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Menai Bridge 1818–26

Evolution of design[*]

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The first significant period of iron suspension bridge building in modern times occurred in North America about 1800. This development stimulated interest in Britain, and an era began which led to the establishment of the suspension bridge as the means of achieving the largest spans. This period, dominated by Menai Bridge, effectively began in 1811 and was one of substantially progressive development for about two decades, followed by a time of consolidation and occasional improvements. The art spread to France about 1823 onwards with the subsequent emphasis, particularly after 1830, on suspension from wire cables. At the approach to the middle of the century the mainstream of development returned to the USA.

The experimentally based design practice of an American judge, James Finley,[1] exemplified in the Merrimack Bridge, Massachusetts, of 244 ft span and built in 1810, had little influence on British practice, although his bridges, in demonstrating the practicability of the wrought iron suspension bridge concept, gave impetus generally to the development of this type of structure. The attitude of contemporary British engineers to Finley's work is reflected in Telford's comment that 'British dexterity upon superior materials' would improve on the North American bridges.[2]

The origins of the evolution of the Menai Bridge design can be traced to a Telford proposal of 1811 for a cast-iron bridge to carry the London to Holyhead Road over the Menai Strait, close to the site eventually adopted for the suspension bridge. A 500 ft span cast-iron arch was proposed, and because of the impracticability of

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providing adequate support for the arch centering from the bottom of the deep and rocky tideway in fast moving water, Telford proposed suspending the centering from above (Fig. 1). The centering was to have consisted of four parallel rib frames spanning the waterway in sections and supported by a series of 1½ in. square section iron stays, radiating two to a frame from timber side towers of quadrant elevation. Each stay was continuous (presumably welded) from the rib frame to about 50 ft from the tower, where it was attached by a flexible chain to a winch.[3]

Telford's proposed use of continuous iron bar suspension members in preference to link chains, which would have had to be heavier to provide the same strength, demonstrates an efficient approach and furnishes one of the earliest examples of what is now modern practice in respect of the use of steel wire cables. In his calculations Telford assumed the breaking stress of a bar to be 80 000 lb/sq. in. (35.7 tons/sq. in.) and multiplied this figure by the cross-sectional area of the bar to give a 'suspending power' of 180 000 lb.[4] He did not use the term 'stress', which came into general use later, but in applying a proportionality factor it is evident that he understood the concept of the term. The design was optimistic in terms of strength, reflecting the general inadequacy of 'strength of materials' knowledge at that time. Nevertheless, there is little doubt that this ingenious concept, which is typical of Telford's bold and imaginative approach to civil engineering design, could then have been successfully put into effect if the political decision to proceed with the project had been taken. In its use of wrought-iron bars in direct tension as a principal means of support, this proposal can be considered the precursor of the ambitious proposal Telford put forward for a suspension bridge at Runcorn.

Runcorn Bridge project, 1814–18

The experimentally based design work undertaken by Telford in connection with the Runcorn Bridge scheme undoubtedly was the next stage in the evolution of the Menai Bridge design. Although never implemented, this project exercised an important influence on the general development of suspension bridges. The bridge, which was to have crossed the River Mersey at Runcorn Gap, was part of a plan to improve road communication between Liverpool, the Midlands and London. Telford, who became engineer for the

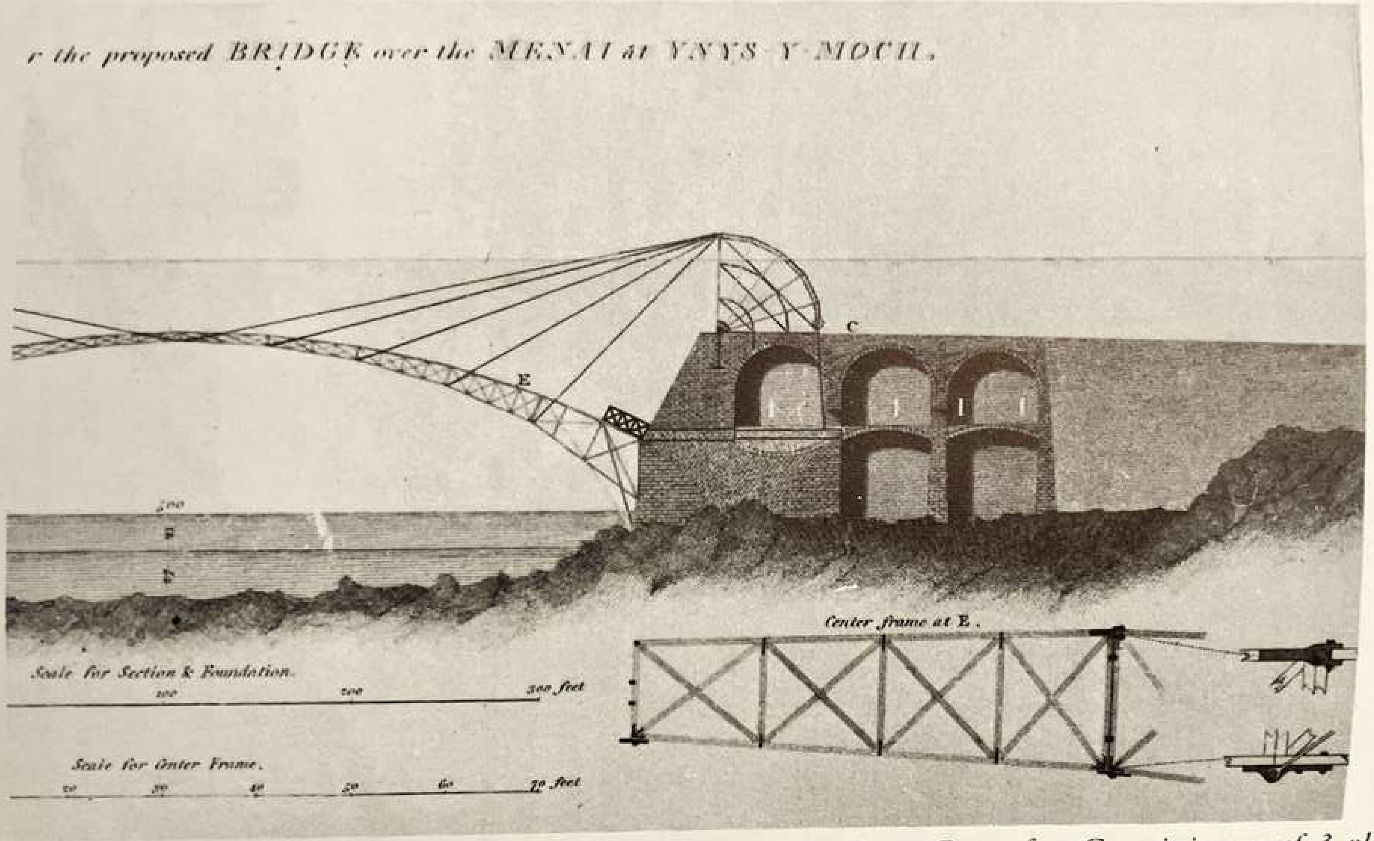


Fig. 1. Menai Bridge cast iron arch proposal 1811: suspended centering design (From *Report from Commissioners*; ref. 3, plate II)

project in 1814, considered a suspension bridge to be the only practicable way of achieving the crossing, for navigational and foundation reasons, and proposed a structure 2000 ft long with a central clear span of 1000 ft.

A wrought-iron suspension bridge of this magnitude was then quite unprecedented in terms of design, construction and technology, and it was necessary for its projectors to demonstrate its practicability. To provide a basis for his design, Telford made in the spring and summer of 1814 and mainly at Brunton's London cable manufactory:

> '. . . 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 3 oz) 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 . . .'[5]

In some of these experiments the forces measured were first that at which the permanent elongation of wrought-iron bars began, and then that at which breaking occurred: in modern terms the determination of 'elastic limit' and 'ultimate tensile strength'. From these experiments, which in respect of elastic limit were among the earliest to be conducted, Telford was led to believe that stretching occurred at about 18 tons/sq. in. Later technology would suggest 12–15 tons/sq.in. as a more likely figure. However, he adopted 15 tons/sq. in. and 27 tons/sq. in. for the stretching and breaking limits of wrought-iron bars[6,7] and just under 40 tons/sq. in. for the breaking limit of 0.1 in. dia. iron wire.[8]

Using these strength data Telford made out two sets of calculations and estimates for the bridge, one based on the use of wire cables and the other on the use of bar cables. The principal dimensions of the bridge were the same for both arrangements, namely a central span of 1000 ft, side spans of 500 ft and two pyramidal towers about 140 ft above high water level. The main support was to have been from sixteen cables in four rows, each with a curvature depth from their chord line at mid-span of 1/20th of the span. The roadways were to have derived additional support from a further 26 cables (eight underneath, fourteen at the sides and four diagonal) with a curvature depth of 1/50th of the span, thus introducing a 1 in 12½ maximum longitudinal gradient in the deck adjoining the towers. This arrangement would have provided a headroom of nearly 80 ft above the deepest navigable channel, which was close to the south pier (Fig. 2).

