Proc. Instn Civ. Engrs., Part 1, 1975, **58**, Aug, 415–426

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DISCUSSION

Brunel and the design of the Clifton suspension bridge

R. F. D. PORTER GOFF

Dr R. F. D. Porter Goff

I should like to explain how the Paper came to be written.

62. A few years ago it occurred to me that one might be able to study design in the context of design competitions. I thought that in a competition a number of alternatives would be proposed and justified as meeting a given design situation. I anticipated that an argued judgement would then be made on the merits of the proposals submitted and I supposed that one might be able to see general principles emerging which could form the basis of a university course in design.

63. The choice of Clifton was fortuitous: I merely knew that I. K. Brunel had won a competition there. It proved, however, a rewarding choice from three aspects. First, it was possible to study both sides of the project. The minute books of the Clifton Suspension Bridge Trustees have survived as well as the records of Brunel. Secondly, the Clifton project belongs to a period of rapid development of suspension bridges. At first in the United States, subsequently in Britain and on the Continent —notably in France—there was a considerable blossoming of this particular form of structure in the first half of the 19th century. Thirdly, the study introduced me not only to the work of Brunel and his contemporaries but also to their personalities.

Mr P. S. A. Berridge, formerly Assistant Engineer (Bridges), British Railways, Western Region

It is incorrect to say Brunel designed but one other suspension bridge, the Hungerford Bridge, besides Clifton (§ 6). The so-called truss spans of Brunel's famous railway bridges at Chepstow and Saltash were in fact suspension bridges.

65. The bridge across the River Wye at Chepstow (one 308 ft and three 100 ft spans, separate for each railway track) was opened in 1852. In the two longer spans, Brunel used riveted wrought iron tubes, 9 ft in diameter, as struts to counter the inward drag of the ends of the suspension chains (Fig. 9). The tubes were not self-supporting. Fabricated on the low ground on the right bank of the river, each tube was built with a camber of 18 in. at the centre and was temporarily trussed prior to being launched across the river and hoisted more than 100 ft to the tops of tall towers. On the river pier the tower was built of cast iron, imported from The Irish Engineering Co.'s Seville Works in Dublin; on the limestone cliff on the left bank of the river, the tower was of stone masonry. The tubes had fixed bearings on the cast iron tower, and on the masonry they rested on rollers.

66. Once each tube had been set on its bearings, Brunel completed the erection of the structural framework; two verticals and the plate girders which carried the

Paper published: *Proc. Instn Civ. Engrs*, Part 1, **56**, Aug., 303–321.

