THE LIFE

OF

ROBERT STEPHENSON.

VOL. II.

LONDON
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R Stephenson

THE LIFE

OF

ROBERT STEPHENSON, F.R.S.

ETC. ETC.

LATE PRESIDENT OF THE INSTITUTION OF CIVIL ENGINEERS.

BY

J. C. JEAFFRESON

BARRISTER-AT-LAW

WITH DESCRIPTIVE CHAPTERS ON

SOME OF HIS MOST IMPORTANT PROFESSIONAL WORKS

BY

WILLIAM POLE, F.R.S.

MEMBER OF THE INSTITUTION OF CIVIL ENGINEERS.

IN TWO VOLUMES.

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CONTENTS

OF

THE SECOND VOLUME.

CHAPTER I.

THE BATTLE OF THE GAUGES.

(ÆTAT. 40–42.)

CHAPTER II.

IRON BRIDGES.

CHAPTER III.

THE BRITANNIA BRIDGE.

CHAPTER IV.

THE HIGH LEVEL BRIDGE AT NEWCASTLE-ON-TYNE.

CHAPTER V.

AFFAIRS, PUBLIC AND PRIVATE, DURING THE CONSTRUCTION OF THE CHESTER AND HOLYHEAD RAILWAY.

(ÆTAT. 42-47.)

CHAPTER VI.

ROBERT STEPHENSON AS POLITICIAN AND MEMBER OF THE HOUSE OF COMMONS.

(ÆTAT. 44-45.)

CHAPTER VII.

ROBERT STEPHENSON IN LONDON SOCIETY.

(ÆTAT 47-55.)

CHAPTER VIII.

THE GREAT VICTORIA BRIDGE OVER THE RIVER ST. LAWRENCE IN CANADA.

CHAPTER IX.

CONCLUDING YEARS AT HOME AND ABROAD.

(ÆTAT. 47-55.)

CHAPTER X.

LAST SCENES.

(ÆTAT. 55.)

ILLUSTRATIONS IN VOL. II.

THE LIFE

OF

ROBERT STEPHENSON.

CHAPTER I.

THE BATTLE OF THE GAUGES.

(ÆTAT. 40–42.)

Great Western Railway in 1833 — Brunel's Scheme for a Broad Gauge — History of the Narrow Gauge — Advantages anticipated by Brunel from a Broad Gauge — Brunel's Report of 1838 — Theory of Railway Districts—Break of Gauge first takes place at Gloucester in 1844—Goods Traffic, not Passengers, the grand Cause of Difficulty at 'Breaks of Gauge'—Gauge Pamphleteers—The Oxford and Wolverhampton Contest in 1845—Lord Dalhousie's and Mr. Cobden's Motions—Royal Gauge Commission appointed—Brunel's Inconsistencies—The Railway Clearing House, instituted under the Auspices of Mr. Glyn and Mr. Hudson—Its leading Principles and its Returns for 1845—Witnesses examined by the Gauge Commissioners—Brunel left alone—Robert Stephenson's Character as a Parliamentary Witness—His Evidence before the Gauge Commission—Brunel's Expedients for obviating the Evils of 'Break of Gauge'—The Commissioners' Report—The last Argument in favour of Competition advanced by the Broad Gauge Party and answered by Mr. Thornton Hunt—Illustrated Evidence—The Gauge Act—Robert Stephenson's Report on Double Gauges.

WHILST Robert Stephenson was proving that the locomotive was superior to atmospheric propulsion in economy and adaptability of power, he was involved in another controversy, of not less importance, which brought him again in collision with the brilliant engineer, who was throughout life his constant professional opponent, and warm private friend. The relations that subsisted between him and Brunel could not have endured between rivals endowed with merely ordinary generosity. Continually as they were pitted against each other, much as the reputation of the one was exalted by the failures of the other, they not only preserved strong mutual affection, but in their gravest periods of public trial were always ready to assist each other with counsel and support. When Robert Stephenson with fearful anxiety was watching the floating of his first enormous tubular bridge to the piers, Brunel stood by his side; and when Brunel was heroically contending with the gigantic difficulties of launching the Great Eastern, Robert Stephenson disregarded the claims of failing health, in order that he might be on the spot to encourage and advise his brother engineer. Two nobler adversaries the world never witnessed.

Whilst ordinary men were admiring the phenomena of railway developement, Brunel was criticising George Stephenson's system and planning improvements. It struck him that iron roads were not all they might be, or ought to be; and it was not long before he struck out a novel method for their construction. At the first projection of the Great Western Railway in 1833, it was contemplated that that line and the London and Birmingham Railway should have a common terminus in the metropolis. The combined opposition of the Eton and Oxford authorities threw out the Great Western Bill in its first parliamentary campaign, and before the renewal of the contest, Brunel, as engineer of the line, proposed to some of the directors that their gauge, or distance between the rails, should be 7 feet instead of 4 feet 8½ inches. This suggestion was submitted to Robert Stephenson, and was by him promptly rejected. Under ordinary circumstances there would have been an end of the novel scheme; but Brunel was gifted with no ordinary powers of persuasion, and the directors of the Great Western were induced by him to separate themselves from the London and Birmingham Company, and make their line according to his wishes.

As the reader is well aware, the gauge of George Stephenson's first public railway was 4 feet 8½ inches, which had been the gauge of the colliery tramways of Northumbria from the time of their first construction. In the Life of Lord Keeper North, A.D. 1676, it is recorded—

> The manner of the carriage is by laying rails of timber from the colliery to the river, exactly straight and parallel; and bulky carts are made with four rollers fitting those rails, whereby the carriage is so easy that one horse will draw down four or five chaldrons of coals, and is an immense benefit to the coal merchant.

Made to be drawn by horses, these wagons differed little from the carts previously used, the innovation consisting only in finding for them smooth wooden ways, and wheels adapted to those ways. When the wooden trams were first cased with metal, and later on the introduction of iron rails, the same width was continued. The introduction of the locomotive brought with it no new conditions inviting men to change the usage of the country; and George Stephenson therefore made his lines in accordance with the ancient custom. This 4 feet $8\frac{1}{2}$ inches was the original tramroad gauge.

Other gauges were in existence. In some of the mineral districts of England, where the tramways have to meander down hills and into positive gullies, a gauge of two feet had been adopted. In such a country, and for the carriage of minerals, a very broad gauge was clearly not to be thought of. But for comparatively open and level regions no objection to the introduction of greater width between the rails presented itself, to counterbalance the advantages hoped for from the change. Those advantages Brunel expected to find in greater speed, ease of motion, and economy of working. With the wider way, the engineer contemplated the use of larger carriages and more powerful engines. From his engines fitted with wheels ten feet high he looked for a vast increase of speed; and he hoped to effect greater safety by placing his passenger-carriages between instead of over the wheels. According to his calculation one grand advantage of the wide gauge would be diminution of oscillation at high speeds.

The most obvious objection to a wider gauge, at that period of railway history, was the increase it would necessarily effect in the expenses of constructing a line—especially where tunnels, earth-works, and viaducts were frequently needed. The next point for criticism to fix upon was the inconvenience that would ensue to the public wherever lines with different gauges ran into each other. These two difficulties Brunel handled with characteristic adroitness, treating the former as of little weight with regard to the works he contemplated, and finding in the latter an argument actually in favour of his scheme.

Making the most of his theory that each district of the country should have the gauge most adapted to its geographical features, he reminded his opponents that it was no part of his plan to do away with the two, three, and four feet gauges of mineral districts, or to oppose the 4 feet 8½ gauge in countries where that width had already been used or was likely to be most serviceable, but only to introduce his wide gauge in regions, comparatively open, sparsely populated, and untried by railway engineers. London and Bristol, he argued, were separated by a sweep of country offering (except at two or three points) comparatively few obstacles to the maker of iron roads. The difference of cost, therefore, between a wide road and a narrow road would be slight—at least slight compared with the advantages of a system which would convey with unexampled rapidity an entire army of passengers from the metropolis to the capital of the West, in a single train. So cleverly was the objection of expense thus put aside, that shareholders were almost ashamed of their folly in raising the question. The next point—the inconvenience, namely, of 'break of gauge,' as it was soon called—Brunel treated in a very different way. It was true the inconvenience of a break of gauge would be grave, if it occurred; but then he maintained it never would occur.

In his report of 1838 to the directors of the Great Western, he said:—

I shall now consider the subject of the width of gauge. The question of the disadvantage of differing in point of gauge from other railways, and the consequent exclusion from communication with them, is the first. This is undoubtedly an inconvenience; it amounts to a prohibition to almost any railway running northwards from London, as they must all more or less depend for their supply upon other lines or districts where railways already exist, and with which they most hope to be connected. In such cases there is no alternative.

The Great Western Railway, however, broke ground in an entirely new district, in which railways were unknown. At present it commands this district, and has already sent forth branches which embrace nearly all that can belong to it.

Such is the position of the Great Western Railway. It could have no connection with any other of the main lines, and the principal branches likely to be made were well considered, and almost formed part of the original plan, nor can these be dependent upon any other existing lines for the traffic which they will bring to the main trunk.

Such was Brunel's language in the early stages of the gauge controversy, and such it had been when he prevailed on the directors of the Great Western to adopt his innovation.* Briefly stated, his argument was this:—

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* Mr. Brunel's evidence before Gauge Commissioners, Oct. 25, 1845, gives the particulars of the origin and growth of his preference for the Broad Gauge.

'You are the engineer of the Great Western Railway?—I am.

'Was the line surveyed under your direction?—Yes.

'And you decided on its course?—Yes.

'In what year was that?—In 1833.

'That was three or four years subsequently to the formation of the Manchester and Liverpool Railway?—Yes.

'Had you, before you took the direction of the Great Western Railway, any employment in railway matters?—No.

'That was the first line upon which you were engaged as an engineer?—Yes, the first line upon which I was engaged which was constructed; I had looked over other lines of country.

'With a view to railways?—Yes.

'At what period did it occur to you to change the gauge from 4 feet 8½ inches to 7 feet?—I think, in my own mind, it occurred to me in the course of my surveys in 1833 and 1834.

'That a change of gauge would be desirable?—Yes.

'But the exact amount of the change you had not then decided upon?—I think not, and I think I never mentioned it to anyone.

'Will you favour the Commissioners with the reasons which induced you to think that 4 feet 8½ inches was insufficient at that early period?—*Looking to the speeds which*

The west country at present has no railways, it lies open to our enterprise. Let us seize the opportunity, and drive a grand trunk line with a few important branches through it, making our gauge such that no line of the old gauge can run into our roads and suck our traffic. By adopting this course we shall have a monopoly of the west country.

At first Brunel met with little encouragement from the directors. They were not alarmed at the novel proposals, nor did they condemn them as chimerical, but commercial caution made them apprehensive that they might sink in public estimation if they declared themselves the leaders of a revolutionary movement. Brunel's suggestion, however, of a monopoly of the west country, from the impossibility of narrow gauge lines acting harmoniously

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I contemplated would be adopted on railways, and the masses to be moved, it seemed to me that the whole machine was too small for the work to be done, and that it required that the parts should be on a scale more commensurate with the mass and the velocity to be attained.

'The trains at that period were comparatively light to what they are now, both in goods and passengers? —Yes.

'You had probably travelled a good deal upon other railways, and had seen much of other railways that then existed? — Yes, as much as I possibly could. I think the impression grew upon me gradually, so that it is difficult to fix the time when I first thought a wide gauge desirable; but I dare say there were stages between wishing that it could be so, and determining to try and do it, and I cannot at this moment distinctly remember the time.

'Do you recollect at what period you determined upon submitting the 7 feet gauge to the directors of your company? — It must have been almost immediately after the passing of the Act, which was in 1835, and I think I must have mentioned it to the directors long prior to that, because I made great efforts to get the clause omitted which fixed the gauge, and I communicated certainly with Lord Shaftesbury early in 1835.

'Therefore the omission of that clause, which was a very proper omission perhaps, was the result of your communication? — It had been omitted, fortunately perhaps for me, in one Bill previously. I think that the Commissioners will find that in the first Southampton Railway Act it was omitted. It was omitted in the first Great Western Bill, and there I must have taken steps with reference to the gauge early in 1835.'

with broad gauge lines, sunk deep in the minds of the projectors, and bore fruit.

There is no ground for thinking that Brunel acted disingenuously towards his directors. He saw in railways only the future channels of communication between important centres of manufacture and commerce—not the means of passage between petty market towns and secluded hamlets. Each range of country would have its grand trunk, with its limited number of branches to cathedral towns and harbours; but it was not on the list of chances that the branches of these gigantic arteries would multiply, extend, and cross each other—that the surface of the island would be one patch of network. Holding this view (which was the view almost universal in 1833), Brunel gave his directors honest counsel.

He gained his object. The bill was obtained, and the line was made in accordance with his wishes. It was true that its construction was attended with costly accidents and vain experiments. The engines with the huge wheels turned out failures, in consequence of their being deficient in boiler power; but at length the railroad began its career with dazzling *éclat.* The Great Western was the topic of 'the season.' Everyone was in raptures with the smoothness of its way, the height of its speeds, and the luxury of its first-class carriages. As far as the drawing-rooms of May Fair were concerned, the success of the broad gauge was established. Many a humble family has cause to lament that experience, and vulgar calculations of pounds, shillings, and pence have signally falsified this flattering verdict.

A few years gave the public an opportunity of judging how far the theory of distinct fields of railways, not running into each other, was likely to be realised in practice. The plans of projectors soon indicated that iron roads would refuse to run to the capital without inter-communication, and the year 1844 saw the Western and Midland counties in actual collision. The extension of the line between Birmingham and Gloucester, uniting the latter town with Bristol, had, in order that it might accord with the line of which it was a continuation, been planned on the narrow gauge. The directors of the Great Western, seeing in this narrow gauge extension, known as the Bristol and Gloucester, an alarming irruption into their broad gauge field, contrived by a stroke of finance to gain control over its company. Their control was of course exercised to convert the proposed narrow gauge into an actual broad gauge. The result was that on the opening of the extension in 1844, the two scales of road-way met, and Gloucester had the honour of being the scene of the first 'break of gauge.' At first 'the break' attracted but little attention beyond engineering circles. The public were not sufficiently familiar with railways to be highly critical. If passengers from Birmingham to Bristol had to get out of narrow gauge carriages at Gloucester, and crossing over a platform with their baggage, had to seek fresh places in the broad gauge extension, the trouble was trifling compared with that of the shiftings from stage-coach to stage-coach to which travellers had been accustomed. When 'the battle of the gauges was at its height,' pamphleteers were pathetic on the sufferings of delicate ladies and young children, compelled to 'change places,' and pass through the raw night air on their way from one gauge to the other.

Had passengers only been affected by 'break of gauge,' little attention would have been paid to their discomfort and complaints; for the hardship is slight which an ordinary traveller sustains in changing his carriage once in half a hundred miles. The real inconvenience of 'a break of gauge' was found in the conveyance of goods.

Railway communication had not existed many weeks between Birmingham and Bristol, before the manufacturers of Birmingham and the railway officials at Gloucester knew what was the real difficulty. The heavy goods, sent from Birmingham for shipment at Bristol, had to be shifted from gauge to gauge by the Gloucester porters. Packages were misplaced, delayed, or missent. Complaints daily increased; and 'Birmingham men' learnt the discomfort of having a break of gauge between themselves and the Bristol Channel. In due course a comparison of the goods traffic on the Grand Junction, the London and Birmingham, and the Midland lines, with that on the route between Birmingham and Bristol, gave a triumph to the opponents of the broad gauge.

'Break of gauge' was no longer a matter of speculation, but an evil in actual existence. The agitation it aroused soon attracted the attention of the legislature. In the session of 1845, the London and Birmingham and Great Western Companies were in the field with rival bills for a line of railway between Oxford and Wolverhampton. The manifest evils of 'break of gauge' induced the railway department of the Board of Trade to decide against the pretensions of the Great Western. The House of Commons, however, set aside the decision of the Board of

Trade, and without offering any opinion on the advantages of uniformity or variety of gauges, gave the preference to the Great Western on the ground that it was the better line, their choice being endorsed by the House of Lords. Thus for the moment victory was with the broad gauge party, but the facts brought to light by the contest between Robert Stephenson's company and Brunel's company induced both Houses of Parliament to ask for further investigations.

The battle now began in earnest. All the preceding encounters were mere skirmishing, compared with the tug of war which now set in. On the one side were drawn up the forces of narrow gauge, on the other appeared those of broad gauge, double gauge, and mixed gauge; whilst hovering on the flanks of the two armies were the scattered companies of the medium gauges.

The revelations of the Oxford and Wolverhampton Committee were followed by the motions of Lord Dalhousie in the Lords and Mr. Cobden in the Commons, which resulted in an address, unanimously voted, for a Royal Commission to ascertain 'whether in future private acts for the construction of railways, provision ought to be made for securing an uniform gauge; and whether it would be expedient and practicable to take measures to bring railways already constructed, or in progress of construction, into uniformity of gauge.' Without delay the commission was appointed. It was composed of Colonel Sir Frederick Smith, of the Royal Engineers, who had previously acted as Inspector-General of Railways; Professor Barlow, of the Woolwich Military Academy (ex-commissioner of Irish Railways), and Professor Airy, the Astronomer Royal.

The men whose memories survey seven years with accuracy are few. But the few who bore in mind Brunel's position in 1836, '37, and '38 were not a little amused with the line he adopted before the Oxford and Wolverhampton, and the Gauge Commissions. Of course, inconsistencies and plausible arguments in their support were looked for from the man who, in the full observation of men of science and the general public, appeared as the champion of two novelties in railway locomotion, involving diametrically opposite principles. While the broad gauge demanded larger and heavier locomotives than the narrow gauge, the atmospheric system was represented as immeasurably superior to the locomotive system, because the grinding weight of the travelling engines (such as were used on narrow gauge lines) caused ruinous damage to the rails. That is to say, Brunel, at one and the same time, was exclaiming against the destruction of rails by the use of heavy locomotives, and urging the employment of locomotives of an unprecedented weight. On the broad gauge Brunel asked for easy curves; while he represented that the peculiar merit of the atmospheric system was the capability which it afforded of constructing lines with very sharp curves. In railway administration, argued the engineer of the broad gauge lines, the first object was to limit the traffic to a few heavy trains; but changing his tone, the versatile engineer, in pleading for the atmospheric system, insisted that the exigencies of the public required trains to be many and light.