Wire cable design, 1814. The proposal to use cables consisting of many hundreds of small diameter near-parallel wires totalling nearly 13 000 miles in length (Table 1) represents a remarkable design innovation and one that is conceptually close to modern practice. It was supported by the construction and testing under load of a scale model 50 ft in length. Nearly a decade was to pass before Messrs Seguin of Annonay introduced wire suspension bridges on the Continent.

The method of calculating the 'power of suspension' of 2443 tons for this design is illustrated in Table 1. The weight to be suspended, exclusive of that of the cables themselves, as in the experiments, was calculated at 1200 tons, and the safety margin was therefore 1243 tons, which represents a much lower safety factor than that eventually adopted for Menai Bridge. This design can be assumed to have been prepared under Telford's direction by William A. Provis, who first worked for him in 1805 and from 1808 as his pupil, later becoming Resident Engineer for Menai Bridge. The design was not adopted, probably more on grounds of cost rather than because of any doubts about its technical feasibility. Even allowing for the greater strength of the wire cables, the estimates indicate that they would have cost about 60% more than the bar cables.

Bar cable design, 1814. In the alternative bar cable design, each cable in the upper curve was to have consisted of 36½ in. square 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 (Fig. 3). Waterproofing was to be achieved by filling interstices with a mixture of beeswax and resin, covering

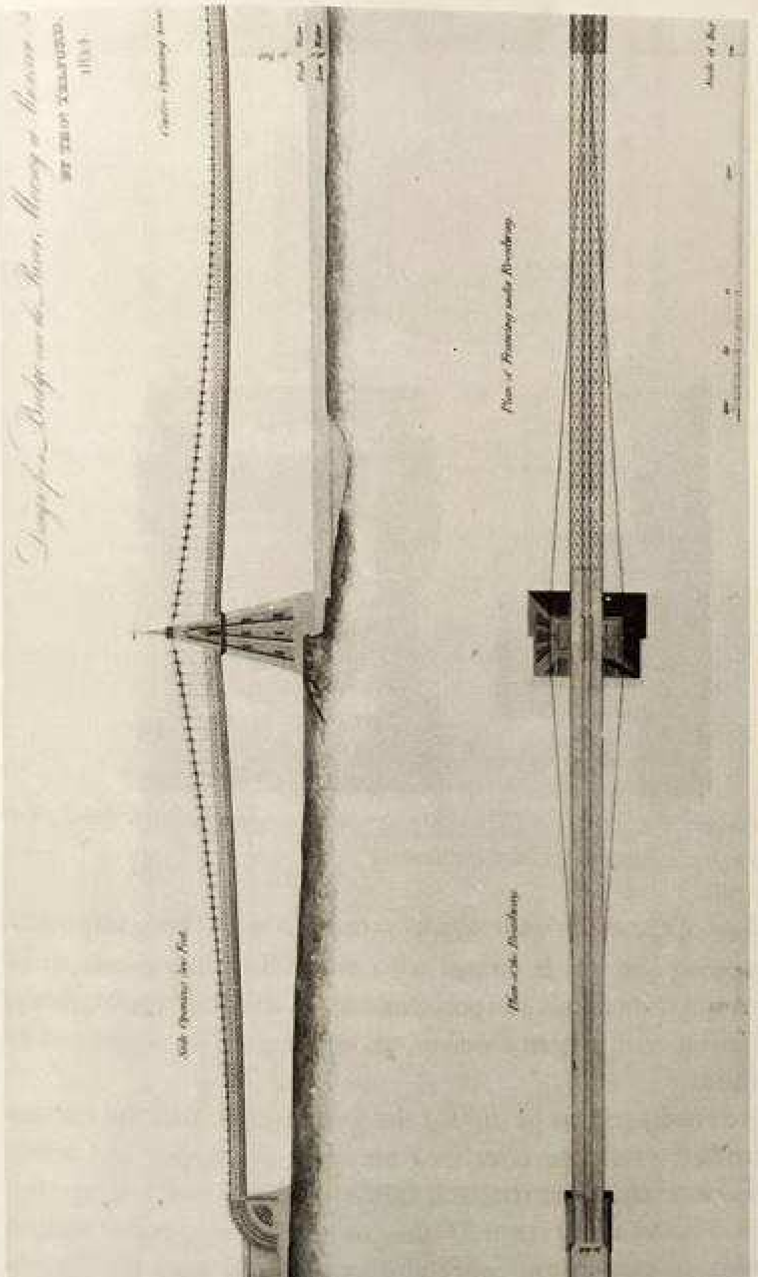


Fig. 2. Runcorn Bridge proposal 1814: elevation from mid-span to south abutment (Rickman, plate 83)

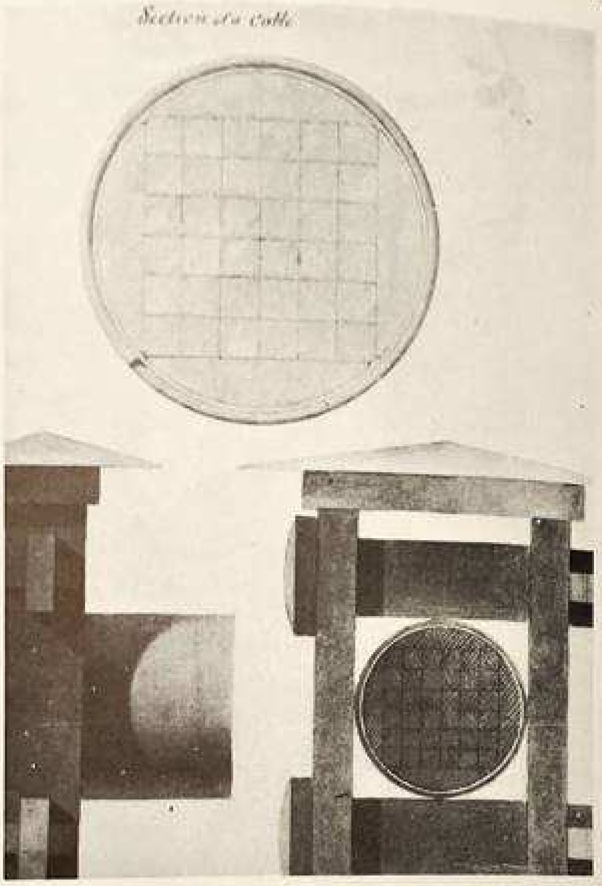


Fig. 3. Runcorn Bridge project 1814–18: proposed composite bar cable detail (Telford drawings, Institution of Civil Engineers)

the surface of the cable with flannel saturated with this compound, and wrapping the whole round with wire. Bucklings were to be provided at 5 ft intervals. A specimen length of cable was made up, in association with Bryan Donkin, an engineer who supported its practicability.

Telford envisaged, as he did for the wire design, that the stresses in the bridge would be equalized between the upper and lower cables. He used the same strength factors as for the wire design but applied to a breaking stress of 27 tons/sq. in. The suspended weight and 'power of suspension' were almost identical with the figures for the wire cable design (Table 1). The maximum stress in the cables on the basis of Telford's experiments would have been about 15.7 tons/sq. in. (15.3 tons/sq. in. from theory) of which nearly 5

Table 1. Runcorn Bridge project, main details of wire cables and their 'power of suspension' as calculated by Telford for 1000 ft span

	Cables		Details of 0.1 in. dia. wires 2010 ft long				
Position in bridge	No and dia., in.	No. cable	Wt wire, lb	Total weight tons	Depth mid span, ft	Ultimate load wire, in*	Power of suspension tons
Below roadway	8 × 3.1	754	65	175.0	20	60 (600 × 0.1)	
Intermediate	6 × 2½	500	65	87.1	20	60	349
15 ft above roadway	8 × 2½	500	65	116.1	20	60	
Main cables	16 × 4	1256	65	583.1	50	228 (684 × 0.333)	2041
Diagonal braces	4 × 2½	500	65	58.0	20	60	53

