Performance of the Menai Straits Bridge

Before and After Reconstruction

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Abstract

This paper describes the original form of the 1826 Menai Straits Suspension Bridge as well as the modifications to it made during construction, right after its opening, ten years after the opening in 1836, after a hurricane in 1839, and after the damaging gale of 1936. Each of these reconstructions to the bridge and the resulting performance under severe wind loading is discussed in this paper. Finally will come some explanation of th eattempt in the 1930s to have the bridge take down in favor of a new design whichy fortunately was never executed.

Generally acknowledged as the first great modern suspension bridge, the 580 ft. main span has suffered wind damage but never a complete collapse. Its designer, Thomas Telford (1757-1834) was the first president fo the Institution of Civil Engineers and was the leading designer of iron bridges in his era.

Original Design

Stimulated by the 1800 union of Ireland and Britain, the Holyhead Road was planned to connect London to Holyhead in Wales and thence allow travel by water to Dublin. Thomas Telford (1757-1834) was asked to make a complete survey to establish the location for such a road in 1810 but after his 1811 report nothing was done until 1815. Then work proceeded under Telford's direction. In 1818 the government directed Telford to determine how best to bridge the Menai Straits, an arm of the sea separating the mainland of Wales from its island of Anglesey.

Telford already had studied the crossing, proposing in 1811 a cast iron arch of 500 ft. in span to be built by an iron scaffold held above the arch by cables connected to temporary shore towers. The cost estimate was 127,133 pounds far lower than the 1802 cast iron arch proposal by Sir John Rennie of 268,500 pounds.[2] Nothing further was done on the Holyhead Road until 1815 by which time Telford had begun to study suspension bridges for a much longer crossing over the River Mersey at Runcorn to shorten the route between London and Liverpool.

In late 1817 the chancellor of the Exchequer asked Telford to restudy the Menai crossing by a suspension bridge. Based upon his Runcorn project, for which he had built and tested a 50 ft. long model, Telford proposed a design in May 1818 for which he estimated a cost of 70,000 pounds and a three-year construction period, but he cautiously added that due to the unprecedented size and type of this bridge, "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."[3]

This was a shrewd precaution since Telford did much further experimentation and was faced with numerous delays. The bridge span increased, the design became more conservative, and the result was a total cost of 178,000 pounds and a construction time of eight years.[4] When completed the bridge spanned 580 ft. with a sag of 43 ft. with a main cable made of 16 chain bars each having five wrought-iron links of cross sectional area 3 ¼ inches by 1 inch. The total cable cross-sectional area was thus 3 ¼ x 5 x 16 = 260 in^2 designed to carry a total bridge load (dead and live) of about 3.24 kips per ft. From these values and assuming a parabolic cable, we find

$$H = \frac{3.24 \times 580^2}{8 \times 43} = 3{,}168 \text{ kips}$$

$$\tan\Phi = \frac{4 \times 43}{580} = 0.2966;$$

$\Phi = 16.5^o$
$\cos\Phi = 0.9587$
T = 3168/0.9587 = **3,304 kips**
f = 3,304/260 = **12.71 ksi**

which is the value calculated by Paxton following a slightly different model.[5] Each of the 35,649 links were tested to a stress of about 22 ksi before being accepted and other tests by Telford showed the breaking strength of these

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wrought-iron links to be 50 ksi. He observed that at half that value the links "showed elongation" by which we might assume yielding. Therefore, his safety factor against yielding was about $25/12.71 \approx 2$ and against breaking about 4.[6]

Telford himself probably never made calculations such as the ones shown here, but he did test chains over pulleys to develop empirically the cable forces for various ratios of span and sag.

