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Menai Bridge (1818–1826) and its influence on Suspension Bridge Development

by

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1: INTRODUCTION

1:1. General. Although iron suspension bridges have existed in China over a timespan of many centuries, the first significant period of iron suspension bridge building in the western world occurred in North America c.1800. This development stimulated interest in Britain and an era began which led to the establishment of the suspension bridge for the largest spans. This period, dominated by Menai Bridge, effectively commenced in 1811 and was one of substantially progressive development for about two decades followed by a time of consolidation and occasional improvements. Iron suspension bridge building spread to France from c.1823 onwards with the subsequent emphasis, particularly after 1830, on suspension from wire cables. At the approach to the mid-century, the mainstream of development returned to the United States.

1:2. Early North American Practice. James Finley, an American Judge, erected a 70ft span suspension bridge for carriage traffic at Jacob's Creek in 1801 *[1]*. His design was patented in 1808 and by 1820 about 40 bridges on his plan are said to have been built in the United States *[2]*. Merrimack Bridge erected in 1810 with a main span of 244ft., marginally greater than the cast iron bridge at Sunderland and the same as Piscataqua timber bridge *[3]*, attracted attention to this type of bridge.

Finley had a reasonably accurate idea of the forces in his bridges. He knew that the maximum tension in the main chains occurred at the supports and also, the approximate extent to which chain tension reduced from the supports to mid-span. From experiments using cord, fixed at one end and passing over a pulley at the other support to a scale pan, he derived a realistic approximation of the relationship between the strength and amount of curvature of a chain suspended between two horizontal points (Table 1, cols 1 & 2). The values he obtained compare closely with the Author's theoretical approximation *[4]* Table 1, col 3).

DEFLECTION/ SPAN RATIO	ASSUMED ULTIMATE LOAD SUSPENDED AT HORIZONTALLY EQUAL SPACING ON 1in sq BAR OF 60,000 lbs/in^2 U.T.S. (lbs)	AUTHOR'S 2(Tsin ϕ) APPROXMN. (lbs)
1/30 (.033)	15,000	15,904
1/14 (.071)	30,000	33,176
1/9 (.111)	45,000	48,780
2/13 (.154)	60,000	64,238

TABLE 1. Finley's Relationship Between the Strength and Degree of Curvature of a Chain Suspended Between Two Points.*[5]*.

Finley's chain form of elongated loop, square bar, links and his recommended curvature were not taken up in Britain but the example of his bridges encouraged development generally. The American tracts, *[1, 6]*, containing details of his experiments and a plate illustrating details of a typical bridge (Fig.1) were almost unknown in Britain although brief details of some of his bridges were published in English periodicals of 1808 *[7]* and 1811 *[8, 9]* and in Pope's bridge treatise *[10]*. In 1817 Telford quoted from Pope that at Merrimack Bridge 'Horses and carriages pass freely at speed without any perceptible motion of the floors'. *[11]*.

Telford's experimental approach to suspension bridge design was similar to Finley's in some respects but this was probably coincidence. In any case Telford considered that "British dexterity upon superior material" would improve on the North American bridges. *[12]*.

2: MENAI BRIDGE PROPOSALS 1810-11 – USE OF WROUGHT IRON IN TENSION

2:1. Telford's Suspended Centering. In 1810 *[13]* Telford was directed to consider the best means of carrying the Holyhead Road across Menai Strait. In April 1811 he proposed suspending the centering for a 500ft. span cast iron arch at Ynys-y-Moch. (Fig.2). The centering was to have consisted of four parallel timber rib-frames spanning the waterway in sections supported by a series of 1½ in. sq. iron stays. These stays radiated in eights, two to a frame, at angles of approximately 12°, 15°, 20°, 30°, and 47° from the horizontal from timber tower-frames at each side of the bridge. Each stay was to have been continuous, presumably welded, from the rib-frame to about 50ft. from the tower-frame where it was attached via a flexible chain to a winch. A timber platform was to have been built across the first set of rib-frames adjoining each abutment. The iron stays were to have supported the leading edge of each timber rib-frame whilst it was being moved forward up the platform and into position. After fixing this frame and the stays, the process was to have been repeated from each side of the bridge until the middle sections met.

In his calculations Telford assumed the breaking stress of a bar to be 80,000lbs/in^2 (35.7 tons/in^2) and multiplied this figure by the cross-sectional area of the bar to give a "suspending power" of 180,000 lbs. His design in respect of the radiating ironwork was optimistic. The assumed breaking stress probably exceeded the true value by about 30% and also, he seems to have overlooked the extent to which the capacity of an inclined stay to support a vertical load reduces as its angle approaches the horizontal *[14]*. Although this was a preliminary calculation its shortcomings do reflect the general inadequacy of 'strength of materials' knowledge at the time.

Although the bridge was not built, the centering proposal was publicised in a parliamentary report *[15]* and Nicholson's Journal *[16]*. Suspension stay bridge designs were subsequently developed by Loudon *[17]*, Anderson *[18]*, Seward *[19]* and J.S. Brown of Redpath & Brown, Edinburgh, who designed and erected a wire stay footbridge of 110ft. span at Peebles in 1817 *[20]*. The basic concept envisaged by Telford eventually developed into an accepted engineering technique for large spans. His idea may have originated from the use of ropes to lower the iron arch ribs into position at Coalbrookdale Bridge *[21]*.

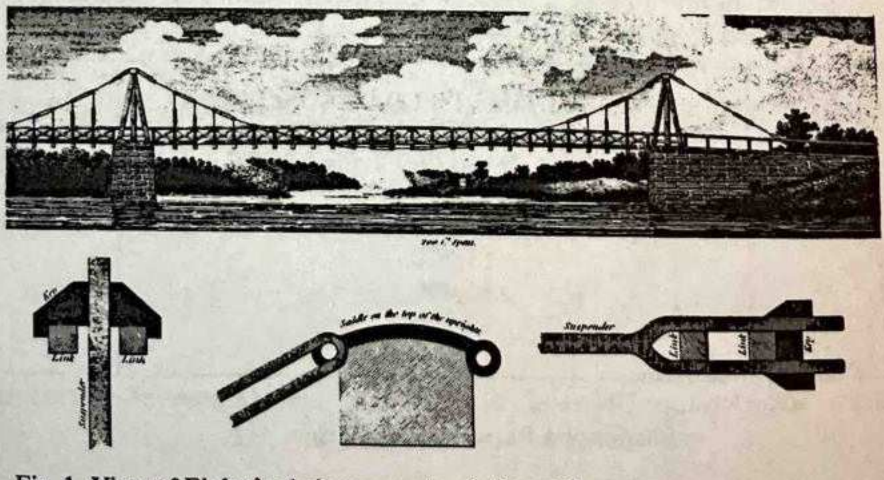


Fig. 1. View of Finley's chain suspension bridge. [6].

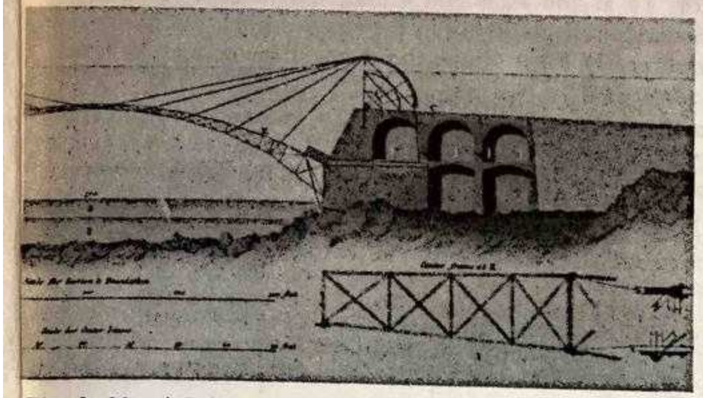


Fig. 2. Menai Bridge cast iron arch proposal 1811 – Design for suspended centering. *[15]*.

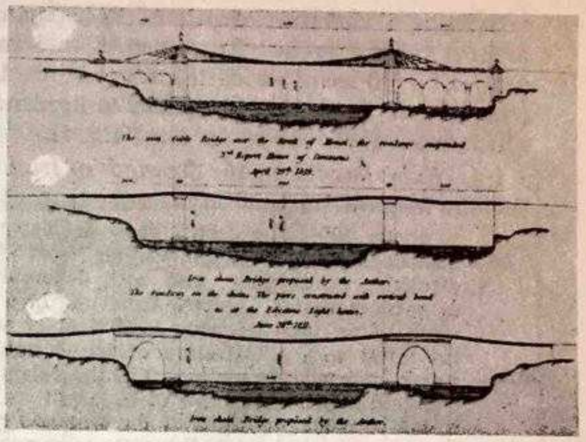


Fig. 3. Menai Bridge proposals – Ware's 1811 elevation (centre), alternative (bottom) and Telford's 1818-19 elevation (Top). *[32]*.

2:2. Ware's Chain Bridge. In June 1811 Samuel Ware, architect, prepared a design for Menai Bridge with a main span of 500ft. and two side spans of 250ft. *[22]* (Fig.3–centre). He proposed to lay thirty flat chain bars 12in. wide and 2.368in. deep, side by side and covered with timber planking to form a 30ft. wide roadway. The deflection at mid-span was to have been 15ft.8in. which would have resulted in maximum roadway gradients of 1 in 8. The proposal does not appear to have been seriously considered by the authorities, probably including Telford, to whom it was submitted. Drawbacks included the steep roadway gradients, the apparent lack of provision against undulation effects, inadequate side protection for traffic and visual unattractiveness.

3. RUNCORN BRIDGE PROJECT 1814-18.

Although never constructed this project is important in the context of the Menai Bridge and suspension bridge development.

3;1. 1814-17 (March) Proposals. In 1813 John Dumbell of Mersey Mills, Latchford, promoted a road scheme for considerably shortening the route between Liverpool and London, in which he envisaged bridge crossings of the Mersey at Runcorn Gap and Latchford being financed from the profits of a proposed fishery. *[23]*. The Runcorn Bridge proposal, which was based on the idea of a 'web of metallic rings', *[24]*, does not appear to have been designed in detail, but the bridge under consideration must have been of large span because it did not have piers in the navigable channel. According to a draft prospectus, the capital required by the Mersey, Irwell, and Weaver Fishery Company to finance the bridges at Runcorn and Latchford was £150,000 in 1500 shares, the first call on which was to be payable on 1 January, 1814. Copies of this prospectus were obtainable from Dumbell, secretary, and others including John Davies of the 'White Hart' inn, Runcorn; Claughton & Fitchett, Warrington; and Mr Nicholson, civil engineer, Bloomsbury Square, London. *[25]*.

