the design of these stupendous bridges which evinces boldness greater than another, it is in the first idea of raising a weight of 1,800 tons, through an elevation of 100 feet, over a rapid stream of 460 feet in width, and utterly without scaffolding of any kind over the opening. The power to be employed for this gigantic purpose, and the manner of employing that power, are two problems of startling novelty, and which threatened to involve immense practical difficulty.

* Correspondent of the *Illustrated London News*, June 30, 1849.

The happy adaptation of the buoyant power of water, so successfully realised in the floating of the tubes, promised no assistance in the raising of them ; yet with the aid of simple machines, actuated by this same liquid, which by a law of its action multiplies to an almost unlimited degree the minimum of power applied to it, these tubes are raised with the utmost facility, and with all the regularity and safety of motion which characterise mechanical operations upon a smaller scale.

These machines, known as *Hydraulic*, or *Hydrostatic Presses*, are adapted for gaining great power; acting, however, through a limited space. The invention of the apparatus belonged to the late Mr. Joseph Bramah, who, on March 31, 1796, obtained a patent for it, under the title of "certain new methods of producing and applying a more considerable degree of power to all kinds of mechanical apparatus and other machinery requiring motion and force, than by any means at present practised for that purpose." The operation of this machine is founded upon the elementary principle in hydrostatics, that "when a liquid mass is in equilibrium, under the action of forces of any kind, every molecule, or part of the mass, sustains an equal pressure in all directions." The consequence of this principle is, that a pressure exerted on any portion of the surface of a confined mass of fluid is propagated throughout the mass, and transferred, undiminished, to the entire surface in contact with the water. In the middle of the 17th century, Pascal suggested the application of this principle to the operation of a press, but to Bramah is due the credit of first realising this suggestion in a practical form. The hydraulic press has been employed to a considerable extent in pressing goods for packing, expressing vegetable oils, and other similar purposes. By its aid, moreover, the performance of experiments upon the strength of various materials has been much facilitated. In the testing of iron girders, anchors, and other similar productions intended to sustain great weights and strains, this powerful apparatus has been usefully engaged for many years in the English dockyards and the establishments of iron-founders and manufacturing engineers. But its most recent and distinguished employment is in the elevation of the tubes for the railway bridges over the river Conway and the straits of Menai.

Hydraulic presses consist of two essentially distinct parts, viz. the *press*, or machine, in which the acquired force is applied, and the *pumping apparatus*, by which the water is forced into the press; these two parts, constituting the entire apparatus being connected only by a pipe through which the water passes from one to the other. The *press* consists mainly of the *cylinder*, into which the water is admitted, and which is solid at one end, and open at the other to receive the *ram*, *plunger*, or *piston*, which is solid and cylindrical, and turned to fit the bored opening in the cylinder. This opening is enlarged at a few inches from the face, so that, although the ram fits it closely along these few inches, an annular space is left within, between the ram and the cylinder, and into this space the water is forced by the pump. The pump needs no detailed description here, being of the ordinary kind used for forcing liquids, and is varied in its parts, form, and dimensions, according to the particular applications of the apparatus. The pump is usually worked by manual labour, with a lever-handle, and the rule for finding the increase of power commanded by the pump is derived, first, from the ratio of the areas of cross section of plunger of pump and ram of press; and, secondly, from the ratio of the leverage of the pump-handle. Thus, suppose the plunger to be ¾ inch, and the ram 10 inches in diameter, and the arms of the lever or handle as 1 to 6, the power will be thus found:

	$\cdot75^2$	:	10^2
Multiplied by	1	:	6
	$\cdot5625$	:	600;

that is, 1 : 1066·66;

and thus a power equal to 20 lbs. applied on the end of the pump-handle will produce a pressure equal to 21,333·20 lbs. on the ram, or 9 tons 10 cwt. 3 qrs. 1·20 lbs.

In order to apply the power of the presses to the lifting of the tube, and, as already said, without scaffolding of any kind under it, it was necessary to act at the ends of the tube. The hydraulic press—well selected as the instrument of elevation, on account of the great power it affords—is, as already stated, adapted to move only through limited spaces. The presses employed at the tubular bridges, although of unexampled size and power, were fitted only for a motion of 6 feet; that is, the ram was susceptible of only 6 feet vertical from the cylinder. Hence the whole elevation through which the tubes for the Britannia Bridge were required to be raised (about 100 feet) could not be effected in one continuous movement, but required a succession of "lifts," each of 6 feet, and sufficient in number to complete the total raising. Now, in order to bring the rams into action for this purpose, they were required either to press upward against the bottom of the tube, and thus push it; or, being placed above the tube, to be made to act upon chains so as to draw them upwards, and with them the tube, fixed to their lower ends. The latter alternative was adopted, and the presses accordingly were firmly located in the upper part of the towers, immediately over the ends of the tube, and at such height as allowed for the total elevation of the tubes, without disturbing the position of the presses. In this manner the tubes for the Conway Bridge were raised by means of two presses, one at each end of the tube. The rams of these presses are 18⅜ inches in diameter, and the cylinders 20 inches internally, so that an annular space $\frac{13}{16}$ of an inch wide remains between them, for the action of the water. The cylinders are 37½ inches in diameter externally, the metal being thus 8¾ inches in thickness. For the raising of the tubes of the Britannia Bridge these two presses are used in combination at one end, viz. in the Britannia tower; and at the other end a single press of larger dimensions is employed. Of this press, the ram is 20 inches in diameter, and the metal of the cylinder 11 inches thick.