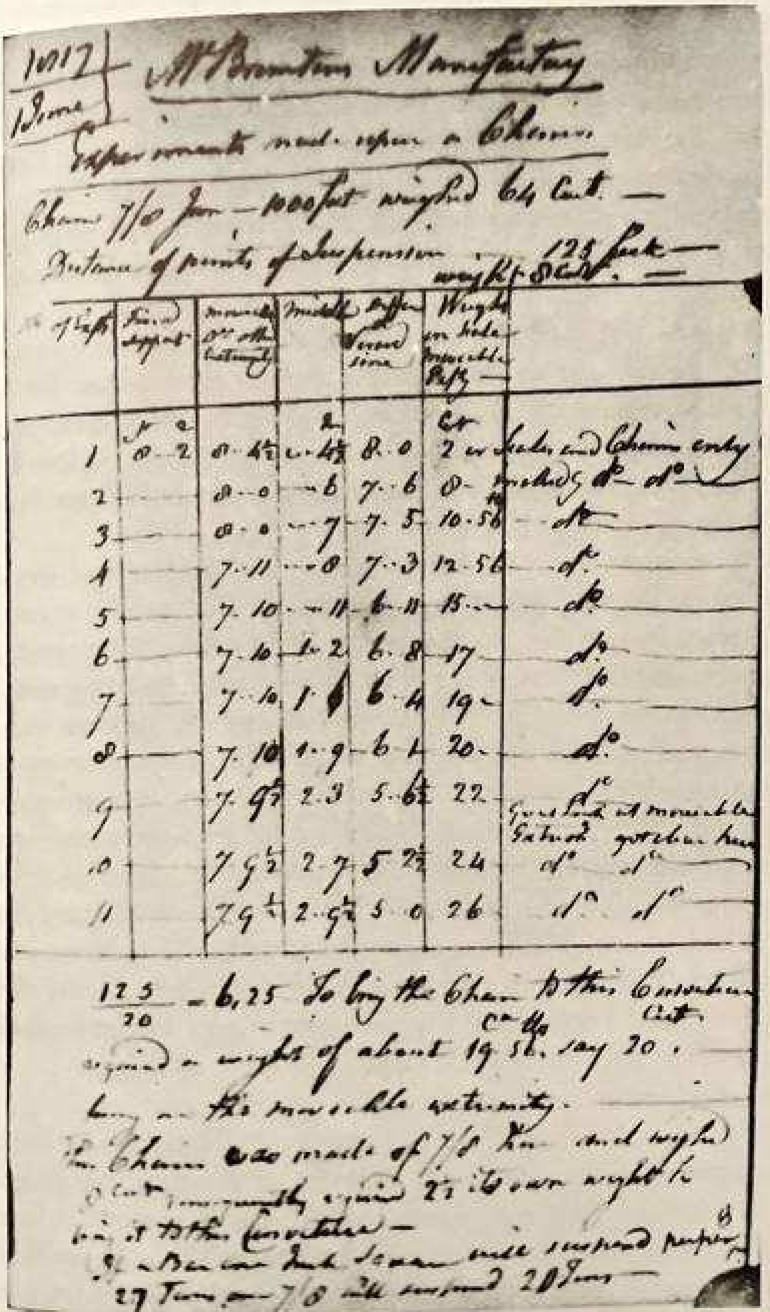
*The factor of 1/10 from Telford's experiments has been applied to produce 60 lb for the cables with a curvature depth of 1/50 of the span and 1/3 to produce 228 lb for the main cables of 1/20 of the span curvature depth.

tons/sq. in. was induced by the self-weight of the cables. This design, based on the inaccurately high 'elastic limit' data, would have been too highly stressed to have provided an adequate safety margin for the bridge. It is difficult to envisage the equalization of stresses taking place uniformly in practice throughout so large a structure.

Work on the project was considered to have matured by September 1814, but finance was not forthcoming, and eventually after a lull of 2 years, much discussion, consideration of other designs and further experiments, a more economical version of the design emerged in July 1817.

Modified bar cable design. The modified design, which can be considered the direct forerunner of Menai Bridge, represented a considerable improvement on its predecessor. The cables under and adjoining the roadway were abandoned, suspension now being solely from the main cables, a change which eliminated the longitudinal sag in the deck. This refinement resulted in considerable saving in ironwork. A further reduction in suspended weight was achieved by adopting a much lighter deck, the result of which with the retention of the previous cable arrangements, had the effect of reducing the maximum design stress to about 11.6 tons/sq. in. Other improvements were the lowering of the cables from 15 to about 7 ft above the roadway at mid-span, whilst maintaining the same cable curvature, and also in achieving a more direct line of anchorage (compare Figs 2 and 8). In the 1814 designs the suspension lines were carried over cast-iron frames of quadrant elevation at each side of the bridge (a development of the 1811 Menai centering proposal towers shown in Fig. 1), from a nearly horizontal alingnment to terminate vertically in the lugs of a large iron casting embodied into masonry.

The modified design was supported by additional experimental work. In May 1817, Telford, Donkin and John Fletcher of Chester, a canal engineer and surveyor, conducted further experiments on the strength of wrought iron at Brunton's works, and continued to obtain results which now seem unrealistically high by about 25%. In one experiment, which is a good example of Telford's practical approach to suspension bridge design, the force required to bring a chain to curvature depths at mid-span of 1/15.6 to 1/20 of its span was determined (Fig. 4). Telford concluded that to achieve a curva-



1817
1 June — At Brunton's Manufactory

Experiments made upon a Chain

Chain 7/8 Iron — 100 feet weighed 64 Cwt. —
Distance of points of suspension 125 feet —
weight 8 Cwt. —

No. of Exps	Fixed support	moveable or other extremity	Middle	Differ versed sine	Weight on scale moveable Exty	
	ft in		in		Cwt	
1	0 2	0 4½	4½	8 0	2 cwt	Scales and Chain only
2		0 0	6	7 6	8	including do do
3		0 0	7	7 5	10.56	do
4		7 11	8	7 3	12.56	do
5		7 10	11	6 11	15	do
6		7 10	1 2	6 8	17	do
7		7 10	1 6	6 4	19	do
8		7 10	1 9	6 1	20	do
9		7 9½	2 3	5 6½	22	do [illegible] at moveable [illegible]
10		7 9½	2 7	5 2½	24	do do
11		7 9½	2 9½	5 0	26	do do

$\frac{125}{20}$ = 6,25 To bring the Chain to this Curvature Cwt.
required a weight of about 19.56 say 20.
hung on the moveable extremity.
The Chain was made of 7/8 Iron and weighed
8 Cwt consequently required 2½ its own weight to
bring it to this Curvature —
[illegible] Brunton [illegible] will suspend [illegible]
27 Tons — 7/8 will suspend 20 Tons —

Fig. 4. Runcorn Bridge project 1817: Telford's experimental determination of force required to bring a suspension chain to different degrees of curvature (Telford notebook, Institution of Civil Engineers)

ture depth of 1/20 span a force 2½ times the weight of the chain was required, a result he used in 1819 for the Menai Bridge design. Although this figure can be calculated quite readily from theory, Telford placed little reliance on such methods, preferring to proceed on the basis of experiment. This *modus operandi* would be scarcely countenanced as a modern engineering technique but it was undoubtedly sufficiently accurate and prudent at the time in the absence of adequately developed and propagated theoretical methods.

Outcome. Although the estimate of £66 565.15*s* for implementing this design was about 25% less than its predecessor, by May 1818 subscriptions had only reached about £25 000, and the bridge was not built. In fact, about half a century was to pass before Runcorn Gap was eventually spanned by the engineer William Baker, using lattice girders.

The unsatisfactory outcome of the 1814–18 project was very disappointing for the promoters, including Telford and his team, but their efforts were not without effect. As Provis commented, the project 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.'[9] In fact, Telford had provided an experimental basis and developed a practicable design for such structures which attracted the support of informed opinion. His experimental results were widely publicized by Barlow of the Royal Military Academy[7] and others. Within a matter of months the opportunity to construct a long-span suspension bridge over Menai Strait occurred, and Telford and Provis, undoubtedly the best qualified engineers of their day for this task, took up the challenge.

In connection with the Runcorn project, mention should be made of the role of Capt. Samuel Brown. Even though he had had very little experience of bridge building at this time, his proposal for the bridge being 'only a sketch of a chain',[9] he was an authority on the design and manufacture of iron chains, the use of which he was anxious to promote. Although Telford did not adopt a long link bar chain of the type developed and promoted by Brown[10] (see Fig. 7), the two men had a useful technical conference relating mainly to the proposed ironwork and timber deck arrangement Brown's support undoubtedly added credibility to the Runcorn