On 14 February, 1814 Davies played host to a meeting to set up a 'Committee of Nine' to inspect and manage Runcorn Town business although he himself did not serve on that committee *[26]*. Shortly afterwards Telford was asked to give his opinion on the most advisable method of crossing the river. He dined with Davies at the 'White Hart' on or about 10 March and met others in the locality *[27]*. Telford seems to have envisaged a suspension bridge at the outset of the project as he immediately began to investigate the form and strength of iron chains already in use. Sites visited included Howell's Colliery on 11 March 1814, Chirk Colliery, an inclined plane for transporting limestone near Pontcysyllte and on 24 March, Black Park Colliery, Salop *[27]*. All these chains were of the short loop type.

Telford recommended that no design should be adopted which interrupted the navigational usage of the river and considered a suspension bridge to be the only practicable proposition *[28]*. After making an extensive series of experiments on the strength of iron he proposed a bridge with a central span of 1,000ft. and two side spans of 500ft *[29]*. It had 16 main cables in four rows each with a curvature depth of 1/20 span [30]. The roadways were to have derived additional support from a further 26 cables (8 underneath, 14 at the sides and 4 diagonal) with a curvature depth of 1/50 span, which introduced 1 in 12½ maximum gradients in the longitudinal profile. This arrangement would have provided a headroom of nearly 80ft. above the deepest navigable channel which was close to the south pier. (Fig.4).

3:1.1. Experiments on the Strength of Iron. In the spring and summer of 1814, mainly at Brunton's London Manufactory and in many instances using a pulley apparatus (Fig.5), Telford made [11]:

> ... above 200 Experiments upon malleable iron, of from one twentieth to one and a half inch diameter, and on lengths varying from 31 to 900 Feet. The Experiments were made perpendicularly, horizontally, and with different degrees of Curvature. The Results were, that a Bar of good malleable Charcoal Iron, one Inch square, will suspend 27 tons, and that an Iron Wire one tenth of an Inch diameter (100 feet of which weighs 3 lb. 3oz) will suspend 700 lbs, and that the latter with a Curvature or versed sine of one fiftieth of the Chord line, will besides its own weight suspend one tenth part of the weight suspended perpendicularly, when disposed at one fourth, one half, and three fourths of its length; and that with a Curvature of one twentieth of the Chord line it will suspend one third of the aforesaid perpendicular weight, when disposed in a similar manner. Experiments upon other diameters correspond sufficiently...

In some of these experiments the force was measured at which the permanent elongation of wrought iron bars began (Table 2).

EXPT.NO.	BAR SIZE (ins)	BEGAN TO STRETCH (t.c.q.lbs) (tons/in^2)	BROKE WITH (t.c.q.lbs) (tons/in^2)
1	7/12dia.	Broke before the force could be ascertained	
2	3/4sq.	15.5.3.4 (21.3) *	27.4 (27.2)*
3	8/10sq.	13. (20.3)	15.15.2.2 (24.6)
4	1&1/12sq.	16. (13.6)	32.6.0.4 (27.5)

Note: The values in brackets have been added by the Author for comparison purposes. The figures marked * have been computed from the corrected values published by Barlow [33] and not those from Telford's note book quoted in cols 3 and 4 above, which he had misnoted.

TABLE 2. Runcorn Bridge Project – Determination of 'Elastic Limit' and Ultimate Strength of Iron Bars in April - May 1814. [27].

From these experiments Telford observed stretching commencing at about 70% of the breaking load or about 18 tons/in^2, a high figure probably due to inaccuracies in Brunton's testing equipment. A value of 12-15 tons/in^2 would have seemed more appropriate. In design Telford adopted 15 tons/in^2 and 27 tons/in^2 for the stretching and breaking limits of wrought iron. [34] John Rennie in 1809 [35] and Capt. Samuel Brown in 1816-17 [36] had also carried out similar experiments but do not seem to have noted commencement of stretching values.

Telford's investigations into chain strength confirmed that the small link chain was not the most appropriate for application to the suspension principle. For this purpose he required that the 'metal should be kept as far as practicable in straight lines and also have few joinings.' [11] In 1814 two principal designs to the before-mentioned 500 ft; 1000 ft; 500 ft elevation were made out, one with wire cables and the other with composite bar suspension cables.

3:1.2. Wire Cables Design 1814. A design with 42 cables consisting of continuous parallel, strands of nominal 1/10in.dia. iron wire totalling nearly 15,000 miles (Table 3) came nearest to Telford's design precepts but was estimated to cost nearly £149,000, [30] about 75% more than the figure published in 1817 [37] for the alternative bar cable design. The respective cost estimates for the wire and bar cables were £56 and £25 per ton [38] for a design strength advantage in the ratio of about 37:27.

In this design a higher ultimate load value per wire was taken for the cables with a curvature depth of 1/20 span i.e. 684lbs (38.9tons/in^2) than for the 1/50 span curvature depth roadway cables i.e. 600lbs which indicates that Telford considered a larger safety factor necessary for the latter. From subsequent experiments at Ellesmere on a 900 ft length of 1/10 in.dia. wire

Telford obtained an average value of 630 lbs (35.8 tons/in^2). *[39]*. He constructed a wire model of the bridge 50ft long and considered to be 1/1200 part of its strength. Each suspension cable was probably represented by a 1/10in.dia. wire. The model, which was without proper joints or bracing, satisfactorily withstood a load of 3000 lbs, which was equivalent to about 1½ times the dead load on the central span. According to Provis the model would have carried considerably more weight without being injured. *[40]*.

POSITION IN BRIDGE	CABLES	DETAILS OF 1/10in.dia. WIRES 2010ft. LONG.					
	No. & Dia. (ins)	No. per Cable	Wt per wire (lbs)	Total weight (tons)	Defln mid span (ft)	Ultimate load per wire (lbs)	Power of Suspension (tons)
Below R/way	8 x 3.1	754	65	175.0	20	60 (600 x 0.1)	
Intermediate	6 x 2½	500	do.	87.1	do.	do.	349
15ft above Roadway	8 x do.	do.	do.	116.1	do.	do.	
Main cables	16 x 4	1256	do.	583.1	50	228 (684 x 0.333)	2041
Diag. braces	4 x 2½	500	do.	58.0	20	60	53

TABLE 3. Runcorn Bridge Project – Main Details of Wire Cables and their 'Power of Suspension' as Calculated by Telford for 1000 ft. span. *[30]*

In 1814 Telford also designed a wire cable suspension bridge of about 200ft. span to cross the Mersey at Latchford, near Warrington, probably at the site above Howley Weir mentioned by Dumbell in 1813 *[41]*. It was to have been a dual 12ft carriageway bridge with 6ft. central footway, a longitudinal roadway curvature depth of 1/50 span and a main cable curvature depth of about 1/14 span and estimated to cost £10,331.15s. *[42]* The suspension points were to have been about 24ft above the roadway. It was assumed that the main cables would suspend half of their ultimate strength i.e. 350lbs., which was much more efficient than the other curvatures proposed by Telford. William Alexander Provis, Telford's pupil from c.1805 *[43]* and later Resident Engineer for Menai Bridge worked out the details for both the Runcorn and Latchford Bridge designs. *[30]*.

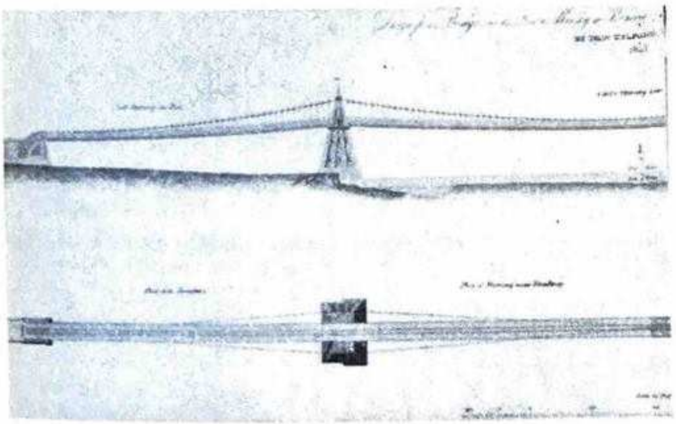


Fig. 4. Runcorn Bridge proposal 1814 – Elevation from mid-span to south abutment. *[32]*.

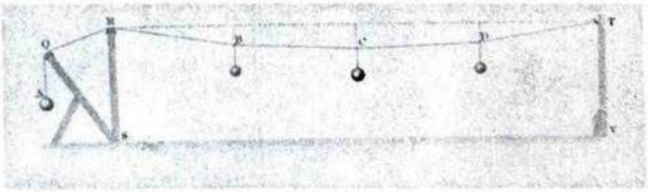


Fig. 5. Runcorn Bridge project 1814-18 – Apparatus for testing iron wire. *[32]*.

3:1.3. Bar Cables Design 1814-17. The bar cables in the upper curve were each to have consisted of 36 ½ in.sq. bars butt-welded to form continuous elements and making a 3 in. square, with an iron segment on each face to enable the bars to be pressed firmly together. *[34]* (Fig.6). Waterproofing was to have been achieved by filling interstices with a mixture of beeswax and resin, covering the surface of the cable with flannel saturated with this composition, and the whole firmly wrapped round with wire. Bucklings were to have been provided at 5ft intervals. A specimen length of cable was made up in association with Bryan Donkin, civil engineer, who supported its practicability. *[45]*

Telford envisaged, as he did for the wire design, that the stresses in the bridge would be equalised between the upper and lower cables and he used the same strength factors, *[11]*, but applied to a breaking stress of 27 tons/in^2. He designed for a maximum stress under dead and live load of about 13.2 tons/in^2. *[46]* But, on the same basis as for his experiments, this was exclusive of the stress induced in the suspension members by their own weight. On the same equalisation assumption the maximum stress in the cables due to a self weight of 530 tons would have been 4.9 tons/in^2 and the total stress, $13.2 + (0.52 \times 4.9) = 15.7$ tons/in^2 which compares with the value calculated in Table 4. This figure is too close to the probable true yield point of wrought iron, not the high value of 18 tons/in^2 obtained from Brunton's equipment, to have provided an adequate safety margin for the design.