For the purpose of forcing the water into the cylinders of these presses, two steam engines, each of 40-horse power, are employed. The cylinders of these engines are arranged horizontally, 17 inches in diameter, and 16 inches stroke. The piston-rods work through stuffing-boxes in both ends of the cylinder, and, being continued, form the pistons of the forcing-pumps. These pumps are $1\frac{1}{16}$ inch in diameter, and 16 inches stroke. The pipe for conveying the water into the cylinder is $\frac{1}{2}$ inch bore, and $\frac{1}{4}$ inch thick, so that its external diameter is 1 inch, made of wrought iron. The power applied to the pump is thus increased in the ratio of the areas of $1\frac{1}{16}$ to 20 inches, or as 1 to 355. If the full power of the engine, equal to that of 40 horses, were exerted, the available power thus produced in the press would equal the product of 355 and 40, or that of 14,200 horses. The actual work done by the one large press at one end of the tube, or the two smaller ones at the other, is of course equal to raising half the tube, or 900 tons. The power exerted by the head of the ram, 20 inches diameter, is thus equal to 2·25 tons, or 5,040 lbs., per circular inch.

An accident which occurred to the large press in the Anglesea tower during the lifting of the first of the Britannia tubes deserves notice, because we may thence deduce an useful lesson for future guidance in similar cases, and moreover it accounts for a considerable delay in the raising of the tube, which might otherwise appear inexplicable in the history of the bridge. On Friday the 17th of August, 1849, after three of the 6-feet lifts had been successfully accomplished on previous days, the lifting was proceeding, and $\frac{5}{12}$ of a lift, or 2 feet 6 inches, attained, when, between 11 and 12 o'clock in the morning, the bottom of the cylinder "burst out," and being entirely separated from the remainder of the casting, it fell with terrific force—weighing about $1\frac{1}{2}$ ton—on to the top of the tube below, a depth of from 70 to 80 feet. The resistance to the weight being thus suddenly destroyed, the ram of course descended the part of the lift accomplished, and the tube would have also fallen through a similar space of 2 feet 6 inches, had not a most wise precaution been adopted by Mr. Stephenson, viz. following up the ascending tube with packings of wood 1 inch thick, which are introduced within the recess as rapidly as the tube rises. These packings are then carefully removed, piece by piece, and the spaces filled in with brick-work in cement, so as to be nearly flush with the outer lines of the tower. As it was, the total falling of the tube was about only one inch. The falling part of the cylinder produced a deep indentation in the top of the tube below, and, unfortunately fatally struck a poor sailor employed on the works, who was ascending a rope-ladder from the tube to the press. We may now again refer to Fig. 37, which is a perspective sketch of the Anglesea tower, and shows one of the tubes as elevated to its place, and its fellow tube as partly raised. It also shows the three cast-iron key-beams already described as drawn out and supported on a bracket platform. When the tube is lifted to its full height, these beams are driven into their permanent places in the boxes which are built into the towers, and thus serve to support the ends of the tube while the chains and lifting frames are detached. The rising tube is also shown as accompanied with a stage, slung in the scale fashion with chains from the tube, and upon which the workmen are supported for the purpose of packing the wooden slabs under the tube as it rises, and building up the recess with brick-work in cement.

As to the cause of the bursting of the cylinder, it has been explained with reference to the peculiar form of the casting at the place of fracture, and to the known liability of cast iron to cool irregularly, and contract unequally, a liability which is dangerously increased in the case of such an immense mass of cast metal as this cylinder necessarily is. The bottom of the cylinder appears to have been nearly if not quite flat internally and externally, and thus not only are continuous angles formed by the meeting of the inner and outer cylindrical and plane surfaces respectively, which always operate against an uniformity of pressure and consequent density or compactness throughout the metal, but the thickness of metal through these angles being greater—as the diagonal to the square—than elsewhere, this part is the last to cool, and consequently the least able to obey its tendency to contract. Hence, as is often observed in similar forms of casting, these parts are comparatively much more open in the ultimate grain of the metal than the other parts, and correspondingly weaker.

At the late meeting of the British Association for the advancement of Science, held at Birmingham in September last, Mr. Stephenson, at the request of the members of the Mechanical Section, explained the nature of the accident, and the precautionary measures he had fortunately adopted, and from the report* of his explanation we quote the following interesting extract:—"Mr. Stephenson explained the machinery adopted for raising the tubes, and stated that the plan originally proposed was by lifting the tube to the height of 6 feet at a time, and then allowing it to be suspended by chains to the cross-head during the time the masonry below was carried up; but this plan was abandoned, fearing that if an accident should take place, either by the bursting of the press or the breaking of a link of the chain, the tube would be totally destroyed if it fell through such a height as 6 feet, or even to 6 inches. He then considered that the only way to proceed was by packing in timbers, inch by inch, under the tube, as it was being lifted; so that, in case an accident did take place, the tube would not have to fall through a greater space than an inch; and this was the plan adopted at the time of the accident. To show how necessary it was to proceed thus, Mr. Stephenson explained, that although the tube fell through the space of only an inch, it broke down iron beams, each sufficient to bear 500 tons weight. It will be seen that by this process the tube was never allowed to be suspended in the air; and as a further precaution, he intended in future, when the raising was again in progress, to pack in underneath the cross-head of the press, by driving in iron wedges as the

* Published in the "Civil Engineer and Architect's Journal" for [illegible]r, 1849.