The Performance of the Original Design

In 1818 when Telford was called to appear before the Holyhead Road commissions, neither he nor John Rennie who also appeared there, thought that the suspension bridge design would be in any danger due to wind. However, as the design evolved to 1825 Telford apparently did consider wind to be a problem and "foresaw the probability of trussing being required, but finally decided upon omitting it in the first instance, and adopting it subsequently should experience prove it to be necessary." For Telford the necessity of designing trusses for the roadway "was the subject of much anxious consideration."[7] Telford had no direct, first-hand experience with wind on suspension bridges so he decided finally to spare the extra expense and watch the performance. In October 1825 Telford asked Thomas Rhodes, his ironwork supervisor on the site, to give him a report on lateral movements and vertical movements (undulations it was called) owing to the wind. Rhodes had observed the chains moving with wind and when the roadway was added, he noted even more movement.[8]

By December 1825, during a storm, it became clear that large motions were occurring and something should be done. These motions consisted of undulations or longitudinal waves which were not the same in each of the four chains; the summit of the leeward chain lagged considerably behind the corresponding summit of the windward chain.[9] This motion implied both a longitudinal and a torsonial vibration of the deck.

Gales again caused the structure to move dangerously on January 4 and 5, 1826 but the bridge opened to the public with great acclaim on January 30 of that year (see Fig. 1). After another serious storm on February 6 an inspection revealed 48 broken suspenders. These were replaced, slight modifications made to the deck, and the bridge remained open.[10]

W.A. Provis wrote in 1828 that he believed the problem in 1826 to have been the vibrations of the chains rather than, as we now know the motions induced by wind on the deck. Therefore, Provis proposed that the four chains be braced together by lateral trusses and this was done in the early summer of 1826.[11] As he reported in 1828 the maximum amplitude of undulations was 18 inches before he added the truss and never exceeded 6" thereafter.[12] He must have discussed this with Telford, who had to agree with any design changes. Presumably the issue of longitudinal trussing arose again and was considered unnecessary.

From 1826 until 1836, two years after Telford's death, the bridge did not move dangerously and performed as Telford had believed it would. This successful performance led the engineers to think that their remedial work of 1826 had corrected the problem with the wind. Then on January 23, 1836 a strong gale cause huge undulations on the deck of the order of 16 feet between the upward and downward maxima. The deck moved far more than the chains and Provis now realized that the deck needed the longitudinal trusses that had been earlier discussed. Provis and Rhodes recommended stiffening the deck right away but they could not get the necessary approvals.

It seems likely that had Telford been alive and active, his great prestige would have led to the deck stiffening that he had foreseen as a possibility in the mid 1820s. It is well known that political authorities will often only respond to people of great reputation or to disastrous crises and in the case of Menai they did finally respond after a storm on January 7, 1839 tore part of the roadway from its supports and made the bridge impassable to carriages.

The central walkway remained fully in place and workmen reconnected one carriageway after five days of replacing broken suspenders and floor beams. The second carriageway was in operation by January 21, 1839. Later reports describing the Menai Bridge as having collapsed were thus greatly exaggerated. Since January 30, 1826 it had never been reported to have been out of service longer than these five days in 1839.

Following the reopening Provis made a detailed report and recommended that the deck be modified by adding substantial weight and much increased longitudinal stiffness. This time his recommendations were approved and by the summer of 1840 they had been carried out.[13] Provis' wooden-deck design (see Fig. 2) lasted 53 years without any reported failure and was replaced in 1892 by a steel deck designed by Sir

Benjamin Baker (see Fig. 3), designer of the 1890 Firth of Forth Bridge.

A careful investigation in 1922 revealed the bridge to be still serviceable but in need of some repair. Less than 4% of the links exhibited serious corrosion. The main problem lay with increasing traffic loads not envisioned in the original design. The bridge had been posted for 4 ½ tons and vehicles were required to maintain a 50 ft. spacing and creep across at 4 mph.[14] Sometime in 1936 a gale did some damage that was quickly repaired but that stimulated the desire to reconstruct the bridge to permit it to carry the much heavier traffic loads appearing in the 1930s.[15] To remedy this situation a thorough rehabilitation took place between 1938 and 1941.[16] The chains were replaced and the deck rebuilt to permit a single 23 ft. traffic way and one 5 ft. wide sidewalk on each side[17] (see Fig. 4).