Nothing daunted Brunel. His theory of railway districts had signally broken down. At the outset of his crusade against the narrow gauge, he had argued that break of gauge could never happen — partly because railway lines would have a natural tendency towards London, and partly because the enormous and manifest inconveniences of 'a break of gauge' would deter any line of one width from running into another. But the break, which he maintained sheer terrorism would render an impossibility, had through his instrumentality occurred. The case was unquestionably an awkward one, but he could meet it. He stood up, and smiled at the *fears of his opponents.* It was true that breaks of gauge, if the broad gauge system were extended, would be frequent,* but they could be easily dealt with. With

* 'The completed or projected branches of the Great Western Railway itself,' says Mr. Wyndham Harding in his pamphlet—'The Gauge Question; Evilsof Diversity of Gauge, and a Remedy'—'which was expected, as we have seen, to have no connection with any other existing line—now join it to most of the other main lines in the country. For instance:

'To the Grand Junction, and to the projected Shrewsbury and Birmingham Railways, at Wolverhampton.

'To the Grand Junction, London and Birmingham, and Midland Railways, at Birmingham.

'To the London and Birmingham, the Midland, and the proposed Trent Valley and Churnet Valley lines, at Rugby.

'To the London and Birmingham Railway again, at Warwick.

'To the Birmingham and Gloucester Railway, at Cheltenham and Worcester.

'To the South Western Railway, at Basingstoke and Salisbury.

'To the projected Dorchester and Southampton Railway, at Dorchester.

'To the proposed Welsh Midland line, at Hereford and Swansea.

'To the Bristol and Gloucester line, with which it is already connected, at Bristol and Stonehouse.

'[All these are narrow gauge lines, with the exception of the last, which is a broad gauge line at present, but its proprietors have announced their desire and intention of obtaining powers to convert it into a narrow gauge line.]

'And if the Great Western Railway, with its broad gauge branches, do not go to these lines, they with their narrow gauge branches will come to the Great Western, thus connecting by railway almost every county and town in the kingdom with every other.

'What are all these branches projected for, except to bring traffic from inexhaustible fertility of resource, he enumerated various expedients by which the gigantic evil of 1838 could in 1845 be reduced to a merely nominal inconvenience. The passengers could be left to take care of themselves. As for goods, porters could shift small packages by hand. Heavier goods might be packed on carriages, so constructed that their bodies by the aid of a mechanical apparatus might be shifted, without unpacking their contents, from frames with narrow wheels and axles to broader frames with wheels and axles suited to the wide gauge. He was even prepared to shift the narrow gauge carriages, wheels and all, and place them on broad gauge frames. Coals and other minerals might be packed in loose boxes made of iron, two of which when shifted from the narrow roads would fill one broad gauge truck. He invented telescopic axles which enabled carriages to travel on either gauge. Or he would lay down narrow gauge lines within his broad gauge rails. Of course these expedients involved great additional expense, in porters and machinery and time. But pecuniary expense was a consideration to which Brunel was indifferent.

A few extracts from his evidence before the Gauge Commissioners will show how little care he now had for expenditure in an arrangement which was in the first instance recommended to the public on the score of economy.

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the lines and districts with which they communicate, or to take traffic to them from one extremity of the country to another, and therefore over the narrow gauge on to the broad gauge, or over the broad gauge to a narrow gauge? The difficulties attending a change of gauge then, which, as was admitted, would in 1838 "have entirely prevented in the north such a course" as one railway adopting different dimensions from the rest, now have "existence in the west."'

As regards goods (he said in the conclusion of his long answer to interrogatory 4029), *it is of course a mere question of money*; and if there is a considerable stream of goods in one line, and it is the interest of two parties meeting at a certain point to interchange those goods, I believe the inconvenience *and expense will be so trifling that it is hardly worth consideration,* if there are other important considerations in the question of the change of gauge.

When, however, he was pressed as to the details of his plans for interchange, he became even more vague :—

4048. Having dealt with the passengers, and having had now some considerable time to think of the question of goods, since it was brought forward in the last session of parliament, have *you made up your mind at all as to the mode in which you would arrange respecting them?*—No; because it must depend upon what other companies choose to do on the other side; if they do not afford assistance, I will not say if they throw impediments in the way, but if they do not afford assistance to exchange, the mode must be different from that which it would be if they did. As regards coal, there is no doubt that there would be every facility, because the mode of carrying an article in large quantities like coal, will no doubt be influenced by the wishes and desires of the coal-owners, and the coal-owners will, of course, be desirous of doing whatever will encourage their trade with Oxford.

4049. You would have no difficulty with them?—I think we shall have no difficulty whatever with them. As regards general goods, it must depend upon what the other companies may choose to do; the worst that could happen, of course, would be the entire unloading and reloading of goods; *even that does not amount to anything in time or money that would be much felt by the public.*

A reference to the returns for the year 1845 of the Railway Clearing House will show how far interchange between railways could be hindered or disturbed, without causing the public serious inconvenience. Under the auspices of Mr. Hudson and Mr. Glyn, the Railway Clearing House was established on January 2, 1842, to relieve railway companies of the burdensome calculations consequent on a system of correspondence which had grown up since the opening of the public lines of railway between London and Liverpool. The leading principles of the Clearing House system are three.* *Firstly*, passengers are booked through at all principal stations, and conveyed to their destinations without change of carriage—horses, cattle, goods, being in like manner sent through without change of conveyance. *Secondly*, companies respectively pay a fixed rate per mile, for such carriages and wagons, not their own property, as they may use; and a further sum per day by way of fine or demurrage for detention, if kept beyond a prescribed length of time. *Thirdly*, no direct settlement may take place between the companies in respect of any traffic, the accounts of which have passed through the Railway Clearing House. This is no place for a minute description of the Clearing House operations. It is enough to say, that through them 'the transactions of one company with all other companies, amounting frequently to many thousand pounds a week, are cleared weekly by a sum seldom exceeding a few hundred pounds.'

An institution so manifestly adapted to commercial exigencies met with immediate success. With a few very unimportant exceptions, all the narrow gauge companies joined the association as soon as they came into existence, and had need to correspond with other companies. The

* 'The Origin and Results of the Clearing System which is in operation on the Narrow Gauge Railways.' A pamphlet printed for private circulation.

transactions of the House soon became very heavy; their returns for 1845 showing,

that 517,888 persons were in that year each conveyed through an average distance of 146 miles, the average length of the lines travelled over being forty-one miles, so that each passenger travelled over four railways on the average, and must have passed three junctions or points of convergence. To accommodate these passengers, 59,765 railway carriages, and 5,813 carriages, were sent through. There were also sent through in the same year, 7,573 horse-boxes, 2,607 post offices, and 180,606 goods wagons, besides wagons conveying minerals, of which no record is kept in the Clearing House.*

Of course the extension of the broad gauge would have crippled, if not altogether put an end to this admirable system of correspondence. The Clearing House, therefore, was another powerful antagonist to the broad gauge, and its returns, giving the aggregate of railway correspondence throughout the entire country, furnished the advocates of uniformity of gauge with valuable facts and illustrations for their arguments.

The witnesses examined by the Gauge Commissioners in 1845 were forty-six† in number, and they included every

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* 'A Brief History of the Gauge Question.'

† The following classified list of the forty-six witnesses will be interesting both to the public and to professional readers:—

In favour of uniformity and a narrow gauge:

1. Bass, William, agent to Messrs. Pickford.
2. Bidder, George Parker, C.E.
3. Bodmer, George, locomotive manufacturer.
4. Braithwaite, John, C.E.
5. Brown, James, manager of Sir John Price's iron and coal-works.
6. Buckton, Thomas, secretary to the Brighton Railway.
7. Budd, James P., manager of copper-works and coal-mines, and deputy-chairman of the Welsh Midland Railway.
8. Chaplin, W. James, chairman of the South Western, head of the carrying firm.
9. Clarke, Peter, manager of the Brighton Railway.

person eminent in the railway world as an engineer, a manufacturer of locomotives, a manager, a secretary, a

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10. Creed, Richard, secretary to the London and Birmingham Railway.

11. Ellis, John, deputy-chairman of the Midland Railway.

12. Fernihough, William, locomotive superintendent of Eastern Counties Railway.

13. Harding, Wyndham, late manager of the Bristol and Gloucester Railway.

14. Hawkshaw, John, C.E.

15. Hayward, Joseph, of the firm of Pickfords', carriers.

16. Horne, Benjamin W., carrier.

17. Hudson, George, M.P.

18. Huish, Mark, Capt., general manager of the Grand Junction, and Liverpool and Manchester railways.

19. Jones, Evan, agent for Chaplin and Horne, carriers, at Camden Station.

20. Laws, R.N., Capt. J. M., general manager of the Leeds and Manchester Railway.

21. Locke, Joseph, C.E.

22. M'Connell, James Edward, superintendent of the locomotive department on the Birmingham and Bristol Railway.

23. Martin, Albinus, C.E., resident engineer and superintendent of the South Western Railway.

24. Mills, T. C., manager of the goods department of the London and Birmingham Railway.

25. O'Brien, Capt. William, late secretary to the South Eastern Railway.

26. Rastrick, J. U., C.E.

27. Stephenson, Robert, C.E.

28. Whitaker, Thomas, C.E.

29. Woods, Edward, C.E.

30. Wood, Nicholas, C.E.

In favour of an intermediate gauge, theoretically, and against the broad gauge, but favourable to uniformity of gauge:

1. Bury, Edward, locomotive manufacturer.

2. Gray, John, locomotive superintendent, Brighton Railway.

3. Pasley, Major-General, R.E., inspector of railways.

4. Roberts, Richard, locomotive manufacturer.

5. Vignoles, C., C.E.

In favour of an intermediate gauge, expressing no decided opinion as to uniformity of gauge:

1. Cubitt, Benj., late locomotive superintendent of the Croydon and South Eastern Railways.

2. Cubitt, William, C.E.

3. Landmann, Col. R.E.

Opposed to break of gauge, but expressing no opinion about gauge:

1. Burgoyne, Major-General Sir John, Quarter-Master General.

2. Gordon, General Sir Willoughby, Quarter-Master General.

3. Downs, Richard, contractor.

4. Jackson, Thomas, ditto.

In favour of broad gauge, and against uniformity:

1. Brunel, Isambard Kingdom, C.E.

2. Clark, Seymour, superintendent of traffic on Great Western.

3. Gooch, Daniel, superintendent of locomotives on Great Western.

4. Saunders, Charles Alexander, secretary of the Great Western.

carrier, or an amalgamator. Of them, only four were in favour of a seven-foot gauge and against uniformity. Three offered no opinion as to the desirability of a uniform gauge. But all the others—i. e. 39 out of 46—were so impressed with the inevitable evil consequences of break of gauge, that they concurred in desiring uniformity of road width, though five of that number had a theoretical preference for an intermediate gauge, and four others refrained from offering an opinion as to which gauge was best.

Brunel found himself alone. Not one member of his profession sided with him. Indeed his only companions in 'the forlorn hope,' of which he was the leader, were three gentlemen holding office under the Great Western Company, and pledged in honour to fight to the death for the broad gauge. At this date it is easy to see how Brunel fell into his error, but it is difficult to judge him with the generosity he merits. He was betrayed into an embarrassing position not so much by seeing less, as by seeing farther, than ordinary men. Of the crowd of witnesses who came against him in 1845, there were few who in 1834 and 1835 thought of the consequences of 'a break of gauge.' He, however, foresaw them, and fancied that by seizing a wide tract of country he could by the fear of those very consequences drive off competition. Had he been a few years sooner in the field, he might possibly have succeeded so far as to make his gauge the gauge of the southern districts of the country, and in some counties not only to have checked, but even to have supplanted the narrow gauge. When witness after witness came up to beat down his fallacies before the Gauge Commissioners, they were only proving to him what he had seen ten years before, and they had only learnt by recent experience. It is true that Robert Stephenson had seen farther than Brunel. He had not only foreseen the evils that would arise from 'a break of gauge,' but with his clear vision, and thorough familiarity with the powers which he and his rival were contemplating, discerned that in spite of those obstacles, different fields of railway would run into each other.

As Robert Stephenson had been the first to foresee the evil consequences of diversity of gauge, he was, apart from being the recognised chief of his profession, selected as leader of the narrow gauge party before the Commissioners. In this position, therefore, he was the first to give his evidence before the Commission on August 6, 1845. On all occasions Robert Stephenson's evidence was peculiarly impressive. If he saw the truth, he stated it, although it was against his interests. With equal honesty, he declined answering a question of opinion, if he had not sound and valid reasons wherewith to support his reply, even when he might feel confident that a quick off-hand statement, agreeable to his interests, would gain a point. 'I cannot answer that question,' was often heard from his lips. This straightforward candour at first told against him, but the influence of his testimony was in the long run enormously enhanced by it. When it was stated in railway discussions, that 'Robert Stephenson *said* such or such a thing,' it was understood that the statement, be it right or wrong, was the conscientious and deliberate opinion of the first practical engineer of his day.

Before the Gauge Commission, Robert Stephenson's evidence was temperate and convincing, as it was when-ever he spoke on a subject connected with his profession. At the outset he admitted that at one time the narrow gauge had appeared to him too confined; and then he succinctly stated the changes which had removed the considerations on which that opinion was based.

As an engine builder (he said), at one time when I was called upon to construct engines of greater power than we commenced the line with, I felt some inconvenience in arranging the machinery properly; we were a little confined in space, and at that time an increase of three or four inches would have assisted us materially, and to that extent I thought at one time that an addition to five feet would have been desirable, but on no other account, looking at it as a mere engine-builder. Since that time the improved arrangements in the mechanism of the locomotive engines have rendered even that increase altogether unnecessary; at present, with the inside cylinders, which is the class of engine requiring the most room between the rails, and the cranked axle with the four eccentrics, we have ample space, and even space to spare.

With reference to space, in the arrangement of the machinery, which is the main question having reference to the width, the working gear has been much simplified, and the communications in the most recent engines, between the eccentric and the slide valve, have been made direct communications; whereas formerly it was made through the intervention of a series of levers, which occupied the width. But even without that which I have just now alluded to, which gives us an extra space with the engines on the South Western and on various lines in this country by the improvements which have been made, there is quite space enough for the whole of the working gear.

Then with reference to the increase of power, the size of boiler is, in point of fact, the only limit to the power, and we have increased them in length on the narrow gauge, because we have always made the boiler as wide as the narrow gauge would admit of, but we have increased their length both in the fire-box and in the tubes; we have obtained economy, I conceive, by lengthening the tubes, and we have obtained an increased power by increasing the size of the fire-box; in fact, the power of the engine, supposing the power to be absorbed, may be taken to be directly as the area of the fire-grate, or the quantity of fuel contained in the fire-box.

After enumerating the different items—roadway, tunnels, embankments, viaducts, bridges—which would absorb the funds of a broad gauge company in the process of construction, he took into consideration the various expedients suggested by Brunel for effecting transfer of goods. The loose-box system, experience, he said, had proved to be a failure.

Whilst I think the Great Western has obtained no advantages by the wide gauge, I think its introduction has involved the country in very great inconvenience, beoause wherever a meeting of the gauges takes place, it must create an inconvenience, and a very serious one; in fact, it is nothing more or less than tantamount to asking the Great Western or the London and Birmingham Company to move their passengers at Wolverton; that is an exaggerated case perhaps, but still it is one which, if it takes place in the midst of a large traffic, would, I believe, give canals or another existing mode of communication a decided advantage over a railway. I stated in my evidence before the Wolverhampton Committee, that from Rugby, to which point it is proposed that the wide gauge should come, the Derbyshire coal-owner, or the Leicestershire, would inevitably send their coal by canal, in preference to changing the gauge, because they would have to transfer their coals there; it is proposed in order to avoid the actual removal of the coals, to move them in boxes, and to have loose bodies to the wagons. Now, that is a system which has been tried over and over again, and which has failed. It was tried on the Liverpool and Manchester line originally. There was a great coal-pit about 200 or 300 yards from the line of railway; they wanted to send coals to Liverpool, and small wagons were placed on the backs of large wagons, and carried to Liverpool; that was soon abandoned. Loose boxes were tried at Bolton for the purpose of leading the coal into the town by horses, without changing at the station; they were eventually abandoned. I tried the same thing at Canterbury, and we were obliged to abandon it, because sometimes we had loose boxes and we had no frames, and sometimes we had underframes when we had no boxes, and we could not fit them in. It is almost impossible to make this intelligible to any one who has not come directly in contact with the inconvenience of the system. Rather than introduce the loose-box system, it would be far better to move the coals by hand from wagon to wagon, because there would be an end of it. It also involves this, which I felt particularly at Canterbury: when the body of the wagon is attached, and made part of, and formed at the same time with, the frame, it strengthens that frame, and it strengthens also the body itself; but when they are made to separate, they are both of them weak, and they both get rickety, and they are exceedingly costly to maintain in repair.

The continuation of this portion of his evidence went to show that the evils enlarged upon were not so much defects from want of good management, but defects from which the system could not be freed.

As to the expedients proposed for shifting bodies of wagons by machinery, he showed that the time required for their application would render them commercially impracticable.

With similar force the witness unfolded the objections to the double gauge, i. e. the system which employs both gauges, by putting down narrow gauge rails within the broad gauge; and to the mixed gauge, or system which accommodates both broad and narrow carriages, by putting within the broad gauge a single rail at such a distance from the outer rail of the broad gauge that a narrow gauge line is thereby formed.

His evidence made it clear that uniformity of gauge was imperatively demanded for the transaction of business; that the expedients proposed for overcoming the discomforts of 'break of gauge' would scarcely mitigate them;

and that since an uniform gauge throughout the country was required, no gauge was so well adapted as the 4 feet 8½ inches for all varieties of country.

Uniformity of gauge being the grand object, the following table* of the lines completed, in progress, and projected, in 1845, will show how strong a case the advocates of the narrow gauge had for maintaining that in regard to comparative interests involved, apart from all other considerations, the preference ought to be given to their system.

NARROW GAUGE RAILWAYS.	Miles	BROAD GAUGE RAILWAYS.	Miles
Completed	1844	Completed: Great Western, Bristol and Exeter, Cheltenham and Great Western (just completed), Bristol and Gloucester . . .	278
In progress	614	In progress	52
Projected	6918	Projected	1311
	9376		1641
Or, as . .	5¾	To . . .	1

To strengthen the case of the narrow gauge, on this ground, it was advanced that already various lines in England and Scotland (like Mr. Braithwaite's *Eastern Counties'*) constructed with an intermediate gauge of 5 feet, had for the sake of uniformity been reduced to 4 feet 8½ inches. Thus the proposition could never for an instant be entertained that to please an innovating minority, an overwhelming majority should alter arrangements which they had been at great cost to complete.