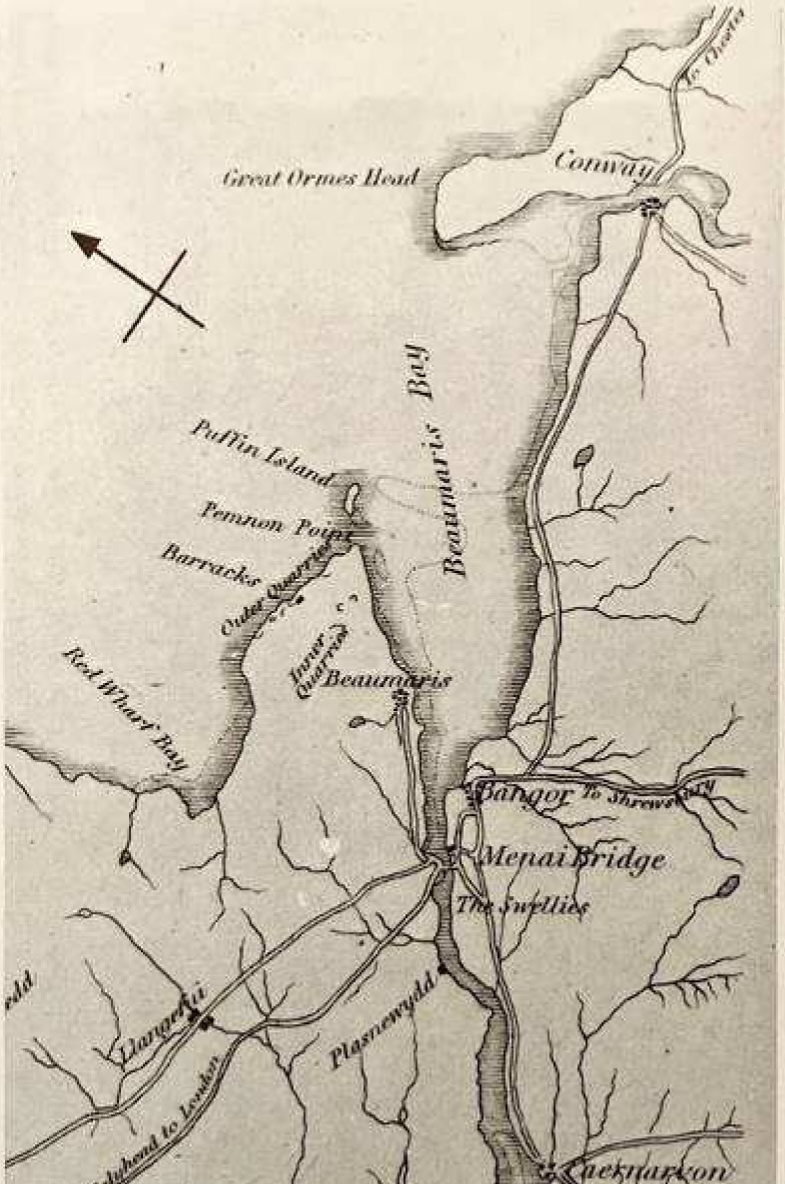


Fig. 5. Menai Strait showing bridge and quarry sites. (Provis, ref. 9, plate 1)

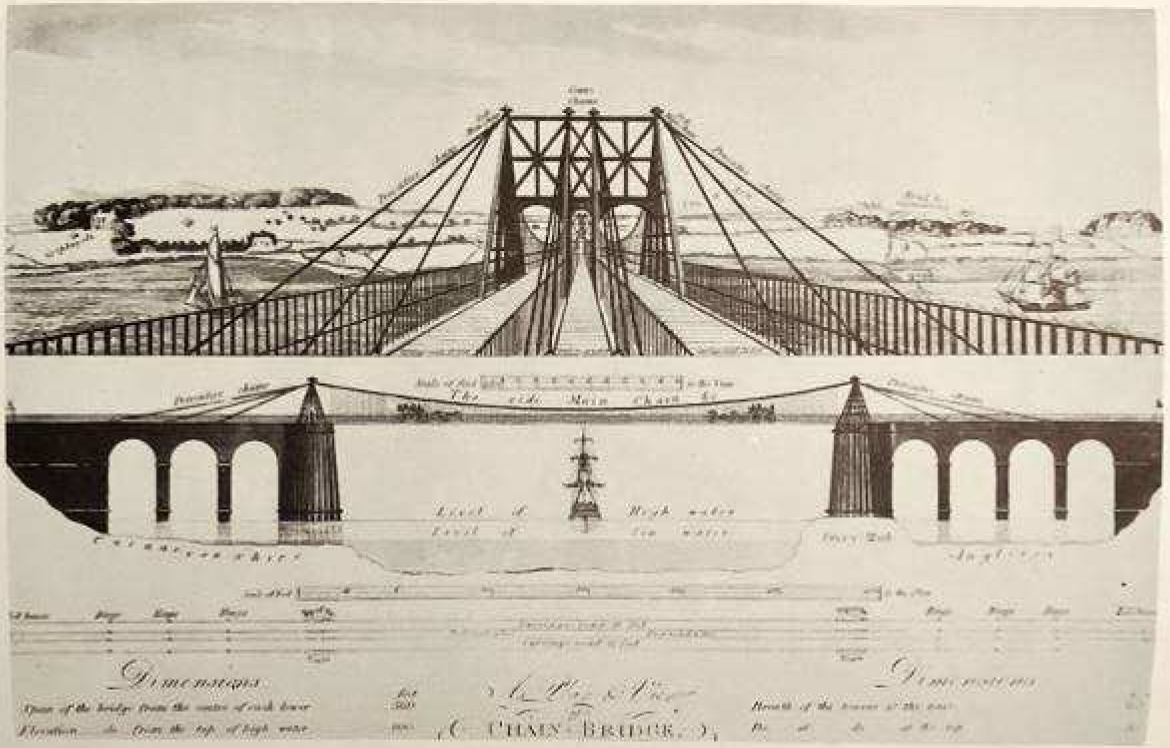


Fig. 6(a). Menai Bridge 1818–19 (Aquatint by J. Taylor). The extent of the design evolution after this period was considerable. The backstays were abandoned in favour of rock anchorages; the towers were increased in height; chains were substituted for cables; and the centre span was increased. The suspenders above the masonry arches were supplied for visual effect and to dampen chain vibration

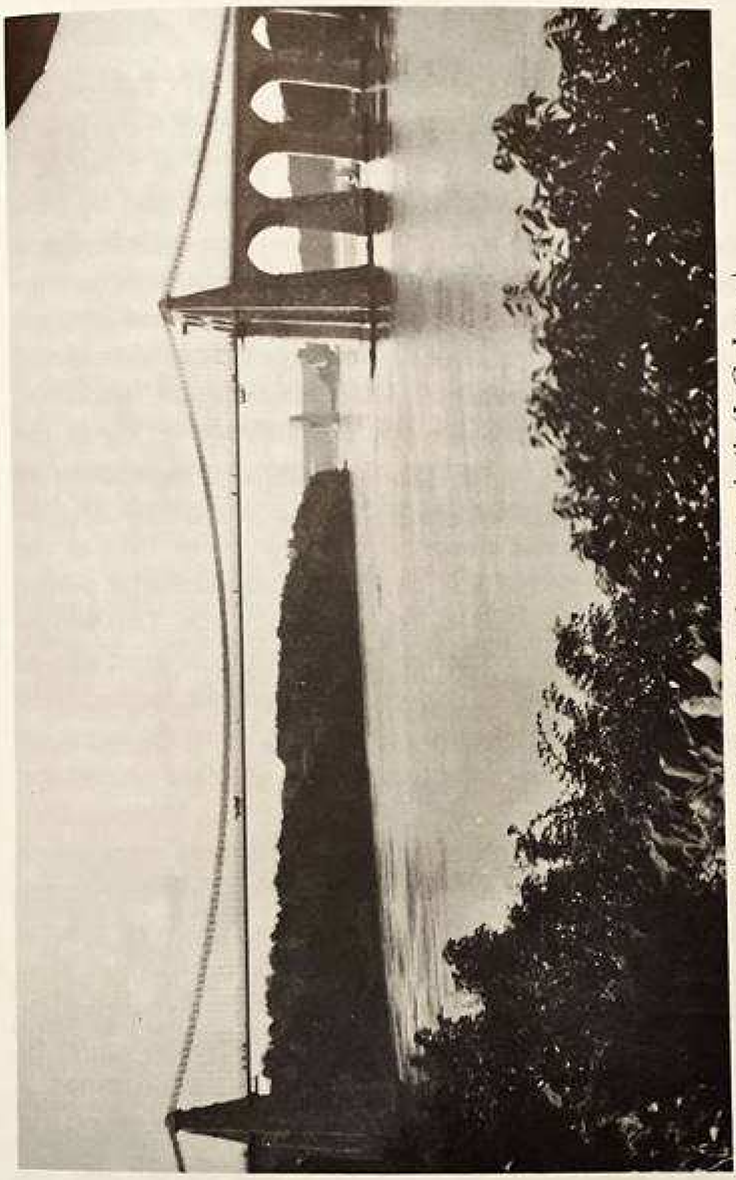


Fig. 6(b). Menai Bridge elevation as built (J. G. James) project, which, in turn, created much wider interest in the subject than he had been able to engender with his works model bridge of 1813 or 1814,[11] and helped him to become established as an iron bridge and pier builder.

Menai Bridge, 1818–26

1818–19 cable bridge proposal. In the latter part of 1817 Telford was asked by the Chancellor of the Exchequer to report on the practicability of carrying the Holyhead Road across the Menai Strait on a suspension bridge. In February 1818 he was on site, and by May had proposed an outline plan and report for a sixteen cable bridge at Ynys-y-Moch (Fig. 5) with a 560 ft central chord opening, supported from cast-iron tower frames with backstays tied into the masonry approach arches (Fig. 6(a)). Although Telford considered this proposal practicable and substantial, he forewarned 'I shall certainly during the time the stonework is constructing, claim the privilege of repeating and extending my experiments, in order to arrive at the most perfect mode this principle is susceptible of'.[12] In fact, the design process was almost continuous from 1818 to the completion of the bridge in 1826, the timing of particular design elements being dictated by the progress of other work. This procedure, which resulted in the evolution of a much improved design by allowing more time and, in consequence, greater flexibility in the design process, proved to be very necessary due to the unprecedented nature of the bridge and the technology required for its construction.

In May 1818 Telford 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. At first, Telford proposed to use bar cables (Fig. 3) as the principal means of support; John Rennie preferred chains. Neither Telford nor Rennie thought that there would be any injury to the bridge from wind. Professor Barlow and William Chapman, a Newcastle civil engineer, had made theoretical calculations on the strength of the bridge and gave the proposal their support.