The Bridge Today

The reconstruction followed close detailed inspections, one in 1906, one in 1917, and a last one in 1922 by Maunsell under the direction of Sir Alexander Gibb, who was a President of the Institute of Civil Engineers and a biographer of Telford.[18] Gibb did the design and supervised the reconstruction that now exists (1994).

The rebuilt structure has the same overall dimensions with a span of 580 ft. and a sag of 43 ft. But there are now only two chains each made up of 12 parallel links each having a width of 10 inches and a thickness of 1 ¾ inches; the total cross-sectional area A = 2 x 12 x 10 x 1 ¾ = 420 in^2. The total deadload is approximately 5.26 kips per foot and if the liveload is about 1.4 k/ft for two lane traffic[19] then

$$H = \frac{6.66 \times 580^2}{8 \times 43} = 6{,}513 \text{ kips}$$

$$T = 6{,}513/0.9587 = 6{,}794 \text{ kips}$$

$$f = 6{,}794/420 = 16.18 \text{ ksi}$$

Maunsell gives the results of tests on one link which yielded at 300 tons and failed at 627.5 tons so that he takes the yield stress f_y = 600/10(1.75) = 34.29 ksi and the breaking strength f_u = 1,255/17.5 = 71.71 ksi.[20] Therefore, the new safety factor against yielding would be about 34.29/16.18 = 2.1, or just about the same as originally designed by Telford.

A major difference between the present and original designs is the stiffening truss, one running longitudinally on each side of the 23 ft. roadway with the sidewalks on the outside (see Fig. 5). The trusses are about 9.5 ft. deep and provide substantial stiffness to the previously only slightly stiffened structure (see Fig. 6). The effect is to increase the vertical stiffness by a considerable amount and thereby to reduce drastically the danger of vertical oscillations in the wind. Our own site observation of the bridge in the summer of 1992 revealed the structure to be in good shape, with no obvious defects of a significant structural type. We are unaware of any important difficulties encountered with the behavior of the bridge since its 1940 reconstruction. Indeed there does not appear to have been any notable failures of the bridge elements since the storm of January 7, 1839.

The Replacement Threat

The issue of replacement versus reconstruction is not easily dismissed in the case of older bridges. Furthermore the nature of the reconstruction itself is almost as crucial as whether or not to scrap the old bridge entirely. Some notable examples of bridges subjected to such questions are Roeblings Niagara, Cincinnati, and Brooklyn Bridge, the Britannia Bridge nearby Telford’s Menai structure, and the recent highly-publicized Williamsburg Bridge case.

For Telford’s Menai Bridge the issue came up following the inspection of 1922 when the newly created British Ministry of Transport concluded that it would be almost impossible to strengthen the bridge. The ministry decided to have a new design made by the Considère Construction Ltd. of London. Named for one of the major French pioneers of reinforced concrete, this firm had proposed a reinforced-concrete arch of the extraordinary span of almost 600 ft. To get the required clearance of 80 ft. over a channel width of 460 ft., the arch would have sprung from the base of the old main towers and continued above the roadway over the central part of the span with the roadway about at its present level suspended from the arch.[21]

The chief engineer (roads department) for the Ministry of Transport, Sir Frederick Cook reported later that "It was, however, ultimately decided (and all would agree with the widsom of the decision) that every effort should be made to preserve Telford’s masterpiece as near to its original form as the new conditions permitted." Thus the idea for the reinforced concrete arch was dropped.[22] So much for reports which state that an historic work cannot be strengthened.

Once that threat was put aside, the reconstruction proceeded and was done so well that the appearance was largely unaltered except for the stiffening truss when viewed from on the roadway.

In his discussion of 1945, Cook compares the 1817 Waterloo Bridge in London by John Rennie to the Menai Bridge by Telford:

> "the former was entirely rebuilt and the new bridge opened to traffic in 1942; the latter was reconditioned - definitely not rebuilt - in 1940. The bridges were of entirely different types, as were the traffic and subsoil conditions with which their respective engineers had to deal. Waterloo Bridge failed not as a result of external forces, but by inherent defects in the design of the foundations. In the case of the Menai Bridge, trouble was confined to the suspended portion, due largely to the ever- increasing loads which came upon it, but the reconditioning of the bridge would not have been possible had not the main structure - the foundations, piers, towers - been found to be in as good condition when the work of reconditioning was carried out as when it was first put together.[23]

The so-called permanent stone arch bridge in London had to be torn down and completely redone. Telford's pioneering suspension bridge could be reconditioned to its almost original form.