In the January of 1846, the Gauge Commissioners made a report, recommending,—

* 'Railways: The Gauge Railway Question,' &c. By Wyndham Harding, with a map. 4th ed.

(1) That the gauge of four feet eight inches and a half be declared by the legislature to be the gauge to be used in all public railways now under construction, or hereafter to be constructed in Great Britain.

(2) That unless by the consent of the legislature, it should not be permitted to the directors of any railway company to alter the gauge of such railway.

(3) That in order to complete the general chain of narrow gauge communication from the north of England to the southern coast, any suitable measure should be promoted to form a narrow gauge link from Oxford to Reading, and thence to Basingstoke, or by any shorter route connecting the proposed Rugby and Oxford line with the South Western Railway.

(4) That as any junction to be formed with a broad gauge line would involve a break of gauge, provided our first recommendations to be adopted, great commercial convenience would be obtained by reducing the gauge of the present broad gauge lines to the narrow gauge of four feet eight inches and a half; and we, therefore, think it desirable that some equitable means should be found of producing such entire uniformity of gauge, or of adopting such other course as would admit of the narrow gauge carriages passing, without interruption or danger, along the broad gauge line.

On the appearance of this judicious report the agitation of the two great parties whom it especially concerned, and of society at large, was indescribable. Articles and pamphlets of an acrimony unusual even in party warfare were published in every quarter; and the farces and extravaganzas of the theatres were full of allusions to the quarrel. Of the more eccentric literature of the contest, the 'Dialogues of the Gauges' first published in the 'Railway Record' may be read with amusement by the curious.

Beaten successively on all the engineering points, Brunel and his party endeavoured to persuade the public that their interests were concerned in maintaining a spirited competition between broad and narrow lines. This extraordinary view the engineer put before the Gauge Commissioners in the following words:—

I think the spirit of emulation and competition (said Mr. Brunel before the Gauge Commissioners) kept up between different railway interests, both as regards the comfort and the construction of the carriages, and the times and mode of travelling, will do much more good to the public than that uniformity of system which has been talked of for the last two or three years.

After the publication of the Commissioners' Report, this plausible fallacy was reiterated; and it was gravely maintained that the public would be benefited, if railway companies (composed of that same public) would lay down rival roads side by side, and ruin each other by competition. To this ridiculous proposition Mr. Thornton Hunt replied: *—

It is not possible. There are not enough railways, nor likely to be enough to create a real competition. For the most part railways branch off in different directions. Where they run in somewhat similar directions, the competition would occur between very few parties. Where parties are so few, so well-organised, managed by councils possessing so much of a deliberative character, and where the bad results of competition would be shown so tangibly, and in such large amounts, a continuous and injurious struggle for any length of time would be practicably impossible. 'I look upon it,' says Mr. Laing, 'as inevitable, that if a rival line is made, the two must sooner or later agree to charge the rate of fares which will be the most productive.'

This argument, based on the supposed advantages of competition, is interesting, as it stands out to mark the

* '*Unity of the Iron Net Work: showing how the last argument for the break of gauge, competition, is at variance with the true interests of the public.*' By Thornton Hunt. 3rd ed. Smith, Elder, & Co., Cornhill.

extreme point to which Brunel was driven from the ground on which, at the outset of the memorable war of the gauges, he had taken his position.

Amongst laughable occurrences that enlivened the committee rooms during the gauge contest, was a scene occasioned by parliamentary counsel putting in as evidence, before the committee on the Southampton and Manchester Line, a printed picture of troubles consequent on a break of gauge. The picture was a forcible sketch, that had appeared a few days before in the pages of the 'Illustrated London News.' Opposing counsel of course argued against the production of the work of art as testimony for the consideration of committee. After much argument on both sides the chairman decided in favour of receiving the illustration, which was forthwith put, amidst much laughter, into the hands of a witness, who was asked if it was a fair picture of the evils that arose from a break of gauge. The witness replying in the affirmative, the engraving was then laid before the committee for inspection.*

Fortunately for the immediate peace and the permanent interests of society, the conflict was concluded by legislation which in its chief principle accorded with Robert Stephenson's views. By 9 & 10 Vict. cap. 57 (An Act for Regulating the Gauge of Railways, August 18, 1846) it was enacted :—

That after the passing of this act it shall not be lawful (except as hereinafter excepted) to construct any railway for the conveyance of passengers on any gauge other than four feet eight inches and half an inch, in Great Britain, and five feet three inches in Ireland. Provided always, that nothing hereinbefore

* Vide 'Railway Chronicle,' June 13, 1846.

contained shall be deemed to forbid the maintenance and repair of any railway constructed before the passing of this act on any gauge other than those hereinbefore specified, or to forbid the laying of new rails on the same gauge on which such railway is constructed, within the limits of duration authorised by the several acts under the authority of which such railways are severally constructed.

Possibly somewhat at the expense and to the detriment of the public, sections II. III. and V. of the same Act paid full measure of respect to existing broad gauge interests. There is ground for the opinion that too great consideration was displayed to the interests of individuals whose action threatened to be, and already had been prejudicial to the state. But it must be remembered that the gauge party was compact, united, and animated with a determination to fight to the last. Nor was its influence solely dependent on its spirit and organisation. In the houses of parliament it numbered many devoted and powerful adherents, and it had a strong hold on the opinions of those who, believing in the broad gauge as a system capable of supplying the public with greater and easier speeds than the narrow gauge, regarded the question from a selfish point of view, and placed personal comfort before commercial utility. Strong, therefore, within the walls of parliament, and strong without, the broad gauge party, even at the time of its overthrow, was to be conciliated. With 9 & 10 Vict. cap. 57, the gauge question, as far as the general public felt concern in it, was set at rest. An important professional question however was still to be discussed by engineers. A limit had been put to the construction of broad gauge lines. The question now to be considered was — how best to introduce the narrow gauge into broad gauge lines, so that the two systems might be worked together, where break of gauge could not be otherwise avoided? Ought two distinct pairs of lines for each gauge to be put down? or would it be better to use only three rails, one of them being common to both gauges? At first sight the choice, apart from the difference of original expense between putting down three lines or four lines, might seem unimportant. But practical men knew otherwise. Robert Stephenson's opinions on these questions were published in a report.

CHAPTER II.*

IRON BRIDGES.

Mr. Stephenson's large Practice in Iron Bridges—His Article on the Subject in the *Encyclopædia Britannica*—Modern Use of the Material—Early Bridges—First Iron Arch Bridges—Tom Paine's Bridge—Full Development of the Iron Arch Bridge—First Use of Wrought Iron—Suspension Bridges—Captain Samuel Brown—Mr. Telford—The Menai Bridge—Introduction of Railways—Consequent large Demand for Iron Bridges—Return to the Form of the simple Beam—Comparison of the three different Systems of Iron Bridges—Advantages of the Girder System—Cast-iron Girders—Compound Girders—The Dee Bridge—Royal Commission on Iron Railway Structures—Introduction of Wrought-iron Girders—Different Varieties of Girders—Examples—The Aire Bridge—The Benha Bridge—Last Work of Mr. Stephenson's Life, Restoration of Tom Paine's Bridge.

BRIDGES have always formed important works in the practice of the civil engineer, and there are scarcely any eminent members of the profession whose names are not associated with structures of this kind, of greater or less magnitude. Mr. Stephenson, in the course of his large railway practice, must have erected vast numbers, but his name is preeminently connected with three bridges, so important in their objects and so bold in their design, that they have acquired for their author a world-wide fame. These are the Britannia Bridge, carrying the Chester and Holyhead Railway over the Straits of Menai, in North

* This chapter is contributed by Professor Pole.

Wales; the High Level Bridge, for road and railway, across the Tyne at Newcastle; and the great Victoria Bridge over the St. Lawrence in Canada. It is proposed to give a brief account of each of these structures; but the description of their peculiarities will be simplified by making some general preliminary remarks on bridge building in iron—a material which now enters so largely into the practice of the modern engineer. This will also give the opportunity of referring to some other bridge works of Mr. Stephenson's, which afford interesting and instructive subjects for comment.

In this task it happens that we have an aid peculiarly appropriate and useful. The subject is one in which Mr. Stephenson took so great an interest, that he was induced, in the midst of his heavy professional engagements, to write the article 'Iron Bridges' for the eighth edition of the 'Encyclopædia Britannica.' The essay is, of course, limited in its scope, and it is somewhat damaged by typographical errors; but still it treats the subject in its historical, theoretical, and practical bearings in a very clear and able manner, and with as much fullness as the space at the author's disposal would permit. We are fortunate therefore in being enabled to base our account of this subject on data of his own compiling, and frequently to give his own words.

'The exclusive use of iron in the construction of bridges is of modern date, though no other material is so peculiarly adapted to such a purpose; its use was, however, long delayed, not so much because its advantages were not appreciated, as from the great cost, and even impossibility, of obtaining iron in large masses. It is now most extensively employed in bridge construction, and though in elegance or durability it cannot compete with stone, where the span is moderate, yet there are numberless cases where its adoption has been the means of solving many of the great problems of modern engineering. Its use has more especially become an absolute necessity in railway-bridge construction, where headway is so frequently of paramount importance, and where rapidity of execution is often a more necessary consideration than even economy or durability; while the defective foundations that have so often to be contended with, render the lightness, the independent strength, and the pliable character of iron of the utmost value for such structures.'

The early attempts at forming a platform or bridge over an open space must have been by means of *beams*; that is, by pieces of timber, or some other material sufficiently long to stretch from one side to the other, and strong enough to carry the load required. But both the length and strength of such contrivances must have been naturally very limited; and as the building arts advanced, a most important step was gained in the invention of the *arch*, by which a far greater span could be covered and a far greater weight supported, than by the simple beam. The arch is of very ancient date, having been traced back in Egyptian antiquities to many centuries before the Christian era. The Romans took advantage of it with great zeal and skill for the erection of bridges in vast numbers, and of large size and great constructive merit; and it has been used for the same purpose in all succeeding times down to the present day, wherever masonry has been the material employed for the structure. Yet it is a remarkable fact, that the development of the use of the more modern material, *iron*, for the purpose of bridge building, has just reversed this order of things. Iron bridges were first made by imitating the more advanced form of structure, the masonry arch, and for a long period none but arched bridges were constructed in iron; but with the increase of knowledge in the use of the material, and with the attainment of greater skill in its manufacture, the design of the structures reverted to the primitive form of the beam, in which by far the great majority of iron bridges, including those of the most colossal dimensions, are now made.

The history of iron bridges commences in the 16th century, when such structures were first proposed in some Italian works. In 1719 the subject was again revived by Dr. Desaguliers, the well-known mechanical philosopher, but nothing like an attempt at construction was made till 1755, when an iron bridge was proposed and partly manufactured at Lyons; but the design was subsequently abandoned from motives of economy, and a timber bridge was substituted.

The credit of erecting the first iron bridge belongs to this country, the work having been done immediately after the time when, by the impulse given to the iron manufacture by smelting with coke, cast iron had superseded timber in numerous details of mechanical construction. This bridge, erected in 1779, was a cast-iron semicircular arch of 100 feet span across the Severn at Coalbrookdale, a work which still stands, and which, considering that the manipulation of the material was then completely in its infancy, evinces a boldness and skill highly creditable to its designers.

Shortly after this, some propositions for an extension of the principle were made by French engineers, but not one was carried into execution.

In 1794 two small iron bridges were erected in Germany, but the principle became much further developed in England before it was taken up in earnest in any other country. The celebrated Mr. Telford was one of the first to take advantage of the new material, and in 1796 he erected an iron bridge with a single arch of 130 feet span, also over the Severn, a little below Shrewsbury. In the same year, however, was finished a much larger iron bridge over the Wear near Sunderland, which Mr. Stephenson characterises as one of the boldest examples of arch construction in existence. It is also very remarkable in its paternity and history, its author being no other than the well-known Tom Paine, of sceptical and republican notoriety. This singular being, having a great aptitude for mechanics, proposed in 1790 to construct cast-iron arches, in what was then a novel manner, namely, of framed open panels in the form of voussoirs; and with characteristic energy he put his views to the test by making an experimental arch of 88½ feet span, which was exhibited at Paddington, and was completely successful. It happened that in the same year a committee was appointed for investigating the inconvenient and dangerous state of the ancient ferry in the middle of the harbour at Wearmouth; and as it was decided that a bridge should be built of cast iron, the ideas of Paine were adopted in its design, and part of the ironwork of his experimental arch was used in its construction.* The

* Mr. Murray, the engineer of the Sunderland Dock, who has had occasion to examine this bridge very carefully, believes that he has succeeded in identifying in it the particular portion of ironwork here referred to, which differs in manufacture from the rest.

span of this bridge, which is in one segmental arch, is no less than 236 feet, only 4 feet less than the centre arch of Southwark Bridge, the largest in existence, and yet it contains only about one-fifth the weight of iron!

If (says Mr. Stephenson) we are to consider Paine as its author, his daring in engineering certainly does full justice to the fervour of his political career; for, successful as the result has undoubtedly proved, want of experience and consequent ignorance of the risk could have alone induced so bold an experiment; and we are led rather to wonder at, than to admire, a structure which, as regards its proportions and its small quantity of material, will probably remain unrivalled.

To complete the singular history of this bridge, it was sold in 1816, by a lottery, for £30,000, £3000 more than its original cost twenty years before; and certain alterations to it which will be described hereafter, formed the last work of Robert Stephenson's engineering career.

In 1801 a remarkable design was given in by Messrs. Telford and Douglas for replacing London Bridge by a single cast-iron arch of 600 feet span; and the works were even put in hand; but the scheme was afterwards abandoned on account of the great and inconvenient rise that would be required in the approaches.

Iron bridges now began to be generally adopted. In 1802 a large arch of 180 feet span was erected over the Thames at Staines, by the same engineers and on the same plan as the Sunderland Bridge. The abutments were of insufficient strength, and the bridge subsequently required supporting; but it remained till the erection of the handsome stone structure on a neighbouring site by Messrs. Rennie in 1832, when it was taken down.

Iron bridges soon afterwards found their way into France. The Pont du Louvre, erected in 1803, was the first, and this was followed in succeeding years by the Pont d'Austerlitz and others, in Paris and in other parts of the country. In England they began to multiply fast. In 1816 Vauxhall Bridge was opened, and three years afterwards Southwark Bridge, which Mr. Stephenson declares stands confessedly unrivalled as an example of the cast-iron arch bridge, whether as regards its colossal proportions, its architectural effect, or the general simplicity and massive character of its details. The central arch is 240 feet span, the largest in the world; and the two side arches are each 210 feet. The bridge cost £800,000, and the quantity of iron in it is nearly 6000 tons.

At that time, therefore, the first form of iron bridge, that of the arch, may be considered as having arrived at its full development. Great numbers have been constructed in this and other countries, but there is nothing connected with them that needs further notice here.

Meanwhile, in the forty years that had elapsed since the first introduction of the iron bridge, great advancement had taken place in the manufacture of iron generally, and particularly in that of *wrought iron.* Cast iron had been eminently suitable for the arch bridge, as being specially adapted for resisting the strain to which arches were exposed, namely, direct compression or crushing. But to the use both of this form and of this material there was a necessary limit, from the massive construction and consequent great weight necessary, when employed for very large spans.

Wrought iron, by its greater tenacity and less liability to fracture, offered an extension of the limit of size possible for iron bridges. It was distinguished from cast iron by its property of withstanding a great *tensile* strain with a light weight of material, a property very valuable for bridge construction; the only problem being so to design the structure as to bring the material under this kind of strain. Hence arose a new construction of bridge, altogether differing from the arch, namely, the *suspension bridge*; the principle of which was, that the strain of the load was thrown upon a chain, keeping it in a constant state of tension, instead of upon an arch, in a constant state of compression.

The idea of forming a communication between opposite shores of a ravine or river, by suspending ropes across it, and attaching a roadway thereto, is of great antiquity, bridges of this description having existed in China, and indeed among less civilized nations, from time immemorial.

But the suspension bridge formed of iron chains, to the construction of which the resources of modern art and science have been applied, is of comparatively recent date. The first of which there is any account in England, or indeed in Europe, was a small foot bridge erected in 1741 across the Tees, near Middleton, in Durham, for the use of the miners. It was 70 feet long and 60 feet above the river, the roadway being 2 feet wide, of planking, with a handrail on each side; but no further particulars are recorded as to its details, and probably it was a very primitive affair.

In the commencement of the present century, however, the subject was taken up by an energetic naval officer, Captain Samuel Brown, who appears to have had a knowledge of iron-work and of general construction worthy of an engineer of the present day. It was he who first introduced into the naval service the use of chain cables; and for this and his other services to the country, among which his part in the introduction and improvement of the suspension bridge was not the least important, he was knighted by the Queen in 1838.

Captain Brown's great improvement was the adoption of chains made of long iron bars instead of common link cables, which had been used up to that time. In 1813 he constructed a large model of a bridge on this plan, and in July 1817 he took out a patent for his invention.

The first bridge actually erected by him, and indeed the first suspension bridge ever constructed of much engineering pretensions, was the Union Bridge across the Tweed, five miles above Berwick, which was begun in August 1819 and opened in July 1820. It was a large bridge, being 450 feet span and having 30 feet deflection of chain. The roadway was 18 feet wide, and the chains were composed of link bars 15 feet long.

Captain Brown in following years also erected several other large structures on the same principle, among which, perhaps, the one best known is the chain pier at Brighton, opened in 1823.

In the meantime Mr. Telford was led to see the advantage of the suspension principle. About 1814 he had been requested to report on the practicability of forming a bridge at Runcorn over the Mersey. The plan of bar chains does not seem to have been then known to him, but he entered into a series of investigations and experiments to test the capabilities of the suspension principle generally, and its adaptability for the object he had in view. The strength of iron was not at that time so well determined as it is now, and one of Mr. Telford's objects was to ascertain, by direct experiment, the tensile power of the material when applied in the form of a suspended chain.

Nothing came of this proposition at the time, but Mr. Telford treasured up the knowledge he had gained, and a few years afterwards he had the opportunity of bringing it into practical application.