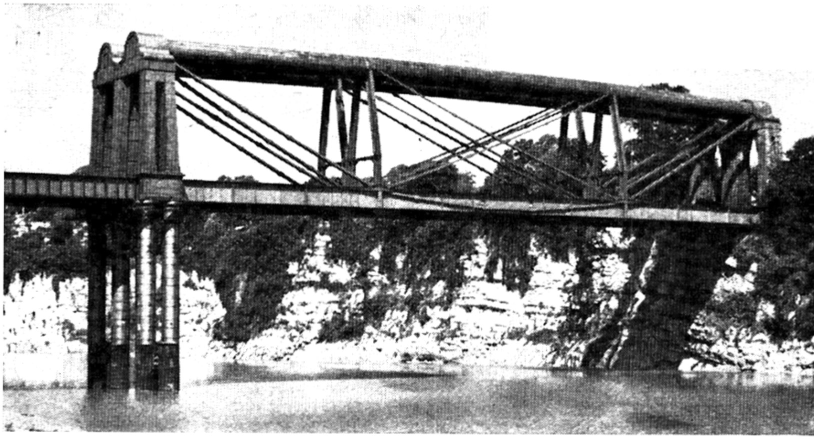

Fig. 9. Brunel's suspension bridge spans at Chepstow

Fig. 10. Oak folding wedges which kept chains taut at Chepstow

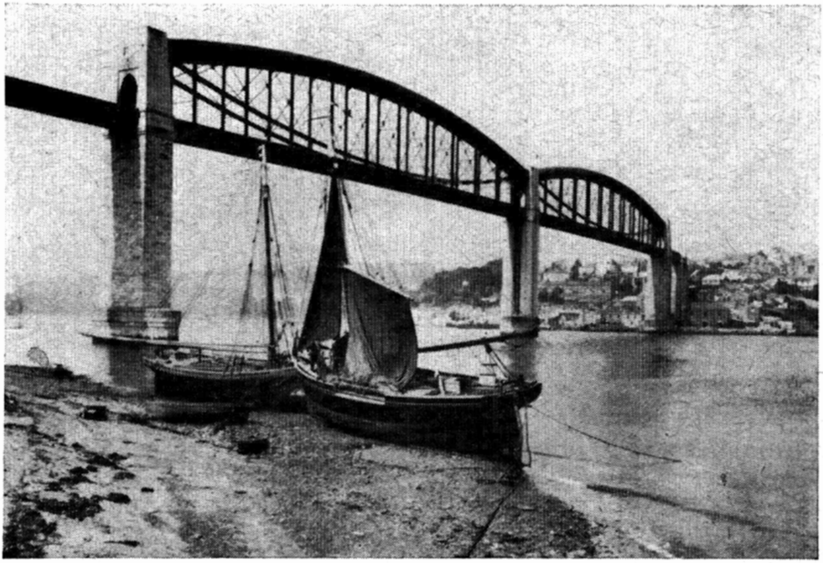

Fig. 11. Suspension bridge spans at Saltash, as Brunel built them in 1859

bridge floor and the single line of broad gauge railway. Then he slung the suspension chains, wedged them taut at the foot of each vertical and, at two more bearing points in the middle panel of the continuous plate girders, he further increased the tension with massive screws. The suspension chains were not fixed to the framework: under the wedges (Fig. 10), there were rollers, and the sides of the chains had brass or gunmetal rubbing strips to facilitate longitudinal movement within the wrought ironwork. In an endeavour to keep the shape of the suspension chains constant during the passage of trains across the bridge, Brunel prestressed the chains and increased the camber of the tubes to 30 in. Finally he added the diagonal bracings which were pinned to the suspension chains just below the rollers.

67. When reconstructing these historic spans in 1962, it was necessary to destress the suspension chains. Using gauges on hydraulic jacks in windows cut in each vertical, it was found that the load superimposed on each chain by the wedging below each vertical was 27 tons.

68. In the 455 foot spans of the Royal Albert Bridge at Saltash (Fig. 11) Brunel used the same technique as at Chepstow. In each span he dangled eleven pairs of standards (his name for the verticals) from an overhead oval-shaped tubular strut which anchored the ends of the suspension chains. Again each tube (this time arched upwards to mirror the downward curve of the chains) was fixed at one end and was on roller bearings at the other, the outward thrust at the ends of the arch countered solely by the inward drag of the suspension chains. Again the chains were preloaded by folding wedges of wrought iron, driven tight at the foot of each standard. And to keep the standards truly vertical and the catenaries in proper shape, Brunel introduced a system of slender diagonal bracing between those uprights and extended them below the chains as hangers to support the track girders. The standards were pinned initially to the tube, and pins at the tops of the hangers also