3:1.4. General Progress. By 9 September 1814 Telford's work on the Runcorn Bridge project had 'matured'. *[47]*. Local discussions and meetings were held and although there seems to have been general agreement as to the usefulness of such a bridge no further steps were taken towards an actual start for about two years. *[40]*. On 22 August 1816, a public meeting to progress the project was held at Sandbach and adjourned to Runcorn until 22 October to receive plans. *[48]*. Plans and estimates were sought and received. The meeting on 22 October held at the 'White Hart', with James Cropper, a Liverpool merchant, in the chair and a numerous attendance, confirmed that it would be highly advantageous to have a bridge. *[49]*. John Fitchett of Warrington was chosen as Secretary and a Committee including local noblemen and gentry was formed to further the matter. Several plans were produced and referred to the consideration of the Committee. William Turner of Whitchurch required site information to enable him to complete a proposal.

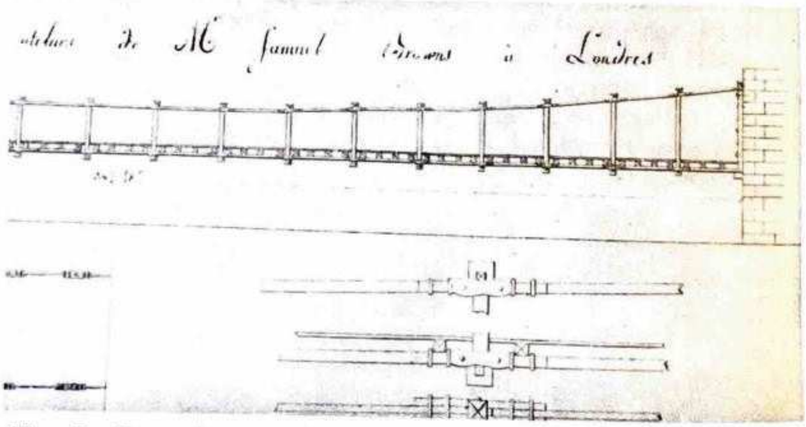


Fig. 7. Capt. S. Brown's large scale model bridge c.1814 – Half elevation. *[53]*.

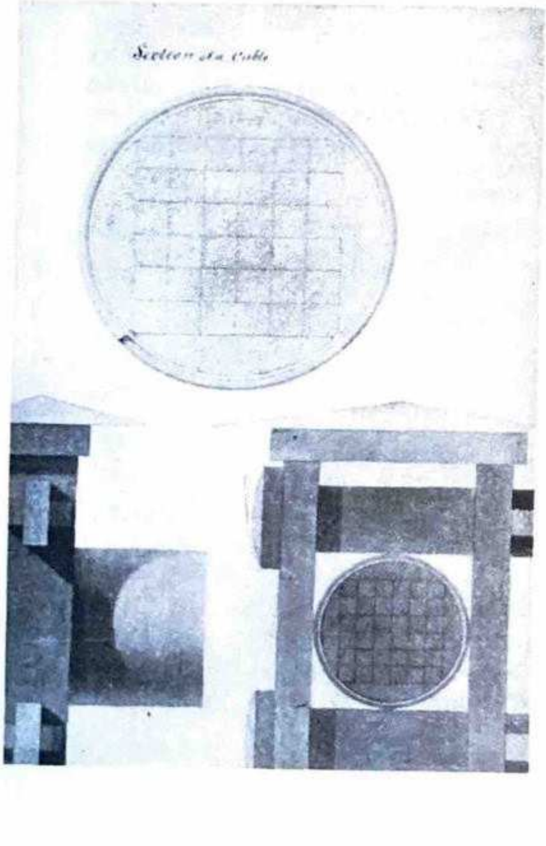


Fig. 6. Runcorn Bridge project 1814-18 – Proposed composite bar detail. *[44]*.

John Fletcher of Chester, canal engineer and surveyor and long-standing associate of Telford, offered to make and furnish a survey and section of the river at his own expense. The Committee found it impossible to discuss and decide on the matter at general meetings and on 27 January 1817 a Select Committee which included Fletcher, was set up under the chairmanship of Cropper to report on the most practicable and expedient mode of effecting the undertaking. Telford was consulted and asked to report on the best means of achieving this objective. *[50]*. In February Fitchett visited him in London and handed over for consideration the designs from 'engineers and artists from various parts of the kingdom'. *[50]*. On 13 March Telford reported in person to a Select Committee meeting at Liverpool in favour of a suspension bridge and commented on the designs received that only the plan submitted by Capt. Brown corresponded with the required principle. *[28]*. According to Provis, Brown's proposal was 'only a sketch of a chain'. *[40]*.

3:1.5. Telford and Capt. Brown. In February 1817 Telford and Fitchett visited Brown's chain cable manufactory on the Isle of Dogs and examined and travelled across a large scale model of an iron suspension bridge, presumably the one of about 100 ft span which Brown later stated that he had erected in 1813 *[51]* or 1814 *[52]*.(Fig. 7). They had *[28]*:

> ... a full conference with CAPTAIN BROWN in London, in the course of which he very distinctly explained his Ideas, and they in general very nearly corresponded with my own. I then communicated to him the whole of my Operations in 1814, which...first disclosed to him the true situation in which a Bridge was required, and convinced him of the propriety of having one great opening of 1000 Feet and one of 500 Feet on each side. He was also convinced of the propreity of having at least Eight Rods or Bars in the great Suspending Line of the upper Curve, (I prefer having still more) and likewise, instead of throwing the whole bearing on them, as he had formerly proposed, that a great advantage may be derived by forming the Roadway....in a Curve of one fiftieth part of the Chord line; thereby gaining additional strength, instead of leaving it merely a dead weight. His roadway is very ingeniously contrived of Timber...and...I think it had better in the first instance be adopted....I pointed out to CAPTAIN BROWN the manner in which his Roadway should be supported, tied and braced. This new view of the subject having deranged the proposals he had laid before the Committee, I furnished him with an outline of my Plan, to enable him to fill up and estimate the Expense of the Iron work under the sundry regulations upon which we had agreed.

The outline was received in Liverpool on 12 March 'with CAPTAIN BROWN's general notions as to the Iron Work and Expence' but Telford submitted his own modified proposal and estimate of £84,990 to the meeting on the following day as 'CAPTAIN BROWN still, in my opinion requires more local information and discussion to enable him to give a correct estimate.' *[28]*. The Brown design as modified, according to Telford, consisted of 8 main chains of flat 5 in. x 1½ in. links and the same at the roadway, to the spans and curvature depths of the 1814 Runcorn proposal. Brown's design had a suspending power of only 700 tons, *[38]* (Table 4), less than 1/3 of that provided by Telford's proposal. *[46]*. This implies a very light deck, probably 3 in. thick planks in a single layer resting on bearers, and in consequence a low cost estimate. The Committee decided unanimously that 'the principle of the proposed Bridge by suspension as recommended by Mr. TELFORD in his Report, is the one most applicable to the situation'. *[50]*.

This conference between Telford and Brown seems to have been the first technical meeting of the two leading British suspension bridge projectors of the early 19th century. Their work had developed on independent lines up to that time and continued to do so afterwards. Brown's qualifications and experience were inappropriate for building a major bridge, except in respect of his ironwork experience. For several of his subsequent bridge projects, including Union Bridge near Berwick, Brown worked in conjunction with an established bridge engineer. For example, Rennie designed the masonry system of Union Bridge, c 1819. *[54]*. Telford and Brown seem to have been unable to agree on the form, cross sectional area and curvature to be adopted for the main suspending members of the Runcorn project and, in the circumstances, there seems to have been little basis for a joint scheme. From April 1817 onwards they almost certainly developed their proposals independently. Within about four months Brown had prepared and submitted a patent for iron suspension bridges *[55]* which included a 1000 ft. span example in which the number of main chains was increased to 16, 4 rows of 4 flat bars. *[51]*. A model existed in 1817 which was probably for this proposal. *[56]*. Brown's patent not only included eye-bar links but also an arrangement that was almost identical with the square core of Telford's cable, except that the continuity of the bars was achieved by hooked, scarfed joints (Fig.8, near bottom). The patent did not cover individual chains consisting of a series of parallel eye-bars, possibly so as not to infringe Hawks' patent, *[57]*, although his links were much shorter.

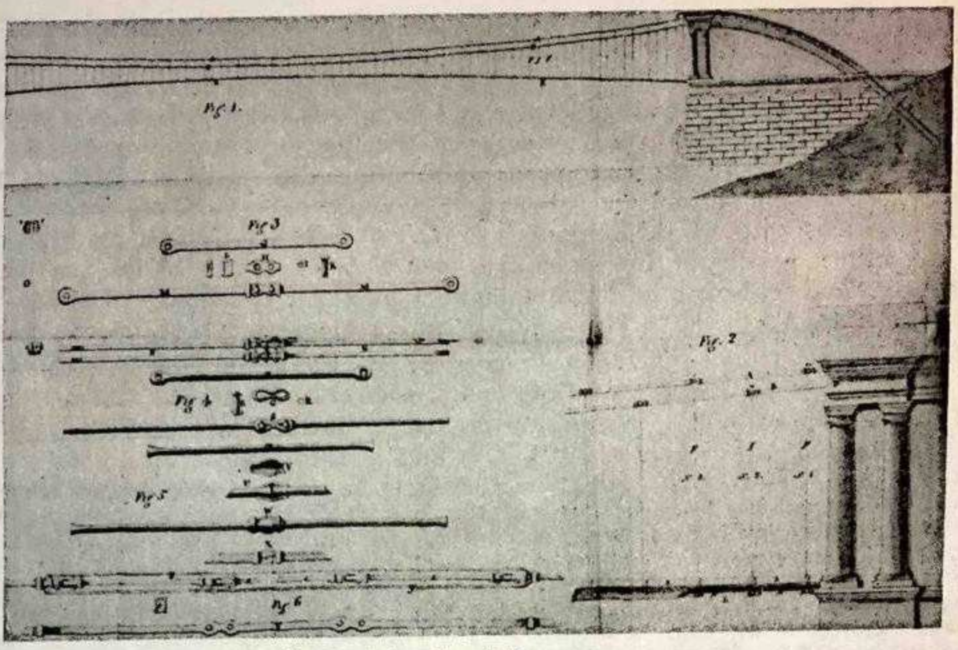


Fig. 8. Part of Capt. Brown's patent drawing. *[51]*.