Telford advised that the bridge could be built for £70 000 and within three years. This sum was much lower than the previous estimates for cast-iron bridges, of £127 331 (1811) by Telford and £268 500 (1802) by Rennie. In fact, the bridge took eight years to complete and cost about £178 000[13] exclusive of approach road and ferry compensation (not the usually quoted figure of £120 000), but the structure as built was larger and stronger than originally envisaged.

William Provis was appointed Resident Engineer in June 1818. In August he and the masonry contractors, Straphen and Hall, laid the foundation stone to the Anglesey pier. On 24 April, 1819, Telford reported to the Parliamentary Select Committee for the Holyhead Road that the suspended weight of the bridge

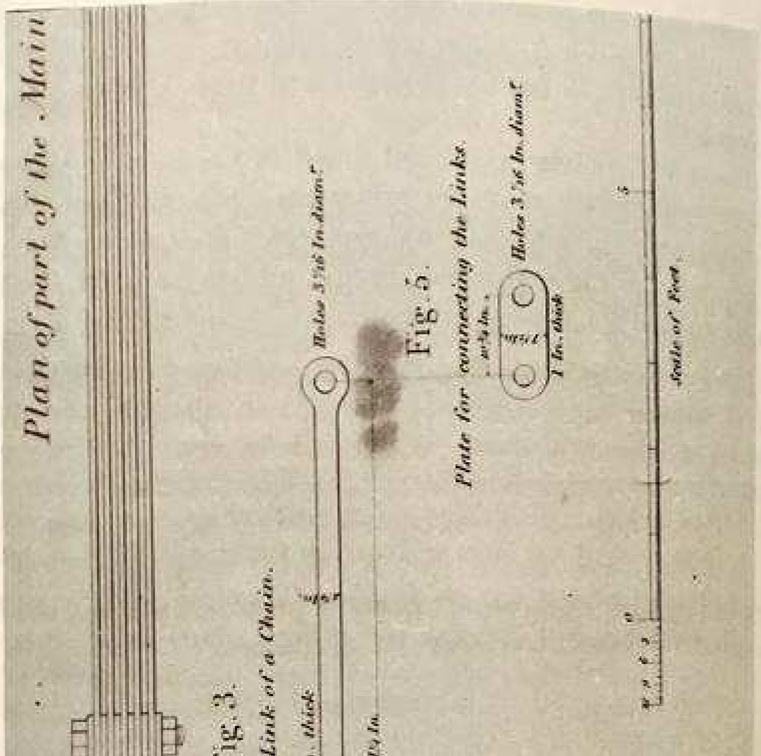
> 'is 342 tons: by numerous experiments . . . it appears that with a chord line of 560 feet, and a versed sine of 37 (or a curvature of 1/15th) a bar of good iron, one inch square, will, besides its own weight, carry 10½ tons, and about one half of that weight before it begins to stretch. For the Menai 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.'[14]

In this account there is an inconsistency in that the 'two and a half times' pull relates to a curve with a central deflexion of 1/20 span (Fig. 4) or say 30 ft, in this case, and not the 'versed sine of 37' as he supposed. It seems clear from the application of the experimental result and scaling from the drawing that Telford intended the central deflexion to be 30 ft at this time. The proposed dead load design stress of 5¼ in/sq. in. was much safer than previously proposed and it is evident that Telford had catered for temperature changes, and also, as far as his knowledge would allow, for undulation. Rennie and Donkin were called before the Select Committee and continued to support the proposal, although Rennie advised increasing the strength of the chains by about 20%.

As it transpired, more time was available for design work than


Plan of part of the Main
Fig. 3.
One Bar or Link of a Chain.
1 In. thick
9 Ft 1½ In.
Holes 3 5/16 In. diamr.
Fig. 5.
Plate for connecting the Links
1 In. thick
Holes 3 5/16 In. diamr.
Fig. 4.
Screw Pin.
3 In. diamr.
Scale of Feet
5

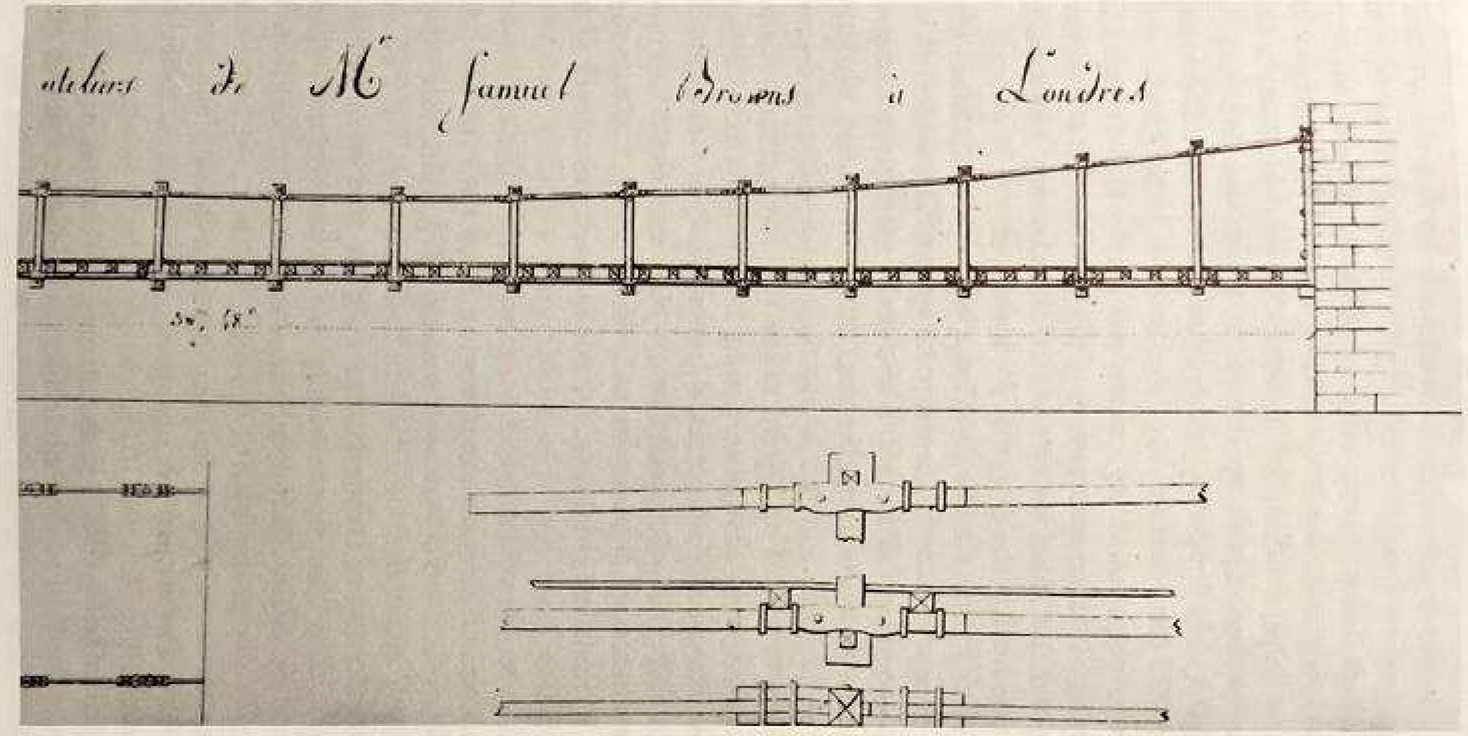


Fig. 7. Menai Bridge chains (facing page, Provis, ref. 9, plate 10) compared with Brown's works bridge chains of 1813 or 1814 (above, Dutens J. Memoires sur les travaux publiques de l'Angleterre, 1819, plate 9)

had been first anticipated because of delay to the masonry work. The hard limestone of which the bridge is built was transported by sea from quarries near Penmon Point, Anglesey (Fig. 5). From 1818 onwards many storms affected delivery of stone shipments and caused delays on the project to be in terms of years. In 1822 alone, three ships, the *Sally* (of 70 tons), the *Alice-Ann* and the *Winsford* were wrecked. The resignation of Straphen and Hall from their contract after only 8 months was another contributory factor to the delay. In 1820 this contract was taken over by John Wilson, one of Telford's principal masonry contractors on the Caledonian Canal works, which by then were substantially complete. It was not until the middle of 1821 that the advance of the masonry work made it necessary to finalize the design of the ironwork.

Design modifications, 1821–23. The principal modifications to the original design included increasing the span to almost 580 ft, raising the towers from 37 ft to 50 ft above the roadway, substituting masonry for cast iron, lengthening the main chains, anchoring them in solid rock, and increasing their cross-sectional area and depth of curvature. With regard to the two latter points, Telford did not consider any change necessary, but deferred to the opinion of Rennie in respect of an increase in cross-sectional area and to that of Davies Gilbert, a mathematician and Holyhead Road Commissioner, and Professor Barlow, for an increase in depth of curvature. A cross-sectional area of 260 sq. in. was adopted and a depth of curvature of 43 ft.

The decision to abandon the composite bar cable in favour of chain bars was taken some time between April 1819 and July 1821, probably in 1820. Telford was undoubtedly influenced in this matter by Captain Brown's eye-bar links, possibly by their successful application at Union Bridge over the Tweed in Berwickshire. He may also have wished to accommodate Rennie's preference for chains. Whatever the reason, the bar link was the most practicable proposition at the time. Telford employed it in a more ingenious way than Brown, by cross-bolting the bars in parallel instead of resting T bar hangers on the top of the individual lines of chain (Fig. 7).