tube is raised, as well as under the tube: thus, if the press were to break down, neither the cross-head nor the tube could fall through a greater space than an inch. He described the nature of the fracture which occurred through the angle of the bottom, and when it fell out the piece formed the frustrum of a cone. At the time the presses were at work, there was not 1 ton pressure to the square inch, the area of the fracture being 1,316 square inches, and the weight suspended on the press 1,000 tons. The press was calculated to bear 3½ tons, a pressure to which hydraulic presses are frequently subjected for manufacturing purposes. When lifting the Conway tubes, they commenced by lifting both ends simultaneously; but when the engines had been at work for a short period, it was observed the tube had got into a tremulous motion, like a wave. In consequence, this operation was stopped, and a consultation held, when it was considered that it was occasioned by working the pumps at each end of the tube simultaneously, and it was decided to work the engines at each end alternately. By adopting this mode the motion was got rid of. Mr. Stephenson believed the fracture took place in consequence of the unequal cooling of the iron at the angle of the cylinder; he has therefore decided upon having two cylinders cast in some other form,—one with a hemispherical bottom of the same thickness as the cylindrical part; and the other with an open bottom or neck formed through it, having an internal shoulder on which a plate may be laid to close the opening." A new cylinder, formed in the first of these improved shapes, has subsequently been applied, and has successfully raised the tube to its final elevation.

Cast-iron Frames, for strengthening the Ends of the Tubes, and for attaching the Lifting Chains.—It has been already stated that the ends of the tubes are strengthened with massive frames of cast iron fitted to the interior, and bolted to the plates of the tube, and also to each other, at the joints.

Fig. 38.

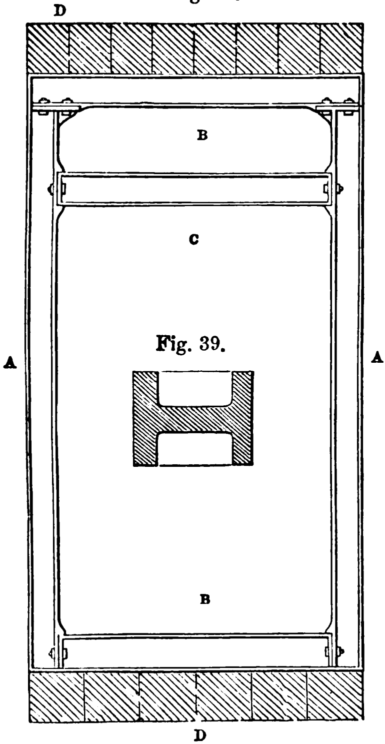


Fig. 39.

Figs. 38 and 39 represent the frames employed for this purpose. In Fig. 38, A A are vertical side frames of cast iron, fitted to the inside of the plates, and bolted to them; B B are horizontal frames similarly secured, firmly bolted, and closely fitted to the vertical frames; C shows the manner in which other cross girders were connected with the vertical frames, for the purpose of connecting the chains. In the Conway tubes, two of these lifting frames were used at each end of the tube, one over the other. In the Britannia tubes, three are employed, similarly arranged, one over the other, the ends of them fitting under deep notches or shoulders formed in the vertical frames, and firmly bolted thereto. By way of providing additional safety, two very thick straps of wrought iron pass over the upper pair of cast-iron beams from a central point above, and descend in the inclined positions of the sides of the letter A into the bottom cells, where they are secured with strong wrought-iron keys. The vertical partitions forming the bottom cells are, for a length of from 8 to 12 feet at each end of each of the tubes, strengthened with thick cast-iron cheeks, or flitches, of the same width as the plates, 1 foot 9 inches; one of these cheeks being placed on each side of each of the vertical plates, and firmly bolted through. Fig. 39 shows a transverse section of one of the strengthening frames (A A, Fig. 38), which are 12 inches deep, 15 inches wide over the face, 3 inches thick in the outer flange, and 2 inches in the inner one.

Figs. 40 and 41 show the combined arrangements for lifting the tubes of the Conway Bridge, with the hydraulic press, chains, &c., and the cast-iron lifting-frames. Fig. 40 is a transverse section through the tube and front elevation of the press. Fig. 41 is a longitudinal section of the end of the tube and section through the middle of the press. Referring to these figures, we will describe first the parts which permanently belong to the construction of the tube and its connection with the tower, and afterwards the temporary apparatus employed for the purpose of lifting the tube.

A A are the two side and top and bottom beams of cast iron, forming one of the sets of castings used to strengthen these parts of the tube, as already described.