In 1819 he commenced the celebrated bridge over the Menai Straits, which magnificent work would, if he had done nothing else, have itself sufficed to render his name immortal. It was finished and opened in 1826, and its success made the principle popular; suspension bridges of large magnitude having since become very common.

About the year 1830, therefore, there were two great classes of iron bridges in use; the cast-iron arch bridge, heavy and of limited size, but rigid and strong; and the wrought-iron suspension bridge, lighter and much more capable of large expansion, but slender and less steady. Each kind had been brought to a state of great perfection, but the number of bridges built was not great, and the completion of a single large structure of the kind was an event in history.

But now arrived an epoch in civil engineering, which at once enlarged tenfold its sphere of action, and gave the application of iron for bridge purposes an entirely new direction. This was the introduction of railways.

Hitherto, bridges had been applied generally to common roads; if the arch was adopted, inclined approaches were of small importance; and in determining the rise of his arch, the engineer selected any headway he thought proper, while every other consideration was likewise made subsidiary to the problem of constructing the bridge itself. If the suspension bridge was chosen for the purpose, the passing load was light, and its speed of transit could be easily reduced to suit the comparatively unstable nature of the structure.

But on the introduction of railways, hundreds of roads, rivers, and valleys had at once to be spanned with bridges perfectly level, and of a strength and rigidity sufficient to allow the dashing across of the ponderous and swift locomotive, instead of the light coach or the quiet team. Moreover, a series of new conditions arose for these bridges, which complicated the problem still more. Their time of construction was an important element; so was economy of their first cost; while every conceivable difficulty arose from their limited headway, their bad foundations, their oblique directions, their gigantic dimensions, and the necessity of bridging over navigable waters or crowded thoroughfares without interfering with the traffic upon them. The number of bridges required also became something quite unprecedented; Mr. Stephenson estimated that up to 1856 at least twenty-five thousand railway bridges must have been built in the United Kingdom alone.

The simple arch of masonry or brickwork was applied wherever it was practicable, but in many situations it was inapplicable, and the engineer, to whom the use of iron was now becoming every day more familiar, naturally turned to this material to supply the desideratum.

Of the two kinds of iron structures then in vogue, one, the suspension bridge, was, from its want of stability, quite out of the question ; but the other, the iron arch, was favourable in certain situations, where its well understood qualities of rigidity and strength warranted its adoption. Some of the most elegant and efficient railway bridges have been erected on this plan. The London and Birmingham and other early railways have several of this kind, and it is still used in situations where appearance is of importance, as the arch bridge may generally be made a handsomer structure than any other rigid form.

It was found, however, that the cast-iron arch bridge, from its great weight, and the small span of which it was capable within reasonable limits of cost, was but of comparatively limited application to railway requirements: hence it became necessary to discover some other kind of iron structure more generally suitable, and happily this was found by reverting to the earliest form of all, the primitive straight *beam*. This would seem, no doubt, a retrograde step from the elaborate and elegant structures on which so much scientific investigation and mechanical skill had been bestowed; but the retrogression was only apparent, for no sooner had the beam been established as the normal model for railway bridges, than the attention of scientific and practical men was at once called to its development, and under this stimulus it soon outgrew its original simple form and dimensions. Improvements and extensions of the principle were gradually introduced, and the simple beam is now scarcely to be recognised as the parent of the many magnificent structures which, far exceeding the largest arches in dimensions, have become our most prominent monuments of engineering enterprise and skill. Still, however, we cannot fail to be struck with the curious reverse order of progress in the history of iron bridges, when we find that the appliances resulting from ages of improvement have been rejected, to adopt a principle identical with the earliest attempt of the uncivilized savage.

It may be well here to explain the principal points of difference between the three different systems of bridges above referred to, and to show on what grounds one of them alone has proved so specially applicable to railway purposes. When any structure is employed for carrying weight over an open space, the laws of mechanics require that the vertical forces due to the gravity of the load should produce strains or thrusts in other directions more nearly approaching to the horizontal. In an arch, the essence of which is that it should curve downwards on each side from the crown, a compressive strain is produced along the whole line of the curve, which, operating at its extremities, tends to thrust the abutments outwards; and this thrust must be efficiently resisted by massive solidity and strength of the abutments, to keep the bridge in equilibrium.

In a suspension bridge, this effect is reversed. The essence of the structure is that the suspending chain must curve upwards on each side from the centre, and must sustain along its whole length a tensile strain, which tends to draw the ends inwards; and this is usually provided against by securing the ends of the chain firmly into the ground on each side.

Now the beam is a sort of compound of these two principles. It is usually straight, neither turning downwards at the ends like the arch, nor upwards like the suspension chain; but it comprehends within itself the characters of both as regards the strains upon it; for the effect of the load is to divide, in principle, the beam into two longitudinal parts throughout its whole length; the upper part bearing a horizontal strain of compression, like the arch, and the lower a horizontal tensile strain, like the chain; these two strains being, moreover, as an essential condition of the equilibrium, equal and contrary to each other. Hence the strength of a beam is entirely self-contained, and all its horizontal forces are perfectly self-equilibrated; the consequence of which is, that no resisting power whatever is required at the abutments or ends, further than is necessary to support the *vertical* pressure of the beam and its load, a condition capable of the simplest and easiest application. From these principles it will be seen that the advantages of the beam, or girder, as it is also called, for railway bridges consist in five great properties.

1. It supersedes the chain by its firmness and rigidity, being subject only to a slight deflection under its load, which is of no practical disadvantage.

2. Compared with the arch it has the great advantage of straightness, not requiring to be curved downwards at the ends, and so not only making a level road above, but also leaving a uniform height of headway underneath, which is often a vital necessity. It will be seen hereafter that it was this condition that determined the use of a beam for the Britannia Bridge.

3. As the beam requires no preparations in the

abutments for resisting any horizontal or oblique thrust, the construction of these parts of the bridge, particularly as regards their foundations, is rendered very much simpler, more expeditious, and less costly.

4. The ironwork required for a beam is generally very much less in weight than for an arch of the same span and strength.

5. The self-contained strength of the beam, and its capability of being fixed in many cases without scaffolding, much facilitate its erection; not only as saving cost and time, but also in avoiding interference with navigation or traffic below.

The earliest iron beams of which any account is preserved were used by Messrs. Boulton & Watt in building a cotton mill at Manchester in the year 1800; and as soon as confidence became established in the material, and the improvements in the manufacture of iron enabled large castings of this description to be made with tolerable certainty as to quality, and at reasonable price, iron beams soon began to supersede the use of timber for many building purposes, as being much less liable to decay, or to destruction by fire.

In 1822 Tredgold wrote his celebrated 'Practical Essay on the Strength of Cast-Iron,' the principal object of which was to define the theoretical laws that governed the construction of iron beams, and to put them into such a shape as should be useful to the practical mechanic and builder. Two or three years afterwards cast-iron girders of 50 feet span, the largest then constructed, were erected by Mr. Rastrick at the British Museum.

It was natural that the first engineer who had railways of any importance to make, should first find out the applicability of the beam to railway-bridge construction; and accordingly the first bridges of this kind were erected by George Stephenson about the year 1830 on the Manchester and Liverpool Railway.

The girders used for this purpose were made entirely of cast-iron, in fact, were simple cast-iron beams, similar to those before used for other purposes; but as the object they had to serve soon became much more important, and the spans required much larger, more attention was called to the principles of their construction both from a theoretical and practical point of view.

The theoretical part was taken up by Mr. Eaton Hodgkinson soon after the erection of the first girder-bridges, and he corrected some errors that had been entertained as to beams of cast-iron, and established greatly improved rules for their proportions, by which their strength was much increased and their cost greatly reduced.

In a practical point of view the attention of engineers was soon drawn to the uncertainty and weakness of cast-iron, when exposed to a tensile strain in the lower flange of the girder. The proper function of cast-iron had been developed in the arch, namely, to withstand compression; for a strain in the contrary direction it was peculiarly unfitted, not only by its want of cohesive strength, but still more from the almost inevitable existence, in all large castings, of hidden flaws and defects. Little benefit was obtained by increase of thickness, for the treacherous character of the material increased rapidly with the mass in which it was cast; and the difficulty of uniting cast-iron rendered impracticable the attempt to build up such girders of separate castings, so that the new girder-bridges were limited in their dimensions to very moderate spans.

In order to meet this difficulty the girders were in some cases made double, so as to diminish the dangerous influence of possible unsoundness; but still an obvious necessity arose for some new combinations of the material which should meet the desired end with greater aptitude.

The first important contrivance springing out of the necessities of railway bridges was a modification of the cast-iron arch. The chief obstacle to the use of the ordinary arch was the practical difficulty of meeting the thrust at the abutments, and of obtaining the requisite stability in the foundations; a difficulty much enhanced by the diminution of rise or versed sine which the use of iron allowed, giving a consequent augmentation of the thrust, and a more unmanageable direction of its action. To meet this difficulty, in cases where headway was not of importance, the device was hit upon of connecting the two ends of the arch together by a wrought-iron tie rod, which, by taking upon itself a horizontal tension, deprived the ends of the arch of the tendency to thrust outwards, and so relieved the abutments of all except vertical pressure. The structure thus became essentially a girder, as it contained within itself the perfect equilibration of all its horizontal strains; and as the form resembled that of a bow, having the tie rod for a string, it was called the Bowstring Girder.

Another advantage followed from this construction. It was soon found that by suspending the tie rod strongly from the arch, it might be made to carry the rails at a lower level; the depth of the girder being thus above the roadway instead of below it; by which the attainment of one of the greatest and most troublesome requirements of railway bridges, namely headway underneath, was greatly facilitated.

The earliest railway bridge on this plan was designed by Mr. Robert Stephenson in 1834, and erected in 1835 or 1836, to carry the London and Birmingham Railway over the Grand Junction Canal near Weedon. This kind of structure has since been much used, and the finest example of it is the High Level Bridge at Newcastle-on-Tyne, of which a more complete account will be given hereafter.

But this construction was expensive and cumbrous; and attention became again turned towards the improvement of the simple cast-iron girder. The most prominent defect of this consisted, as already stated, in the weakness of the lower flange; and the most natural attempt to remedy the evil was by strengthening it with wrought-iron rods, so arranged as to take the tension upon themselves, and thus relieve the more defective cast metal from the tensile strain which it was so little able to bear. The wrought-iron rods were attached by screws at each extremity of the girder to its upper flange, and at the centre were brought down below the bottom flanges, being then tightened up by the screws to such a degree of tension as might be thought desirable. The girder was thus a compound one, of cast and wrought-iron together, and from the peculiar trussing up of the wrought-iron rods it was called the Trussed Girder. Such a beam, if made with due attention to the strains, was evidently less liable to accident than the simple casting, and was capable of application to much larger spans.

The first trussed compound girder, of 60 feet span, was erected about 1839 by Mr. Bidder, in conjunction with Mr. Stephenson, for carrying the Cambridge branch of the Great Eastern Railway (then called the Northern and Eastern) over the River Lea near Tottenham; others followed on the same and other lines, one of the best known being that over the Minories, on the Blackwall Railway. The plan was beginning to be somewhat extensively adopted in railway practice when an occurrence took place which at once checked its use, and which, from Mr. Stephenson's connection with it, must be noticed at some length. This was the memorable and fatal accident that occurred through the failure of the bridge at Chester, in May 1847.

The Chester and Holyhead Railway crosses the River Dee immediately after leaving Chester, and from the Chester station to a little beyond the crossing the line is also used, under an agreement, by the Chester and Shrewsbury Company, who, after running over this portion of railway, diverge to the westward by a line of their own.

The Dee Bridge, forming part of the works of the Holyhead line, was designed by Mr. Robert Stephenson, their engineer. The width of the river at this point is about 250 feet, and the railway is elevated nearly 40 feet above low water. The bridge was originally intended to consist of five brick arches, for which the piling was actually commenced; but apprehensions as to the foundations caused the engineer to change his design, and to substitute a bridge of iron girders, altering the number of openings from five to three, and increasing their spans accordingly. The bridge was considerably askew, forming an angle of 51° with the river, or 39° with the perpendicular crossing line; and the length of the girders was 98 feet clear span. There were four main girders to each span, twelve in all.

The girders were on the principle above described, i. e. cast-iron trussed with wrought-iron tension bars. Each was made in three lengths, bolted together, and was 3 feet 9 inches deep, or about one-twenty-sixth of the span, having flanges at the top and bottom. The trussing or tension rods, placed on each side, formed a chain of three long links; the middle link horizontal, and placed about the level of the bottom of the cast-iron girder; the two outside links rising up obliquely towards their ends, which stood at a height of about four feet above the top of the girder, and were bolted to large shoulders or bosses, projecting upwards above its top edge. The lower parts of these chains were caused, by means of screws, to press upwards against the cast-iron girders, and so to afford it support by suspension, the links forming essentially suspension chains.

The girders were probably designed in 1845 or early in 1846. In September of the latter year one line of the bridge was passable; on October 20 it was examined and approved by the Government inspector, and immediately afterwards it was opened for traffic, not by the Holyhead Company, to whom it belonged, but by the Shrewsbury Company, who were the first ready to use the bridge for public traffic. The Holyhead line was not opened till some time after the accident. From the time of the opening, the bridge was constantly used, not only for Shrewsbury passengers, but also for heavy trains of materials for both lines; but up to the day of the accident, May 24, 1847, nothing occurred to attract attention. It happened that about this time one of the Great Western bridges had been burnt down by cinders from an engine, and alarmed by this disaster, the authorities of the Chester Railway had laid down on the Dee Bridge about 18 tons of broken stone as a protection to its wooden platform. This was done on the afternoon of the day in question, and the first train that traversed the bridge afterwards was the fatal one. Leaving Chester, the engine passed safely over the first and centre openings, but when it arrived about the middle of the third opening, the left-hand or southern girder broke into three pieces, and the carriages fell into the river, at 36 feet below. Five people were killed, and all in the train more or less injured, except the driver; the engine, which ran on beyond the fracture, being the only vehicle that remained on the line.

This accident made naturally a great sensation, not only from the gravity of the casualty, but from the importance of the consequences to railway engineering. It was felt that the bridge was upon its trial, and as it was soon found that nothing was defective in the *manufacture* of the ironwork or the quality of the material, the investigation became directed to the *principle* of the girder, and to the question whether the strength of beams of this description could be depended on.

The enquiry before the coroner was a very lengthened one. A great deal of engineering evidence was brought forward; two referees, Mr. James Walker, civil engineer, and Captain Simmons, R.E., being also appointed by the Government to investigate the matter.

Mr. Stephenson was naturally looked to for his opinion, which he gave in a report addressed to the Railway Directors, and subsequently enlarged upon in oral evidence before the coroner. He stated that a few hours before the accident, on his way to Bangor, he had narrowly inspected every part of the bridge, and saw nothing to indicate weakness or imperfection. He confidently concluded that every part was firm and sufficient, a conclusion in which he conceived he was justified by the fact of the Chester and Shrewsbury traffic having been uninterruptedly carried on from October to May. He had examined carefully the appearances after the accident, and could arrive at no other conclusion than that the fracture of the girder arose, not from inability to support the weight, but from a violent blow given by the tender, which he conceived to have got off the rails, probably from the fracture of one of the wheels, while passing the bridge. Mr. Stephenson had full confidence in the proper strength of the bridge, in which he was confirmed by an extensive experience in the combination and use of similar structures, tried under circumstances that demonstrated their capabilities to meet all the ordinary contingencies of railway traffic. An objection had been made that the wrought-iron tension rods did not act well in concert with the rigid cast-iron girder; but he had well considered this, and had had experiments made which had satisfied him there was no force in the objection. If the tension rods were properly screwed up, they would bear the whole strain from the weight passing over the bridge, and would thus take the place of the cast-iron girder, and that was what he sought most to rely upon. He did not maintain that the two principles could be brought into strict union at one and the same time, but he urged that they might mutually aid each other. Mr. Stephenson added that he had erected, in twenty years, more iron bridges than any other member of the profession, being more partial to them, and this was the first failure he had had, large or small.

Mr. Locke and Mr. Vignoles supported the opinion of Mr. Stephenson that the fracture arose by a blow, and that the girder was sufficiently strong. Mr. Locke did not, however, like iron bridges, preferring those of brick or stone.

Mr. Robertson, the engineer of the Chester and Shrewsbury line, reported to his Directors his conclusion that the girder broke in the middle from its weakness to resist the strain, increased by the laying on of the extra ballast immediately before.

The referees appointed by Government made their report on June 15, 1847. After stating the facts and describing the bridge, they considered the strain of the girder and the action of its parts, the effect of temperature, of oscillation, &c., and summed up their opinion, that though the bridge was of sufficient strength if the cast and wrought-iron were supposed to act together, each taking its equal proportion of the strain, yet neither, separately, was sufficient for perfect stability; and that there was great difficulty in ensuring the joint action. They did not agree in Mr. Stephenson's view that the fracture was caused by a blow.

This report was communicated to the coroner's jury the last day of their sitting, and seems to have guided them in their decision. They gave a verdict, through Mr. E. Walker, their foreman, of accidental death; adding, however, that they were of opinion the girder broke from being made of a strength insufficient to bear the pressure of quick trains passing over it; that they considered the remainder of the bridge unsafe; and that for the security of the public, they recommended a Government enquiry as to the safety of such bridges in general.

The propriety of this verdict was questioned at the time, but it must be recollected that at that period the nature of the strains in compound girders was very little understood, and therefore we may be quite prepared to admit that the girder may have been imperfect in design without in the least disparaging Mr. Stephenson's credit as an engineer.

Indeed, we cannot offer a better description of the defects of this kind of girder than is given by Mr. Stephenson himself in his Essay of 1859. He says:—

> The determination of the strength of such girders is a difficult task. They are, in fact, compound girders, formed by combining the truss with the simple girder, the upper flange doing duty as a compression bar in both systems, and being thus subjected to two independent strains. It is evident, therefore, that if the upper flange is simply proportioned to its duty, as the top flange of the simple girder, it will be of insufficient strength for its additional duties as part of the truss. It has been argued that from the perfect union of the top flange with the vertical rib, a considerable portion of the whole girder might be taken as forming part of the truss. It is, however, evidently impossible by calculation to say how far such assistance may be relied on; and a still greater objection exists in the fact that such girders consist of two systems, the ultimate deflections of which are utterly different; the girder, for instance, may be broken before the truss attains half its ultimate deflection or has done half its duty. The objection to this girder is common to all girders in which two independent systems are attempted to be blended; and, as a general principle, all such arrangements should be avoided.