In the latter part of 1822 progress on pier building made necessary the finalization of the saddle and anchorage designs. A comparison between the revised Runcorn Bridge and the improved anchorage in rock at Menai is shown in Fig. 8. The piers had reached roadway level, and before proceeding further it was decided to increase the tower heights by a further 2 ft in order that the roadway at mid-span could be lifted by a similar amount, thus obviating visual unattractiveness due to the deck sagging with temperature changes below a horizontal line. The propriety of this degree of design sensitivity became apparent later, when a winter/summer differential of 11 in. at mid span was observed, associated with a movement of about 1½ in. at each saddle.

The dowelled masonry towers, one of the most remarkable and successful features of the bridge, were completed in 1824. They were designed not only to take the vertical load, but also a significant horizontal force, caused by the angles of the chains being nearly 2° different from the horizontal at each side of the Caernarvonshire tower. This was to allow more headroom on the approach road, which turns under the north chains near the toll house. The expense of the masonry, the most costly single element of the bridge, amounted to about £88 000.

Ironwork

The contract with William Hazeldine for the manufacture and delivery of the ironwork was entered into soon after the drawings had been made in July 1821. The ironwork was manufactured at Upton Forge and finished and tested in Hazeldine's Coleham workshops in Shrewsbury. Most of it was transported via the Ellesmere and Chester Canals and then by sea from Chester to Menai. Every operation in connection with the manufacture, finishing and testing of the ironwork was performed under the control of John Provis, brother of William Provis. The scale of the work was unprecedented. The sixteen main chains were each 1710 ft long and consisted of 14 960 eye-bars about 9½ ft long, some 16 000 connecting plates about 1½ ft long, and 6000 3 in. dia. screw-pins 16 in. long (Fig. 7).

Hazeldine'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. In the winters of 1822–23 and 1823–24 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

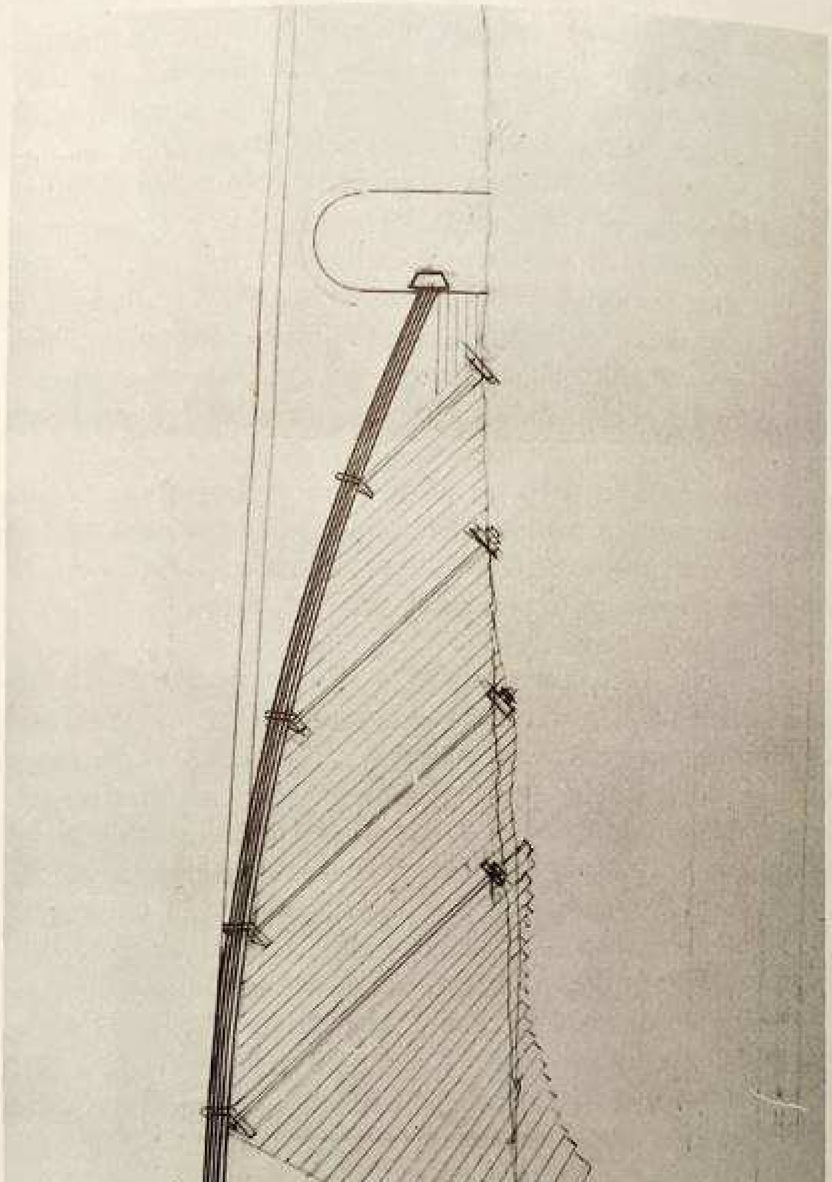


Fig. 8(a). Anchorage evolution: 1817 Runcorn Bridge proposal (Telford drawings; Institution of Civil Engineers)

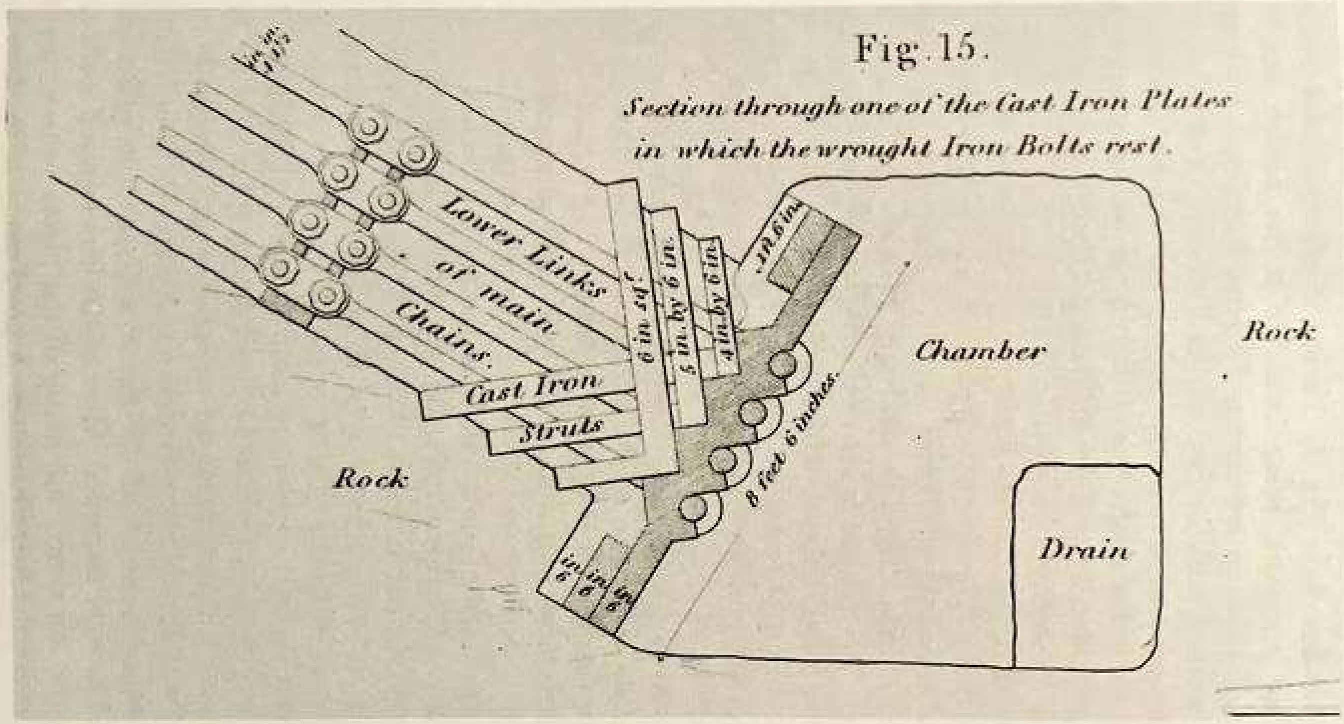


Fig. 8(b). Anchorage evolution: Menai Bridge as built (Provis, ref. 9, plate 9) onwards they were cold-drilled on site using a specially constructed machine. Even so, it did not prove an easy task to achieve the parallel five-bar chain (Fig. 7). These and other setbacks resulted in insufficient ironwork being available at the bridge site in the summer of 1824. In retrospect, Thomas Rhodes, who had previously worked with Telford on the ironwork of the Caledonian Canal and who supervised the ironwork fixing at Menai Bridge, thought that link manufacture could be improved in future by turning the pins true, boring the links correctly to length and passing their ends through a rolling mill.