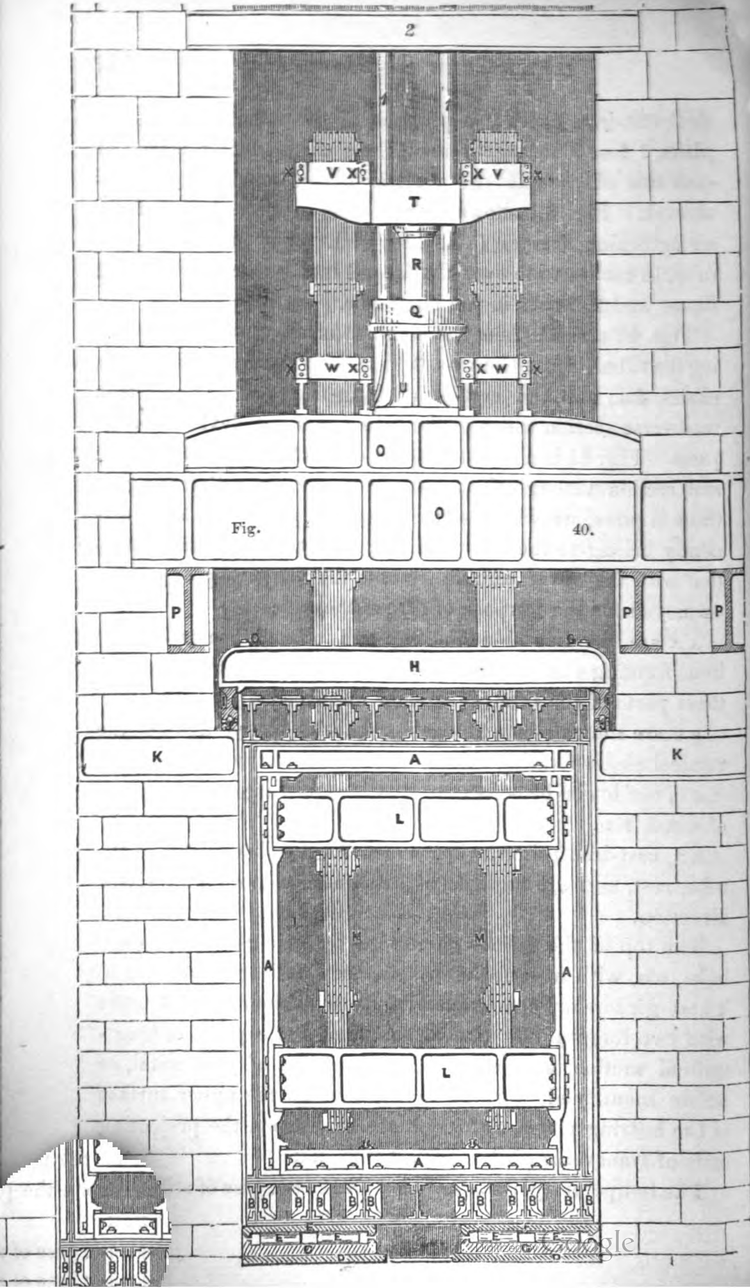
B B are the cast-iron flitches or cheeks bolted against the vertical plates forming the partitions of the lower cells.

C C, the lower bed-plates of cast iron, resting upon bearings of wood, D D.

E E, cast-iron rollers, upon which F F, the bed-plates of the tube, rest, and are capable of longitudinal motion in either direction.

The top of the tube is connected by strong wrought-iron bolts, G G, with a series of transverse cast-iron girders, H H These girders are connected by sockets in their lower flanges with two longitudinal girders, I I, which are capable of longitudinal motion, as they rest upon spheres of gun-metal, as before mentioned, working in a groove on the upper surface of the bearing plates, J J, which are fixed upon the projecting ends of transverse girders of cast iron, K K.

The temporary parts introduced for the purpose of stiffening



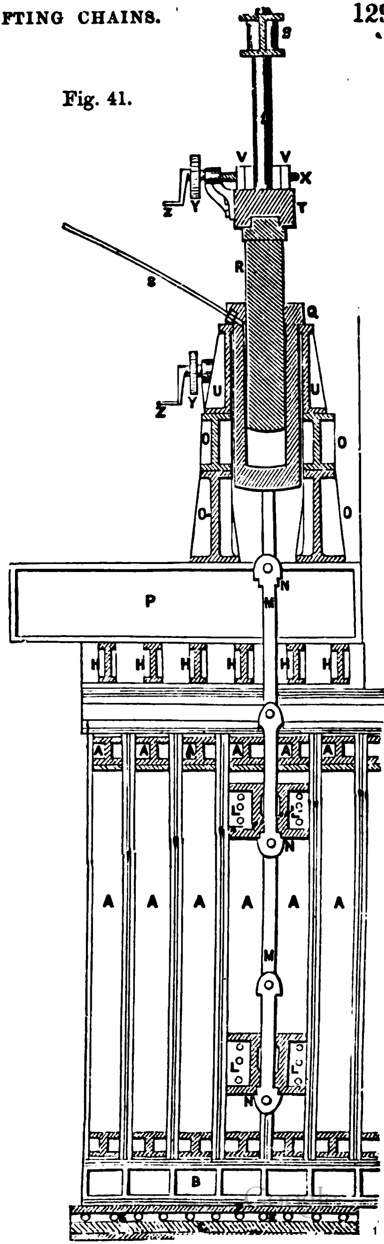
2
V X
X V
T
R
Q
W X
X W
U
O
O
P
P
P
H
K
K
A
L
M
A
A
L
A
Fig. 40.

the ends of the tube during the raising and also of connecting the lifting chains are as follows:—

L L, two pairs of cast-iron girders or lifting frames, fixed horizontally across each end of the tube, and bolted within recesses formed in the vertical cast-iron frames, A A. In the Britannia tubes, three pairs of these girders were used, the upper and under ones for the purpose of attaching the lifting chains, and the intermediate one to assist in supporting the sides of the tube.

The lifting chains, M M, are formed in links with notches at one end of each alternate link, as shown at N N, Fig. 41. These notches fit into corresponding ones on the lower flanges of the cross girders, L L; and when these are bolted in their places the links are, as shown in Fig. 41, held firmly between them.

Fig. 41.