3:2. **Modified design 1817 (July).** The Select Committee reported to the General Meeting on 8 April and a subscription list was opened but only £7100 was subscribed, including £100 from Brown. *[58]*. Liverpool Town Council's decision in February 1817 not to take any part in the scheme was a major setback. *[59]*. Efforts were made to produce a more economical design. The cables under and adjoining the roadway were abandoned, suspension being solely from the main cables. This measure eliminated the curved longitudinal roadway profile.

At a meeting on 20 May 1817 attended by Cropper, Harrison and Fletcher, Telford was directed to reconsider modifications including the bridge height to be 65ft. at the pyramids and 75ft at the centre, the main chains to come down to the bottom of the roadway at mid-span, the roadway to be 12ft: 4ft: 12ft. wide and formed of deal baulk and ash planks, the mode and dimensions of joining bars and the ironwork strength to be calculated at 14 tons/in^2. *[60]*. Fletcher seemed destined for a key role in the project under Telford's direction if it had gone ahead. Earlier in the year he had suggested to Telford making the main cables and the roadway of equal curvature thus making the suspenders of equal length. *[61]*. The question of suspender form and method of connection to the chains was also discussed.

In May Telford, Fletcher and Donkin conducted further experiments on the strength of iron at Brunton's and continued to obtain results which not seem unrealistically high by about 25%. *[62, 27]* Another experiment included the determination of the force required to pull each cable into position. A 7/8 in. sq. bar chain was suspended between points 125ft. apart and the forces required to bring the chain to curvature depths of 1/15.6 to 1/20 span were ascertained. Telford concluded that for a curve with a central deflection of 1/20 span a force of 2½ times the weight of the chain was required, *[27]*, a finding which he later applied in the design of Menai Bridge.

Following further reconsideration, the design given in Telford's supplemental report of 22 July 1817 emerged. It included for a timber roadway 10ft: 5ft: 10ft. wide and 70ft. navigational headroom for shipping. The main cables were brought down by 8ft. at mid-span to about 7ft. above the roadway. The height at which the roadway passed through the pyramids was lowered, which, associated with an increase in the approach gradients on the side span roadways resulted in a considerable saving in height of the abutments and approaches. *[62]*. The reduction of suspended weight on the central span by about 470 tons and the retention of the same main cable arrangements resulted in a maximum design stress of about 11.6 tons/in^2. (Table 4). The estimated cost of this modified design was £62,565.15s. *[63]*. The reports of the Select Committee and Telford were then printed. By 11th August the amount promised by subscription had reached only £12,500, *[58]*, a very disappointing outcome, but efforts to promote the project continued.

The Committee decided to verify for themselves, independently of Telford, *[64]* the strength of iron at the full span. An experiment was made using a rod of iron 1000ft. long over a valley near Liverpool and the strength of the iron was found to exceed the values calculated by Telford. This outcome and public exhibition of the findings resulted in greater support for the scheme and by May 1818 subscriptions had reached about £25,000, *[64]*, but this was still insufficient. A 20ft to 1 in. scale model of the bridge was made, probably in 1817, and existed at Ellesmere Port in 1905. *[65]*.

As Provis commented, the project had established a new era in the art of bridge building and 'the publication of Mr. Telford's design led to the construction of bridges and piers on the suspension principle in almost every part of the kingdom'. *[40]*.

4: MENAI BRIDGE 1818-26

This section of the paper partly supplements the information in Provis's finely illustrated classic folio, *[13]*, on the design and construction of the bridge.

4:1. 1818-19 Proposal. From 1815 onwards Telford was engineering the Holyhead Road across North Wales and it was becoming more urgent to decide on the method of bridging the Menai Strait. The suggestion for a suspension bridge probably resulted from the publication of Telford's Runcorn Bridge reports in 1817. *[43]*. In the latter part of 1817, *[66]*, Telford was asked by Vansittart, Chancellor of the Exchequer, to report on the practicability of a suspension bridge. On 16 February 1818, *[43]*, Telford was on site and by May had submitted an outline plan and report, *[67]*, for a 16 cable bridge at Ynys-y-moch (Fig.9) with a 560ft central chord opening, supported from cast iron tower frames with back-stays tied into masonry approach arches. (Figs. 3&10). He and other technical witnesses were called before the Holyhead Road Commissioners to give evidence on the practicability of a suspension bridge. The project received general agreement. Rennie preferred a chain to a cable but thought that there would be no injury to the bridge from wind. *[70]*. He had not made calculations as to the strength of the bridge but Barlow, *[71]*, and Chapman, *[72]*, had, although based on incorrect dimensions. Telford advised that the bridge could be built for £70,000 and within 3 years. This sum was much less than the previous cast iron bridge estimates by Telford and Rennie of £127,331 (1811), *[15]*, £268,500 (1802), *[73]*, respectively. In fact the bridge took about 8 years to complete and its constructional cost was about

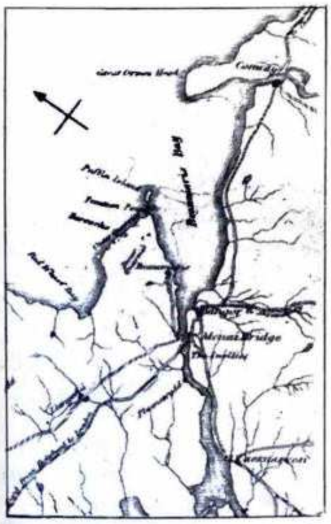


Fig. 9. Map of Menai Strait showing the bridge and quarry sites near Penmon Point, East Anglesey. *[68]*.

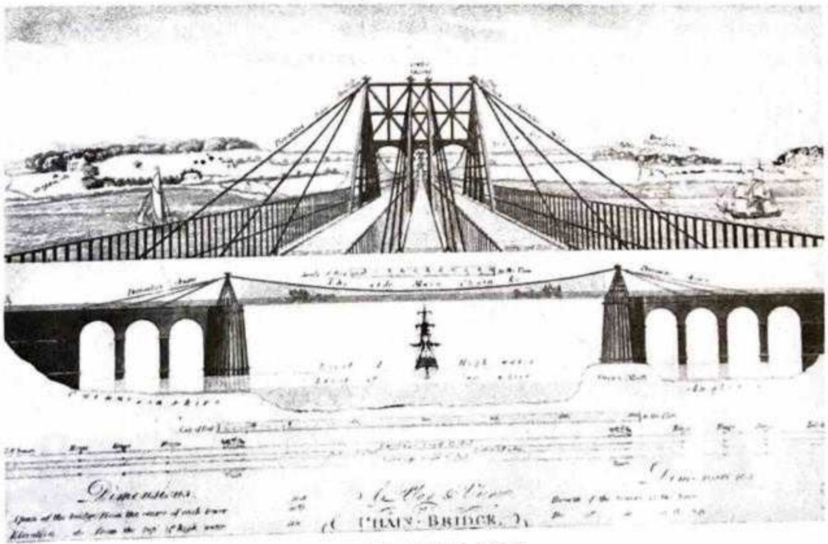


Fig. 10. Menai Bridge as proposed in 1820. *[69]*.

£178,000, (74), and not the usually quoted figure of £120,000 *[75, 76]*, but the structure as buil was larger and stronger than originally envisaged.

Provis was appointed Resident Engineer in June 1818 and preparatory work commenced. *[77]*. By the year end 30 masons, 100 quarrymen and others were engaged on preliminary work. *[78]*. The Act for the bridge was obtained in July 1819. The foundation stone of about 3 tons weight was laid in the base of the Anglesey pier on 10 August by Provis and Straphen & Hall, the masonry contractors. *[79]*. On 24 April 1819 Telford reported to the parliamentary Select Committee that the suspended weight of the bridge, *[80]*:

> ...is 342 tons: by numerous experiments...it appears, that with a chord line of 560 feet, and a versed sine of 37 (or a curvature of 1-15th), a bar of good iron, one inch square, will, besides its own weight, carry 10½ tons, and about one half of that weight before it begins to stretch. For the Menai bridge, I have taken a section of 192 square inches, which at 5¼ tons to each square inch, will support 1008 tons.

To guard against undulation effects he proposed making the roadway sides of framed ironwork. He continued:

> With a bridge 30 feet in breadth, and 532 feet in length there is not much to be apprehended from side vibration... contraction or expansion... with a difference of 90 degrees of Fahrenheit... about 5 inches upon 700 feet... The weight of the bridge is 489 tons, upon which, if 300 tons additional are placed, they make 789 tons. The pull of this weight at the abutments... is found by my experiments over a pulley... equal to about two and a half times the weight on the other side, or 1972 tons.

In this account Telford seems to have mistaken the tower height of 37ft for the central deflection instead of 30ft. as indicated by the drawing and his experimental result (sect.3:2). Rennie and Donkin, *[81]*, were called before the Select Committee and continued to support the proposal although Rennie advised increasing the strength of the chains by about 20%. *[82]*.

4:2. Design Modifications 1821 (July) and 1823. The principal modifications to the original design included, increasing the span to almost 580ft., raising the pyramids from 37 to 50ft. in height above roadway level, lengthening the main chains and anchoring them in solid rock and increasing their cross-sectional area and depth of curvature. *[83]*. With regard to the last two points Telford did not consider any change necessary but deferred to the opinion of Rennie in respect of cross-sectional area and Gilbert, *[84]*, and Barlow, *[83]*, for the depth of curvature. The cross-sectional area of the main chains was increased from 192 to 260in^2 and their central deflection from 30 to 43ft. Another important modification was the abandonment of the composite bar cable in favour of chain bars. This decision was taken some time between April 1819 and July 1821, probably in 1820. Telford was undoubtedly influenced in this matter by Brown's use of eye-bar links, although arranging the bars in parallel in an individual chain, represented an improvement on Brown's practice of parallel chains acting in individual lines. The Menai Bridge chain consisted of five parallel, rectangular cross-section, eye-bars screw-pinned together near their ends to short connecting plates to which the suspenders were attached. (Fig.11). The chains were arranged in 4 rows of 4 with suspension from alternate pairs in each line. The above modifications considerably increased the bridge cost.

