# SUSPENSION BRIDGES IN BRITAIN IN THE EARLY NINETEENTH CENTURY

by

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## *Introduction*

The author of this paper spent two years researching the history of the Clifton Suspension Bridge as a Business Enterprise. The emphasis was therefore on commercial and financial matters as they related to the project. As the study progressed, it became increasingly clear that to isolate the Clifton Suspension Bridge from its wider commercial setting in this way made little sense. The enterprise had to be evaluated as a business in terms of its own time and setting. It followed that if this was true for the bridge as a business, it probably applied to engineering matters as well. To understand the Clifton Suspension Bridge technically, it has to be evaluated in the light of the technology available at the time.

Because much of what has been written about the Clifton Suspension Bridge has been part of a biography of Isambard Kingdom Brunel, or, alternatively a stand alone account of its construction, much has been left unsaid. Where did Brunel get his ideas from, were they his own, or did he draw on the experience of others? What help and advice were available to him: did he take it? This paper attempts to address these matters by asking and attempting to answer two questions. How did suspension bridge technology develop in the closing decades of the eighteenth century and the opening years of the nineteenth in Britain, and how did Davies Gilbert and John Seaward use this knowledge when they assessed the various submissions to the Clifton Suspension Bridge design competition in March, 1831?

## *Before Clifton*

What facilitated the rapid development of suspension bridges during the early years of the nineteenth century was the improvements in iron manufacture and working[1] which were taking place at the time. The enhanced techniques resulted in a much more consistent quality of iron, cast, malleable and wrought[2], being available, a characteristic which was most important when the material was used in tension rather than in compression. The result was that the first three decades of the nineteenth century were a seminal period in the design and construction of “bridges of suspension”. In short, the design and construction became much more ambitious in both the length of the suspended deck of the bridge and in its width and load bearing capabilities.

The term “bridges of suspension” was a general description. It meant that the deck or carriageway of the bridge was suspended. It did not indicate how this was done. The present usage of the words “suspension bridge” invariably means that the deck is hung using rods or chains placed at intervals along the length of the bridge, from two or more cables or chains which are, in their turn, hung from towers at each end of the deck. .

The description “bridges of suspension” covered this type of structure. It also included bridges where the deck was suspended from towers by a series of chains, cables or bars which ran direct from the top, or a series of points on the tower, to the bridge deck, such that a chain, cable or rod was secured to the deck at a series of, usually equally spaced, points along its length. This type of bridge would be called a “cable stayed” design today. In addition to the word “suspension”, the use of the description “pendant” or “hanging” was quite common. Further, “suspension” could be used when some form of truss

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[1] In addition to improved iron casting, forging and welding techniques, the demand for drawn wire from the textile industry resulted in improved manufacturing techniques for this product as well.

[2] Before 1784 malleable iron was difficult and expensive to manufacture. After Henry Court introduced his ‘puddling’ process, the cost fell progressively so by 1800 not only was iron cheap, it was also abundant. The invention of the steam hammer in 1795 made forging easier to control and so improved the quality of the work: in particular, welds were sounder. So by 1800 chains could be manufactured in quantity and quality economically. (Day 12, 13)

arrangement was being described. Contemporary records must be read with care if misunderstandings are to be avoided.

To be added to the engineering potential offered by improved iron manufacturing and processing techniques was the economic effect. Whether the bridge was suspension or cable stayed, it was a cheaper, and often much cheaper, way of crossing a particular space than what had been available hitherto.

This paper has two themes, which are linked, first how the design of bridges of suspension developed up to 1831, and second how this technology was applied to the scheme Isambard Kingdom Brunel submitted to the second design competition sponsored by the Trustees of the putative Clifton Suspension Bridge of March that year.

Fortunately, for the purposes of this paper, a lack of knowledge about suspension bridge technology was widespread in the 1820s and early 1830s, so Charles Stewart Drewry took it on himself to write a "memoir" on the subject. It was published in 1832. It includes Brunel's design for Clifton although a start had not been made to building the Bridge when the memoir was written.[3] [4]

Although from the earliest times a chasm could be crossed using a rope bridge, suspension bridges as we know them were not built until the middle of the 18th century. The earliest were usually light iron structures across small "gaps", invariably for foot passengers only. The first, a link chain

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[3] Charles Stewart Drewry, A Memoir on Suspension Bridges, 1832. "Drewry".

[4] Other sources have been used as well, in particular T. G. Cumming's Description of the Iron Bridges of Suspension now erecting over the Strait at Menai, at Bangor, and over the River Conway in North Wales etc., 1824. "Cumming 1824". Description of the Iron Bridges of Suspension erected over the Strait at Menai, at Bangor; and over the River Conway in North Wales etc., 1828. "Cumming 1828". There is also Robert Stevenson's paper a "Description of Bridges of Suspension". Edinburgh Philosophical Journal, Vol. 5, 10th October, 1821, 237-256. "Stevenson". Note: this Robert Stevenson was not Robert son of George Stephenson. These sources have been supplemented by accounts of individual bridges of importance where these are available. Modern secondary sources have been used sparingly and then only to make supporting statements or to make comments.

construction[5], was built across the river Tees two miles above Middleton in 1741. It was 70 feet long with a span of 59 feet, just over 2 feet wide and was used by miners crossing the river to get to their work.[6] Other suspension structures followed intermittently but at increasingly frequent intervals in Britain, France and elsewhere in continental Europe but more significantly in the United States of America. A bridge of some substance was built at Jacob's Creek in Pennsylvania. It was 70 feet long when completed in 1796. This bridge was designed by Judge James Finley, of Lafayette County in the same state, who is widely thought of as the pioneer of the level suspended deck suspension bridge. It used a form of bar chain.[7] [8] Another bridge, this time 145 feet long and 30 feet wide across the Brandywine at Wilmington, Delaware followed.[9] This was overtaken by a much larger structure in 1810. This bridge, which was 516 feet long overall, with a central span of 244 feet, was at Newburyport, Massachusetts over the river Merrimack. By this time the engineering was assuming significant proportions. The suspension abutments were 47 feet long and 37 feet high, superimposed on these were pillars made of wood 35 feet high. The two roadways, each 15 feet wide, were supported by 10 chains. The chains were grouped 3 – 4 – 3, three on each side of the bridge deck with the remaining four supporting the deck

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[5] There were several different means by which a bridge deck could be suspended. The simplest was by the use of a single "wire". There was then a bundle of wires either woven or bound together to form a single whole, "wire cable". The third method was by the use of a chain consisting of links, the type of chain one calls to mind when the word "chain" is normally used, that is a linkage made up with relatively small members, "link chain". There were then two types of chain based upon the bar principle. The first was the use of a succession of round bars of such a length as to be of some significance relative to the span of the bridge, joined together, either with or without smaller intermediate members, by pins or bolts, "bar chain". The second was the use of a succession of links, each made up of a number of relatively long flat bars, "laminated" together, that is grouped into a "sandwich" joined together, either with or without smaller intermediate members, by pins or bolts, "laminated bar chain".

[6] Drewry 9 (15). 9 refers to the page number and 15 to the paragraph; Stevenson 239, plate VIII, Fig. 1; The extreme length of the links was 6 inches, Cumming 1828, 41, 42.

[7] Drewry 11 (l8); Finley took out a patent on bar chains in 1801. The author is indebted to Michael M. Chrimes, Head Librarian of the Institution of Civil Engineers for this information. In the pages which follow the attribution "Chrimes" has a similar connotation.

[8] The chains consisted of elongated links made of iron bars square in cross section. Thomas Day states that Jacob's Creek bridge was finished in 1801 not 1796, adding that Finley finished nine more bridges by 1811. (Day 42) Finley published an account of his work in a book entitled "A Description of the patent Chain Bridge". Brief articles appeared in the British press on his work, in particular in the Monthly Magazine, vol. 26 1808, 344; vol. 31 1811, 361; The Gentlemen's Magazine, vol. 81 part 2 1811, 275. (Day 42)

[9] Drewry 12 (19).

between the two roadways.[10] [11] The remainder of this paper will be concerned with suspension bridges designed by British engineers and, with one exception, intended to be built in Britain.[12]

The bridges described so far were actually built and used. That proposed for Runcorn never got beyond the schematic stage. But it is mentioned here for three reasons, firstly it was of enormous proportions, secondly the engineer was Telford, and thirdly, and most importantly, the design was changed significantly after Samuel Brown put forward his ideas. Telford was first consulted about a scheme for bridging the Mersey at Runcorn Gap in 1814. He decided that a suspension bridge was the only realistic answer to the challenge.