The press by which these chains are drawn up, and the tube thus raised, is shown above the tube in the place in which it is first fixed, and which it occupies during the whole operation. In lifting the Conway tubes, each of the presses was supported upon a pair of double girders of cast iron, marked O O in the figures, resting at the ends upon longitudinal girders, P P, built in the masonry. In lifting the Britannia tubes, however, wrought-iron girders are judiciously substituted for those of cast iron. Each of these wrought-iron girders is composed of 12 plates of best iron, 2 feet in width and a full inch in thickness, firmly fastened together, so that the girder consists of a well-connected mass of wrought iron, having a transverse section 24 inches in depth, and 12 inches in width. At the ends, these wrought-iron girders are supported upon cast-iron transverse girders, fixed upon benches formed in the masonry of the towers.

The press consists principally of four parts, viz. the cylinder, Q, the ram or piston, R, the pipe, S, by which the water is introduced from the pumps, and the cross-head, T. The cylinder rests within a cast-iron jacket or casing, U U, supported upon the transverse girders, O O, already described. The forcing of the water into the cylinder causes the ram to rise, forcing up with it the cross-head, T. Upon the cross-head two pairs of clamps, V V, are fixed, which embrace the notched ends of the chain links, and are screwed up tightly against them with screws, X X. These screws have cogged wheels, Y, fitted to their ends, and an intermediate pinion turned by a winch, Z, gives motion to the wheels of the two screws. A similar arrangement of clamps and gearing is fixed below at W W. The action of the press is preserved in a true vertical direction by fixed guide-rods, I I, secured above to a cross-girder, Q, and upon these rods the cross-head slides upward, as the action of the press continues.

The chains here represented are evidently highly important members of the apparatus, as any failure in them would of course, involve the falling of the tube. Each set of links consists of eight and nine alternately, the eight being made somewhat thicker than the nine, so as to contain an equal total strength. Each link is 7 inches wide, about 1 inch thick, and exactly 6 feet in length between the centres of the eyes at the ends. They are manufactured by a process, for which a patent was granted, October 6, 1845, to Mr. Thomas Howard. of the King and Queen Iron Works, Rotherhithe, and entitled "improvements in rolling iron bars for suspension bridges and other purposes." By these improvements wrought-iron bars are rolled with the ends or heads of increased breadth in one entire piece, and chains thus manufactured are worthy of much greater confidence than those of which the links are made in separate bars and heads, and united by the uncertain process of welding. Besides the application of these chains to the lifting of the Conway and Britannia Bridges, they are employed in the permanent construction of the large suspension bridge erected by Mr. W. T. Clarke over the Danube, at Pesth, and of the Russian bridge at Kieff, now in course of erection by Mr. Vignoles.

In concluding this description of the Britannia Tubular Bridge, it should be mentioned that the masonry of the central, or Britannia tower, was commenced in May, 1846; that the first rivet for the tubes was put in on August 10, 1847. It is now expected that one line of railway will be completed through the bridge in March, 1850. If so, or even allowing two months later, four years only will have been occupied since the commencement of the tower; a period remarkably short, when all the uncertainties and possible casualties belonging to so novel and extended a work are considered. The contractors for the masonry and scaffolding are Messrs. Nowell, Hemmingway, and Pearson. One of the large tubes was constructed by Messrs. Garforth, of Dukinfield, Manchester; the remainder of the tubes by Mr. C. Mare, of Blackwall. The hydraulic presses were constructed by Messrs. Easton and Amos, of Southwark.

THE CONWAY BRIDGE, which, as already stated, preceded the Britannia, is erected within a few feet of Telford's suspension bridge, and close beneath the ancient walls of Conway Castle. It consists of one span only of 400 feet, clear width, and two abutments of masonry, of which the design is in harmony with that of its venerable neighbour, the castle. The height of the tubes above the level of high water is inconsiderable when compared with that of the Britannia tubes, being only 18 feet. Each tube, as fitted with the castings for lifting, weighed 1,300 tons. The bridge thus consists of two tubes only, which were built on the adjoining shore, one after the other, and upon the same platform, and floated and raised in a manner similar to the Britannia tubes. The first stone was laid on the 15th of June, 1846 : the first tube commenced in March, 1847, floated 6th of March, 1848, raised 16th of April following, and opened for the passage of the trains on the 1st of May, 1848. The second tube was floated on the 12th of October, 1848, and raised on the 30th of the same month. Mr. Evans was contractor for the whole of the work.

The first of the tubes was tested with a weight of 300 tons of iron, and its deflection at the centre with this load was 3 inches. On the removal of the load, the tube resumed its original position. In the testing of the second tube, it was ascertained before loading that the deflection was 1·86 inch. The weight of ballast applied was 235 tons 14 cwt. and 2 qrs., and which caused an additional deflection of 1·56 inch, which ceased on the removal of the load. The passage of the ordinary train is said to cause a deflection of only $\frac{1}{8}$ of an inch.

INDEX.

'Aaron Manby,' description of the, 14.
Abutments, Anglesea and Carnarvon, described, 96; dimensions, 96.
Admiralty report on the means of communication between London and Dublin, 54.
American bridges, construction of, described; bridge at Columbia described, 35; dimensions of, 36.
Anglesea tower of the Britannia Bridge described, 95; dimensions, 95; design, 96; weight of iron, 96
Arched bridges, principles of, 63, 64; cast iron bridge, description of, 2; principles of, explained, 6.