It is useless (adds Mr. Stephenson) to say more on the subject of this form of girder, as since the adoption of wrought-iron for girders they have been entirely superseded; they were designed when no other means existed of obtaining iron girders of great span, and the melancholy accident which occurred at Chester is the only existing instance of their failure.

Mr. Stephenson, in his evidence before the Iron Railway Structure Commission,* further explained the objection to the design of these girders, which, in the more advanced state of our present knowledge, is clearly perceived to be the want of a due provision for withstanding the inward thrust of the ends of the wrought-iron ties. The bolts to which the tie bars (which acted, in fact, as suspension chains) were attached, were elevated some four feet above the general level of the top of the cast-iron girder, and no direct solid member for resisting the compressive strain existed between them. The cast-iron girder itself, being of such a small depth in proportion to the length, was very weak, and, as Mr. Stephenson stated, the principal reliance was on the wrought-iron bars; but when the heavy strain came upon these, tending, as in a suspension bridge, to draw their ends inwards, nothing existed sufficiently strong to keep them apart, and consequently acting with a strong leverage and in a most trying manner upon the top flange of the girder, they compressed it beyond its strength, and broke it through. That this was the true explanation of the failure is now clear from the form of the two fractures, which (although this does not seem to have been noticed at the time) are identically of the description peculiar to the case where the

* Questions 832, 881, 894.

upper flange of a beam is broken by a compressive strain beyond its resisting power.*

Mr. Stephenson on discovering this defect at once took measures to provide against it in other girders on this plan, by adding properly shaped compression pieces of cast-iron to the top of every girder, so as to fill in, solidly and strongly, the space formerly open between the ends of the ties; and the bridges thus strengthened have never shown any signs of failure.

The Dee Bridge was altered by having inclined struts, bearing against the masonry, placed under each girder, so as to afford support in the middle; and other bridges, made about the same time, were strengthened in like manner.

The last large girders on this principle were some of 96 feet span, made under Mr. Stephenson's directions, in 1847, for the Florence and Leghorn Railway, crossing the Arno, and in these the proper improvements were introduced in the original design.

The matter, however, did not stop here. The Government Commissioners of Railways, on receiving the report of the two engineers to whom they referred the investigation of the accident, became alarmed about the iron bridges used on railways generally. On June 23, 1847, they addressed a circular to the secretaries of the different companies, requesting a return to be made of the iron bridges on all lines then working or constructing, giving their dimensions and particulars of their construc-

* Compare the sketches in the Report of the Commissioners of Railways, 1848, p. 110, with that in Hodgkinson's edition of 'Tredgold on Cast Iron,' 1846, p. 429.

tion; and expressing a hope that wherever the security of such structures was at all doubtful, the companies would take measures to add to their stability, and in the meantime would direct the speed of the trains to be reduced in passing. A few days afterwards they published a minute, to the effect that they repudiated all responsibility for the strength of iron structures which had been inspected and passed by their officers, inasmuch as these gentlemen had only the opportunity of a superficial observation, and no sufficient control over the design.

Another matter of public interest followed. The Railway Commissioners, acting on the suggestion of the coroner's jury, passed a minute calling the attention of the Government to the uncertainty which existed respecting the conditions to be complied with in employing iron in engineering works, and in particular to bridges which had to be traversed by loads of extraordinary weight with great velocity. They had reason to believe, they said, that much difference of opinion existed among the most eminent engineers of the time as to the proper form and dimensions to be given to railway girders of iron for bridge purposes; and they considered it desirable that the subject should be thoroughly investigated by a Commission, to be composed of scientific men and practical engineers, who should be appointed by Government, and should be requested to arrive at such principles, and to form such rules, as might enable the engineer and the mechanic to apply the metal with confidence in their respective spheres.

The Commission was appointed by Royal Warrant on August 27, 1847, and consisted of Lord Wrottesley, Professor Willis, Captain James, R.E., Mr. George Rennie, Mr. (afterwards Sir) William Cubitt, and Mr. Eaton Hodgkinson, with Captain Douglas Galton, R. E., for secretary. They spent nearly a year in examining witnesses, making theoretical investigations, trying experiments, and collecting a great mass of information on the subject, which was afterwards published in a Blue Book of 435 pages, accompanied by a large collection of lithographed plans.

Mr. Stephenson was one of the principal witnesses. He gave much information as to the nature and properties of iron—the construction of girder-bridges, particularly those of the kind used over the Dee—the effect on them of passing trains, &c. &c.; but he strongly impressed upon the Commissioners that any attempt to introduce restrictive legislative enactments in regard to the use of iron in railway structures would be highly inexpedient, and would act prejudicially on professional enterprise and skill. 'My opinion,' said he, 'is rather strong that a collection of *facts* of all kinds is highly desirable, in reference to the shape of girders; but I am convinced that the Commissioners will have infinite difficulty in laying down anything like rules. I cannot conceive myself being tied down in executing such a line, for instance, as the Holyhead, or the London and Birmingham. I cannot conceive myself going on successfully, and being tied down by preconceived rules, or limitations as to the extent to which cast-iron should be used, and the forms that it should be used in. I think a collection of facts and observations would be most valuable; but if you attempt to draw conclusions from those facts, and confine engineers, even in a limited way, to those conclusions, I am quite sure that it will tend to hamper the profession very much.'

In addition to his oral evidence, Mr. Stephenson furnished a valuable statement of the experiments on iron undertaken at his direction for the High Level Bridge at Newcastle; and also brought up before the Commission two of his chief assistants, namely, Mr. Edwin Clark, who gave a full account of the Britannia and Conway Bridges; and Mr. Charles Heard Wild, who described other large girders made under Mr. Stephenson's direction. Mr. Fairbairn and Mr. Hodgkinson also gave full accounts of the comprehensive experiments conducted for the great tubular bridges, so that Mr. Stephenson's opinions and works may be fairly said to have formed the largest and most important part of the information collected by the Commissioners.

Many other witnesses were examined, skilled in the engineering of ironwork, among whom were Mr. Brunel, Mr. (now Sir) Charles Fox, Mr. Locke, Mr. Rastrick, and Mr. Charles May; and much information was also collected in the form of written statements. Professor Willis, aided by Professor Stokes of Cambridge, contributed an elaborate theoretical paper on the deflection of beams under moving loads; and a comprehensive series of experiments was tried by the Commission on various points coming within the scope of their enquiry.

The Report of the Commissioners was presented to Her Majesty at the end of July 1848. They considered that bridges should be made somewhat stronger to meet the additional strains from moving loads; and they recommended that the greatest load should in no case exceed one-sixth of the stationary weight which would break the beam when laid on the centre. They also pointed out that weight is an advantage in enabling a structure to resist concussions. As to designs of iron railway bridges, they merely stated the facts and opinions laid before them by engineers. They testified to the careful and scientific manner in which the forms and proportions of the great tubes of the Conway and Britannia Bridges had been elaborated. They thought that wrought-iron plate girders generally appeared to possess and to promise many advantages. They found engineers to be for the most part favourably disposed towards them; but as no experience had yet been acquired of their powers to resist the various actions of sudden changes of temperature, vibrations, and other causes of deterioration, they were unable to express any opinion upon them. With regard to trussed cast-iron bridges, like that of the Dee, they found that difficulties arose from the different expansions and elongations of the two metals, and considered that the greatest skill and caution were necessary to ensure the safe employment of such combinations. They also stated that there existed a great want of uniformity in practice in many most important matters relating to railway engineering, which showed how imperfect and deficient it yet was in its leading principles (a reproach which unfortunately is almost as applicable in 1864 as it was in 1848); but considering that the attention of engineers had been sufficiently awakened to the necessity of providing a superabundant strength in railway structures, and also considering the great importance of leaving the genius of scientific men unfettered for the development of a subject so novel and so rapidly progressive as the construction of railways, they concurred in Mr. Stephenson's opinion that any legislative enactments with respect to the forms and proportions of the iron structures employed therein would be highly inexpedient.

After the completion of the London and Birmingham Railway, notwithstanding the progress of iron roads in all directions, no important step seems to have been made in the improvement of iron bridges, until the epoch of the Britannia Bridge, the erection of which initiated a complete revolution in this branch of engineering science. As an account of this great structure will be given hereafter, it is only necessary to notice here the effect which it had upon bridge construction in general.

About 1845, when the experimental investigations commenced, the only forms of iron bridges used for railway purposes were the cast-iron arch, the simple cast-iron girder, the trussed compound girder, and the bowstring girder. In all these cast-iron had been the principal element, very little attention having been paid to wrought-iron as a material for girders, although its use had become common and was well understood for suspension chains.

Wrought-iron had indeed been used by Smeaton, in conjunction with wood, to form beams, by bolting an iron plate between two half balks of timber. The plate, being set vertically, contributed important strength to carry the load, while the wood furnished the necessary lateral stiffness. This kind of beam was, from its peculiar construction, called the 'flitch' or 'sandwich' girder, and it was used subsequently—in about 1839 or 40—in forming beams of thirty or forty feet span on the Cambridge branch of the Eastern Counties Railway. Wrought-iron beams, of analogous shape to those of cast-iron, had also been constructed for iron ships, and other purposes, and Mr. Stephenson had himself used them, about 1841, in a small bridge on the above-mentioned Cambridge line; but these were probably the only instances in existence of the use of wrought-iron in railway bridges. Very little was known as to the proper application of the material. The principles of its strength when applied to girders were quite undetermined; no such thing as a *constructed* beam of any scientific pretensions or any large span had been imagined; and even the process of connecting wrought-iron plates together by riveting was scarcely known beyond the boiler and iron shipping trade.

The experimental investigations, however, which were conducted for the Britannia and Conway Bridges threw quite a new light on the subject. From the time of the abandonment of the large arch which Mr. Stephenson at first proposed, it had become evident that cast-iron could not be applied, and that wrought-iron was the only material from which any real success could be expected; and it was therefore to the investigation of the properties of this material, and the best manner of using it, that the experimental enquiries were directed. They had the effect of thoroughly developing the powers of wrought-iron, of making known its peculiar properties, of rendering its use perfectly amenable to theoretical calculation, and of proving in the most conclusive manner its special applicability to girders for bridges of any magnitude. And they further showed the practicability of building up or constructing, in that material, girders of almost any strength and size, by only exercising a skilful and careful attention to the details of the design, based on a correct scientific knowledge of the nature and distribution of the mechanical forces acting throughout the structure. And it is worthy of remark how thorough and how perfect these investigations were; for although nothing was known of wrought-iron girders before they were undertaken, and although since their date wrought-iron girders have come into very general use under the greatest variety of forms, and in preference to all other systems of iron-bridge construction, yet nothing essentially new or important has been added to our knowledge of the principles of their construction beyond what was developed in these investigations, the records of which comprise indeed almost the whole useful information, theoretical or practical, we possess on the subject.

To this date, then, may be referred the first use of *wrought-iron girders* for bridge construction—the greatest step made in iron bridges since their original introduction; as giving them not only the capability of application to larger spans, but making them cheaper, more secure, lighter, more convenient of erection, and clearer in the headway; advantages almost incalculable for railway purposes.

The experiments were commenced in the middle of 1845, and early in the next year so much progress had been made as to lead to the proposition of hollow plate iron girders for railway bridges of considerable span. In July 1846 Mr. Stephenson gave instructions for a bridge on this principle, but with a cast-iron top, for a road at Chalk Farm, crossing over the North Western Railway. This bridge was sixty feet span; it was completed in March 1847, and was the first actual application of hollow wrought-iron girders to the construction of bridges.

Meantime Mr. Fairbairn, who had previously made drawings for a bridge of this kind, foreseeing that the use of hollow plate girders would be considerably extended, proposed to Mr. Stephenson to take out a patent for their application. To this Mr. Stephenson consented; but being averse to his own name appearing in the patent, he refused to accept any share of the profit, though he consented to pay half the expenses of obtaining the patent.* It was taken out October 8, 1846.

Mr. Fairbairn soon began to put the plan into operation, and in July 1847 completed bridges on this principle at Blackburn and Bolton in Lancashire, which answered well. The further progress of the designs for the large Britannia and Conway tubes, and their ultimate success, gave to the engineering world more complete confidence in the use of wrought-iron for bridge girders, and a few years more made its application universal.

It would be foreign to the object of this work to follow out in detail the wide and rapid progress of the art of iron bridge building after the epoch we have been considering; it will suffice to give a general view of the state it has now attained, and to describe briefly some of the numerous varieties which have sprung up in the construction.

Iron bridges may now be divided into three great

* Clark's Britannia Bridge, p. 812.

classes — namely, Iron Arch bridges, Suspension bridges, and Iron Girder bridges.

The first two of these have already been sufficiently described, and we may therefore confine our attention to the third or Girder class, which is a very large one, and may be subdivided into several species somewhat as follows:—

1. Solid beams.
2. Trussed cast-iron girders.
3. Bowstring girders.
4. Simple I-shaped girders.
5. Tubular or hollow plate girders.
6. Triangular framed girders.
7. Lattice girders.
8. Rigid suspension girders.

A beam or girder is distinguished from other means of bridging space by containing within itself the double horizontal strains, the top part of the beam being under compression and the lower part under tension. Hence every beam may be considered as consisting of three distinct parts, each of which has its own special office to perform; first the *top member*, which has to resist crushing; secondly, the *bottom member*, which has to resist being torn asunder; and thirdly, the *vertical part*, which has to connect these two together, and to combine the beam into one structural whole.

In the Solid Beam no distinction is made between the functions of the three parts, the top and bottom merging insensibly into the vertical connecting part. This kind of beam is represented by a stone lintel or a wooden floor joist, the form being never used in iron, on account of its wasteful distribution of material.

The Trussed Cast-iron Girder, which has already been sufficiently described, is no longer in use.

Of the Bowstring Girder, with the bow in cast-iron, we have also given an account; but we may add here, that as soon as wrought-iron came into use, large bowstring bridges were made entirely of this material. Among these may be instanced one of 200 feet span, built by Mr. Brunel in 1849, to carry a branch of the Great Western Railway over the Thames near Windsor; and two by Messrs. Fox and Henderson, carrying the North London Railway over the Commercial Road and the Regent's Canal at Stepney, about 165 feet span, built in 1848.

The I-shaped Girder was one of the earliest used in cast-iron. In it, economy of construction is aimed at by accumulating metal in the shape of flanges at the top and bottom, and connecting them by a vertical rib in the middle of their width, so as to give the whole section the shape of the letter I. This form was also early imitated in wrought-iron beams, and is still one of the simplest and best that can be used when the span is small.

As soon, however, as very moderate limits are exceeded, difficulties arise of a practical nature, in consequence of the distortion of form to which the simple I-shaped girder would be liable, if of great length and supported only on two distant and limited bearing surfaces, more especially as expansion and contraction prevent any rigid attachment even on these.

The Tubular or hollow construction of Wrought-iron Plate Girder was a step in advance to meet this difficulty. It differs from the I-shaped Girder only in that the top and bottom members are connected by two vertical plate ribs, one on each side, instead of a single one in the middle, so that the whole forms a sort of hollow tube, which is a stiffer and otherwise superior construction for large spans. Indeed, this plan may be carried to so large a size that, as in the Britannia and Conway Bridges, the engine and train may pass along inside the tube.

In the Triangular-framed Girder, the vertical rib, connecting the top and bottom members, instead of being composed of plates, is formed of a series of frames of a triangular shape, fastened to the top and bottom with large bolts. This form was first tried about 1850, at the London Bridge Station of the South Eastern Railway, and has since been a great deal adopted, with much success.

The largest bridge on this plan is one of 240 feet span, erected in 1852 on the Great Northern Railway over a branch of the Trent near Newark. A structure also very remarkable is a viaduct at Crumlin in Monmouthshire, erected in 1857. It consists of a series of seven triangular-framed girders, each 150 feet span, crossing a wide valley at an altitude of 200 feet, and supported by piers of framed ironwork, of great lightness of construction. The singular appearance of this structure can scarcely be imagined without seeing it, and it is certainly one of the engineering curiosities of Great Britain.

In the Lattice Girder, the vertical plates are replaced by a number of bars crossing each other so as to form a lattice-work, the strength of these bars being proportioned, by known rules, according to their places in the girder. The lattice principle was early used to a great extent for timber bridges, particularly in America. One of the largest, as also one of the earliest structures on this principle in iron, was the bridge or viaduct erected in 1855 on the line of the Dublin and Belfast Railway over the river Boyne near Drogheda. It consists of three spans, the centre 264 feet, and the sides 139 feet each, the height above high water being 90 feet.

The Rigid Suspension Girder is placed in a separate class on account of its use by Mr. Brunel in two magnificent iron bridges of gigantic dimensions and economic construction over the Wye at Chepstow, and the Tamar at Saltash. The former, completed in 1853, has a single span of 300 feet, at a height of 46 feet above high water. The girder is, in fact, a rigid suspension bridge, the tension of the chains being resisted, not in the usual way, by anchorage in the ground at each end, but by a huge cylindrical wrought-iron strut or column, stretching across from side to side, at a height of 50 feet at the centre, above the roadway. The whole is well braced together, and it thus forms a colossal trussed girder.

The Saltash Bridge, with the viaduct which forms its approach, carries the Cornwall Railway over the estuary and valley of the Tamar near Plymouth. The whole structure comprises nineteen openings, and is 2,240 feet long; but the bridge itself, crossing the river, consists of two spans of 450 feet each, at a height of 100 feet above the water. The main girders, or trusses, are in principle analogous to those at Chepstow; but here the compression tubes, which resist the pull of the suspension chains, are curved instead of being straight, the rise of the tube being equal to the drop of the chains. The tube thus partakes of the nature of an arch, and in fact the whole girder is a kind of intermediate between the Chepstow truss and the old bowstring girder.

The centre pier was a work of considerable difficulty on account of the great depth of water. The substructure is a solid cylindrical pillar of granite, 35 feet in diameter, resting on a rock foundation 86 feet below high-water mark. It was built in a coffer dam or cylinder of plate iron sunk through the bed of the river till it rested on the rock below, and then emptied and kept clear of water partly by pumping and partly by compressed air, to allow of the construction of the granite column inside.

The bridge was commenced in 1853, and was opened in May 1859 by H.R.H. the late Prince Consort, by whose permission it was called the Royal Albert Bridge.