Helped by Bryan Donkin and Peter Barlow[13], amongst others, Telford made an exhaustive series of experiments into the tensile strength of malleable iron and concluded that a suspension bridge of unprecedented dimensions was feasible. The centre span was to be 1,000 feet long, 70 feet[14] above the spring high water level of the Mersey, with two side spans of 500 feet each. He proposed to suspend the bridge deck, which was to comprise two carriageways, each 12 feet wide with a central footpath 6 feet wide, from wrought iron cables, the deflection of which was to be 50 feet, designed by Thomas Brunton. There were to be 16 such cables each formed from 36 half inch square iron bars[15] bound together and enclosed by segments of iron cylinders 4¼ inches in diameter. The cables were to be grouped in 4 sets of

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[10] Drewry 12, 13 (20); Stevenson 239, 240

[11] On occasion the information given in Drewry and Stevenson does not agree. If a clash occurs, this is pointed out in the text or in a footnote. If, however, one of the sources is unlikely to be correct, the more credible is selected for this text.

[12] In France where bridge design was guided by the thinking of the Ecole des Ponts et Chaussees, suspension bridges used wire cables until some catastrophic failures occurred in 1850 and the years following. Chrimes.

[13] Barlow gave particular attention to the suspension chain. He used Poisson's catenary theory to assess Telford's design. From this he was able to calculate the ultimate tensile stress in the cables. Telford himself used empirical methods. It can be assumed that Isambard K. Brunel and Davies Gilbert were aware of Poisson's work. Chrimes.

[14] Sixty feet in the Stevenson account. Stevenson 240.

[15] Each of the 36 bars was made up of shorter bars welded end to end until the required overall length was reached. Telford also considered using cables made from wires as distinct from bars. There were 16 such cables in 4 rows, each cable being 4 inches in diameter, each consisting of 1,256 wires 0.1 inches in diameter. There were also secondary cables. Chrimes

4, one set on each side of the deck and one set each side of the footpath. Each cable, when complete, would have been nearly half a mile long.[16]

During the time he was preparing his plans for Runcorn, Telford seems to have been unaware of the work Samuel Brown was carrying out on suspension bridge design.[17] In addition to conducting experiments to determine the strength of malleable iron, as Telford had done, Brown was developing a different design of suspension chain using bars. As soon as Telford heard of this he got in touch with Brown. He recognised what Brown's ideas had to offer and said as much to the Parliamentary Select Committee appointed to determine the practicability of the Bridge.[18] After reminding the Committee that "Chain bridges have long been employed with success over very considerable openings".[19], Telford compared his design with Brown's. "His (Mr. Brown's) Suspenders, Cross Ties and diagonal Braces, correspond precisely with mine. His main suspending Links of the Upper Curve instead of being composed of flexible Rods, as in mine, consist each of one Rod, or Bar, of malleable Iron united by Forelocks. From four of these it is proposed the whole structure should be suspended, and according to this CAPTAIN BROWN had constructed a Model 100 Feet in length at his Patent Chain Cable Manufactory, opposite Deptford. Your solicitors and I (Telford) examined the Model and drove a Hackney Coach over it. We afterwards had a full Conference with CAPTAIN BROWN in London, in the course of which he

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[16] L. T. C. Rolt, Thomas Telford 1958, 118, 119; "Rolt". Drewry 13, 14 (20, 22, 23, 24); Stevenson 240, 241. William Alexander Provis, An Historical Account of the Suspension Bridge erected over the Menai Strait at Bangor in North Wales, with a brief Account of the Conway Bridge, 1828, 15. "Provis".

[17] Samuel Brown was a retired naval captain. He first came to the fore when he designed and manufactured wrought iron chains for anchoring ships, particularly warships. Such chains soon replaced the hemp ropes which had been used previously, although the Royal Navy bought most of its chains from Thomas Brunton not Brown. Brown, nevertheless, established three factories to produce chains, one in London which was eventually sited at Millwall, the second at Pontypridd in South Wales and the third at Liverpool. From being a designer and manufacturer of anchor chains, he moved into the production of chains for suspension bridges. He also took out a patent on suspension bridge design and designed bridges on his own account. Brown was not, however, over protective of his ideas. Amongst his licencees for chains was the partnership D & A Acraman of Bristol, a firm and family well known to Brunel. Daniel Acraman was a Clifton Suspension Bridge Trustee. (Day 1, 4, 5, 80 et seq.)

[18] Thomas Telford, Report of the Select Committee appointed to consider the most practicable and expedient mode of effecting the proposed Bridge at Runcorn submitted to the General Committee on the 8th April, 1817. "Select Committee".

[19] Select Committee 11.

very distinctly explained his Ideas, and they in general very nearly correspond with my (Telford's) own. I then communicated to him the whole of my Operations in 1814,[20] which have already been detailed in this Report, and shewed him the Drawing I had then made".[21] So by 1817, when the Runcorn scheme was about to be abandoned, Telford was considering a bar chain design instead of Brunton's cables.[22]

More precisely, what Brown had proposed to Telford was the use of straight wrought iron rods or bars, 5 to 15 feet in length with welded eyes, or holes drilled out, at their ends. These long links were joined by much shorter links and bolt pins. The bridge deck was carried by rods which dropped vertically from the short links to the deck below.[23] Brown decided to patent his ideas.

In his patent specification Brown wrote that his object was to substitute his bar chain system for "common" link chains and wire cables in the construction of suspension bridges. Using Brown's terminology the bars were united by coupling plates and bolt pins or by welding. A succession of bars so joined formed the suspension chain which would therefore be of uniform strength throughout its length, whatever length that might be. Wire cables, which were necessarily made from small section bars or wires, were unsuitable for major bridges due to the large number of parts needed and the complications of joining them.[24] [25] The patent specification included a design for a 1,000 foot

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[20] This was a reference to Telford's tests to determine the strength of wrought iron.

[21] Select Committee 13.

[22] Rolt 119.

[23] Drewry 31, 32 (53).

[24] Drewry commented on the respective merits of wire cables and bar chains in suspension bridge construction in his Memorial. His opening shot was to say that some French engineers preferred the use of wire to bar as drawn was stronger than hammered iron. Further, bridges built with cable suspension were easier and quicker to assemble than bar chain structures. Heavy machinery was not needed; they could be built without any but the most common tools Drewry 150 (165, 166). Having noted the arguments of the French engineers, Drewry went on to discredit them. He much doubted if wire was stronger per square inch when a number of wires were bound together to form a cable due to the "inequality of loads" born by individual members. There was no means by which every wire could be stressed to the same amount; the loads could not be evened out. This was his primary concern. The secondary one was that for a given cross section of cable a greater area was exposed to oxidation and corrosion for wire cables than for bar chains. Both Drewry's points were soundly based. The problems of putting up a bridge were "once for all" difficulties. When the bridge was up, that was the end of the problem, except for maintenance difficulties which should be small and infrequent in a well engineered structure. Drewry 151 (166).

span bridge.[26] The patent application was enrolled at the Petty Bag Office in Chancery Lane on the 10th July, 1817 and granted on the 9th January, 1818.[27] It should be noted, and this feature became very important later in connection with Brunel's winning entry in the design competition for the Clifton Suspension Bridge, that Brown's patent provided for small coupling plates which linked adjacent bars of the chain from which the bridge deck was suspended.[28] Brunel's proposal did away with these coupling plates. In his proposal one bar was joined directly to the next by a bolt pin from which the bridge deck was also suspended. Brown had provided for several alternatives to his basic design but not for this possibility.

Brown's bar chain design was eventually to become largely the standard for major suspension bridges built in Britain or by British engineers abroad. Wire construction continued to be used on the Continent and in the United States of America throughout the period this paper is considering and its use continues today, although in a much improved form.

The bridges which were built in the years immediately after the Runcorn proposals were abandoned were much smaller and less ambitions than what Telford had in mind. The first, a footbridge, was at Galashiels across Gala Water. It was 111 feet long with slender suspension wires.[29] The next was built across the Tweed at Kings Meadow just below Peebles. This wire footbridge, 110 feet long and 4 feet wide, was made by Redpath and Brown of Edinburgh in 1817 at a cost of £160.[30] It was followed by a similar but slightly larger structure 125 feet long, a wire bridge designed and built by Captain Napier to replace a rope bridge. It spanned Etterick Water at Thurlestane

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[25] Individual wires can now be drawn to any length that is likely to be needed so the strength of the bridge is no longer governed by the soundness of the very numerous welded joints linking one wire to the next.