Bars, iron manufacture of, described, 13; forms of, 13; patents for, 13; uses of, 14; experiments on the transverse strength of wrought-iron bars, 70; table of results, 71.
Beams, cast-iron, best form of, 67; action of pressure upon, 62; Bernouilli's theory of beams, 62.
Bernouilli's theory of the action of pressure upon beams and girders, 62; neutral line defined, 63.
Blackburn bridge, Fairbairn's, 25; dimensions, 25; plan of construction, 26.
Boat, first iron, described, 14.
Boats, construction of iron, illustrated by the 'Megæra,' 15; riveting described, 15; sheathing described, 15.
Bodmer's patent for riveting iron plates, 15.
Brick, tubular, girder, and iron bridge described, 44.
Bridge, Blackburn, construction of, described, 25; Buildwas, Telford's, 3; Burdon's cast-iron arched described, 2; comparison of the cost of a cast-iron trussed girder bridge, with a wrought-iron tubular girdered bridge, 26; compound wrought and cast iron trussed girder described, 38; Conway suspension bridge described, 51; Conway tubular bridge described, 131; the Dee bridge, description of, 9; Fairbairn's, at Gainsborough, construction described, 30; first iron bridge described, 1; iron and brick tubular, near Glasgow, 44; lattice bridge described, 33; wooden lattice, 35; wrought-iron lattice, 36; Osborne's improved lattice, 37; Menai suspension described, 50; Rennie's iron, at Boston, described, 4; Smart's patent iron, 33; Southwark, 4; Stephenson's, proposed for crossing the Menai Straits, 59. Tubular bow-bridge described, 41; over the Ouse, description of, 41; over the Regent's Canal described, 43; Walker's, proposed for crossing the Menai Straits, described, 56; wrought-iron at Sunderland described, 2.
Bridge building, application of wrought-iron plate girders to, 24.
Bridges, American, construction of, described, 34; arched principle of, 63, 64; cast-iron girder principle of, 6; girder, principle of, 63, 64; iron arched described, 6; suspension, principle of, 63, 64; Stephenson's suspension, report on, 59; trussed girder described, 7.
Britannia Bridge; Anglesea and Carnarvon towers described, 95; ditto abutments, construction described, 96; Britannia tower described; 94. Fairbairn's experiments to determine the form of tube, 74; cylindrical tubes, table of the tests applied to, 75; results described, 76; elliptical tubes, table of the results of experiments on, 78; results explained, 79; rectangular tubes, results of experiments on, table of, 81; results described, 80. Hodgkinson's reduction of Fairbairn's experiments, 87; cylindrical tubes, 87; elliptical tubes, 88; rectangular, 89. Hodgkinson's experiments, 89; table of results, 90; results explained. Observations of Mr. Fairbairn on the effects of the experiments on the tubes, 84; tabular comparison of the results of the experiments on the different shaped tubes, 87; remarks on the construction of the tubes, 82. Tubes, dimensions of, 96; scaffolding for building the land described, 97; construction of, see tubes of the Britannia Bridge; floating the tubes, 112; pontoons for, 112; towing described, 113; depositing in the towers, 114; preparations at the towers for receiving the tubes, 115; floating the first tube, 117; lifting the tubes, 118; hydraulic presses for, described, 122; application of the power, 121; accident to, 122; packing under the tubes, 123; frames for strengthening the ends of the tubes, 125; connecting the tubes in the towers, 127.
Britannia rock described, 93. Britannia tower described, 94; dimensions, 94; solid content, 94; weight of masonry, 94; weight of iron, 94; construction described, 94.

Burdon's cast-iron bridge described, 2; cost, 3; method of erecting, 3.

Cable stoppers, Wild's, described, 113.
Caissons, manufacture of, described, 16; use of, 17.
Carnarvon, tower of the Britannia Bridge described, 96; dimensions, 96; design, 96; weight of iron, 96. Abutment, 96.
Cast-iron arched bridge described, 2. Cast-iron bars, experiments to determine the strength of, 66; beams, best form of, 67. Cast and wrought iron trussed girder bridges, 38. Cast-iron trussed girder bridge, comparison of cost with a wrought-iron tubular girdered bridge, 26. Cast-iron girders, defects of, 8. Table of the properties of cast compared with wrought iron, 72.
Cement, iron, 5. *Note.*
Chester and Holyhead Railway described, 46, 52; length, 47; stations on, 47; works at Penmaen Mawr described, 53; plans for crossing the Menai Straits, 60; Britannia Bridge, 92.
Columbia, lattice bridge at, described, 35.
Compound wrought and cast iron girder bridges, 38; wrought and cast iron girders, described, 39.
Conway suspension bridge, Telford's, description of, 57.
Conway tubular bridge described, 131; tubes described, 132; testing the tubes, 132; floating the tubes, 112; pontoons for, 112; lifting the tubes, 127—130; chains for, 129; apparatus, 130.
Corrugated iron girders described, 40.
Cort's invention of malleable iron, 11; process of puddling described, 12.
Cylindrical tubes, Fairbairn's experiments on, 75; results, 76. Hodgkinson's reduction of Fairbairn's experiments, 87; comparison of results, 87; table of the strength of cylindrical tubes, 75.

Dee bridge described, 9; failure of, 10.