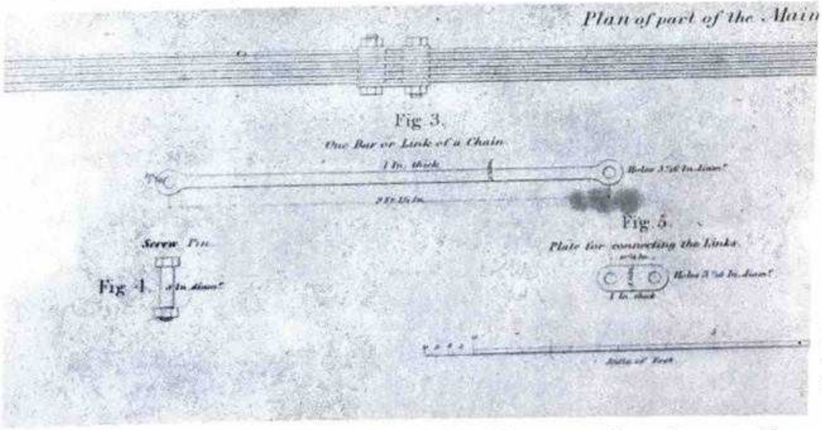


Fig. 11. Menai Bridge – Part of main chain, link, screw-pin and connecting plate. *[85]*.

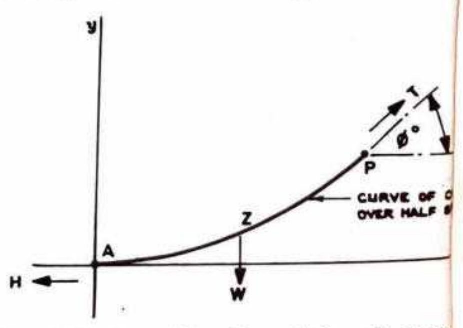


Fig. 12. Arc AP of a chain of comm catenarian form with horizontal force H maximum tension T. *[4]*.

Towards the end of 1823 the tower heights were increased by 2ft. so that the roadway at mid-span could be lifted a similar amount to avoid deck sagging with temperature changes. *[86]*. Later, a winter-summer differential of 11 ins. at mid-span was observed associated with a movement of about 1½ in at each saddle. *[87]*.

4:3. Theoretical Calculation 1821. The recommendation of Davies Gilbert, mathematician and Holyhead Road Commissioner, for increasing the strength of the bridge by adopting a deeper main chain curvature stemmed from the results of his investigations into the properties of the catenarian curve as applicable to suspension bridges in 1820. He calculated the maximum tension in the main chains of the 1818-19 Menai Bridge design to be equivalent to nearly three times the weight of the chains but assumed a central deflection of only 25ft. instead of 30ft. Gilbert then demonstrated that if the depth of curvature was doubled to 50ft., the maximum stresses would be reduced by nearly half and that in all cases likely to occur in practice the points of suspension of a bridge could not be too high. He simplified the use of catenarian equations by assuming that the maximum values of x and y (Fig. 12) would occur when the proportional rate of increase of chain tension T equalled that of y, which occurs when x is about 2/3 of y.

He also derived the following approximations for determining the forces in a chain at any point P :

$$H = \frac{zy}{2x} \quad \text{and} \quad T = \frac{z\sqrt{4x^2 + y^2}}{2x}$$

Chapman subsequently carried this approximation a stage further, where W is the total weight on 2y, by putting:

$$z = \frac{W}{2} \quad \text{and} \quad \sqrt{4x^2 + y^2} = y = \frac{L}{2}$$

in Gilbert's equation to give:

$$H = T = \frac{WL}{8x}$$

which he applied to a Tyne bridge proposal for linking North and South Shields in 1825. *[88]*.

In 1827 Gilbert was 'highly gratified' in acquiescing to Telford's request for permission to include a reprint of the paper of 'our learned scientific master', *[89]*, on the mathematical theory of suspension bridges in Provis's work. *[90]*. Gilbert, then president of the Royal Society, considered Menai Bridge one of the greatest undertakings ever executed. Telford was elected F.R.S. in the same year.

Ware published a calculation in 1822 claiming that the 1818-19 design was deficient in strength and that nearly 50 cables were required instead of the 16 proposed. *[91]*. His calculation was however incorrect being based on an unconfirmed strength value and the mistaken assumption that a wind force of 49.2lbs/ft^2 acted vertically. *[92]*. He also made this assumption in calculations for his own proposal. *[22]*. (Table 4).

Although experimental procedures were adopted for all the bridge design processes, Telford had recourse to calculation on at least one occasion. In March 1821 he requested James Jardine of Edinburgh, mathematician and civil engineer, to calculate the maximum tension in the main chains for the 1818-19 design due to their self weight with central deflections of 35, 40 and 45ft. *[93]*. This information supplemented his experimental findings (sect.3:2) for smaller degrees of curvature and enabled the design to be finalised without recourse to further experiments at that time. In 1823, these values were determined experimentally. *[94]*.

4:4. Masonry Work. The stone used in the bridge is a hard limestone obtained from quarries near Penmon Point, Anglesey. (Fig. 9). Straphen & Hall were the original masonry contractors for about 8 months until 30 March 1820. After remonstrations that they were not proceeding with sufficient energy they resigned their contract. *[95]*. It was taken over at the same rates by John Wilson, one of the principal masonry contractors for the Caledonian Canal. From 1818 onwards repeated storms affected the delivery of stone shipments by sea and caused delay in terms of years. In 1822 alone three ships, the *Sally*, of 70 tons, the *Alice-Ann* and the *Winsford* were wrecked. *[96]*. By 1823 the masonry was mainly completed to roadway level. *[97]*. The dowelled masonry towers were completed in 1824. *[98]*. The expense of the masonry work, the most costly part of the bridge, amounted to about £88,000. *[74]*. This work is still in very good condition today.

4:5. Ironwork Manufacture. The contract with William Hazledine for the manufacture and delivery of the ironwork was entered into soon after the drawings had been made in July 1821. *[99]*. The ironwork was manufactured at Upton Forge *[97]* and finished and tested in Hazledine's Coleham, *[100]*, workshops at Shrewsbury. Most of it was transported to Menai via the Ellesmere and Chester Canals and by sea from Chester. Every operation in connection with the manufacture, finishing and testing by ironwork was performed under the inspection of John Provis, brother of William Provis. The scale of the ironwork was unprecedented. The 16 main chains were each 1710 ft long and consisted of 14,960, *[101]*, eye-bars approximately 9½ ft long, about 18,000 connecting plates approximately 1½ ft long and some 6000 3in dia. screw-pins 16 in. long. *[85]*.

Hazledine's facilities were originally inadequate to meet the technological challenge of the work and the first cargo of main chain bars was not delivered at Menai until 31 October 1822. *[96]*. In the winters of 1822-3 *[97]* and 1823-4 *[94]* the forge at Upton was flooded several times. Considerable difficulty was experienced in obtaining bars of the correct length when the holes were hot-formed and from 1823 onwards they were cold-drilled on site using a specially constructed machine. These and other setbacks resulted in an insufficient quantity of ironwork at the bridge in the summer of 1824. *[102]*.

On 30 June 1824 the Commissioners expressed concern about the great delay in finishing the ironwork and asked Telford to consider and report whether it might not be advisable to offer the Conway Bridge ironwork to some other contractor. *[103]*. This did not prove necessary as measures taken by Hazledine at Shrewsbury to improve the production rate were already taking effect, including new workshops and a larger steam engine to power machinery for turning saddle rollers, punching eyes and cutting screw-pins.

A question that has arisen subsequently in connection with the ironwork is whether Hazledine sub-contracted any of the link-making to the Penydarren works at Merthyr? This provenance is not acknowledged in the publications of Provis or Telford, but according to Wilkins, a later writer with knowledge of the Welsh iron industry, Penydarren Works made 'cable...for the bridge which spans the Straits of Menai'. *[104]*. In April 1826 the Commissioners received a memorial from Hazledine stating he had undertaken the contracts at very low prices and that from the unexpected and unprecedented rise in the price of iron from £8.10s. to £14.10s. per ton, he had, especially during the last 9 months, sustained very heavy losses. *[105]*. Telford was sympathetic to the claim and computed that the increase had been £3131 and £1042 for Menai and Conway Bridges respectively, but the claim does not seem to have been met. Payments to Hazledine for Menai Bridge commenced about August 1821 but by December 1822, *[106]*, had amounted to only £2645 out of an eventual total of about £68,000. He received £6593 for Conway Bridge ironwork. *[107]*.

4:6. Ironwork Proving and Fixing. Every main chain bar and connecting plate was proved by John Provis with a force of 35 tons or about 11 tons/in^2. *[108]*. After testing the bar or plate was tested for permanent deformation and if satisfactory, stamped with Provis's proof mark, an indented cross. Of 35,649 bars and plates tested about 6.7% were discarded, of which most of the bars were either too long or too short and many of the plates imperfectly welded under the forge hammer. *[110]*. A good many of the bars failed near their ends probably from repeated heating and cooling whilst the eyes were being formed.

The saddles and anchorages were designed in the latter part of 1822. Thomas Rhodes, who had worked for Telford on the Caledonian Canal, commenced superintendence of the ironwork fixing in March 1823 and on 31st March the first anchorage casting was fixed. *[97]*. The most intensive period of ironwork erection began in the Spring of 1824. The 1 in. x 3¼ in. bars for the side spans were assembled on scaffolding in close proximity to their final positions. In the tunnels leading to the anchorages the chains were fixed from the castings towards the piers to meet the chains fixed from the saddles downwards. On completion of the side spans the chains for the central span were floated out. attached to a tail end of chain hanging down the face of the Caernarvonshire tower, (Fig.14), and then hoisted up to the saddles on the Anglesea tower by means of specially designed capstans. All 16 chains were erected from 26 April to 9 July 1825, 9 of them taking less than 2 hours to put up. *[112]*. Payments to Rhodes amounted to about £11,000 in respect of Menai Bridge and £2087 for Conway Bridge. *[107]*. About £3200 of the Menai sum was spent in combating undulation and its effects during the months immediately following the opening of the bridge on 30 January, 1826.