[26] This could, of course, have originated in the, by then, defunct Runcorn scheme.

[27] Drewry 31 (53), 32 (54), 33 (55). Brown's patent is discussed in more detail in Appendix 1.

[28] Drewry, Plate 2, Figs. 4& 5, 11 &12, Plate 4, Fig. 2.

[29] Drewry 24 (43); Stevenson 241; Cumming 1824, 46.

[30] Drewry 24 (43), Plate 1, Fig. 5; Stevenson 242, 337, Fig. 2. The possibility that Drewry and Stevenson were not independent sources must be borne in mind. Drewry could have drawn on Stevenson for part of his material as a comparison of these two references makes clear. Cumming 1824, 47.

Castle.[31] A 260 foot long and 4 foot wide chain footbridge was built across the Tweed at Dryburgh Abbey, again in 1817. The architects were John and William Smith of Melrose.[32]

All four of these bridges just mentioned had two things in common. Firstly, they were in the Scottish Borders, this had no engineering significance except that a successful technology in one district was used again nearby and secondly, they were of a similar design, a matter of technical importance. All four were “cable stayed” bridges. The deck was supported by a system of wires or chains which “radiated” from one or more points at the top of each suspension tower.[33]

In 1818, six months after it was completed, a gale caused the chains suspending the Dryburgh Bridge deck to vibrate, the longest chain broke and the deck was carried away by the wind. The vertical motion, just before the deck fractured, was as great as the horizontal movement being “sufficiently violent (as) to have thrown a person off the bridge”. The whole bridge was destroyed.[34] Following the Dryburgh disaster this form of construction was abandoned for large suspension bridges, although its use continued for small structures.[35] [36]

The Dryburgh Bridge was rebuilt. The new structure was a “conventional” catenary suspension bridge consisting of 4 main chains while retaining cable stays. The chains were made of rods, 1 5/8 inches in diameter and about 10 feet long with eyes at their ends, united by oval coupling links about 9 inches long. The roadway was suspended by vertical rods ½ inch in diameter, the upper ends of which were retained by a crosshead which rested on the upper

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[31] Drewry 25 (43); Stevenson 243; Cumming 1824, 47.

[32] Drewry 25 (45), Plate 1, Fig. 8; Stevenson 243, 337 Plate III, Fig. 3. Although as mentioned in a footnote above, Drewry and Stevenson may not be independent sources, on this occasion they used different sketches of the Dryburgh bridge. Cumming 1824, 47.

[33] See Drewry, Plate 1, Figs. 5, 7.

[34] Ibid 26 (45).

[35] Ibid 26 (46).

[36] The “cable stayed” design has been revived in recent times. The modern civil engineer has much more sophisticated techniques and materials at his disposal. The problems evinced at Dryburgh can be avoided today. The Second Severn Crossing is an excellent example of a modern “cable stayed” bridge.

edges of the coupling links. The lower ends of the rods passed through the side members of the roadway which was retained firmly by nuts set to the correct position on the screwed ends on the underside. The new bridge was also strengthened with a trussed hand rail.[37] The redesigned and reconstructed bridge proved to be satisfactory. This was the first time that bar chains were used in Britain. The Smiths antedated Brown.[38]

The first large bar chain bridge was, appropriately, designed and built by Samuel Brown. The Union Suspension Bridge spanned the Tweed 5 miles above Berwick. Work started in August, 1819. The structure was completed and opened in July, 1820 just before a start was made to Telford's Menai Bridge. The distance between the points of suspension was 449 feet, the deflection of the chains, that is the drop height from where the chains pass over the saddles at the tops of the 60 foot high towers to the low point reached by the chains at the mid point of the span was 30 feet. The main chains, which numbered 12, were arranged in pairs and placed in three ranges one under the other on each side of the bridge. Each set of bar links was a separate chain.[39]

The chains consisted of iron bars 2 inches in diameter and 15 feet long joined by coupling links which were 6¾ inches long, centre to centre, and made of 1 1/8th inch square iron bars . The 1 inch diameter suspension rods, which were 5 feet apart and passed through these coupling links, carried the bridge deck. The roadway was 387 feet long and 18 feet wide consisting of a carriageway 12 feet wide with a 3 foot footpath on each side.[40] The whole design accorded with Brown's patent. The completion of the Union Bridge was a seminal event in the evolution of suspension bridge design in Britain.

Telford's original proposal for Menai, despite the demonstrable weaknesses of his design for Runcorn, and his knowledge of Brown's pioneering work, included suspension cables. Fortunately, how the design evolved from this

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[37] Drewry 28 (48), 29 (49), Plate 1, fig. 8; Stevenson 244 - 247, 337 Plate VIII, fig. 3.
[38] Day 52.
[39] Drewry 37 (59), 39 (60), 40 (61); Stevenson 248, 249.
[40] Drewry 37 (59), 39 (60), 40 (60, 61) Plate II, figs. 1 - 6; Stevenson 248, 249.

into what was eventually built is recorded by T. G. Cumming. He published two accounts of the Menai Suspension Bridge, the first in 1824[41] and the second in 1828.[42] Both "editions" purported to give a comprehensive account of suspension bridge engineering at the time it was written by recording exemplars of each stage of the evolving technology. To that extent, the purpose of Cumming's works was similar to that of Drewry, but Menai changed between 1824 and 1828 so a comparison between the two accounts of the bridge is instructive. The first and second designs differ principally in the nature of the suspension cables / chains, the extent of the deflection of those cables / chains and how and where the cables / chains were anchored. As first proposed, the design was started in February, 1818, the Menai Bridge had 4 lines of suspension cables, each line consisting of 4 cables placed successively one beneath the next. There were thus 16 cables in all. The individual wires of the cables were formed from half inch square malleable iron bars of differing lengths welded together to give the overall length needed. 36 such wires were secured together in a 6 x 6 matrix using iron segments to bind them together. The resulting wire cable was nearly 4 inches in diameter. The whole was then bound with fine iron wire and coated with a preservative. The result was a well engineered but complex structure. The road deck was suspended beneath the 4 "clusters" of cables by 1 inch square wrought iron suspension rods 5 feet apart. The height of the towers above the roadway was 50 feet, which itself was 100 feet above the spring high tide level. The distance between the points of suspension at the top of the towers was 560 feet, the "deflection", or "versed sine" as Cumming called it, that is the drop from the points of suspension to the lowest point of the cables, was 37 feet.[43] The ends of the cables were secured in a mass of masonry built over the stone arches which were each 50 feet in span, 4 on the Anglesey side and 3 on the Caernarvon side of the strait.[44] [45] Before proceeding to

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[41] Cumming 1828.

[42] Ibid 1828.

[43] Cumming 1824, 19, 20, 22, 25; Provis 17, 18.

[44] Cumming, having described the cables, went on to try to demonstrate that they were adequate for their purpose. The total cross section area of the 16 suspension cables was 192 square inches. Using a maximum stress allowable of 5¼ tons per square inch, this put the maximum load permissible on the suspension chains at 1,008 tons. In Cumming's view, this provided a fully adequate margin of safety as the total weight of the bridge between the points

describe how the design came to be changed, it is necessary to back track to the origins of the Menai Bridge proposal.

One of the results of the Act of Union of Great Britain and Ireland was a desire to improve the communications between the two countries. To further this purpose, an Act of Parliament was passed on the 11th July, 1815 to facilitate the upgrading of the London to Holyhead road, Holyhead being a port of embarkation for Ireland.[46] The Act appointed Commissioners to oversee and manage this extremely ambitious and potentially expensive scheme. Amongst the Commissioners appointed was Davies Gilbert.[47] The Committee appointed Thomas Telford as their Engineer and William Alexander Provis as his Resident Engineer.[48]

Gilbert, while not a professional engineer, was, in the terminology of the time, a “man of science”: he was to become a President of the Royal Society in 1827.[49] Further, he had his own ideas on suspension bridge design and wrote papers on the subject later, probably drawing on his Menai Bridge experience.[50] As will become more obvious, when this study moves on to consider Gilbert’s views on the various designs put forward in the Clifton Suspension Bridge competition, it is reasonable to assume that when he criticised Telford’s proposals for Menai, Gilbert had three principal concerns, namely that a certain maximum stress of his selection should not be exceeded in the suspension chains, the design principles used in these should be compatible with Samuel Brown’s ideas and the deflection of the chains should be between 1/10th and 1/15th of the distance between the suspension points.