Engineer, duties of an, 11.
Engineers' reports on the means of communication between London and Dublin, 55.
Elliptical tubes, Fairbairn's experiments on, table of, 78; results described, 79; Hodgkinson's reduction of the above, 88; comparison of results, 87.
Fairbairn's experiments on the best form of tube for the Britannia Bridge, 61, 74; cylindrical tubes, table of results, 75; results explained, 76; elliptical tubes, table of the results of the experiments, 78; results explained, 76; rectangular tubes, table of the results of the experiments, 81; explanation of the results, 80; remarks on the construction of tubes, 82; observations on the effect of the experiments on the tubes, 84; tabular comparison of the results of the experiments on the different shaped tubes, 87; Hodgkinson's reduction of Fairbairn's experiments, 87.
Fairbairn's experiments on the strength of cast-iron bars, 66; iron plates for sheathing described, 15; method of riveting, 16, machinery for riveting, 19; wrought-iron plate girders described, 23; first use of, 24; application to bridge building, 24; bridge at Gainsborough, 30; Blackburn bridge, 24; Liverpool landing stage, 27.
Fielder's compound cast and wrought iron girders described, 39.

Gainsborough, Fairbairn's wrought-iron girder bridge at; construction described, 30; dimensions, 30.
Garforth's riveting apparatus, description of, 20.
Gibbon's patent girders described, 39.
Girder bridges, principle of, 6, 63, 64; trussed girder bridges described, 7; defects of, 8.
Girders, action of the load upon, 64; best form considered, 64 – 67; strength of the materials used for, 65; experiments on the strength of cast iron, 66; cast iron, defects of, 8; best form of cast and wrought iron, 73; compound cast and wrought iron, described, 39; corrugated iron, described 40; experiments on, 40; Gibbon's, described, 39. Lattice girders, French experiments on, description of, 37; Moulton's, described, 38; Rider's, described, 38; wrought-iron plate girders, first method of constructing, 21; first use of, 21; first form of, 21; tubular form described, 23; Fairbairn's, described, 23; first use of Fairbairn's, 24.
Glasgow, iron and brick tubular bridge near, description of, 44.
Gussets described, 107.

Harrison's tubular bow-bridge described, 41.
Hodgkinson's reduction of Fairbairn's experiments on the best form of tube for the Britannia Bridge, 87.
Hodgkinson's experiments on the strength, &c., of the tubes for the Britannia Bridge, 89; results, 90; experiments described, 91; experiments on the strength of cast-iron bars, 66.
Holyhead and Chester Railway described, 46—52; length, 47; stations on, 47; works at Penmaen Mawr described, 53; plans for crossing the Menai Straits, 57.
Holyhead Road, jurisdiction of the commissioners, 48; length of, 49; described, 49—52; Menai Straits bridge described, 50; Telford's account of the works executed, 48.
Howard's patent links described, 131.
Hydraulic press described, 119; construction, 120; power of, 120; principles of, explained, 119; uses of, 119; application to lifting the tubes of the Britannia Bridge, 121; hydraulic presses for, described, 121; accident to the presses, 122; Stephenson's account of the accident, 124; hydraulic power, 122.
Hydraulic press for lifting the Conway tubes, described, 131.
Hydrostatic press, application of, to the

purpose of punching, shearing, and riveting metal plates, 18.

Iron, first employment of, in the construction of bridges, 1.
Iron bar, manufacture of, 13; forms of, 13; patents for, 13; uses of, 14.
Iron boat, the first, described, 14; boats, manufacture of, illustrated by the 'Megæra,' 15.
Iron bridge, the first, described, 1; lattice, described, 33; Smart's patent, 33.
Iron, cast, bars of, experiments on the strength of, 66; girders, defects of, 8.
Iron cement, 5. *Note.*
Iron, compound cast and wrought, girders, 39.
Iron, malleable, manufacture of, described, 11; puddling, 12.
Iron plates, improvements in the manufacture of, 13; process of rolling, 11; uses of, 14; use of, in the manufacture of caissons, 16; Fairbairn's machine for riveting, 19; Fairbairn's thick edged plates described, 15; Garforth's riveting apparatus described, 20; application of the hydrostatic press to the purposes of punching, riveting and shearing, 18; shearing described, 20.
Iron rivets, manufacture of, 17; use of, with brick, in bridge building, 44.
Iron, wrought, its use with cast, in the formation of bridges, 7; error of using with cast explained, 8; bars of, experiments to test the strength of, 70; wrought plate girders described, 21.

Kennedy and Vernon's patent for improvements in the manufacture of bar iron, 13.

Lattice bridges, construction of, 33; wooden, description of, 35; wrought-iron, described, 36; Osborne's improved, 37.
Lattice girders, French experiments on, 37; Moulton's, described, 38.
Links, Howard's patent, described, 131.
Liverpool landing stage, construction of, described, 27.

'Megæra,' construction of, 15.
Malleable iron, manufacture of, described, 11.
May's application of the hydrostatic press to the purposes of punching, riveting, and shearing metal plates, 18.
Menai Straits, first plans for crossing the, 56; Rennie's proposed bridge described, 57; shores described where the Britannia Bridge is erected, 93; Stephenson's plan, 58; described, 60; Telford's suspension bridge described, 50; dimensions, 51.
Moulton's wrought-iron lattice girders described, 38.
Neutral line defined, 63.

Osborne's improved lattice bridges, 37.
Ouse, tubular bow-bridge over the, described, 41.