References

1. Thomas Telford, Life of Thomas Telford, Ed. John Rickman, London, 1838, pp. 203-213, 218.
2. Roland A. Paxton, "Menai Bridge 1818-1826: Evolution of Design", Thomas Telford Engineer, Ed. Alastair Penfold, London, 1980, p. 98.
3. Ibid., p. 98.
4. Ibid., p. 99.
5. Roland A. Paxton, The Influence of Thomas Telford (1757-1834) on the Use of Improved Constructional Materials in Civil Engineering Practice, Masters Thesis, University of Edinburgh, December, 1975, pp. 390-391.
6. Telford, op. cit., pp. 223-224.
7. C.W. Pasley, "Description of the State of the Suspension Bridge at Montrose...", Journal of the Institution of Civil Engineers, Vol. 3, 1839, p. 227. The quotes are from a note at the paper's end.
8. Paxton, op. cit., 1980, p. 109.
9. W.A. Provis, "Observations on the Effects Produced by Wind on the Suspension Bridge Over the Menai Strait...", Transactions of the Institution of Civil Engineers, Vol. 3, 1842, pp. 357-359.
10. Paxton, op. cit. 1975, pp. 147-150.
11. W.A. Provis, "An Historical and Descriptive Account of the Suspension Bridge Connecting over the Menai Strait", London, 1828. This report is quoted repeatedly in Paxton, op. cit., 1975.
12. See Paxton, op. cit., 1975, p. 150.
13. Paxton, op. cit., 1980, p. 111-112. For a detailed description of the redesigned deck see Thomas James Maude, "Account of the alternations made in the structure of the Menai Bridge during the repairs in consequence of the damage it received from the gale of January 7, 1839", Transactions of the Institute of Civil Engineers, London, Vol. 3, 1841, pp. 371-375.
14. Paxton, op. cit., 1975, pp. 153-156.
15. Engineering News-Record, March 18, 1937, p. 422.
16. G.A. Maunsell, "Menai Bridge Reconstruction", Journal, Institution of Civil Engineers, Nov. 1945 to Feb. 1946, paper no. 5260, pp. 165-206.
17. Engineers News-Record, August 3, 1939, page 37.
18. Maunsell, op. cit., pp. 168-170. Two reports were published: E.G. Rivers and E.H. Morris, "The Repairs to the Menai Suspension Bridge", Min. Proceedings Inst. Civil Engineers, V190 (Session 1911-1912, Part IV), p. 293, and H.T. Tudsbery and A.R. Gibbs, "An Account of an Examination of the Menai Suspension Bridge", Min. Proceedings Inst. Civil Engineers, V217 (Session 1923-24, Part 1), p. 208.
19. We have estimated the weights from the figures in Maunsell's paper and his statement that the weight of deck lifted (includes concrete) = 800 tons:

Lifted deck	= 800 x 2/580	= 2.76 kips/ft
Cables	= 420 x 3.4	= 1.43
Trusses	= 100 x 3.4	= 0.34
Asphalt	= 1½ inches x 23 ft.	= 0.23
Sidewalks	= 50 psf x 10 ft.	= 0.50
Total Deadload		= 5.26 kips/ft

20. We take the liveload to be about 700 lbs per foot per lane, hence 1.4 kips/ft.

21. See Maunsell, op. cit., pp.174, 178, 188, and Plate I, Fig. 4.

22. Maunsell, Ibid., p. 175.
23. Engineering News-Record, Sept. 29, 1927, p. 499.
24. Sir Frederick Cook, Discussion (of the Maunsell paper), op. cit., pp. 193-94.
25. Ibid., p. 194.