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of suspension was only 489 tons. Further, “There is not much reason to expect undulation from any weight which will be laid upon any particular part”. (Cumming 1824 22, 23)

[45] Provis 18.

[46] Ibid 17.

[47] Another Commissioner was William Smith MP. He took a particular interest in roads and bridges. Marc Brunel asked him to sponsor the Thames Tunnel. He became the first Chairman of the Thames Tunnel Company. Provis 17.

[48] Provis 17.

[49] Dictionary of National Biography.

[50] Davies Gilbert, On the Mathematical Theory of Suspension Bridges, Philosophical Transactions of the Royal Society 1826, 202 - 208.

Although the Treasury had granted £20,000 to the Commissioners, thus enabling preparatory work for Menai to start, Asheton Smith, a local landowner, took advantage of the Commissioners' need for a further Act of Parliament to empower them to construct a road across Anglesey from Menai to Holyhead, to raise his objections for a second time. He had already opposed the first Bill. Telford was called before a Parliamentary Committee and asked to justify his design again. What he said differed little from what he had said before. Rennie, when called to give evidence, was supportive of the proposal but he recommended some strengthening of the main suspension cables. Bryan Donkin, who was also called before the Committee, expressed the view that sufficient strength had already been provided.[51] The result of these less than fully consistent submissions was that the design of the bridge was re-opened and reviewed.

The results of Gilbert's review of Telford's original proposals, taken with Rennie's input and Brown's ideas, were extensive. The cable suspension system was abandoned and replaced by a bar chain design. The bars were of rectangular section rather than circular and laminated with bolts through both ends of the bars as described in the next paragraph. The cross section area was increased from 192 to 260 square inches. The height of the suspension towers was increased to 52 feet to allow for the greater deflection of the chains, which increased from 37 to 43 feet, and for the bridge deck rising 2 feet in the middle. The distance between the suspension points at the tops of the towers was 579 feet 10½ inches. The suspension chains passed over cast iron saddles at the tops of these towers. The cast iron saddles themselves rested on horizontal rollers 3 feet 8 inches long and 8 inches in diameter. The chains lay in grooves in the saddles and the saddles could move a few inches to accommodate any expansion or contraction of the chains.[52]

The number of chains was 16, each consisted of 5 laminated wrought iron bars 10 feet long, 3¼ inches wide and 1 inch thick. The overall length of the chains was 1,600 feet. There were 4 catenaries, one under the other, on

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[51] Provis 17, 23.

[52] Drewry 58 (73); Provis 24, 25.

each side of the central footpath and 4 further like catenaries on each side of the bridge deck. The chain bars were united by coupling links consisting of 6 laminated plates 16 inches long, 8 inches wide and 1 inch thick. The roadway was suspended, at a height of 102 feet above the spring high water mark, from the coupling links by 1 inch square bars 5 feet apart. The breadth of the roadway overall was 28 feet consisting of a central footpath of 4 feet and two carriageways of 12 feet width each. The suspension chains were carried through tunnels cut into the solid rock. The extreme ends were fastened by strong holding bolts in chambers made at the ends of these tunnels. The chains were thus attached to a solid mass of rock. Bolts 9 feet long and 6 inches in diameter rested in sockets in cast iron plates 6 inches thick. There was a total of 12 holding bolts. There were 3 tunnels for chains, each 5 feet square for the two central chains and the two side chains. The bars of the chains in the tunnels were 7 feet 6 inches long, 4 inches wide and 1½ inches thick. The coupling bolts were 4 inches in diameter. The span of the arches was increased from 50 feet to 52½ feet.[53] [54] The revised design was adopted. The Bill was passed. The first stone of the much changed bridge was laid on the 10th August, 1819 by William Provis, the Resident Engineer, as Sir Thomas Mostyn and Sir Henry Parnell, two of the Commissioners, refused to do it as no public ceremony was involved.[55]

Despite the care Telford had taken and the extensive involvement of Brown, Barlow and others in the design of the bridge, problems soon started to emerge, particularly from wind loading even when subject to a relatively light side breeze. These difficulties were known to Gilbert, as a Commissioner, well before the Clifton Suspension Bridge competition was announced and were no doubt taken into account when he and John Seaward adjudicated on the second set of submissions in March, 1831. The problems at Menai were first addressed by transverse chain bracing but the difficulties remained. In 1836 undulations of nearly 16 feet occurred in the deck. By this time Telford

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[53] Drewry 52 (68), 54 (71), 55, 56 (73), 57 (73) Plate IV, Fig. 102. The dimensions given by Cumming are, in certain instances, different from those given by Drewry. Provis could be different again. Cumming's dimensions are quoted in brackets. Cumming 1828, 5, 6, 8, 12, 15, 16, 17; Provis 14, 47.

[54] Each bar was proved to 11 tons per square inch before use. See Appendix II.

[55] Provis 24, 25.

was dead so the responsibility for corrective action fell to W. A. Provis. He recommended stiffening the deck. Nothing was done, however, until after a storm, which caused severe damage, in January, 1839, not only to the bridge deck but also to the suspension rods. Provis put forward major modifications and the roadway was strengthened by bracing the deck in 1839 – 40.

When the possibility of constructing a pier at Brighton was first considered, it was in response to the rapid growth of the town as a fashionable marine resort for the aristocracy and otherwise well-to-do people in late Georgian England. During this period Brighton had developed as a port for France and Belgium. But loading and unloading ships was difficult and somewhat hazardous. Passengers were ferried in small rowing boats to and from the sailing packets lying offshore. Horse, carriages and luggage were moved on rafts.[56]

A prospectus for a Chain Pier was issued in 1821. The preferred engineer was Samuel Brown. He had his successful design and construction of the Trinity Pier at Newhaven, Leith on the Firth of Forth to demonstrate his capabilities. Further, he was prepared to back the Brighton Pier project with his own money. Construction was put in hand in October, 1822. The pier was opened on the 15th October, 1823.[57]

The structure was quintessentially Samuel Brown: all eye to grandeur and visual appearance. The entrance to the pier was by a “beautiful esplanade”, 1,250 feet in length and 33 feet in breadth. The pier ran out to sea upwards of 350 yards. The infrastructure of the pier deck consisted of 4 clumps of piles driven 10 feet into the solid chalk rock of the sea bed. The tops of the piles were 14 feet above the high water mark. The first 3 clumps consisted of 70 piles each and the 4th, which was at the seaward end of the pier and in plan T shaped, had 150 vertical and diagonal piles in all. The platform, which formed

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[56] John George Bishop, The Brighton Pier in Memoriam. Its History from 1823 to 1896 with a Biographical Notice of Sir Samuel Brown its Designer and Constructor, 1896, 2, 3, 4 . “Bishop”.

[57] Bishop 7, 9, 10.

the end of the structure, was 80 feet long on the sides parallel to the shoreline, 40 feet wide and covered with Purbeck marble.[58]

The clumps of piles were 250 feet apart. The cast iron towers, which were positioned on the clumps, were 25 feet high. Each tower consisted of two side structures joined by an arch. The suspension chains, of which there were four, two on each side of the pier, passed over the tops of the towers. At the landward end the chains were secured in the body of the chalk cliff, at the seaward end each pair diverged from the line of the pier by about 81 degrees and the ends were secured in the chalk rock of the sea bed.[59]

All four of the suspension chains consisted of 170 links. The deflection was 18 feet. Each rod link was 10 feet long overall, 6¼ inches in circumference, or two inches in diameter, with eyes formed by forging and boring holes at each end. These links, which each weighed 1 cwt. were joined one to the next with side plates and the whole secured with 2 inch diameter bolts. The pier was 1,134 feet long and 13 feet wide. The deck was supported by 2 iron side members which ran the full length of the pier. These side members were suspended from 362 rods 1 inch in diameter and 5 feet apart, of varying length which in their turn were secured to the plates joining the suspension chain rods together. The suspension rods had a cross T at their ends to facilitate this. The pier deck itself consisted of cross timbers.[60]

Once completed, the pier was an immediate success. In addition to sailing packets, steam packets started to use the pier. The "Rapid" began to run from Brighton to Dieppe three times a week in May, 1823. In June she carried 5 carriages as well as 60 passengers to France. The transit time was only 8 or 9 hours, a vast improvement on what had gone before.[61]

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[58] Bishop 13. Drewry 69 (83). Bishop's and Drewry's figures on occasion disagree. Drewry's are given in brackets

[59] Bishop 13; Drewry 69 (83).

[60] Bishop 13, 14; Drewry 69 (83), 70 (84, 85).

[61] Bishop 21.