Subsequently to the erection of the great works in North Wales, Mr. Stephenson designed three other iron bridges of considerable magnitude. The first was over the Aire, on the York and North Midland Railway, erected in 1850. The span was 225 feet, and Mr. Stephenson adopted the tubular girder, similar to the Welsh bridges, the trains passing inside the tube; but in this bridge, the span being so much smaller, the cells were dispensed with, and the top and the bottom were formed of simple plates. The tubes were originally constructed of a tapering section, narrower at the top than the bottom, but after they were erected and the bridge was opened, the narrowness at the upper part was objected to by the Government Inspector, and the top plate had to be cut through longitudinally and widened *in situ* by the insertion of a strip of iron all along; a delicate and unprecedented operation, but which, under great care, was perfectly successful.

In 1855 Mr. Stephenson erected a large wrought-iron bridge on the Egyptian Railway over the Damietta branch of the Nile near Benha. It consists of ten spans or openings, each of 80 feet, except the two centre ones, which are 60 feet each, and are made to open, forming what is called a swing bridge, one of the largest hitherto attempted. The girders for this bridge were also tubular, but from their small size the roadway is carried upon the top of the tubes, and not in their interior. The total length of the swing beam is 157 feet; it is balanced at the middle of its length on a large central pier, so that when open to the navigation, a clear waterway of 60 feet is left on either side. Each half of the beam sustains its own weight as a cantilever 66 feet long.

The piers consist of wrought-iron cylinders, 7 feet in diameter below the level of low Nile, and 5 feet diameter above that level. They were sunk by the pneumatic process to a depth of 33 feet below the bed of the river, through soil of a peculiarly shifting character, and were filled in with concrete. There are six of these cylinders in the central pier which supports the swing bridge, and the adjacent piers on either side of the centre have each four cylinders. Each of the remaining piers has two cylinders only. This plan of obtaining the foundation of piers by sinking large iron cylinders has been a most important modern advance in bridge-building. One of the latest examples is in the bridge carrying the Charing Cross Railway across the Thames.

The beams or tubes are 6 feet 6 inches deep, and 6 feet 6 inches wide at the bottom, tapering to 6 feet wide at the top. They rest at their ends on rollers working between planed surfaces, to admit of the motion caused by expansion and contraction. The tubes carry a single line of railway on their tops, the rails being laid on longitudinal sleepers; and there is also a roadway four feet wide on either side, supported by wrought-iron brackets bolted to the sides of the tube.

The revolving machinery for the swing part of the bridge consists of a turntable 19 feet diameter, running upon eighteen conical rollers, connected by what is called a 'live ring.' The whole of this machinery is most carefully fitted and susceptible of the most accurate adjustment. The bridge is turned by a capstan connected by gearing with the moving parts, and which can be worked with facility by two men.

In 1853 Mr. Stephenson took up the subject of the Great Victoria Bridge over the St. Lawrence in Canada, a work of immense magnitude, of which a separate notice is given in a subsequent chapter.

The last work of his life had to do with one of the earliest iron bridges ever erected, and one in which he had always taken particular interest. This was the strengthening, and indeed almost the entire reconstruction, of the celebrated bridge over the Wear at Sunderland, which has been already noticed in the early part of this chapter.

At the request of the authorities of the town Mr. Stephenson had several times examined this bridge, and expressed his conviction that its stability was extremely precarious; and as they concurred in this opinion,

Diagrams of several large Iron Bridges,
all drawn to the same scale.

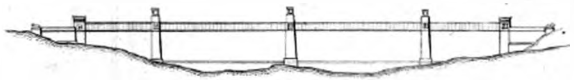
BENHA BRIDGE, EGYPT.
1855.

SUNDERLAND BRIDGE.
1790.

HIGH LEVEL BRIDGE, NEWCASTLE ON TYNE
1849

SOUTHWARK BRIDGE.
1819.

BRITANNIA BRIDGE.
1850.



VICTORIA BRIDGE, CANADA.
1860.

SCALE

London. Longman & Co.

H. Adlard sc.

he was in the year 1857 requested to undertake its repair. He was then in failing health, and reluctant to burden himself with further work, and he accordingly entrusted the details of the operation to one of his earliest friends and assistants, Mr. G. H. Phipps, by whom it was carried to completion; Mr. Stephenson, however, giving his advice and opinion, and occasionally visiting the bridge during the progress of the works. The work consisted of the introduction of three new tubular arched ribs of wrought-iron between the original cast-iron ribs of the bridge; the latter being firmly bolted to the new girders, and thus being relieved of the chief part of their load.

The width of the bridge between the hand-railings was also increased from 32 feet to 41 feet 1½ inch, and the road over the bridge and on the approaches was much improved, its inclination, or gradient, being lessened from 1 in 17 to 1 in 50.

One of the chief difficulties was the construction of a timber scaffolding, supported by pile work from the bed of the river, which should be sufficiently substantial to carry the weight of the arches, and should at the same time allow of the passage, with their masts standing, of the large amount of shipping frequenting the port; this scaffolding also formed a temporary bridge, both for carriage and foot traffic, during the progress of the alterations.

The work was let by contract, towards the end of 1857, to Mr. B. C. Lawton, by whom it was satisfactorily completed, and the bridge was re-opened for traffic in the summer of 1859, a few months prior to Mr. Stephenson's death.

The accompanying plate contains diagrams of several large iron bridges all drawn to the same scale, from which a comparison of their respective magnitudes can be made. The two small figures are the Sunderland Bridge and the Southwark Bridge; the others represent the four principal bridges erected by Mr. Stephenson, namely the Benha Bridge, the High Level Bridge, the Britannia Bridge, and the Great Victoria Bridge in Canada.

W. P.

CHAPTER III.

THE BRITANNIA BRIDGE.*

The Port of Holyhead — The Holyhead Trunk Road — Interruption by the Menai Strait — Attempts to establish a Passage — Telford's Suspension Bridge — Introduction of Railways — Chester and Holyhead Railway — Proposal to use Telford's Bridge for Railway Purposes — Mr. Stephenson designs an Independent Bridge — The Britannia Rock — Proposal for a Bridge of two Arches — Opposition in Parliament — First Idea of the Tubular Construction — Its Novelty — Preliminary Experiments: Mr. Fairbairn and Mr. Hodgkinson — Important Principles derived from the Experiments — Mr. Stephenson's Report — Commencement of the Masonry — Further experimental Inquiries — Means of placing the Tubes in their Positions — Contracts for the Tubes — Their Manufacture — Floating and Raising — Description of the Bridge — Principle of Continuity — Tubes — Mr. Stephenson's Explanations of Peculiarities in their Construction — Towers and Abutments — Architectural Design — Cost — The Conway Bridge.

THIS celebrated structure has for its object to carry the line of the Chester and Holyhead Railway, the main artery of communication between the English and Irish capitals, across the Straits of Menai, which separate the island of Anglesea from the mainland of North Wales.†

* This chapter is contributed by Professor Pole.

† After the completion of the bridge, a full account of it was published by Mr. Edwin Clark, the resident engineer, with the sanction and under the supervision of Mr. Stephenson himself, the object being 'to preserve the history of a conception as remarkable for its originality as for the bold and gigantic character of its application.' Mr. Stephenson gave, in his own words, an account of the early history of the design, and he paid the author of these chapters the compliment of

The port of Holyhead, lying at the western extremity of the island, and forming the nearest point of land to Kingstown Harbour, has always been considered the most eligible place of departure for the passage across the Irish Channel, when certainty and speed of transit have been concerned. Liverpool has, it is true, carried on hitherto, and will doubtless continue to carry on, a large trade with the Irish capital by direct steamers, but it appears certain that in this case, as in the traffic with the Continent, that route must always be considered of the most importance which involves the least exposure to the perils and comparatively slow navigation of the sea.

Long before railways were thought of, the great Holyhead Trunk Road had made the fame of the engineer who constructed it, Thomas Telford; and this work presented, in one or two points of its course, difficulties so analogous to some of those which were vanquished in the Britannia Bridge, that they may be treated as common to the works of both engineers.

The island of Anglesea is separated from the mainland of Carnarvonshire by a narrow Strait, deeply sunk below the general level of the land, and with rocky and precipitous banks on either side. The length of the Strait is about $11\frac{1}{2}$ miles, its width of water-way varies from about 1,000 feet to three-quarters of a mile, and the average height of the shores on each side is above 100 feet.

For a long time the land traffic to Holyhead had been

requesting him to contribute the theoretical illustrations of the principles of the structure. The work was magnificently got up, partly at Mr. Stephenson's own expense, and has now taken an acknowledged position as one of the best standard engineering works of the present age.

In the present notice, the data given in that work are adhered to as closely as possible.

made to descend the bank, cross by a ferry, and ascend again on the other side; but the inconvenience, loss of time, and often positive danger of this passage, prompted at a very early period efforts to establish a permanent roadway across the ravine. Bridges of timber or stone, embankments with drawbridges for the passage of vessels, and tunnels, had all been suggested; and as early as 1785 a petition was presented to Parliament for the means of carrying into effect one of these schemes; but the measure had not at that time assumed such an importance as to warrant the necessary large expenditure. When, however, Ireland was united to Great Britain, in 1801, the intercourse between the two kingdoms rapidly increased; the inconvenience and danger to travellers were naturally and justly complained of; and the attention of Government became seriously directed to the provision of a remedy.

They directed the late Mr. Rennie to survey the Strait, and he prepared four designs of bridges for crossing at different sites, the chief features of all being large iron arches, in some cases as much as 450 feet span, and 150 feet above the water.

Local opposition, however, and a disinclination to provide the large sum required, caused the postponement of the matter till 1810, when a parliamentary committee was appointed to enquire into the state of the roads from Shrewsbury and Chester to Holyhead. After taking much evidence, this committee reported that the whole subject, including the bridge, required further professional investigation; and in consequence of their report, the Lords of the Treasury, in May 1810, instructed Mr. Telford to make an accurate survey of the roads, to report on their improvement generally, and to consider the best mode of passing the Straits. He proposed two plans of bridges—one, a single cast-iron arch of 500 feet span, and 100 feet high; the other, a series of iron and stone arches of smaller size—preferring, however, the former. These proposals were investigated in 1811 by another parliamentary committee, who strongly recommended the execution of the large iron bridge. The great dimensions of opening could not be dispensed with. The Straits, though tortuous and rocky, and of difficult navigation, were yet constantly used by large ships, on account of their sheltered situation, and the saving which they afforded of about 60 miles extra journey round the exposed and dangerous coast of the island; and hence it was absolutely prohibited that any fixed structure should be thrown across, except of such width and at such height as would allow the passage of large vessels underneath without inconvenience or danger.

Notwithstanding the approval of the parliamentary committee, still nothing was done, till a circumstance that occurred elsewhere gave a new turn to the design. In 1814 Mr. Telford was engaged in investigating the possibility of throwing a bridge across the Mersey at Runcorn, and finding the ordinary plan unavailable, he had proposed a large bridge on the suspension principle, which about that time was being brought into notice by Captain Brown. In 1815 a parliamentary commission was appointed to carry into effect the various improvements required in the Holyhead roads, Mr. Telford being appointed their engineer; and, after the general road works had proceeded for about two years, the enquiry arose whether the suspension principle might not be advantageously applied to the crossing of the Straits. Mr. Telford therefore again directed his attention to the subject, and early in 1818 submitted a report, design, and estimate, so strongly in favour of the suspension plan, that it was at once sanctioned by Government, and the works were put in hand in the latter part of the same year.

This resulted in the well-known magnificent suspension bridge, which, while it carries the road over the chasm at a convenient level, offers an uninterrupted water passage of nearly 550 feet wide and 120 feet high at high-water, dimensions sufficient to allow the largest ships using the Straits to pass under in full sail. Considering how little experience had been gained at that time in the use of iron for bridge construction, this bridge, so novel and daring in design and so successful and elegant in execution, has conferred lasting and well-merited fame on the engineer to whom its erection is due.

Telford's bridge was opened in 1826, but in a few years after that time the new system of communication began to supersede the ordinary roads. The metropolis of England was soon brought into railway connection with the great commercial port of Liverpool, and public attention began to be directed to a similar improvement of the communication with Ireland. A railway was projected for the land part of the journey; but, before its direction could be decided on, a question arose as to the merits of Holyhead as a point of departure, compared with another port on the main land, somewhat further south, named Port Dynllaen. Each of these had its advocates as a packet station, and various investigations were entered upon, and reports made, both by civil engineers and naval officers.

These discussions ended in a decision in favour of Holyhead, which led to the adoption of a line of railway to that port from Chester, to be connected by a branch with the Birmingham and Liverpool Railway at Crewe. This line, called the Chester and Holyhead Railway, was first surveyed by Mr. George Stephenson about 1838, but was subsequently taken up and carried into execution by his son.

The Act was obtained (with a certain hiatus which will be hereafter referred to) in 1844, and the railway was opened for its entire length, including the passage across the Britannia Bridge, in 1850.

Few railways have exceeded this line, either in public importance or in engineering interest. The natural difficulties have been great, and a series of engineering works of almost unrivalled magnitude characterise its whole length of 84½ miles. It emerges from Chester through a tunnel, and passes over a viaduct of 45 arches to the bridge by which it crosses the River Dee. From thence it follows the embanked channel of this river and its estuary, and farther on the shore of the Irish sea, having here and there important works, until it is stopped by the bold headlands of the Great and Little Orme's Head. It then leaves the coast, and, passing through the narrow valley that separates these headlands from the main land, crosses the River Conway, beneath the castle walls, by a wrought-iron tubular bridge of 400 feet in one span. Passing through the town and under the walls by a short tunnel, it again reaches the coast at the Conway Marshes, and continues its course along the shore through the green-stone and basaltic promontories of Penmaen Bach, and Penmaen Mawr, the terminating spurs of the Snowdon range, which it passes by two tunnels cut in the solid rock. Beyond these it is carried for some distance along the beach, partly on a viaduct of cast-iron. The sea walls and defences on the one hand along this exposed coast are all on a large scale; whilst on the other side of the line, a timber construction, similar to the avalanche galleries on the Alpine roads, protects the line from the *débris* rolling down from the lofty and almost overhanging precipices above. The road again turns inland to Bangor, and thence rises continually to a proper level for crossing the Straits. In this space it passes through a very rough country. The River Ogwen is crossed by a viaduct 246 yards in length, and the Cogyn by one of 132 yards long and 57 feet high; and three ridges of hills are perforated by tunnels, 440, 920, and 726 yards in length respectively, through hard primitive and trap rocks. In Anglesey the road passes over a marsh, and through a tunnel 550 yards long, and enters Holyhead by partly making use of an embankment previously constructed by the commissioners for the turnpike road.

When the Bill for the line was presented to Parliament in 1843–4, the chief engineering work involved in it was the bridge over the River Conway. The passage of the Menai Straits was proposed to be effected by permanently appropriating to the railway one of the two roadways of Telford's great suspension bridge. As the strength of this bridge, however, was deemed inadequate for the safe transit of heavy locomotive engines, it was intended to convey the trains across, in a divided state, if necessary, by means of horse power, another locomotive being in readiness on the opposite side—the passage of engines being thus entirely obviated. The Commissioners of Woods and Forests, however, refused to allow a permanent appropriation of the half of the bridge in this way; and as the expense to be incurred was inconsistent with the idea of a *temporary* expedient, the Railway Company were driven to abandon this part of their plan, and to propose an independent bridge for their line. The Bill was accordingly passed with a hiatus of five miles at this part, to give time for the arrangement of the plans.

The directors at once instructed Mr. Robert Stephenson, who had then become their engineer, to select a suitable place for crossing; and, after studying the subject well, he decided on a site about a mile to the west of Telford's bridge. The tide-way is here somewhat contracted; but the feature which principally determined the choice was the existence of a rock or island in the middle of the stream, called THE BRITANNIA ROCK; and from this, and not, as is often supposed, from any allegorical allusion, the bridge takes its name.

As the rock gave the opportunity of building a large pier, and so dividing the span into two parts, it was proposed to construct the bridge of two cast-iron arches, each 350 feet span, with a versed sine of 50 feet, the roadway being 105 feet above the level of high-water at spring-tides. The difficult problem of erecting these gigantic arches, in a situation where no centering or scaffolding would have been possible, was proposed to be solved by Mr. Stephenson in a very ingenious manner, and the Company prepared, at the end of 1844, a bill based upon this plan to go before Parliament the ensuing session.

As soon, however, as it became known what kind of a bridge it was proposed to build, a storm of opposition arose from the parties interested in the Straits, on the ground that such massive constructions would seriously interfere with the navigation. In March 1845, the Admiralty, in whom the guardianship of the navigation was vested, instructed three eminent engineers to examine the site and to report on the proposed plan; and as they stated that, in their opinion, the cast-iron bridge was ineligible, and that a clear passage of at least 100 feet high throughout the whole span should be insisted on, the proposal was abandoned.

Mr. Stephenson had already anticipated and prepared for this decision. He had fallen back upon the idea of the suspension bridge, and had begun to consider whether it was not possible to stiffen the platform so effectually as to make it available for the passage of railway trains at high velocities. His attention was directed to a suspension bridge at Montrose, where great stiffness had been afforded by a judicious system of trussing; and, carrying out this idea further, he conceived that sufficient strength might be obtained by the combination of the suspension chains with deep trellis trussing, having vertical sides, with cross bearing frames at top and bottom; the roadway being thus surrounded on all sides by strongly trussed framework. But as this idea was dwelt upon, difficulties arose about the material in which this trussed framework should be made. Timber was deemed inadmissible by reason of its perishable nature, and the danger from fire; and Mr. Stephenson, reverting to the design he had made for a small bridge in wrought-iron in 1841, was led to consider the application of this material, by substituting for the vertical wooden trellis trussing, and the top and bottom cross beams, wrought-iron plates riveted together with angle-iron. The form which the idea then assumed was, consequently, that of a *huge wrought-iron rectangular tube, so large that railway trains might pass through it*, with suspension chains on each side.

The conception having reached this stage, only a little farther careful consideration was necessary to arrive at the idea that such a tube would, if properly designed, serve the purposes of a *beam or girder*. The top and bottom of the tube, which it was intended to compose of thick wrought-iron plates, would evidently correspond with the top and bottom flanges of a common cast-iron girder, and might be made to perform their duties and take their strains; and having reference to this consideration, Mr. Stephenson began now to regard the tubular platform *as a beam, comprising in itself the main element of its supporting power*, and to which the chains were merely auxiliaries. Rough calculations were made, which though necessarily very imperfect, gave confidence in the feasibility of the design; and Mr. Stephenson's reliance on it was further strengthened by some practical examples brought to his notice of the great strength shown by large iron vessels accidentally placed under circumstances of peculiar strain and trial. Mr. Stephenson, fortified by these facts, even went so far as to propose to dispense with the auxiliary chains altogether.