4:7. Undulation. In October 1825 when work was in progress on the deck, Telford asked Rhodes for a report on side vibration and vertical undulation. Rhodes had observed that when the chains were hanging singly with a gale of wind the vibration was from 6in. to 8in. each way. If the wind struck obliquely the undulation was considerable but when the chain was connected with the short suspenders these motions were reduced. When the roadway was begun the undulation and vibration was very great and the men had great difficulty in standing:

> ...the motion resembles much a ship riding at anchor when blowing fresh ...we are now nearing the first tier of plank down to the roadway bars & at every strake that is fastened I perceive it gets stiffer... *[113]*.

By the end of December, after a storm, the question of additional ironwork was under active consideration. Rhodes suggested restraining the movement of the chains by 4, 5, or more lines of rods 1 inch square radiating from the corner of the base of the suspension pillar at the roadway. *[114]*. On 4 and 5 January 1826 more gales occurred resulting in very considerable undulations which compelled the workmen to leave the bridge. *[115]*. On 10 February 48 suspenders were found to be broken at the roadway bar bolt holes. *[116]*, (Fig.15). Several days later a considerable number more were broken. Rhodes suggested the introduction of a pin-jointed section to replace the roadway ends of the suspenders *[117]*, but this idea was not adopted at that time. Rhodes and Provis believed that gusts of wind first deranged the chains and then deck undulation followed. Transverse chain bracing was incorporated into the bridge during the early summer of 1826. The maximum undulation in the severest storm before its provision was said to be about 18in. and afterwards never exceeded 6in. (to 1828). *[118]*.

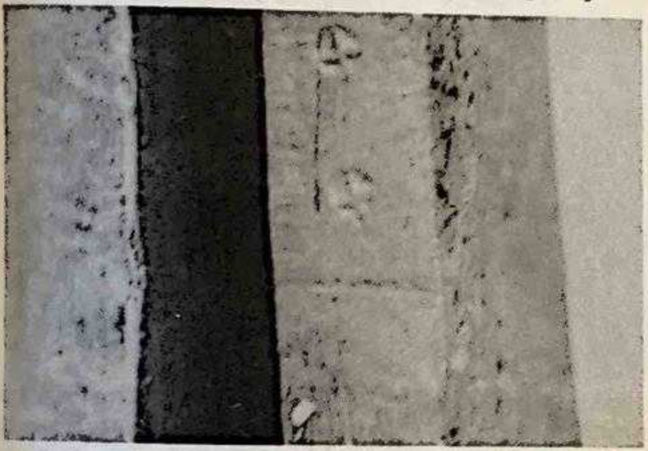


Fig. 13. Menai Bridge main chain bar – Provis's proof mark on 1" edge. *[109]*.

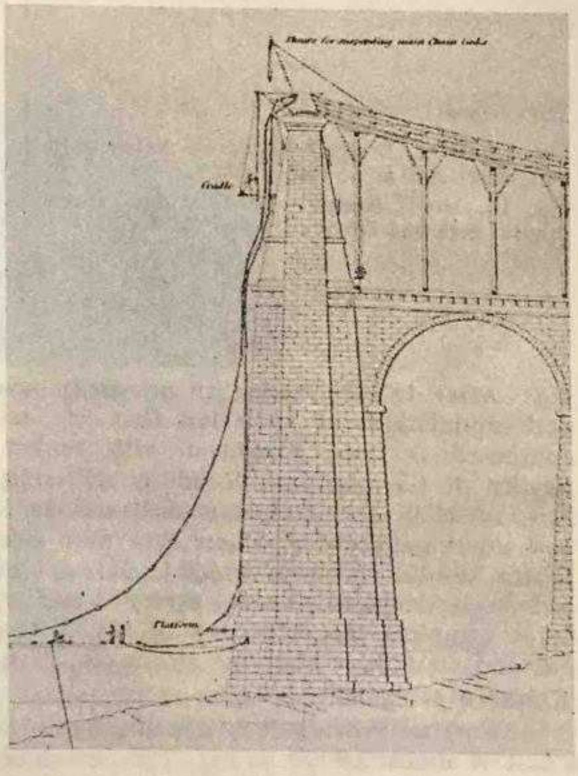
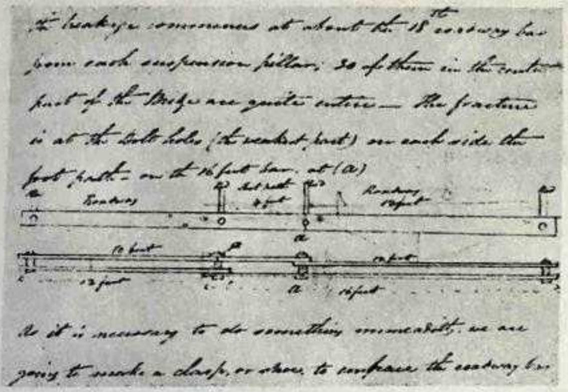


Fig. 14. Menai Bridge – View of Caernarvonshire tower immediately before the first chain was erected on 26 April 1825. *[111]*.

Henry Palmer, who had assisted Telford during the early years of the project, later confirmed that the probability of deck trussing being required had been foreseen, but that Telford, after anxious consideration, had decided to omit it initially and to adopt it later if necessary. *[119]*. In 1832 the bridge was said to be 'unimpaired and in perfect security' *[120]* and it was not until 1836, after Telford's death, that further problems arose.

The torsional undulations problems at Menai Bridge made Telford cautious about extending the spans of suspension bridges, although in July 1826 he proposed a road bridge at Runcorn with a central opening of 800ft. and estimated to cost £155,872. *[121]*. This may be the bridge, although it seems unlikely, that Telford had in mind when he reviewed the Menai Bridge design with Rhodes in October 1825. *[113]*. Rhodes would have retained the 5-bar chains but of 1 in. x 3½ in. dimensions and 15ft. long arranged in 4 rows of 3 with suspenders at 5ft. intervals hanging from each chain in turn, which would have been a better suspension arrangement than at Menai Bridge. He also thought that the link manufacture could be improved by turning the pins true, boring the links correctly to length and passing the ends through a rolling mill.

For Clifton Bridge, with its deck 200ft. or more above the river, Telford considered 600ft. to be a proper span limit. *[122]*. This constraint influenced Brunel's accepted design early in 1831 although, shortly afterwards, he adopted a span of 702 ft with a suspended roadway length of 636 ft. *[123]*.

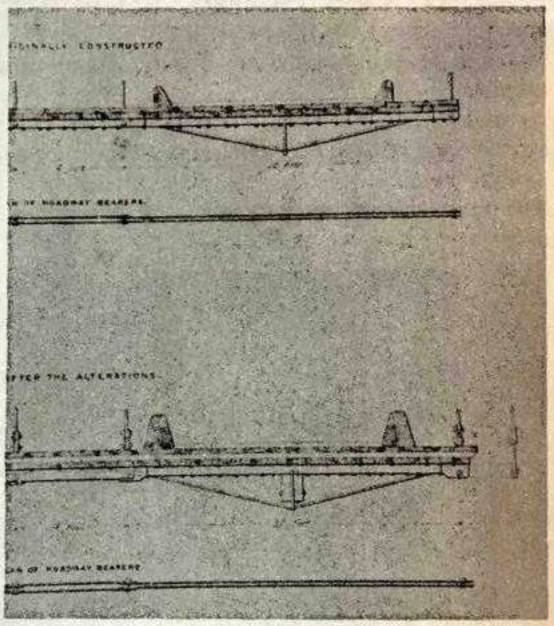


the breakage commences at about the 18th roadway bar from each suspension pillar; 30 of them in the centre part of the Bridge are quite entire — the fracture is at the bolt holes (the weakest part) on each side the foot path — on the 16 feet bar, at (a)

As it is necessary to do something immediately, we are going to make a clasp, or shoe, to embrace the roadway bar

Fig. 15. Menai Bridge – Rhodes's sketch showing suspender bars fractured at the roadway bar bolt holes a-a. *[116]*.

Fig. 16. Menai Bridge – Part of the cross-section of the original deck and Provis s 1839-40 deck. *[127]*.



4:8. After 1834. During an unusually severe gale in January 1836 the Bridgemaster observed deck undulations of 'little less than 16 feet' amplitude. *[124]*. Provis considered that ten years continued friction, combined with timber shrinkage, had considerably affected the original rigidity of the platform. Roadway stiffening was recommended but nothing was done and on 7 January 1839 the deck sustained serious damage in a storm. The suspending rods were bent backwards and forwards where they were held fast at the roadway surface and many broke. Damage to the central footway, which could still be crossed, and to the main chains was slight, three bars being damaged. Rhodes surveyed and reported on the damage to Provis who prepared plans for a complete reconstruction of the platform. In the meantime immediate repairs were carried out and four days after the storm one carriageway was reopened and by 21 January the whole bridge was reopened. *[125]*.

Work on Provis's deck was in progress in May 1839 and completed by the summer of 1840 at a cost of almost £9000. *[126]*. The new deck was 130 tons heavier than the original. New features included longitudinal stiffening beams under the roadways, hinged cross beams and pin-joints in the suspenders close to the roadway surface. (Fig.16). Hazledine was paid £1510 for ironwork, Blundell Falk & Co. £2245 for timber and Provis £4765. *[126]*. The timber was kyanised and the Anti Dry Rot Co. were paid £109 for corrosive sublimate. Provis's deck lasted 53 years being replaced in 1893 with a steel deck designed by Sir Benjamin Baker. *[128]*.

In 1922 Tudsbury and Gibbs made a thorough examination of the bridge. The chain bars in the tunnel sections leading to the anchorages were little corroded and did not give rise to any anxiety. Of the main chain bars in the open air the majority were found to be in good condition. 110 bars were considered to be badly corroded and 7 excessively corroded. In respect of the 110 bars, in no case did any chain of 5 bars contain less than the intended design cross-sectional area. *[129]*. Strain gauges were applied to the chains at several locations. The maximum recorded dead load stresses near the supports were found to be in the range of 5.76 to 8.18 tons/in^2. *[130]*. Later investigations using the Maihek extensometer indicated values between 6.5 and 7 tons/in^2. *[131]*. The breaking stress of bars tested by the National Physical Laboratory ranged from 18.4 to 23.4 tons/in^2 and the yield stress from 12.2 to 15.1 tons/in^2. *[132]*. After being continually stressed for about a century the iron still possessed what was probably its original order of strength. The saddle rollers did not rotate, one examined being badly corroded but the dowelled masonry of the towers was in good condition. The general condition of the saddles was considered very unsatisfactory, but in general the bridge emerged creditably from its inspection.