But as early as November, 1823 the risks inherent in the pier's exposed and unprotected position became more evident. On the 24th of the month it was damaged in a storm. Problems continued down the years as to survive in such an exposed position a structure like a pier has to be rigid. By its nature a suspension pier is flexible and the deck moves easily as it responds to wind and wave. The pier was removed in 1866.

Marc Brunel designed two suspension bridges for the Ile de Bourbon. This small island, now renamed Reunion, is in the Indian Ocean and remains a French possession to this day. The drawings were completed and delivered to Sequier, the French government's agent in the United Kingdom on the 16th April, 1822.[62] This was before work started on the Brighton Chain Pier in October, 1822 so it is reasonable to assume that Brown and Brunel were working on their designs in parallel, rather than at different times.

The two Bourbon bridges spanned the river St. Suzanne and the river du Mat. The latter was the longer of the two, both spans of which were 131 feet 9 inches long. The two cast iron towers, which were placed on a masonry pier, in the middle of the river were 25 feet high. There were 3 sets of main suspension chains 9 feet 8 inches apart, allowing 2 roadways 8 feet 9 inches wide between them. Each of these main catenary chains consisted of 2 series of wrought iron bars forged into links 4 feet 8 inches long and 1.36 inches in diameter. These long links were connected by shorter links 8¾ inches long made of l.36 inch by 1 inch iron bar. There were thus 6 chains in all. They dropped 23 feet from the high point of the central towers to anchorages on each side of the river. In addition, every fourth rod was an adjusting link which was used to equalise the length of and stress in each chain. Packing pieces were used to achieve this purpose. The suspension rods were 1¼ inches in diameter, 5 feet apart and hung from the connecting links.[63] A novel feature of the design was the addition of 4 lesser chains to the underside of the bridge. They were, effectively, inverted catenaries, 2 on each side of the towers, the purpose of which was to stabilise the structure should side winds

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[62] Marc's Diary 16th April, 1822.
[63] Drewry 75 (89), 76 (90), 77 (90); Cumming 1828, 49.

agitate the bridge deck. This was the first time that such a device was installed.[64] [65]

The second Ile de Bourbon bridge was a more conventional suspension bridge design: a catenary over the river St. Suzanne with the chains forming back stays on the two banks of the river. The distance between the points of suspension was 131 feet 9 inches. The cast iron towers stood 15 feet 5 inches above the deck of the bridge. The deflection of the chains was 9 feet 7 inches. Like the two span bridge, there were lesser chains on the underside of the bridge deck, an inverted catenary to give the bridge more stability.[66] Neither of Marc Brunel's Bourbon bridges was particularly successful. The single span structure was damaged in 1828 and the carriageway was reduced as a result. The bridge finally closed in1862. The longer bridge failed under a herd of cattle in 1838. It was repaired but replaced in 1856.[67]

In 1824 George Buchanan, a civil engineer, reported on their instructions of the 28th February, 1823 to the Montrose Bridge Commissioners on "the Present State of the Wooden Bridge at Montrose (over the river South Esk) and the Practicability of Erecting a Suspended Bridge of Iron in its Stead". He recommended that this "is the most advisable to be erected in lieu of the present bridge of wood", going on to say "I am convinced the present state of the arts, and I may add also of science will enable us to raise a structure of this nature superior in point of strength, stability, and accommodation to any thing of the kind which has yet been erected".[68] It is difficult to imagine a more positive recommendation.

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[64] Drewry 75 (89, 90); Clements 75.

[65] Cumming recorded certain dimensions for the Du Mat bridge differently from Drewry. The spans were 140 feet, and the links were 4 feet 9 inches long and 1½ inches in diameter. The fall of the curve was 23 feet Cumming 1828, 49. Further details of the design are given in Marc Isambard Brunel's Plan of a bridge on the principle of suspension representing the catenary combination in the construction of several bridges for the Ile de Bourbon, 1824 Institution of Civil Engineers Library Archives Department.

[66] Drewry 81 (94).

[67] Chrimes

[68] George Buchanan, Report on the Present State of the Wooden Bridge at Montrose and the Practicabiliiy of Erecting a Suspended Bridge of Iron in its Steady, 1824, 6. Institution of Civil Engineers Library, Archives Department. "Buchanan".

Hovever, after considering a design by Buchanan, the Committee turned to Samuel Brown. He proposed a suspension bridge. The overall length was 432 feet, the length of the suspended roadway was 412 feet. There were two rows of bar chains, one above the other, 12 inches apart, on each side of the bridge. The chains were made of flat bars, 5 inches by 1 inch, identical with those used at Hammersmith, with one difference, at Montrose they were 1¼ inches longer. In every other respect the chains, as assembled, were the same as those used in London. The coupling links, the bolts and the other details were identical. The deck was suspended from the coupling links by 1¼ inch diameter bars hung from alternate chains. The deflection of the suspension chains was 42 feet and the width of the roadway was 26 feet. The suspension chains passed over cast iron saddles at the top of the towers and were secured in the masonry on each side of the river 10 feet below ground. Construction eventually started in the latter part of 1828 and was completed 16 months later in December, 1829. This was the first time Brown used chains made of laminated flat bars on a bridge of his own design. Telford had been the first to use them at Menai and Conway. Clark used laminated bar chains made by Brown's firm at Hammersmith.[69]

The bridge was, like Menai, essentially unstiffened and the deck lacked substance. On the 19th March, 1830 a crowd of about 700 people was on the bridge watching a boat race. They moved from one side to the other as the boats passed beneath it. One of the chains broke and the bridge was badly damaged. Telford suggested increasing the number of chains but J. M Rendel, who had taken over as Engineer, recommended the addition of 2 bars to the width of the existing chains and this was accepted.[70] The bridge collapsed again in 1838. Brown played no part in its restoration. This was again done by Rendel. This much improved structure remained in use until 1931 when it was replaced by a cantilever bridge.[71]

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[69] Day 128, 29.

[70] Chrimes.

[71] Day 130; J. M. Rendel, "Memoir of the Montrose Suspension Bridge", Minutes of the Proceedings of the Institution of Civil Engineers Vol. 1 1841, 125.

Two further bridges will be considered before we move on to the competition which led to Isambard Brunel's scheme being preferred for the bridge across the Avon at Clifton. The first is the suspension bridge built over the Thames at Hammersmith. It was designed by William Tierney Clark using the bar chain principle. Work commenced in 1824 and was completed in 1827 when the bridge was opened to wheeled and foot traffic. The overall distance between the points of suspension was 422 feet 3 inches, with a chain deflection of 29 feet 6 inches. The total width of the waterway was 688 feet 9 inches with an opening of 400 feet 3 inches between the piers which rose from the river bed. The distance from the "Surrey" pier to the bank was 145 feet 6 inches and there was a gap of 143 feet between the "Middlesex" pier and the bank on the north side of the river.[72]

The main chains, of which there were 8 were made in Samuel Brown's factory and were arranged in 4 double lines: two directly above each side of the carriageway which ran down the centre of the bridge. There were 2 smaller chains, one under the other, on the outside of each footpath: these ran down the sides of the bridge. There were thus 4 small chains in all. The small chains each consisted of 3 laminations made up of bars which were 8 feet 10 inches long eye to eye, 5 inches wide and 1 inch thick. The large chains were made of similar components but they had 6 laminations each. The bars of both the small and large chains were joined by coupling links of 4 and 7 lamination plates respectively. There were, therefore, 36 bars in the total cross section giving an area of 180 square inches. The suspension chains, from which the road deck was suspended using 1 inch square iron bars, passed over roller carriages positioned on the tops of the 2 towers rising from the river bed.[73] The chains were carried through tunnels into abutments on each side of the river. The abutments were 2 feet wide for the small chains and 3 feet wide for the large. The ends of the chain bars passed through cast iron holding plates which bore against a large surface at the back of the masonry and were secured in position by cross pins.[74] The bridge was better

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[72] Drewry 82 (95); Cumming 1828, 62.
[73] Drewry 83 (97); Cumming 1828, 63, 64, 65.
[74] Drewry 84 (98).

designed than most of its contemporaries.  It was rigid under extreme wind loading as the deck was stiffened by deep trussed girders.  Though Brown's firm was involved to a degree as mentioned, the rest of the iron work came from Gospel Oak in Staffordshire.  Clark also designed the Marlow Suspension Bridge in Buckinghamshire.  Work started on this in 1829 but it was not completed until 1832.[75] [76]