Thus the matter stood at the beginning of April 1845, when the reports to the Admiralty put an end, as Mr.

Stephenson had anticipated, to the scheme of a cast-iron arch-bridge. The forethought and prudence with which he had prepared for this contingency, strikingly illustrate an element in his character, which was prominent through his whole professional career. Though he had strong confidence in his own views, when they were the result of sound reasoning and careful consideration, he never trusted with too sanguine an expectation to the favourable result of uncertain chances. He never undertook a doubtful course, without previously having determined a way of escape if it turned out contrary to his expectations; and to this admirable prudence is due, without doubt, much of the success which attended his professional labours.

The extinguishing of a favourite scheme, for such the arch-bridge was, would have damped the ardour of many men; but no sooner had it occurred than Mr. Stephenson announced to the directors of the railway that he was prepared to carry out a bridge of such a kind as would comply with the Admiralty conditions; and, after he had explained his views, they--not, however, without some misgivings—gave him their confidence and authorised him to lay his designs before Parliament.

The Bill came before the Committee of the House of Commons early in May. Mr. Stephenson's proposals, given on the first day, were received with much evident incredulity, and the Committee desired further evidence, and especially that of the Inspector-General of Railways, General Pasley, before they could pass the Bill authorising the erection of such a bridge as that which he had proposed. The Inspector concurred in the soundness of the idea, but most decidedly objected to the removal of the chains; and Mr. Stephenson, though he still expressed confidence in the sufficiency of the tube alone, thought it expedient to defer to this opinion, and to acquiesce in their retention. This satisfied the Committee, and the Bill in due course became law, by receiving the Royal assent, the 30th of June 1845.

It was now necessary to take steps in earnest for designing the tube. The calculations already made had been very rough: for such constructions being entirely novel, no experimental data were in existence of any use for practical purposes. No wrought-iron beam of any magnitude had ever been made or designed at all, and though the general properties of the material had been to some extent ascertained in suspension bridges, iron ships, and other wrought-iron constructions, the way to apply it in the best manner, so as to render its strength available in forming a large girder, was quite unknown. It was not the mere arrangement of the materials to resist the transverse strains which formed the difficulty of the problem. It was rather the practical design of any such structure at all—the difficulty of obtaining the iron in the forms required, or of adapting such forms as were obtainable to new purposes—and of devising a beam, not merely strong enough for its ultimate use as a bridge, but of sufficient independent rigidity for keeping its form when erected, and for sustaining the complicated and trying processes connected with its first construction, its floatation, its conveyance to the site, and its elevation and fixing in place.

Mr. Stephenson, therefore, considering the magnitude of the matter at stake, at once decided on supplying the want of data by a series of experiments on a large scale, before committing himself to the design for the tube. His own knowledge of the properties and manufacture of iron was very considerable, having been engaged from his youth up so actively and prominently in the manufactory at Newcastle; but, with the unassuming modesty of true merit, he did not think fit to rely on himself alone, for he felt that, considering the responsibility which he had publicly assumed, he would be doing injustice to the Board of Directors, who had placed such confidence in him, if he did not avail himself of all the practical and scientific aid within his reach. He accordingly entrusted the performance of the experiments to Mr. William Fairbairn, of Manchester, whose practical experience he estimated very highly, and with whom he had consulted on the subject previously to the parliamentary investigation. A short time afterwards, also, at Mr. Fairbairn's suggestion, he engaged the assistance of the late Mr. Eaton Hodgkinson, whose valuable contributions to engineering science, more especially in regard to iron structures, had attracted much notice in the profession.

The experiments, which were designed and proceeded with under Mr. Stephenson's personal superintendence, were not at first specific in their object. It was necessary rather to determine what kind of information was required, than to pursue any definite course—to ascertain generally in what manner tubes might be expected to fail, and to what extent their strength might be modified by form. The first idea of the tube was a rectangular section, but this was afterwards thought objectionable, and attention was directed to the circular or elliptical form. Model tubes of these sections were accordingly made and carefully tested; but they failed in strength, and, after due discussion and consideration of the experiments, it was decided that these shapes were ineligible, and the original rectangular form was reverted to. Trial tubes of this shape proved more satisfactory, and, in February 1846, Mr. Stephenson was able to report to the half-yearly meeting the general conclusion that had been arrived at. He stated that, after carefully studying the results as they developed themselves, he had satisfied himself that the wrought-iron tube was the most efficient as well as the most economical description of structure that could be devised for crossing the Straits—that the form of the tube must be rectangular—that the general disposition of the material had been determined—and that the only problem remaining was that of the necessary strength to be given: that apparently greater strength was required than had been at first proposed; but to establish the formulæ of calculation more positively, as well as to settle doubtful points regarding the use of the chains, it was desirable to carry the experimental researches still further.

It was in this preliminary series of investigations that the remarkable and unexpected fact was brought to light that the power of wrought-iron to resist compression was much less than to resist tension, being the reverse of that which held in cast-iron. This discovery had not only an important bearing on the design for the tube, but it has since formed a valuable datum in regard to the engineering use of the material generally.

Another point having important influence on the subsequent design was also brought out for the first time. It was found that in all the earliest trials of thin tubes the top part, which was exposed to a compressive strain, failed not by the direct crushing of the material, but by the buckling or collapse of the plates. This was a new fact altogether, and one which had never been taken into account in any of the formulæ for strength previously employed. It indeed annihilated at once their practical utility; and, prominent as it became in subsequent experiments, it threatened temporarily even to frustrate the consummation of Mr. Stephenson's design. It was, therefore, at once treated as the most important object of investigation. In some of the elliptical tubes a sort of cell or fin was introduced; but as this form was just then abandoned, the same difficulty arose with the rectangular tubes, the tops of which, when formed of thin flat plates, buckled up under the pressure. At length corrugations were made in the plates, which were found to add much to the stiffness; and this led to the formation of the top in a series of tubes or cells, which, while they gave the necessary rigidity, offered great facilities for the manufacture, as well as convenient access to all parts of the material; an object which had been always prominent in Mr Stephenson's mind.

The publication of Mr. Stephenson's report on these preliminary experiments, which was accompanied by others from Mr. Fairbairn and Mr. Hodgkinson, formed an important epoch in the history of the bridge. Public attention was now for the first time drawn to the subject, and the directors of the Company were relieved from some anxiety by the more definite details submitted to them. But still the necessity for further experiments was obvious. Everybody had some doubts and fears to suggest—dismal warnings came in on all hands, suggesting every imaginable apprehension. The necessity for chains was still advocated, not only by General Pasley, but by Mr. Hodgkinson himself. Many doubted the efficiency of riveting to unite such a mass of plates; some foretold the most fatal oscillation and vibration from passing trains, sufficient even to destroy the sides of the structure; while others asserted the insufficiency of the lateral strength to resist the wind. In fact, with few exceptions, scientific men generally either remained neutral or ominously shook their heads and hoped for the best, and even the most sanguine waited for further experimental investigation. All this was so discouraging, that Mr. Stephenson, strong as his faith was in his own plans, could not avoid appearing at times disheartened, when he withdrew from the turmoil of his metropolitan parliamentary duties to deliberate on the weighty difficulties he had to encounter in his gigantic undertaking in the distant hills of North Wales.

At this time, too, another serious matter presented itself. The preliminary considerations, discussions, and experiments summed up in Mr. Stephenson's report had occupied much longer time than had been anticipated; but the work on the other portions of the line had been steadily progressing, and it became evident that the Britannia and Conway bridges would be ultimately the chief cause of delay in the completion of the line. Hence the directors became impatient that Mr. Stephenson should sufficiently mature his plans to allow of the commencement of the masonry; and, while they did not hesitate to sanction the continuance of such further experiments as he might deem advisable, they, with a confidence in his proposals which few shared with them, entreated him without delay to commence operations simultaneously at both sites, and to complete his designs as he proceeded. This gratifying resolution added considerably to his anxiety, as he wished first to complete the smaller structure—the Conway Bridge, in order to obtain for the larger one the benefit of any experience it would afford. The plans of the masonry were however at once prepared. They were ready for contract by the middle of March 1846, and the first stone of the Britannia Bridge was laid April 10 in that year.

The further experiments which were needed for the completion of the design of the tubes, were of two kinds. In the first place it was considered necessary to make a model tube, very much larger than any of the previous ones, and representing more nearly the principles of the structure itself; with a view of putting it to every possible test, and by constant correction of its weak points of arriving gradually at the best form and proportions possible. And, secondly, it was found that, in order to give the power of reasoning from this model up to the structure itself, many more experimental data were necessary than were yet in existence, as to the qualities of the materials and the workmanship proposed to be used, and the influence of strains upon them.

These latter specific enquiries were undertaken by Mr. Hodgkinson. They consisted of careful and elaborate experiments and deductions on the compression, flexure, and crushing of materials and manufactured compound structures under direct pressure—on the extension and tensile strength of materials—on riveting—on the shearing of iron exposed to transverse strain—and on the transverse strength of beams and tubes of various kinds. They were, it is true, more particularly aimed at the question then pending; but they form a mass of general information of the most useful description, and probably, as a whole, unrivalled in extent and value.

The large model was constructed at Mr. Fairbairn's works at Millwall, near London, in order that it might be tested under Mr. Stephenson's more immediate inspection. The proportions having been thoroughly discussed, it was commenced in April 1846, and completed in July, and the experiments upon it were immediately put in hand. It was rectangular in shape, with a top composed of one row of cells, and its dimensions were determined in reference to the requirements for the Britannia Bridge, every dimension being one-sixth of the eventual magnitude then thought necessary. Thus the Britannia tube being 450 feet long in the clear, the length of the model between the bearings was 75 feet—the depth 4 feet 6 inches—and the width 2 feet 8 inches: forming a large bridge-girder of itself. The weight was between five and six tons. It was supported at each end on a pier, and weights were hung on the centre till it gave way. In the first experiment it broke with 30¼ tons by the rending asunder of the bottom plates. These were then repaired and strengthened, when it bore 43 tons, giving way at the sides, which were then strengthened in turn. Next the bottom gave way again several times, each time having larger dimensions; and so the trials and alterations were continued until at length a proportion was arrived at which proved to be about equally strong all over. As thus perfected, the tube bore 86 tons, or 2½ times that of the first trial, although in the strengthening only one ton of iron had been added—such being the effect of a judicious application of the material.

The experiments on this model directly proved what at first had appeared problematical, namely, that with such extensive horizontal developement of the top and bottom flanges, the whole of their sectional area would act effectually in resisting extension or compression throughout the entire width. In fact, when the model beam was broken, the tearing asunder of the bottom plates actually commenced at about the middle of the tube, and not at the outside edges—showing thus that the principles of simple girders were directly applicable to this construction also.

The experiments on the large model were continued till April 1847; but in the meantime the designs for the tube had not been neglected. During the first half of the year 1846 a great number of tentative drawings, models, and calculations were made; and although many of these attempts were necessarily discarded, as clearer views resulted from increased experimental information, yet some of the designs thus sketched out remarkably anticipated the ultimate plan. In July, when the experiments on the large model were commenced, a design for the great tubes had been made out in considerable detail. This was gradually improved as further information was obtained; and more perfect drawings were completed in the beginning of November. These, however, were further modified from time to time, the most important change being in the arrangement of the cells of the top, effected in February 1847, in accordance with certain principles resulting from the enquiries of Mr. Hodgkinson.

In March the correct lists of the plates were made out, and the first complete working drawings for the tubes were finished, although still further improvements were introduced as the work went on.

There is little doubt that this gradual growth and constant improvement of the designs conduced much to their perfection; and at a much later period, when wrought-iron girders had been greatly developed by the experience of subsequent years, and the talent of engineers had given rise to numberless elegant and ingenious practical combinations in bridge construction, Mr. Stephenson declared that he found it difficult to conceive any better means than those adopted of solving the problem.

While the design of the tubes was thus being considered, another question of scarcely less importance had also called for investigation, namely, the means by which they were to be placed in their position. For it scarcely need be remarked that the immense size and weight of the tubes, and the peculiarities of the situation, put them completely out of the range of all ordinary experience.

Many suggestions for this purpose were made and discussed at various times. An early idea of Mr. Stephenson's, when the cast-iron arch-bridge was proposed for Conway, was to float it to its place on pontoons; and the merits and difficulties of this plan had been fully discussed. When the arch was superseded by the tube in both localities, this mode of placing the tube was again considered, as the form which the bridge had assumed was evidently favourable for such an operation; and it was accordingly proposed to construct the tubes on the beach, and to float them to their ultimate position. This presupposed sufficient strength in the bridge independently of chains; but Mr. Stephenson, at that time, considered that the insurance afforded by chains against any accident from unforeseen causes would be a consideration of vital importance; and he did not, in that stage of his experience, feel justified in throwing away such a security. He therefore determined on availing himself of these auxiliary suspension chains, in the first instance, for supporting a temporary platform or scaffolding, along which the tubes constructed on the land could be rolled into their places. This plan was maturely considered; the designs for the platform,—which would of itself have been a large suspension bridge—were prepared; and much attention was bestowed on the manner of making the chains available as additional means of security to the tube, after their temporary office as scaffolding had been performed.

As, however, the progress of the design in the early part of 1846 gave more confidence in the self-supporting power of the tubes, and as the completed estimates for the suspension platform, with the then high price of wrought-iron, were very large, the subject was again discussed; and in July, Mr. Clark, who had accidentally obtained what he considered a good practical suggestion of a mode of raising the tube, urged upon Mr. Stephenson, with Mr. Fairbairn's assistance, a renewal of the floatation scheme. The subject was carefully and candidly reconsidered by Mr. Stephenson, and ultimately the chains were abandoned; and it was decided to put the tubes together upon the shore of the Straits; to float them to their site on pontoons; and to raise them to the required high level by hydraulic power; and this was the plan carried into practice.

Meantime it became urgent that arrangements should be made for the manufacture of the tubes, which the directors decided to put out to contract, reserving to themselves, however, the right to purchase the iron, and to supply it to the makers of the tubes at a fixed price per ton. In July 1846, the plates were contracted for by seven of the principal iron makers in the midland iron district; and shortly afterwards negotiations were commenced with several manufacturers for the construction of the tubes, but it was May 1847, before the arrangements were finally concluded. The first stipulation had been that the makers should construct the work at their own manufactories, in large sections, to be delivered on the shore of the Straits, and there put together; but as this plan involved difficulty, it was afterwards decided that the manufacture should be entirely done on the shore. On this understanding the contract for one large tube was given to Messrs. Garforth, of Manchester, and for the other seven to Mr. Charles Mare, of Blackwall. The site for the construction of the tubes had been determined some time previously. It was necessary that the making of the four large tubes should proceed simultaneously, and the clearing and preparation of the four places where they were to be made was a work of considerable difficulty and labour. Large and strong platforms of timber had to be laid down to build the tubes upon: these were occupied, and the ironwork began to get into shape by July 1847, and the first rivet for putting the tubes together was inserted on the 10th of August following.

The first of the large tubes was finished, and the wood platform was removed from beneath it by the 4th May 1849, leaving the weight of the tube supported on its two ends. This had, however, been anticipated by the Conway tube, finished in the January previous; and as the latter was in reality the first practical test of the great experiment, the anxiety of all concerned was intense to see the result as the timbers were gradually cut away. A deflection of 2 or 3 feet had been predicted, and many high authorities had affirmed that the tube could not support its own weight; while others foretold the buckling of the top, the distortion of the sides, the crushing of the extremities, and all sorts of failures. These forebodings were set at rest, and all fears at an end, when the platform was cleared away, and the tube took its own weight with just about the calculated deflection, and without the slightest appearance of undue strain or damage in any part.

The second tube was finished a few weeks after the first, the third in October 1849, and the fourth in February 1850.

Two other operations yet remained, each as gigantic and novel as the construction of the tubes, and attended with as much anxiety; namely, their removal by floating from the shore where they were constructed to the site of the bridge, and the hoisting of them up to their required level.

In the Conway Bridge these operations had been undertaken by the contractors; but, in the more important case of the Britannia Bridge, Mr. Stephenson preferred that they should be done immediately under his own direction.

The arrangements for them had accordingly occupied his attention during the latter part of the year 1848, and to facilitate the study a model was made of considerable size, with real water, on which the whole operation could be imitated; so that by constant rehearsals of the process on this miniature pool the plans for floating were matured. Each tube was to be floated on eight pontoons, introduced in cuttings in the rock under the tube, and which, on a certain day, were to be emptied and allowed to rise by the flowing tide till they lifted the tube off its bearings, and took its weight upon themselves. They were then to be hauled out into the stream, in order that it might float them and their burden to the bridge, being carefully guided and controlled by hawsers attached to the shore on either side. This was to be done near high-flood, so that the tube might arrive at the bridge about the turn of the tide at still water, when its ends were to be lodged upon shelves prepared for the purpose at the foot of each tower, and the pontoons floated away. The difficulties of this operation consisted in the magnitude of the moving mass—the great number of departments and of hands entering into the process—the short time it had to be done in (only about one hour and a half)—the great velocity of the tide (about six miles an hour)—and the terrible consequences that might ensue if the operation should fail, and the floating mass become unmanageable under the swift and powerful ebb-tide. Mr. Stephenson's energy, prudence, and foresight were here again admirably displayed. He devoted untiring attention to the organising and teaching of a large body of persons, many hundreds in number, who were to be engaged in the task, directed by his own staff of assistants; and as the work involved operations of a nature new to engineers, he obtained the aid of a large body of sailors and nautical men, under the command of Captain Claxton, R.N., who had acquired much reputation for his successful exertions in rescuing the Great Britain, stranded at Dundrum Bay. And further than this, impressed as Mr. Stephenson was by the immense responsibility of the operation, he invited two of his most eminent brethren in the profession—now, alas! like him, departed from this earthly scene of their labours—Mr. Brunel and Mr. Locke, to give him the benefit of their assistance, a trait of professional good feeling which did him infinite honour. This aid, we need hardly say, was cheerfully afforded, both gentlemen being at his side the whole time.