Although there were some doubts about the strength of the structure, it was not until 1938-41 that Baker's deck and the main chains were replaced to a design by Sir Alexander Gibb and Partners. This reconditioning of the bridge does not seem to have been dictated so much by any particular structural deficiency as old age generally and the need for a greater carriageway capacity to facilitate the movement of an increasing volume of modern traffic. Fig. 17 shows the original carriageway layout.

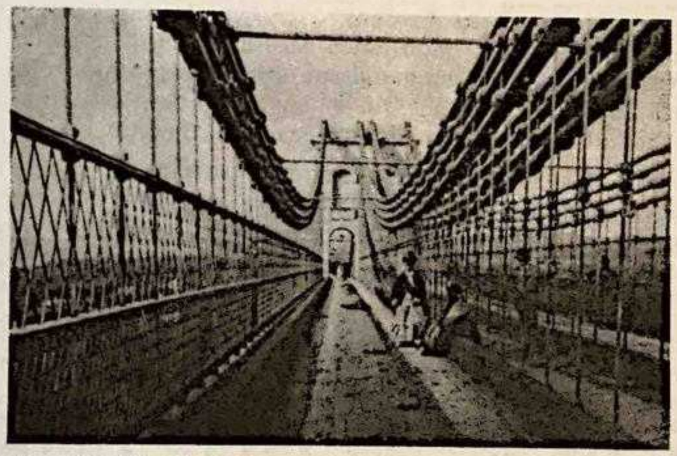


Fig. 17. Menai Bridge – Early view of platform. *[133]*.

The damage to Menai Bridge in 1836 and 1839 followed a succession of suspension bridge disasters at Montrose (1830), *[134]*, Morpeth (1830), *[135]*, Broughton, (1831), *[136]*, Yore (1831), *[137]*. Stockton railway (c 1832), *[138]*, and Brighton Chain Pier (1833). *[139]*. These failures resulted in a disenchantment with this type of bridge generally which seems to have lasted until about the mid-century. By this time Provis's reconstructed deck at Menai Bridge and J.M. Rendel's substantial longitudinal trussing at Montrose Bridge (1840), *[140]*, were proving effective with time. Another factor which tended to increase confidence in suspension bridges was the success of Hammersmith Bridge (1824-7), *[141]*, Hungerford Footbridge (1841-5), *[142]*, and most of the economical Dredge stay bridges of which about 50 had been built from 1836 - 50. *[143]*. The last of the large span, wrought iron, parallel bar chain bridges included

Pesth (Budapest 1840 - 49), *[144]*, Portland Street, Glasgow (1851 - 3), *[145]*, Victoria, Chelsea (1854-8), *[146]*, and Clifton (1830-64). *[147]*.

5: DESIGN INFLUENCES AND CONCLUSIONS.

5:1. Runcorn Bridge Project. The Runcorn Bridge project encouraged the adoption of suspension bridges for achieving clear spans greatly in excess of those of existing bridges of all types. Telford and to a lesser extent Brown provided the technical credibility. Whether their proposed designs would have proved successful in practice is questionable. The main significance of the project is that it provided a basis for subsequent suspension bridge design and construction, particularly for Menai Bridge. Telford's experimental work on the strength of iron in tension was unprecedented in range and detail and contributed to 'strength of materials' knowledge for many years through the publications of Barlow, Navier, Drewry and others. Telford's proposed use of parallel wire cables in 1814 supported by the making and testing of a 50ft. long wire model is of considerable historical significance in the evolution of the suspension bridge, being unprecedented on this scale and conceptually close to modern practice. This proposal and its composite bar successor were probably feasible but eye-bar chains, the promotion of which was greatly forwarded through this scheme, can be considered to have offered a more practicable and economical alternative.

5:2. Menai Bridge Project. The Menai Bridge scheme exercised a fundamental influence on the construction and development of suspension bridges from 1818 for several decades. It established this type of bridge in its true role as the most economic means of providing the largest bridge spans for carriage traffic in the western world. This claim can be made for Brown's Union Bridge, *[148]*, which although started about a year after the Menai Project, was finished first, but Union Bridge was less than one-third of the length, height and weight of the Menai Bridge, *[149]*, and at a sheltered location.

The project also provided a basis for improvements in suspension bridge design practice by example and through the previously mentioned publications of Gilbert, Navier, Provis, Drewry and others, including Cresy, *[150]*. The evolution of underground solid rock anchorages was a development of particular significance. Other improvements relating to the curvature and stresses, undulation and theoretical developments are considered below.

5:2.1. Parallel Bar Chains. This innovation represented an improvement on Brown's arrangement as it was more adaptable to large cross-sectional areas and the catenary of uniform strength. Leading designers, including W.T. Clark and I.K. Brunel subsequently adopted and, assisted by developments in iron technology and structural theory, improved on the basic Menai Bridge chain.

5:2.2. Chain Curvature and Stresses. The Menai Bridge project influenced the adoption of greater and consequently more efficient depths of curvature in suspension bridge chains and also safer chain stresses. (Table 4).
In 1814 Telford and Brown adopted shallow curvature depths of main chain, in the range 0.02 to 0.05 of the span at mid-span, believing that this practice would minimise the effects of vibration and the uncertainties and expense of providing adequate towers. For small spans Telford's practice differed from Brown's. The degree of curvature of the main cables at Latchford Bridge (0.07 span) was about three times more efficient in strength terms than the chains of Brown's works bridge (0.032 span). The published chain curvature depth given by Telford for the mid-span of the 1818-19 Menai Bridge design was 1/15 (0.066) span. From 1821 onwards most designers, including Brown, adopted curvature depths in the range 0.066-0.10 of the span which represented a significant improvement. During the second decade of the 19th century there was a considerable variation of practice in respect of superimposed loading and design stresses, some of the latter probably being beyond the yield point of wrought iron. Finley's practice with regard to design stresses appears to have been efficient, but his work was either unknown to or disregarded by British engineers. Telford's adoption of a dead load maximum stress of about 6 tons/in^2 (9.7 tons/in^2 with 300 tons live load) in 1818 represented a significant step forward. In 1821 these stresses were further reduced to about 4.3 and 6.3 tons/in^2 respectively. Although Brown seems to have been influenced to some extent by this downwards trend in his Union Bridge design he adopted maximum stresses nearly double those of Telford thereafter, and at least two of his bridges, Montrose, *[134]*, and Stockton, *[138]*, suffered

from over-stressing of their main chains. In 1829 Brunel considered 8 tons/in^2 as a maximum working stress but in 1830 he reduced this to 6.5 tons/in^2, almost the Menai Bridge figure, and eventually to 5.0 tons/in^2 in 1838. *[153]*. Navier took a great interest in the Menai Bridge project, *[154]*, and adopted an almost identical span and chain curvature for Paris Suspension Bridge (1823-6). *[155]*.

TABLE 4. APPROXIMATION OF THE MAXIMUM STRESSES ADOPTED FOR THE MAIN CHAINS OF MAJOR SUSPENSION BRIDGE PROJECTS 1810-21 IN CHRONOLOGICAL ORDER *[152]*.

PROJECT DESCRIPTION	MAIN SPAN (ft)	DEFLECTION/ SPAN RATIO	TOTAL LOAD CENTRE SPAN (live in tons)		MAXIMUM CHAIN STRESSES DUE TO:-		
					Chain weight (tons/in^2)	Total dead load (tons/in^2)	Total dead & live load (tons/in^2)
Finley's Proposal, c1810.*[5]*	300	0.154	140			7.2	
Menai Bridge Proposal, Ware, 1811.*[22]*	500	0.031	1314	49.2 lb/ ft2 wind			1.6
Runcorn Bridge Proposal, Telford, 1814. (Bar cables).*[46]*	1000	0.050 and 0.020	1700	100 (a)	4.8	14.4	15.3
Latchford Bridge Proposal, Telford, 1814. (Wire cables).*[42]*	200	0.07 and 0.020	296	16 (b)	1.2	8.1	9.4
Runcorn Bridge Proposal, Telford, July, 1817 (Bar cables).*[34]*	1000	0.050	981	100 (a)	3.3	10.4	11.6
Runcorn Bridge, Capt. Brown's modified proposal, Mar.?, 1817.*[46]*	1000	0.050 and 0.020	451	100 (a,c)	5.5	13.0	16.0
Brown's Patent Proposal, July 1817.*[51]*	1000	0.040	(d)	100 (a,c)	4.2 – 4.8	11.1 – 14.7	12.7 – 16.3
Forth Bridge Proposal, Anderson. 1818. *[18]*	2000	Insufficient details to make a calculation but the project was over-ambitious.					
Menai Bridge Proposal, Telford, 1818-19. *[80]*	560	0.054 (0.066)(e)	789 (789)	300 (300)	1.9 (1.6) (e)	6.0 (5.0) (e)	9.7 (8.0) (e)
Menai Bridge, as built, 1819-26.*[149]*	**579.9**	**0.074**	**940**	**300**	**2.6**	**4.3**	**6.3**
Union Bridge, Berwickshire, Brown, 1819-20.*[151]*	**432**	**0.060**	**172**	**47**	**1.4**	**8.1**	**11.3**

Bold type indicates projects which were actually built.

a. 10 waggons of 10 tons.

b. 4 waggons of 4 tons.

c. Assumed from contemporary data for comparison purposes.

d. Probably between 676 and 892 tons.

e. Based on the incorrect central deflection (4 : 1) published in 1819.