The second bridge was a lesser structure but it has been selected because, like that at Dryburgh in the Scottish borders, it collapsed shortly after it was opened but on this occasion, in contrast to Dryburgh, the reason for this happening is manifestly clear.  The bridge in question was across the river Irwell at Broughton near Manchester.  Of a bar chain construction it was 145½ feet long with a deflection of 12½ feet and a width of 18 feet 3 inches.  The bridge deck was supported by 4 chains, 2 on each side of the roadway.  Each chain rod was 4½  feet long made of 2 inch diameter wrought iron, each end of which was forged into a splay and bored to accept pins which were 7/8 inch in diameter.  The coupling links, which connected the successive rods, carried the 1 inch diameter suspension rods which supported the bridge deck.[77]  It is possible that the Broughton Bridge  was designed by Brown.  Gies said as much but he did not quote his sources.[78]

The bridge failed in June, 1830.[79]  A detailed account of the event appeared in The  Manchester Guardian.  The significance of this was not lost on Brunel, who was, at the time, developing his first set of proposals for a suspension

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[75] Chrimes

[76] Hammersmith Bridge, as it exists today, is very different from that designed by Clark.  It was almost completely rebuilt in 1887 by Sir Joseph Bazalgette.  The piers were strengthened and new towers built.  The iron bar chains were replaced by 2 sets of steel ones on each side of the bridge, one 2 feet above the other.  The 16 foot links were offset so that the suspension rods could be placed 8 feet apart.  The deflection of the chains was 35 feet. Anon, The Engineer 63, 1887, 308, 309, 330, 331.

[77] Drewry 92 (106).

[78] J. Gies “”Bridges and Man” 1964, 174.

[79] Bridge failures were common.  Two are mentioned in this study but there were several others during the period up to 1831.

bridge at Clifton. The press cutting was carefully pasted into his personal diary.[80]

A company of soldiers, 74 in number, consisting of both officers and men of the 60th regiment were returning to their barracks in Salford from a field day on Kersal Moor when the bridge collapsed. About 60 men were marching 4 abreast when "the structure vibrated in unison with the measured step with which they marched, and, as the vibration was no means unpleasant, they were inclined to humour it by the manner in which they stepped. As they proceeded, and as a greater number of them got upon the bridge, the vibration went on increasing until the head of the column had nearly reached the Pendleton side of the river. They were then alarmed by a loud sound somewhat resembling an irregular discharge of firearms; and immediately one of the iron pillars supporting the suspension chains, viz. that which was to the right of the soldiers, and on the Broughton side of the river, fell towards the bridge, carrying with it a large stone from the pier, to which it had been bolted. Of course that corner of the bridge, having lost the support of the pillar, immediately fell to the bottom of the river, a distance of about 16 or 18 feet." Most of the soldiers went into the river with the bridge. Fortunately. no lives were lost.[81]

The writer went on to discuss the cause of the accident. He saw the uniform steps, correctly, as the source of the movements but he did not understand that the vibrations were amplified because the footsteps matched the natural frequency of the bridge. Once started, each footfall increased the amplitude of the movement of the bridge deck. This pulsating movement was transmitted through the rest of the bridge until it reached such proportions that some part of the structure, in this case a chain link; failed. Brunel's view of the failure is unknown. The text of the press cutting was not annotated or commented upon.[82]

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[80] Isambard Kingdom Brunel Private Diary, January 1830 - 2nd September, 1832, 19th June, 1830, 28. University of Bristol Library Special Collections Department. "I. K. B. Diary 1"; Salford Local History Library, press cutting.

[81] I. K. B. Diary 1, 19th June, 1830, 28; Salford Local History Library, press cutting.

[82] I. K. B. Diary 1, 19th June, 1830, 28.

So far this paper has been limited to what may be described as the structural geometry of suspension bridges. There are, of course, other considerations. Until the advent of the suspension bridge, which is dependent on materials in tension, a bridge, or any other load bearing structure, consisted of materials used largely in compression. A traditional masonry, brick or wooden arched structure was relatively massive and usually placed few demands on the material from which it was constructed. It, inevitably, observed Newton's Law; action and reaction are equal and opposite with the materials in compression. Suspension bridges were the opposite, they were relatively insubstantial structures in which action and reaction were balanced by materials in tension. For a load bearing structure this was a revolutionary situation and demanded materials of a consistent and predictable quality for construction purposes. This was without precedent for bridges particularly.

The other factor which has to be borne in mind is that the largest load any bridge has to bear, suspension or otherwise, is its own weight. The vehicles, people and animals which cross it are only a relatively small incremental burden and are only likely to become significant should the bridge deck be completely covered with vehicles, people or animals. A proof test which was on occasion used for a bridge when it was first completed was for a crowd of people to stand shoulder to shoulder until such time as the whole bridge deck was covered.

Against this background, it is not surprising that the engineers, who were concerned with suspension bridge design in the early decades of the 19th century, gave close attention to the characteristics of the principal material they used, malleable or wrought iron. Two of the engineers who had a direct interest in the strength of wrought iron for suspension bridges were Thomas Telford and Samuel Brown. As an engineer, Telford had the advantage as he already had connections with ironmasters, particularly in Shropshire. Brown had no such advice available to him. However, both men conducted very exhaustive tests on representative samples of iron wires. Telford tested wires with cross section areas varying from 0.0018 square inches up to 0.00784 square inches in a number of lengths up to 900 feet. They were stretched between 2 props and loaded with progressively increasing weights hung from one end of the wire. The other end was secured to one of the props. Similar tests were carried out with weights at both ends of the wire. The breaking stress of the various diameters and lengths varied from 35.7 tons per square inch to 42.9 tons per square inch. Telford judged that 38.4 tons per square inch was a reasonable mean figure.[83] These were, of course, static tests. No dynamic tests were conducted. It is unlikely that Telford saw any reason for such an innovation. A bridge was, after all, a static structure.

While Telford's experiments on "the direct strength of cohesion of malleable iron (were carried out) at Messrs. Brunton & Co.'s chain cable manufactory" the parallel work took place at Milwall, "Captain Brown's patent iron cable manufactory on the strength of iron bars and cables".[84] Two points should be borne in mind before discussing Brown's results. Firstly, both sets of experiments took place in workshops which were dedicated to producing chains and secondly, Brown extended his tests to include bars as well as wires. He found that the ultimate strength of wrought iron was 25 tons per square inch. If bent to form links, the strength of the material fell to 21½ tons per square inch. These figures were significantly less than those determined by Telford.

Telford, despite the results of his tests, preferred a maximum of 5½ tons per square inch for bridge design purposes. This was the figure used at Menai and, probably because Davies Gilbert had strong connections with this bridge, it became the preferred figure when the Clifton Suspension Bridge schemes were appraised in March, 1831.

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[83] Drewry 15 (26), 16 (27).

[84] Drewry 17 (30), (32).

## *Clifton Suspension Bridge*

When Brunel was preparing his submission for the second Clifton Bridge competition he had no direct personal knowledge of suspension bridge design. He could draw on his father's experience in the engineering and construction of the two small bridges for the Ile de Bourbon. Beyond that it was what he could find out for himself about current best practice by studying other engineers' work, supplemented by any design input he could make himself, plus, and most significantly, the help his father was prepared to give him. This process continued even after he been appointed Engineer to the Clifton Suspension Bridge Trustees.

The second competition for the Clifton Suspension Bridge elicited 12 designs of which 5 were chosen for detailed consideration. The engineers preferred were Thomas Telford, Isambard Kingdom Brunel, Smith and William Hawks, James M. Rendel and Samuel John Brown. Significantly, W. Tierney Clark, who had already designed and built the Hammersmith Bridge, did not make the short list. The remainder of the 12 contestants had their plans returned to them with a letter of thanks from John Savage, the Mayor of Bristol, who had chaired the meeting of the Clifton Suspension Bridge Trustees at which the various proposals had been considered and the short list prepared.[85] The Trustees decided to ask Davies Gilbert to advise them on their final choice. He selected John Seaward as his assistant after approaching several others unsuccessfully.[86] Gilbert as, by 1831, a past President of the Royal Society, was known to Marc Brunel as well as to Isambard and Thomas Telford. It is difficult to think of anyone else who could fill the role as Telford, Brown and Clark, all well qualified in the field of suspension bridge engineering, were, or had been, amongst the competitors: knowledge of the technology involved was not that widespread.[87] Seaward was of the firm, Seaward and Capel, Canal Ironworks, Millwall. He was a marine engineer but had no obvious

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[85] Clifton Suspension Bridge, Proceedings of Trustees 1830 - 1890, 22nd December, 1830, 33. University of Bristol Library Special Collections Department. "Trustees Proceedings"

[86] Trustees' Proceedings 1st January, 1831, 34; 10th March, 1831, 40.