On 30 June, 1824, the Commissioners expressed concern about the great delay in finishing the ironwork, and asked Telford to consider and report on whether it might not therefore be advisable to offer the Conway Bridge ironwork to some other contractor. However, this did not prove necessary, as the measures taken by Hazeldine at Shrewsbury, which included provision of new workshops and a large steam engine to power machinery for turning saddle rollers, punching eyes and cutting screw-pins, were already taking effect.

Payments to Hazledine for Menai Bridge began about August 1821 and some measure of the difficulties he encountered is reflected in the fact that by December 1822 he had been paid only £2645 from an eventual total of about £68 000. The manufacture and testing of the ironwork was at the forefront of the technology of its time and resulted in considerable design innovation in respect of a whole range of equipment (Fig. 9). From the time of the design and building of the bar tester in 1822 until 1824, the design of equipment for various purposes was virtually a continuous process. Nothing that could be tested or measured was left to chance. Every main chain bar and connecting plate was proved by John Provis with a force of 35 tons (about 11 tons/sq. in.). After testing, the bar was checked for permanent deformation, and if satisfactory, was stamped with Provis's proof mark, a raised cross within a ¼ in. dia. saucer-shaped indentation. Of the 35 649 bars and plates tested, about 6.7% were discarded. Most of the bars rejected were either too long or too short, and many of the plates were imperfectly welded under the forge hammer. A good many of the bars failed near their ends, probably from repeated heating and cooling whilst the eyes were being formed.

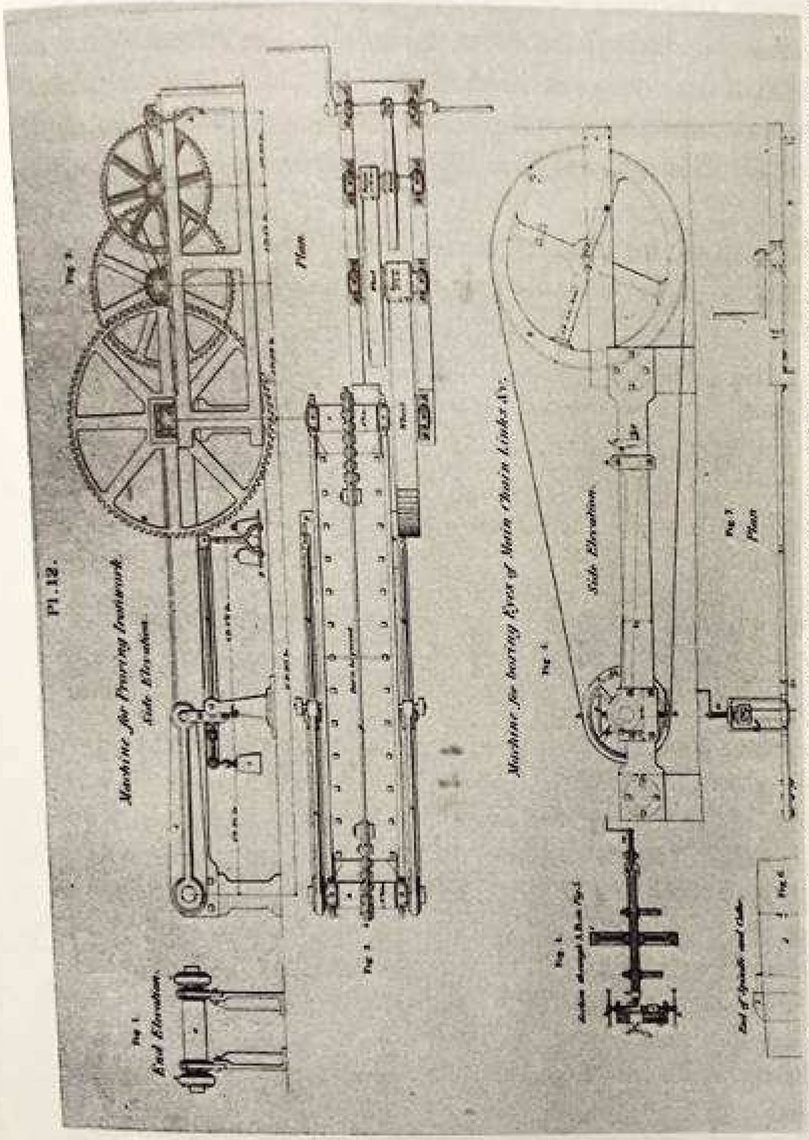


Fig. 9. Two of many items of equipment devised during construction of Menai Bridge (Provis, ref. 17, plate 12)

On 31 March the first anchorage casting was fixed. The most intensive period of ironwork erection began in the spring of 1824. The 1 in. × 3½ in. bars for the side spans were assembled on scaffolding close 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. 10), and then hoisted up to the saddles

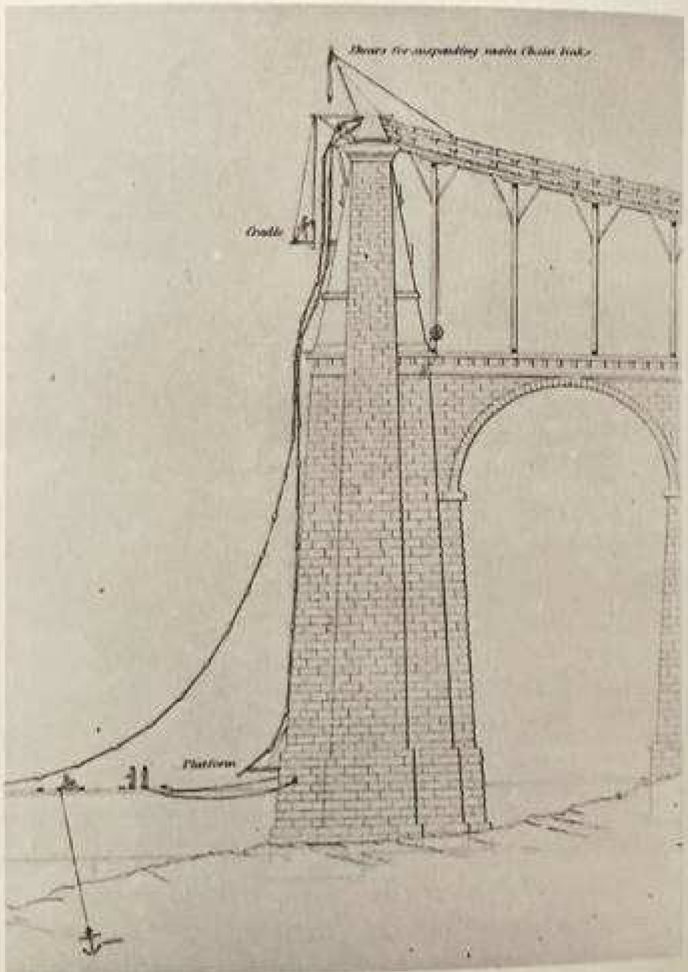


Fig. 10. Caernarvonshire tower immediately before erection of first chain in April 1825 (Provis, ref. 17, plate 4)

on the Anglesey tower by means of specially designed capstans. All sixteen chains were erected between 26 April and 9 July, 1825, nine of them taking less than 2 hours to put up.

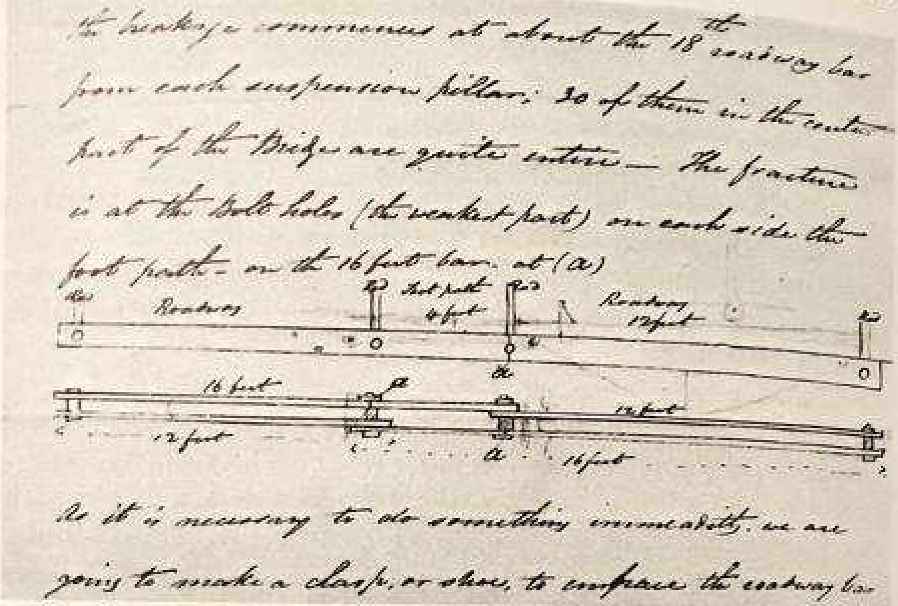
Undulation problems and strengthening

Payments to Rhodes in respect of Menai Bridge amounted to about £11 000. About £3200 of this was spent in combatting the effects of the undulation which became apparent almost immediately after the opening of the bridge on 30 January, 1826 – the last phase of the project.