The floating of the two Conway tubes in March and October 1848, had served as useful preliminary trials, from which much valuable experience had been gained, and which enabled Mr. Stephenson well to mature his plans. Preparations were made for floating the first Britannia tube on the 19th of June 1849, but in consequence of the fracture of a capstan at the commencement, it was postponed to the next day, when it was successfully performed—the lodging of the tube upon the shelves of the towers being greeted by cannon from the shore, and the hearty cheers of many thousands of spectators, whose sympathy and anxiety had been indicated by the unbroken silence with which the whole operation had been observed.

The tube lay across the water, out of reach of the tide, during the remainder of June and the whole of July, while the machinery for raising it to its proper height was fitted in the towers. This apparatus consisted of huge hydraulic presses, placed at the tops of the towers on each side, from which strong chains hung down to the tube. By working these presses, the tube was raised six feet at a time, the ends sliding up in recesses or vertical grooves, which were built up under the ends of the tube as fast as it rose, timber packing being further inserted, so that in case of fracture of any of the suspending machinery the tube would not have far to fall.

On the 10th of August the raising was commenced, and it proceeded slowly till the 17th, when one of the press cylinders burst, allowing the end of the tube to fall 8 or 9 inches on to the packing below—which, slight as the fall was, caused some damage. By the 1st of October the press was again ready: the raising steadily proceeded, and on the 13th the tube safely attained its final elevation.

The second tube was floated on December 6th, and it was in its place by January 7th, 1850. This was in a line with the first one, and, as the two short or land tubes corresponding were already completed, it only required the four lengths to be joined in order to effect a passage across the Straits. These junctions proceeded night and day, and were completed and the rails laid by March 4th. The next day Mr. Stephenson and some friends passed through on a locomotive, followed by an enormous train of forty-five coal wagons and carriages, containing seven hundred passengers, and drawn by three engines. On the same day the last rivet was formally put into the tube by Mr. Stephenson and the contractor, and the passage of the Menai Straits by the Chester and Holyhead Railway became an accomplished fact. On the 15th the bridge was passed by the Government Inspector, and on the 18th it was opened for public traffic. It was worked as a single line for some time. The third tube was floated on June 10th, an operation which the concurrence of several accidents made the most hazardous of all; and it was raised July 11th. The fourth and last tube was floated July 25th, and placed in position on August 12th. The last piece of scaffolding was removed on October 11th; and on October 19th, 1850, the bridge was completed and opened for the double line.

The description of the bridge need only be very brief, as full particulars and views have been made so accessible by publication. It will be confined to an enumeration of such prominent points in the structure as may best illustrate its novelty and magnitude.

The nature of the ravine over which the bridge forms a passage has been described, and the peculiar conditions of navigation of the Straits, have already been alluded to as having influenced the general design. The water-way was about 1,000 feet wide, with a rock in the middle, so that by building a tower of sufficient height on each side, and one on the rock, this space was divided into two equal spans. But as the shelving shore on each bank gave a considerable increase of width at the required level of the roadway, some mode was necessary for filling in this additional space. The simplest plan would have been to build it up from the ground with arches of masonry, as Telford had done in the Menai Suspension Bridge; but Mr. Stephenson resolved to make use of these side spaces to effect an important object in regard to the large tubes, namely, to diminish the strains upon them by making them parts of a *continuous* long beam, instead of leaving each a single isolated span. It is well-known that when a beam extends continuously over several openings —as, for example, in a floor-joist—the strain is much less than when each span is covered by an independent beam of the same size. This, therefore, was the principle which Mr. Stephenson put in practice in this case. He threw the abutments, or land terminations of the bridge, high up the rocks on each side, and filled in the land spans with shorter tubes, so that the bridge became one of four spans —two large ones in the middle, flanked by a small one on each side. As regarded the bridge itself, these smaller land tubes were not required at all: they merely acted, so to speak, as counterpoises for the large tubes, converting them into continuous long beams, and their overhanging weight serving to relieve the centre parts of a portion of their strain. This application of the principle of continuity is a good example of Mr. Stephenson's excellent intuitive practical perception of mechanics. The general fact was, indeed, known, and its explanation had been investigated in mathematical works; but it was not till long after the erection of the Britannia Bridge that it was brought prominently before the notice of the engineering profession, or applied to iron bridges generally, with any view to the advantages afforded by it.*

* See Minutes of Proceedings of the Institution of Civil Engineers, vol. ix. 1849-50.

It does not appear to have formed any important part in the preliminary experiments, or even to have been the subject of any recorded calculations. In all probability its application was dictated almost entirely by Mr. Stephenson's practical judgment, and the test of elaborate mathematical analysis subsequently applied to the work shows how sound and accurate this judgment was.*

The span of each of the long tubes is 460 feet clear of the towers—that of each of the short or land tubes, 230 feet. A separate line of tubes is provided for each line of railway, with a small space between them, but both resting on the same towers. The four land tubes were constructed *in situ*, upon scaffolding built temporarily for the purpose.

Each line of tubes is connected throughout, forming one continuous tube 1,511 feet long, and weighing, with the permanent way, 5,270 tons. This long tube is securely fixed in the centre tower, but its bearings on the side towers and abutments are moveable, that it may expand and contract freely from changes of temperature.

The depth of the tube externally is 30 feet at the centre tower, diminishing to 23 feet at each end, so that while the bottom outline is straight, the top forms a portion of a curve. The internal clear height at the ends is 16 feet 4 inches. The breadth of the tube is about 14 feet, allowing room for a man to stand safely on the side during the passage of a train.

As each span of the tube had to bear its own weight

* See Mr. Clark's work, p. 785.

between the supports before they were connected together, it was necessary, in the design, to treat each as a separate beam. The top and bottom members were the effective portions in resisting the strain, and in them, consequently, the largest amount of material was collected, being disposed in the shape of a series of square cells or flues, eight in the top and six in the bottom, of sufficient size to allow workmen to enter for the purpose of riveting, and also to cleanse and paint the interior. The sectional area of solid metal in the top, at the middle of the length of the large tube, is 648 square inches, of the bottom 585 square inches. This is reduced towards the ends.

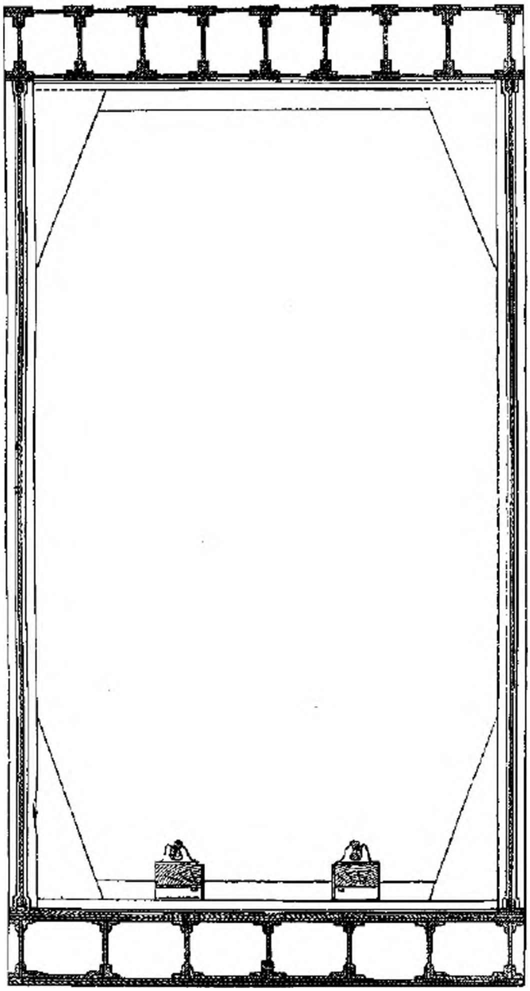
The engraving, fig. 6, represents a section of the tube, and will give a general idea of its construction.

The sides are plain sheets of plates, stiffened by vertical ribs or pillars of T iron, within and without, and also by gussets or corner-pieces, filling up the angles on the inside. The sides increase very much in thickness towards the towers, and are strengthened at the end with massive cast-iron frames.

The entire weight of ironwork in the bridge is 11,468 tons—the rivets in the tubes number above two millions.

The strength of the tubes has been well determined by several modes of calculation. Considering one of the large tubes as an independent beam, it is found that it would not break with less than about 5,000 tons equally distributed along its length. Now the tube itself weighs 1,550 tons, and adding to this the greatest moveable load that could possibly come upon it would make up little more than 2,000 tons, or two-fifths of its ultimate strength. But this is less favourable than the reality, inasmuch as the strength is nearly

Fig. 6.



doubled by the *continuity* of the beam over the several spans.

The strain upon the metal at the middle of the length of the long tube would be about 5¼ tons per square inch, if considered as an independent beam, but is reduced to 2¾ tons by the continuity.*

Mr. Stephenson made, at a later period, some explanations of certain peculiarities in the construction of the tubes which it may be well to repeat here, as they are necessary to explain the objects that guided him in the design.

The *sides* of the tubes weigh nearly forty per cent. of the whole weight. Had they been constructed *in situ*, this weight might have been considerably reduced. But in the operation of floating, the tubes were liable to be supported at any point of their length, besides being subjected to chances of considerable dislocation, and to disasters which, on more than one occasion, did actually threaten their entire destruction. The stiffening frames and gussets, which in an ordinary girder would have only been necessary at the ends, became therefore requisite throughout the whole length; and even the top and bottom were considerably modified, as while overhanging the pontoons at each end to the extent of 70 feet, the top, instead of being in compression, was thrown into extension. Again, the tubes had to be raised by being suspended freely from four chains, requiring provisions for this support of a different character from that which they needed when laid on their permanent bed; and further, the variation in the strains when the four tubes were ultimately joined to form one continuous tube—parts before in tension being then thrown into

* The calculations for determining this, furnished by the author of this chapter, will be found in Section viii. chap. 3, of Mr. Clark's work.

compression, and *vice versâ*—required a suitable arrangement of the material: the effect of all these provisions being to increase the quantity and modify the arrangement of the metal in the tube. In proportioning, therefore, the parts of a structure destined for such usage, the mere consideration of the strain to which, as an ordinary beam, it would be subjected, formed but a part of the problem, and no fair direct comparison can be made between the weight of this bridge and that of an ordinary beam.

Mr. Stephenson was of opinion that some misapprehension existed on the object and importance of the cells of which the top and bottom of the tube were composed, as well as on the choice of form of the tube; and he has given explanations to clear up both these points. He shows that to collect the necessary quantity of material of the top and bottom in single plates would have required the former to be 2·7 inches, and the latter 2·3 inches thick; and had such plates been procurable, nothing better could have been desired, and the cells would have been unnecessary.

At that time, however, it was impossible to procure plates of such a thickness, whose quality could be depended on; and the engineer in this, as in numberless other details, had to adopt what he could obtain. Now, the arrangement of the plates in cells is almost the only conceivable arrangement possible for getting the required section, allowing access, at the same time, to every part for construction and future maintenance. This alone led to their use in the bottom of the tube, where the form was quite indifferent. With respect to the top, however, it was of great importance, since thick plates could not be had, to ascertain the best form of cell for resistance to compression that could be devised with thin plates. A series of valuable experiments by Mr. Eaton Hodgkinson led to the rectangular cells actually used, not because such form presented any peculiar advantage over any other, as some have imagined, but because these experiments demonstrated that cells of that magnitude and thickness were independent of form, and were crushed only by the actual crushing of the iron itself. Under these circumstances the square cells were used as the best practical method of obtaining the sectional area required.

Similar misapprehension has also existed as to the considerations which led to the rectangular form of the tubes themselves.

The result of direct experiments made with round, oval, and rectangular tubes—there being precisely the same section and weight of metal in all three—was that the circular tube was the weakest and the oval tube the strongest, the rectangular form being intermediate. The oval tube was first studied with a view to adoption. Its form, however, was not favourable either for its practical construction, or for its connection with the suspension chains, which were originally intended to be used in the erection; and practical considerations in this case also dictated the use of the rectangular tube. It must also be remarked that the result of experiments made on oval, round, and rectangular wrought iron tubes, when reduced to the same depth and compared, was in favour of the rectangular form—although, within ordinary limits, the form was not proved to be a matter of great importance.

The centre or Britannia Rock tower is 230 feet high. The base is 60 feet by 50 feet, and the size at the level of the tube is 55 feet by 45. The pressure on the base is 16 tons per superficial foot.

The side towers are 18 feet lower than the Britannia tower; the base of each is 60 feet by 37 feet; the size at the level of the tube 59½ by 36½ feet. The great height of the towers above the tubes was necessary for fixing the hydraulic presses which raised these ponderous masses into their places.

The shore abutments are 35 feet lower than the side towers.

The internal work of the towers and abutments is of Runcorn sandstone, with some brickwork. The exterior is faced with Anglesea marble, from quarries in the carboniferous limestone at Penmaen, the northern extremity of the island.

The total quantity of masonry in the bridge is nearly a million and a half cubic feet.

The design of the bridge, as regards its architectural character, must, considering the entire novelty of the form, and the colossal dimensions of the structure, have been an arduous thing to attempt. The object aimed at was the adoption of such a character as would best accord with the tubes, the external appearance of which is simply a representation of beams of gigantic proportions. With this view, a combination of the Egyptian and Grecian styles was thought the most appropriate, the former as applied to the general and more massive portions of the design, and the latter to the less ponderous parts and to the details generally. The colossal lions on the approaches, designed and executed by the late Mr. John

Thomas, were intended as allegorical representations of the strength of the edifice and the boldness of the undertaking.

A colossal figure of Britannia was designed also by Mr. Thomas for the centre tower, but the great expense prevented its construction.

It is unfortunate that the bridge consists of an even number of spans, architectural beauty requiring an opening in the centre and not a pier. But the existence of the rock which determined the site of the bridge left no option on this point.

The total cost of the Britannia Bridge was a little over £600,000. The ironwork cost £375,000 or nearly £33 per ton—a very high price, no doubt; but it must be recollected that at the time these contracts were made iron was very dear, and the character of the work was new. At the present day there would be no difficulty in getting it for about half the sum.

The cost of the experiments was about £5,300.

Since the bridge has been in use the deflection has been carefully tested from time to time, and no perceptible increase has taken place. The painting has been attended to, and the tubes have been covered by a roof to shelter the ironwork from the rain. Mr. Stephenson continued to satisfy himself as to the condition of the bridge until near his death, and gave the opinion that he found it difficult to conceive that even the lapse of centuries could in any way affect such a structure.

It is to be hoped this opinion may be borne out by experience, and that the bridge may prove one of the most durable, as it certainly is one of the most remarkable, monuments of the science and enterprise of the present age.

Drawn by G. Hawkins. Engraved by H. Adlard.

Conway Bridge North Wales.

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Conway Bridge.

A few words must be added relative to the Conway Bridge, which has been mentioned incidentally in the account of the larger structure. The difficulties here, also, were formidable. It was necessary for the railway to cross the Conway River, a large estuary running high up into the land. The average width is about three-quarters of a mile, but advantage had been taken by Mr. Telford of a rocky island intercepting the channel, to reduce the width to a much smaller space, which he spanned with a suspension bridge for the passage of the Holyhead road. There could be no doubt that the proper site for crossing with the railway must be close to that occupied by the road; but it was also evident that, on account of the great depth at this point, 63 feet at high water, and the fearful velocity with which the tide ran through it to fill the large expanse above, it would be impossible either to build any intermediate pier in the water way, or to fix any centring or scaffolding for the erection of the bridge. The span of the suspension bridge is 315 feet, but from the form of the rocks the least span that could be obtained alongside it was 400 feet, and thus the problem became, to erect a bridge of this width in one span and without any fixed scaffolding. It will be recollected that Mr. Stephenson's first idea for the Menai Straits was to construct the bridge of large cast-iron arches, and it was proposed to treat the Conway river in a similar way, one colossal arch spanning the entire opening. The principal difficulty was with the erection; the ingenious plan which Mr. Stephenson had contrived for the Britannia Bridge was inapplicable here, and he proposed to build the arch upon pontoons, which, when the work was finished, were to be floated to the site, and made to deposit the entire structure at once upon its bearings.

When, however, the arch scheme was abandoned for the Menai Straits, it was also put aside for the Conway, as it soon became apparent that the problem was essentially so identical in the two cases, that any design adopted for the larger structure would, in all probability, be the most suitable for the smaller. Hence no further special attention was given to the Conway crossing till the general principles of the Britannia Bridge were settled, after which the two designs progressed simultaneously.

It was, however, at the Conway Bridge, as has been already stated, that the success of the great experiment was first put to the test. The contract for the tubes was let in October 1846 to Mr. Evans, who was already executing the masonry. It was this enterprising man who first proposed to construct the tubes entirely on the site, a plan afterwards adopted at the Britannia Bridge with so much advantage; and in the case of the Conway he undertook, at his own risk, the arduous and perilous duty of floating the tubes and of erecting them complete in their places, which he accomplished very successfully. The contract price paid to him for the tubes fixed complete was only about £4 per ton more than was given for the tubes only at the larger structure. The first stone of the bridge was laid May 12, 1846, but the manufacture of the tubes was not commenced till March 1847; the first tube was tested in January 1848, floated to its place in March, and ultimately raised and in use for railway traffic in April, a rapidity of execution highly praiseworthy. The second tube was floated in October, and the bridge was opened for traffic on the double line in December 1848.

There are two tubes, one for each line of railway; they are 400 feet long in the clear between the supports; the external height in the middle of the length is 25 feet 6 inches, diminishing to 22 feet 6 inches at the ends. The height of the bottom of the tube above high-water line is 17 feet. The general design of the tube corresponds with that in the Britannia Bridge, but the arrangement of the material is somewhat modified, from the circumstance that the latter is designed to act as a continuous beam, whereas the former is an independent one. The tubes were constructed on the shore of the estuary above the bridge, floated down to the site on pontoons, and raised by hydraulic power, as in the Britannia Bridge.

The artistic design of the Conway tube will probably be considered less successful than that of the Britannia Bridge; the situation is picturesque in the highest degree, and the elegant suspension bridge rather added to than diminished its beauty; but the same remark will hardly apply to the subsequent erection.

An attempt was made to give a style corresponding to that of the castle, but alterations subsequently introduced into the construction, and the omission of the ornamental parts to save expense, crippled the design; and the circumstance of the tubular bridge not being parallel to, but considerably askew from the suspension bridge immediately alongside, is a sad eyesore.

The unfettered reign of private enterprise, which, under the dictatorship of the engineer, has of late so much prevailed in this country, has been no doubt a grand source of works of commercial utility, but it has doomed us to much bitter humiliation in matters of art and taste.

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