[87] Davies Gilbert was, however, elected an honorary member of the Institution of Civil Engineers so he presumably had some credibility amongst civil engineers as a corporate body. He was also an honorary member of the Smeatonians. .

qualifications to justify his appointment as a judge to determine the preferred design for a bridge of the magnitude of Clifton.[88] . Despite this, he had on occasion contributed to the debate on the design of suspension bridges.[89]

Telford's proposal was quickly set aside, "on account of the inadequacy of the funds requisite for meeting the cost of such high and massive towers as were necessary for the plan that distinguished individual had proposed", so leaving 4 serious contenders.[90] This happened on the 17th March, 1831, the same day that Davies arrived at Blaise Castle to start work.[91] This left the way clear for the other submissions to be assessed.

Gilbert and Seaward reported to the "Gentlemen of the Committee" in detail on Brunel's scheme "number 3". It was for a span of 600 feet between the suspension points with a deflection from the apex of the towers to the lowest point of the catenary of 60 feet. The total weight of the structure was 1,468 tons, a sum which included the chains, suspension rods, deck, which was 32 feet wide, vehicles and people on the Bridge.[92] The stress at the points of suspension was calculated to be 1,966 tons so, with a total chain cross section area of 470 square inches, the load was 4 1/5 tons per square inch. Davies Gilbert judged this to be satisfactory. However, there was a "material variation from known good plans". Securing the chains by a single pin, as opposed to double pins, was "not judicious". This was presumably a reference to the links of the chain being pinned one direct to the next without a small link which carried the suspension rod being put between the two. This simplification of the structure departed from what was, substantially, standard practice for bar chains as represented by Samuel Brown's patent and the design which had been preferred for Menai. Other causes for concern were the plans for securing the chains in the rocks were wanting, as was the use of

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[88] Rolt 55.

[89] Seaward J., On Suspension Chain Bridges, Mechanics Magazine 22, 339, 340, January 24th, 1824.

[90] I. K. B. Life 53.

[91] Trustees Proceedings17th March, 1831, 41.

[92] For calculation purposes it was assumed that the Bridge was completely covered with people each occupying 2 square feet on average. Note, this was a purely static loading, no account was taken of any stresses that dynamic loading could induce in the structure.

only 2, as opposed to 3 or 4, clusters of suspension chains which Gilbert and Seaward judged as essential. In addition, they thought that “many other particulars may be amended and simplified with considerable advantage”. Further, to crown what seemed to be, on first consideration, a root and branch condemnation of Brunel’s proposals, the cost estimate was criticised as inadequate.[93] This initial assessment must have come as a surprise and big disappointment to Brunel as he had kept Gilbert fully appraised of his ideas as they developed, a process which had started 12 months earlier.

James Rendel’s proposal,[94] Davies Gilbert reported, was for a greater distance between the points of suspension, 780 feet, a deflection of 78 feet, with chains of a smaller cross section than Brunel’s of 300 square inches, giving a stress of 6¼ tons per square inch based upon a suspended weight of 1,378 tons. Gilbert’s view was that the maximum figure permissible was 5½ tons per square inch.[95] Further, if this plan was adopted, extensive redesign was essential. Three or four clusters of chains were necessary; the 2 shown in the drawings were clearly insufficient. Other adverse comments were made and overall Rendel’s proposal was considered “very injudicious”[96].

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[93] Isambard Kingdom Brunel Letter Book 1832, 4, 5, 6. University of Bristol Library Special Collections Department. “I. K. B. Letter Book”

[94] Full particulars of this submission were given in “Particulars descriptive of the accompanying Design for an intended Bridge over the Avon, at Clifton”. James M. Rendel, Plymouth, 1830. “Particulars”.

[95] This was the figure used by Telford for Menai after Gilbert’s intervention in the design for that bridge. As mentioned earlier, Gilbert was a Commissioner for the London to Holyhead road improvement scheme of which the Menai Bridge was part.

[96] If one assumes that the “Particulars” published by Rendel, noting that date of publication was 1830, not 1831, were representative of what was appraised by Gilbert and Seaward, it seems that Gilbert recalculated a number of Rendel’s figures. This was easily done as Rendel laid out his calculations in detail in the “Particulars”. Gilbert had his own methods which were, it appears, on occasion different from Rendel’s. For example, Rendel calculated the total weight of the Bridge, including a test load of 8,000, 12 stone men at “say, 1,800 tons”. Gilbert used a precise 1,861 tons. Further, he probably disagreed with Rendel’s startpoint for his calculations on the size of the chain bars and other iron load bearing members. “I shall assume the ultimate strength of iron, at 25 tons per sectional inch, and that derangement commences when the load exceeds 14 tons”. Particulars, 12, 13. Using his assumptions, Rendel arrived at a safety factor of 2¼ . Gilbert obviously thought that this was not enough.

Smith and Hawks'[97] plans were much better received than Rendel's, even though the stress in the chains of 7 tons per square inch, assuming a suspended weight of 1,226 tons, was significantly higher than in either Brunel's or Rendel's proposals. The span of the Bridge was 620 feet, the drop of the chains was 50 feet, the cross section area of which was 288 square inches. Gilbert commented that if the chains were increased by 50% in size, the stress would be reduced to a satisfactory level or the "decline" of the chains could be greater, which would give the same effect. Except for this, "we (Gilbert and Seaward) very much approve of the general detail and arrangements of Mr. Hawks' Bridge" …….. the "plan appears to have been prepared with care and judgment", further "the mode of connecting the links of the chains are judicious". The estimate for the cost of the ironwork was considered to be " very reasonable" but the judges could offer no opinion on the price of the masonry.

The last design to be assessed was Captain Samuel Brown's.[98]. This submission probably caused Gilbert and Seaward to pause and cogitate as he was the only one of the four contenders who had substantial suspension bridge expertise. The distance between the points of suspension was 780 feet, the drop of the chains 65 feet, the cross sectional area of which was 324 square inches, the width of the roadway was 30 feet and the weight of the suspended structure was 2,700 tons. They calculated that the maximum stress in the chains was 8 1/3 tons per square inch. This was well above what the assessors thought prudent.[99] However, Gilbert went on to say that the design could be easily remedied by increasing the decline and the cross

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[97] The first use of laminated chains, that is chains made of links, which consisted of a number of flat plates pinned together was for winding gear in collieries where flexibility of the chain in one plane only was required. Smith and Hawks took out a patent for such chains in 1813 These chains were very similar in design to those used on suspension bridges. Smith developed production techniques which enabled the parts of the chains to be manufactured very accurately. (Day 22, 23) The author has found no occasion other than Clifton of Hawks showing any interest in suspension bridges.

[98] Brown was always accorded his naval rank when he was mentioned or referred to in his engineering career until such time as he was knighted. So, he was Commander or Captain variously in the period we are considering.

[99] The maximum stress in the bar chains of the Tweed Bridge was 3.9 tons per square inch, Drewry 40 (61), 41.

section area of the chains. In other respects the details of the Bridge and the mode of its construction attracted their "entire approbation".[100]

As has been discussed already, early nineteenth century experiments on the strength of wrought or malleable iron showed that an ultimate tensile stress of 27 tons per square inch was usually obtainable, but excessive deformation due to yielding occurred at about half this stress level so here was nothing sacrosanct in Telford and Gilbert's 5½ tons per square inch. It could be argued that the figure was too high to be safe. There was also the opposite argument that 5½ tons per square inch was unnecessarily low. Brown adopted a maximum stress of 10 tons per square inch for his bar chain design.[101] Other engineers besides Brown also used this figure.

The study of the 4 sets of plans was limited to a consideration of the suitability, strength and durability of the structure. Gilbert and Seaward emphasised this in their report to the Trustees.[102] There were no comments on architecture or visual appearance which were a matter of taste.[103]

When it came to summing up and ranking the 4 designs in order of preference, the judges were somewhat ambivalent. All the plans had some merit. Brunel's proposal "has the important advantage of being adequately <u>strong in the most essential part, namely in the great chains;</u> but at the same time, the other details are very defective". After making some further comments on the other contestants' submissions, the order of merit was declared to be:

1. Hawks
2. Brunel
3. Brown

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[100] I. K. B. Letter Book 2, 4, 5, 6, 7, 8, 9.

[101] National Records Archives (Scotland) 400 MS letter Alexander Mitchell to Samuel Brown 28th July, 1831.