In October 1825 when work was in progress on the deck, Telford had 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 6 to 8 in. each way. If the wind struck obliquely the undulation was considerable, but when the chains were connected to the short suspenders these motions were reduced. When the roadway was begun the undulation and vibration was very great and the men had considerable difficulty in standing:

> '. . . the motion resembles much a ship riding at anchor when blowing fresh . . . we are now nailing the first tier of plank down to the roadway bars & at every strake that is fastened I perceive it gets stiffer . . .'[15]

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 lines of rods 1 in. square radiating from the corner of the base of the suspension pillar at the roadway. On 4 and 5 January, 1826, more gales occurred, resulting in very considerable undulation, which compelled the workmen to leave the bridge. On 10 February, 48 suspenders were found to be broken at the roadway bar bolt holes (Fig. 11). 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, but this idea was not adopted at that time. Rhodes and Provis believed that gusts of wind first deranged the chains and that deck undulation then 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 18 in. but afterwards it never exceeded 6 in.



the breakage commences at about the 18th roadway bar from each suspension pillar; 20 of them in the center 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. 11 Rhodes' sketch showing suspender bars fractured at roadway bar bolt holes (a–a), (Letter to Telford, ref. 15)

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. In 1832 the bridge was said to be 'unimpaired and in perfect security',[16] and it was not until 1836, after Telford's death, that further problems arose.

The torsional undulation problems at Menai Bridge made Telford cautious about extending the spans of suspension bridges, although in July 1826 he did propose a road bridge for the Runcorn site with a central opening of 800 ft. For Clifton Bridge, with its deck 200 ft or more above the river, Telford considered 600 ft to be a proper limit to the span. This constraint influenced Brunel's original design for this bridge, which was accepted early in 1831, although shortly afterwards he adopted a span of 702 ft with a suspended roadway length of 636 ft.

Undulation remained a problem even after 1834. During an unusually severe gale at the beginning of January 1836 the Bridgemaster observed deck undulations of 'little less than 16 ft'[17] in amplitude. Provis considered that 10 years of continued friction, combined with timber shrinkage, had considerably affected the original rigidity of the platform. Roadway stiffening was recommended but nothing was done, and in a storm on 7 January, 1839, the deck sustained serious damage. 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 deck. In the meantime immediate repairs were carried out, and 4 days after the storm one carriageway was reopened. By 21 January the whole bridge was open for use.

Work on Provis's deck was in progress by May 1839 and com-

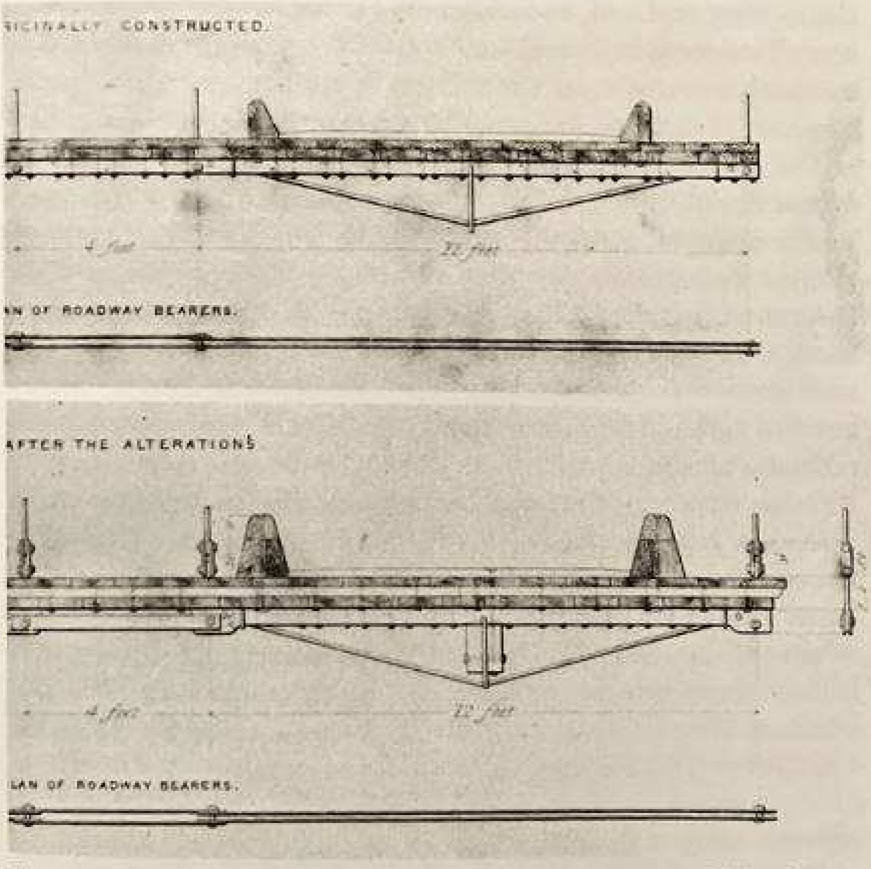


Fig. 12. Part of cross section of original deck and heavier pin-jointed deck of 1839–93. (Maude, ref. 18, plate 17)

pleted in the summer of 1840 at a cost of almost £9000. 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 to the roadway surface (Fig. 12).[18] But the problems had a serious psychological effect and it became 'usual for persons to speak of the Menai Bridge as a complete failure'.[19] This was an over-reaction. The cost of the repairs and the heavier deck that Provis had considered necessary amounted to about 5% of the capital cost of the bridge, and of this sum a considerable proportion was for additional work, not replacement. Provis's deck lasted 53 years, not being replaced until 1892, when a steel deck designed by Sir Benjamin Baker was constructed.

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 does not seem to have been dictated so much by any structural weakness as by the need for a greater carriageway capacity to deal with the increasing volume of traffic.

The reaction may, however, be understandable. The damage to Menai Bridge in 1836 and 1839 followed a succession of suspension bridge disasters, at Montrose (1830), Morpeth (1830), Broughton (1831), Yore (1831), Stockton railway bridge (c. 1832) and the Brighton Chain Pier (1833). These failures resulted in a disenchantment with this type of bridge design, which seems to have lasted until about the middle of the century. By that time Provis's reconstructed deck at Menai Bridge and J. M. Rendel's substantial longitudinal trussing at Montrose Bridge were proving effective. Another factor which tended to increase confidence in suspension bridges was the success of the Hammersmith Bridge (1824–27), Hungerford footbridge (1841–45) and most of the economical James Dredge stay bridges, of which about 50 had been built between 1836 and 1850. The last of the large span wrought-iron parallel bar chain bridges included the Pesth (Budapest, 1840–49), Portland Street, Glasgow (1851–53) Victoria, Chelsea (1854–58) and Clifton (1830–63).

Influence of Menai Bridge

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.

The project also provided a basis for improvements in suspension bridge design both by example and through the publications of its designers and others, including Gilbert,[20] Navier,[21] and Cresy.[22] The development of underground solid rock anchors represented a significant step forward. The parallel bar chain had the advantage over Brown's arrangement that it was more easily adapted to large cross-sectional areas and to 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 for at least six major bridges during the following three decades.

The Menai Bridge project influenced the adopting of greater and consequently more efficient depths of curvature in suspension bridge chains and also safer chain strengths. 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 minimize 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 for a proposed bridge at Latchford in 1814 (0.07 span) being about three times more efficient in strength terms than the chains of Brown's work 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 (0.056 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. Telford's adoption in 1818 of a dead load maximum stress of about 6 tons/sq. in. (9.8 tons/sq. in. with 300 tons live load) represented a significant step forward. In 1821 these stresses were further reduced to about 4.3 and 6.3 tons/sq. in. respectively. Although Brown seems to have been influenced to some extent by this downwards trend in his Union Bridge designs, he adopted maximum stresses nearly double those of Telford thereafter, and at least two of his bridges, Montrose and Stockton, suffered from overstressing of their main chains. In 1829 Brunel considered 8 tons/sq. in. as a maximum working stress, but in 1830 reduced this to 6.5 tons (almost the Menai Bridge figure), and eventually in 1838 to 5.0 tons/sq. in. Navier took a great interest in the Menai Bridge project and adopted an almost identical span and chain curvature for his Paris suspension bridge of 1823–26.

The instructive example of the effects of undulation obtained 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 timber and iron trussing. Brunel, who had observed Menai Bridge in 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. In 1830 he did not consider longitudinal stressing to be necessary for Clifton Bridge, but by 1840 his drawings show timber longitudinal girders.

The example of Menai Bridge also influenced and encouraged the development of theoretical investigations into suspension bridge design. Ware's theoretical investigations[23] and particularly his catenary tables, facilitated suspension bridge calculation from 1822, and Gregory promoted their use in his books of 1825 and 1833.[24] The most significant development was Gilbert's work, and his approximations for determining the forces in a chain curve at any point have continued in use into the present century. Hodgkinson's theoretical investigations and calculations of 1828 relating to Menai Bridge[25] 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 devoted to suspension bridges.[16] From c. 1825 onwards there was a gradual but increasing awareness 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.

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

> . . . 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.'[26]

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 it is Menai Bridge, albeit skillfully and sympathetically reconditioned, 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.

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