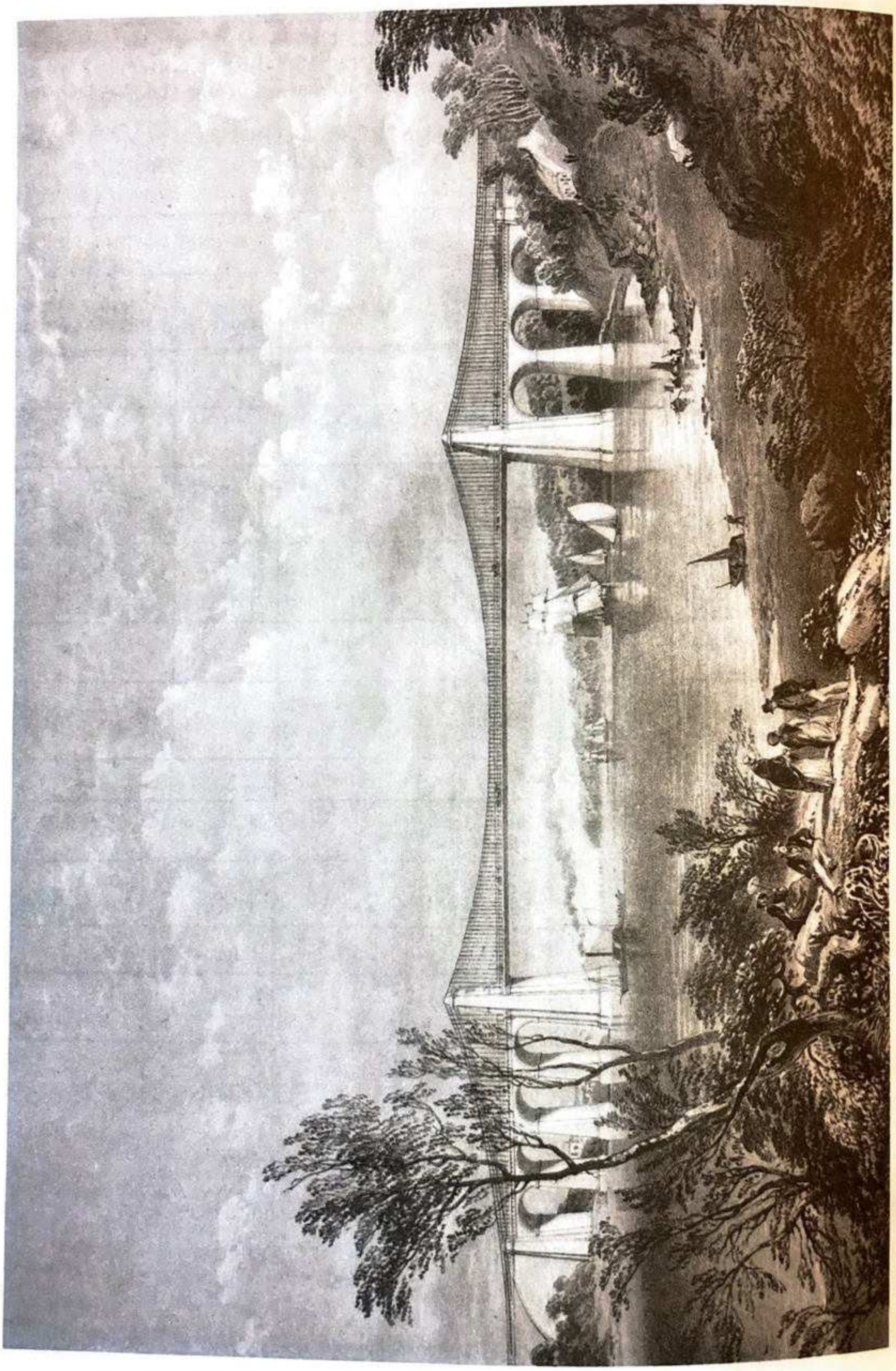


Fig. 18. Menai Bridge c.1850. From a lithograph by G. Hawkins.

5:2.3. **Undulation.** The instructive example of the effects of undulation by observation and through the authoritative accounts of Provis influenced development work towards a solution of the problem by Clark, Rendel, Barlow, Brunel and Provis himself. For Hammersmith Bridge completed in 1827 Clark made and wind-tested a model and devised an arrangement of longitudinal trussed railings to counter undulation. *[141]*. Brunel, who had observed Menai Bridge during a storm, believed that chain vibration commenced before the platform moved and that the unequal length of the suspension rods then caused the undulatory motion. *[140]*. In 1830 he did not consider longitudinal trussing to be necessary for Clifton Bridge but by 1840 his drawings showed timber longitudinal girders of the Pratt truss type. *[156]*.

In 1841 it had become 'usual for persons to speak of the Menai Bridge as a complete failure'. *[157]*. This was an over-reaction. The repairs and Provis's heavier deck amounted to about 5% of the capital cost of the bridge, and of this sum a considerable proportion was for additional not replacement materials.

5:2.4. Theoretical Developments. The Menai Bridge project fostered the development of theoretical methods in suspension bridge design. By 1818 earlier knowledge that 'forces are proportional to the sides of any triangle which are parallel to their directions', *[158]*, had been applied to determine the cross-sectional areas of wrought iron in tension by Ware, *[22]*, Barlow, *[71]*, Loudon, *[159]*, and Chapman. *[72]*. Ware's theoretical investigations, but more particularly his catenarian tables, *[160]*, facilitated suspension bridge calculation from 1822 and Gregory promoted their use in text-books of 1825, *[161]*, and 1833. *[162]*. The most significant development was Gilbert's work and his approximations (para.43) have continued in use into the present century. Hodgkinson's theoretical investigations and calculations of 1828 relating to Menai Bridge, *[163]*, were also of significance in the propagation of a more scientific approach to design. Developments up to 1832 were summarised and evaluated by Drewry in the first British text book entirely devoted to suspension bridges. *[2]*. From c.1825 onwards there was a gradual but increasing awareness amongst leading engineers of the value of a more theoretical approach to suspension bridge design which began to be reflected in the training and practice of the new generation of civil engineers.

POSTSCRIPT

In 1838, during the period when suspension bridges were out of favour, the editors of *The Civil Engineer and Architect's Journal* commented that, *[164]*:

> ...when the material of the suspension portion of the Menai Bridge, shall have perished and consigned to ruin... by atmospheric agents; the granite bridges of London and Waterloo will then exist in the same freshness and vigour of duration as ... the ancient granite monuments of Egypt.

The passage of time has shown otherwise. The foundations of these fine Rennie bridges eventually proved inadequate for the increasing demands made on them and in 1978 it is Menai Bridge, albeit skillfully and tastefully re-conditioned, which has survived. Unlike these London bridges it was built at the frontiers of technology and theoretical knowledge and is today a fitting national monument to the enterprise, courage and dedication of all concerned with its construction and subsequent preservation.

ACKNOWLEDGEMENTS

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MENAI BRIDGE

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DISCUSSION

Mr J.G.B. Hills said that there was a very similar though smaller bridge at Conway which, he thought, had been built in 1819 or 20 and was attributed to Telford. It has been specially preserved because it was said to have been a prototype for the Menai Strait bridge. It used to carry the main Chester-Holyhead road across the Conway estuary. Mr Paxton replied that the construction of that bridge very definitely followed the Menai Bridge; the Commissioners got an economical bridge benefitting from the design and technology developed for the Menai Bridge. The Conway Bridge was in a much more sheltered position and never experienced the difficult weather conditions that beset the Menai Bridge. (The late Mr. D. Morgan Rees afterwards wrote that he had heard from Mr. D.B. Hague of the Royal Commission on Ancient Monuments, Aberystwyth, that the plaque on this bridge only records the action of well-wishers in preserving it. This plaque was put up by the National Trust. Ed.)

Dr R.J. Mainstone asked why Telford had dropped the arch design. Mr Paxton answered that an iron arch bridge would have cost £130,000 - £260,000 whereas the estimate for a suspension bridge was £70,000. At the time of building this more than tilted the decision to the suspension bridge. **Prof. A.W. Skempton** added that Telford had provided estimates for both an iron arch bridge and a suspension bridge and the accuracy of each would be similar, the latter turning out to be approximately one-third of the final cost, a comparison which was common even today. Also the Admiralty required a bridge which did not interfere with navigation and thus preferred a suspension bridge to an arch bridge. Dr Mainstone remarked that the suspension bridge was a new concept at the time and this, he thought, would have led to a less accurate estimate than one for a more commonplace arch bridge.

Mr R.J.M. Sutherland said that the Admiralty had objected to an arch bridge at the site of the Britannia Bridge on navigation grounds and he thought that the same opposition would have applied to the Menai Bridge. He also believed that Telford would probably have infringed Capt. Brown's patent. The author replied that he thought that this patent would not have applied to Telford's chain construction at Menai Bridge. Mr Sutherland went on to ask whether there were any British comments on Navier's remarks about Telford's work? Had Mr Paxton found any documentation of discussions between Telford and Navier? Mr Paxton replied that he was unaware of any discussions but Navier gave the results of Telford's experiments at length in his treatise on suspension bridges. Mr Sutherland said that Mr Paxton had used the term *stress* but this was not in use at that time. Mr Paxton answered that this was true but they did talk of a *proportionality factor,* pounds on a square inch. In 1818, Telford had expressed the load that a structural member could support in a way which clearly showed that he was using the idea but not the word; Mr Paxton believed that Telford was one of the first to apply the concept in this context.

Dr Darling asked how was it ensured that each of the links carried an equal share of the load? Mr Paxton said that a bar tightener had been used and, at the 1922 examination of the bridge, it was found that the stresses in the examined links were very similar to those envisaged by Telford. Dr Darling said that a certain amount of plastic deformation might have acted to equalise the stresses over individual links. Mr Paxton agreed but added that a template was used to make the centre to centre lengths of the individual links equal.

A visitor asked about the use of models; did Telford make any allowances for scale effects or wind? The author replied that simple proportion had formed the basis for the strength test on Telford's model. He had not allowed for the effect of wind which he believed to be much less significant than the direct loading.

Mr N.D. New asked how Ware had obtained the figure of 49.2 $\mathrm{lb/ft^2}$ for the vertical component of the wind force. Mr Paxton replied that Ware had mistakenly used the figure which was probably that given by Rouse to Smeaton as a lateral wind pressure.

Mr D. Morgan Rees asked whether any of the iron members had been made from iron obtained from Capt. Brown's works at Pontypridd. The author answered that he had not discovered any contemporary statement that any of the links had been made in South Wales.

Mr Alan Butcher, proposing the vote of thanks, said that the Society was indebted to Mr Paxton for a most interesting paper and his proposal was carried by acclamation.