[102] Gilbert's report indicated that he arrived at his conclusions on the strength of materials required using his own "theorems and printed Tables. In other respects he was guided but not led by those of Mr. Seaward". Trustees Proceedings 17th March, 1831 45.

[103] Trustees Proceedings 17th March, 1831, 53.

### 4. Rendel[104]

The assessors counselled the Trustees against being influenced by the novelty of a particular design or the lowness of an individual estimate. Davies Gilbert and John Seaward's report to the Trustees was written from Blaise Castle and dated the 16th March, 1831. They had responded very quickly and without meeting the contestants personally.[105]

Brunel was, however, in Clifton when the result was announced and, as soon as he knew what had happened, he arranged through Jeremiah Osborne, the Trustees' solicitor, a meeting with the judges at Blaise Castle.[106] If Brunel's Diary is to be believed, what then followed was a 'tour de force' by the 24 year old engineer.[107] It seems that the details of the scheme which the judges had found to be "very bad" were really Seaward's view of the design and not necessarily shared by Gilbert. Brunel "talked over the old fool (Gilbert) until he returned to his original position viz. approval of all the details. Oh! quel homme!". Later that day, the 18th Brunel met the Trustees "D. G. having recanted all he said yesterday, I (Brunel) was formally appointed and congratulated by everybody".[108]

Other sources record this seminal event differently. According to Gilbert, "Mr. Brunel (Jun.) has given reasons for many of his modifications and explanations of others have proved satisfactory". He has "divided the two masses of chains into four by which security is obtained". Further, he has agreed to put the Bridge beneath the chain "to preserve a catenary entire". This account suggests a rational discussion of the major technical points with Brunel conceding his original position on a number of very important issues.[109] The proceedings of the Trustees for their meeting of the 18th March noted "Mr. Gilbert further stated that these Explanations had materially altered his original impression as to the Details of Mr. Brunel's Plan" and it was "quite

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[104] I. K. B. Letter Book 10.
[105] Ibid 10.
[106] Rolt 56.
[107] Brunel was born at Portsmouth on the 9th April, 1806 so he was 3 weeks short of his 25th birthday when he met Gilbert and Seaward at Blaise Castle.
[108] I. K. B. Diary 1, 17th March, 1831, 106; 18th March, 1831, 106.
[109] I. K. B. Letter Book 11.

equal to those in the Plan submitted by Messrs. Smith and Hawks" but as his plan was superior in strength it was better overall.[110] Gilbert thus rationalised his change of mind. Most importantly, none of the 3 other competitors was accorded an interview or given the chance of submitting second thoughts. Following this the Trustees "Resolved therefore that Mr. Brunel be appointed Civil Engineer for the construction of the Bridge and other Works".[111] The Bridge, as designed, was to be 600 feet between the points of suspension with a drop of 60 feet and a roadway 32 feet wide.[112] What Brunel did not record in his Diary was that he was requested to make the alterations to his design as had been agreed between him and Gilbert and to submit them to Gilbert for his further consideration.[113] Brunel's appointment was thus conditional. The triumphalism in Brunel's Diary must be read with caution, Gilbert had, in fact, prevailed.

Marc was, of course, pleased. He wrote in his Diary "Isambard appointed Engineer to the Clifton Bridge. The more gratifying that Mr. T(elford), Captain Brown & Mr.T(ierney) Clark[114] were his competitors and that, for my part, I have not influenced any of the Bristol people in his behalf either by letter or by interview with any of them".[115] This may have been so, but as soon as Brunel returned from Bristol Marc redoubled his efforts on his son's behalf, he had spent much time on the original submission, and devoted even more to designing the Bridge while Brunel himself continued to commute between his home in London and Bristol.[116] His work covered all aspects of the scheme, including the Egyptian archways. He personally paid Pugin £10 10s. for the exotic design which the Trustees eventually chose.[117] How much of the final engineering was the work of Marc and how much was that of Brunel cannot be determined but it is clear that Marc played a major role in the ultimate

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[110] Trustees Proceedings 18th March, 1831, 56.
[111] Ibid 18th March, 1831, 56.
[112] I. K. B. Life 53
[113] Trustees Proceedings 18th March, 1831, 56, 57.
[114] Marc's choice of engineers here is interesting. These were the only competitors who had direct suspension bridge engineering experience other than, of course, Marc himself.
[115] Marc's Diary 19th March, 1831.
[116] Marc's Diary 22nd, 23rd, 24th March, 8th, 9th, 13th, 15th, 16th, 19th, 21st, 22nd, 25th, 27th, 29th, 30th April, 2nd, 3rd, 6th, 7th, 9th, 11th, 12th, 13th, 14th, 16th, 17th, 18th, 19th, 20th, 21st, 25th, 27th, 28th May, 1st, 2nd, 8th June, 1831 et seq. continuing intermittently into 1832.
[117] Ibid 23rd April, 1831.

design, particularly in the critical aspects of the work such as the suspension chains, the bracing of the structure and other vital matters.[118] By some at least, he was seen as "the engineer of this magnificent work". One newspaper reported "Mr. Brunel, sen." in these terms, when describing the laying of the first stone of the Bridge by the Marquess of Northampton on Saturday, 27th August, 1836.[119]

Captain Samuel Brown reacted strongly to Brunel's appointment as Engineer to the Clifton Suspension Bridge. He said that the erection of the Bridge by any other person than himself would be an infringement of his patent. The Trustees were not prepared to get involved in the dispute so they told him that the alleged infringement was a matter for their Engineer.[120] Although Brunel's design used the bar chain principle, it differed from Brown's patent in that it did not use short intermediate links between the bars from which the rods carrying the deck were suspended. So, arguably, his patent was not infringed. Further, the possibility is that Brown's reaction was largely emotional cannot be discounted. He, no doubt, felt that the manner in which Brunel had approached Gilbert direct concerning his comments on Brunel's plans, when taken in conjunction with the close relationship between Marc, Isambard and Gilbert, was nothing less than collusion.

It is very easy for an observer or commentator 170 years later to accept that Brunel's appointment as no more than his ability justified but at the time his potential was unrealised and only in prospect. Then, as now, hard headed men look for an established track record, if they can get it, rather than potential when they are intending to commit their money. Marc Brunel was the guarantor for the risks they were taking in backing an unknown 24 year old.

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[118] Ibid 9th, 19th April, 1831.

[119] The provenance of the press cutting quoted here has not been determined but it is likely to have been a north east of England newspaper, probably Newcastle-on-Tyne. This cutting was found in a Professional Engineer's scrap book in the possession of the Civil Engineering Library at Imperial College, London. The engineer was probably William Chapman. The scrap book is entitled "Civil Engineer".

[120] Trustees Proceedings 19th March, 1831, 59.

Although Brunel had won the competition, he, with his father, continued to work on the design of the Bridge. It was never finished in Brunel's lifetime. The span was increased almost immediately to 702 feet, a length which, if the structure had been completed, would have made it the longest suspension bridge in the world at that time. Brunel also increased the length of the chain bars from 12 feet in 1831 to 18 feet the following year and finally to 20 feet in 1838 as manufacturing technology had improved between the date at which the bars were first designed to when the chains were finally ordered. He was anxious to minimise the weight and cost of the joints.

Brunel's design for Clifton lacked longitudinal stiffness in the bridge deck. In the years following 1831 he considered several methods by which the deck could be strengthened against side winds but he did nothing positive about it. It was left to John Hawkshaw and William Barlow to improve the design when the Bridge was actually built.[121]

## *Early Nineteenth Century Suspension Bridges in Retrospect*

The early decades of the 19th century saw British suspension bridge engineering develop and take the form it was to follow for the remainder of the century. During this period, it diverged from American and Continental, very largely French, practice, such that the U.K. became the home of a technology which was especially British, a technology which usually only found its way abroad in the wake of British engineers.

The technology was shaped by 2 engineers, Thomas Telford and Samuel Brown, and one scientist-cum-mathematician, Davies Gilbert. There were other "bit" players such as J. M. Rendel, William Tierney Clark, Marc Isambard Brunel and Isambard Kingdom Brunel, all of whom contributed to some aspect of the emerging technology but the main sources of inspiration were Telford, Brown and Gilbert. They were the most cited at the time and highly respected. Telford and Brown built bridges which at first at least appeared to be successful, although some were found to be wanting later, and Gilbert

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[121] Chrimes.

played a seminal part in the theory of suspended structures and was readily available to criticise, advise and assess any particular design.