Paine's wrought-iron bridge, 2.
Patents relating to the manufacture of iron plates, girders, &c.:—Bodmer's for thick edged plates, 15; Cort's, for the manufacture of malleable iron, 11; Fairbairn's, for wrought-iron plate girders, 23; ditto, for riveting metal plates, 19; Fielder's, for compound cast and wrought iron girders, 39; Garforth's, for riveting metal plates, 20; Gibbon's, for iron bridge girders, 39; Howard's, for patent links, 131; Kennedy and Vernon's, for manufacture of iron plates, 13; May's hydrostatic press for riveting, punching, and shearing metal plates, 18; Moulton's, for wrought-iron lattice girders, 38; Porter's, for corrugated iron girders, 40; Smart's patent iron bridge, 33; Wennington's, for shearing metal plates, 20; Wilson and Burdon's, for "connecting metallic blocks for constructing arches," 3.
Penmaen Mawr, railway works at, described, 53.
Pritchard, his first suggestion for the use of iron for bridges, 1.
Pressure, the action of, upon beams and girders considered, 62; Bernouilli's theory of, 62.
Puddling, Cort's process of, described, 12.
Punching, application of the hydrostatic press to, 18; machine for, 17; process of, described, 17.

Railway, Chester and Holyhead, described, 46; length, 47; stations, 47.
Rectangular tubes, table of, Fairbairn's experiments on, 81; results explained, 80. Hodgkinson's reduction of the above experiments, 89; table of results, 90; results explained, 91.
Rennie's iron bridge at Boston described, 4; bridge at Southwark, described, 4; proposed bridge for crossing the Menai Straits described, 57.
Reports on the means of communication between London and Dublin, Admiralty, 54; engineers', 55.
Riveting, application of the hydrostatic press to, 18; chain, described, 24; iron plates, described, 15; Fairbairn's plan, 16; ditto, machinery for, 19; Garforth's machinery, described, 20; the tubes of the Britannia Bridge, described, 108.
Rivets, iron, manufacture of, 17; number of, used in the Britannia Bridge, 108.
Rolling malleable iron described, 11.

Shearing iron plates described, 20; application of the hydrostatic press to, 18; patent machine for, 20.
Sheathing of iron vessels described, 15.
Smart's patent iron bridge described, 33.
Southwark Bridge, description of, 4.
Stephenson's plan for crossing the Menai Straits, 58; described, 60; report on suspension bridges, 59; proposed bridge for crossing the Menai Straits, 60; Admiralty opposition to, 60; proposal of a tubular bridge, 61; experiments on the form of tube to be employed, 61; tubes, his account of raising the, 124.

Suspension Bridge, Menai, described by Telford, 50; Conway, description of, by Telford, 51. Suspension bridges, principles of, 63, 64; Stephenson's report on, 59.

Table of the results of experiments on the strength of cylindrical tubes, 75; elliptical tubes, 78; rectangular tubes, 81; of Hodgkinson's experiments on rectangular tubes, 87; of the results of the different experiments compared, 87; of the properties of cast and wrought iron, 72; of the strength of bars of wrought iron, 71; of the strength of the different materials used for beams and girders, 65.

Telford's iron bridge at Buildwas described, 3; Conway Suspension Bridge, description of, 51; Holyhead Road described, 49; account of the work executed, as engineer to the commissioners, 48.

Thompson's iron and brick tubular bridge, near Glasgow, description of, 44.

Trussed girder bridges described, 7; defects of, 8.

Trussed cast and wrought iron girder bridges described, 38.

Tubes of the Britannia Bridge; bearing rollers, 109; bed plates, 110: cells described, 107; construction of, 101; depositing them in the towers, 114; dimensions, 96, 102. Floating the main tubes, 112; floating the first tube, description of, 117; frames of the tube, 107; ditto for strengthening the ends of the tube, 125; gussets described, 107. Land tubes, scaffolding for building the, 97; weight of ditto, 97; length, 101; lifting the land tubes, 118: hydraulic presses for, described, 122; application of the power, 121; accident to the presses, 122. Main tubes, platforms and staging for building the, 99; length, 99; method of supporting the ends, 110; method of supporting the tubes in the towers, 110; packing under the tubes, 123. Plates described, 103; dimensions, 103; joints, 103; pontoons, 112; preparations for receiving the tubes at the towers, 115; punching, 108; rails, 108; ribs, 105; riveting, 108; rivets, number of, used, 108; sides, construction of, 104; top, construction described, 104; towing ditto, 113; weight of ditto, 111.

Tubes of the Conway Bridge described, 132; chains for raising the, 131; connecting the tubes in the towers, 127; floating the tubes, 112; lifting ditto, 121; arrangements for, described, 127; presses for raising the tubes, 130; pontoons for floating ditto, 112.

Tubes, table of the strength of cylindrical, 75.

Tubular bow-bridge described, 41; over the Ouse, 41; over the Regent's Canal, described, 43.

Tubular girder and brick bridge near Glasgow, described, 44.

Walker's plan for crossing the Menai Straits, 56.

Wennington's machinery for shearing metal plates, 20.

Wild's "cable stoppers" described, 113.

Wooden lattice bridges, 34.

Wrought iron, cohesive power of, 70; experiments on the transverse strength of bars of, 70; table of results, 71; resistance to compression, 72; structure of, 70; table of the properties of, compared with cast, 72; use with cast in the formation of bridges, 7.

Wrought-iron boats, advantages of, 14; ditto bridges, described, 2; ditto lattice bridge, described, 36.

Wrought-iron plate girders, first method of constructing, 21; first use of, 21; first form of, 21; tubular, described, 23; application of to bridge building, 24.

Wrought-iron tubular girdered bridge, cost of, 26.

Wrought and cast iron trussed girdered bridges, 38; compound girders, described, 39.

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Outfall Sewer. Reservoir. Section.
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