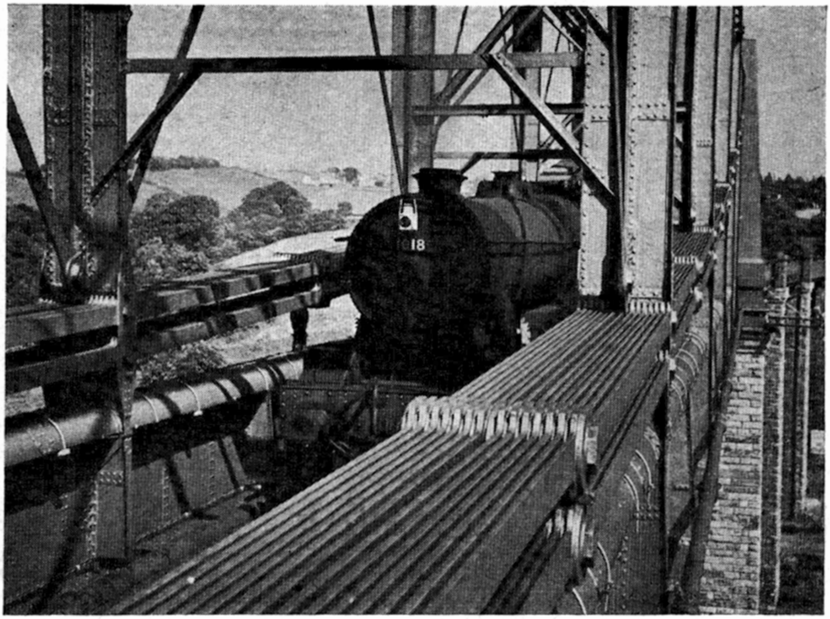

Fig. 12. Suspension chains in Devon span of Royal Albert Bridge

provided articulation while the curvature of the chains was being adjusted and the wedges driven tight; subsequently, standards, hangers and tube were rigidly connected by riveting.

69. The Royal Albert Bridge was opened in 1859. Of the 3 000 or so 20 ft long links in the chains (Fig. 12), 1150 came from Brunel's Clifton Bridge (§ 2) and were made before 1843. In these earlier links the ends, enlarged to accommodate the connecting pins, were forged on to the bars. But the later links were each rolled out of a single piece of wrought iron. According to the method described by Howard,[20] each bar was rolled transversely to begin with to form the enlargements at each end, and subsequently was finished to the required length by rolling the shank longitudinally.

70. These suspension bridge spans at Saltash are unique. They have the only chains which carry main-line railway trains today, and about half the wrought iron links were made more than 132 years ago when they were intended for use in a road bridge that was completed years after Brunel had died and out of respect for his genius (§ 2).

Mr B. J. Thorpe, Howard Humphreys & Sons

My firm has been consulting engineer to the Clifton Suspension Bridge Trust since 1910. I have to confess straightaway that I know less than I should about the history of the bridge, being principally concerned with the structure as it now is. This Paper has, therefore, provided an illuminating background against which to view the bridge.

72. I should like to offer one small contribution which poses an interesting question regarding the depth of Brunel's understanding of the behaviour of the materials he was using.

73. It is known that the wrought iron chains (Fig. 13) were very much a 'Brunel feature'. Although some items incorporated in the bridge were adapted or completely redesigned by Hawkshaw and Barlow, the individual links forming the chains were to Brunel's own design; two thirds of them actually being purchased from the site of the old Hungerford footbridge erected by him across the Thames in the early 1840s.

74. There are three flights of chains, not the two which Brunel originally intended. The third flight was added by Hawkshaw and Barlow as a safety factor. In addition, Brunel arranged each flight as twelve links interleaved with eleven near the towers, while he took advantage of the reduction in chain force to reduce the number to eleven interleaved with ten at the centre point. The behaviour of the chains is very interesting. Inspection and measurement suggest that rotations do not generally occur at the pin joints which simply provided a means of putting in a curved chain using straight bars. The whole flight of chains, stiffened as they are by the girder underneath, act as an inverted arch. As such, the only rotation which occurs is where the chains are pinned at the saddles.

75. Dr Porter Goff has referred to Brunel's design stresses. For wrought iron he was using 8 ton/sq. in. in 1829, 6½ ton/sq. in. in 1830, and 5 ton/sq. in. in 1838. At this time, he was also asking for proof loading to be used. In the chains on the bridge the dead load stress in the parallel sided shanks of the links is only 3 ton/sq. in. and even with Brunel's estimated live load of 100 lb/sq. ft (very unlikely to be reached on the bridge in practice) the axial stress would still be less than 4½ ton/sq. in. These low values arise because of the addition of the third flight of chains by Hawkshaw and Barlow. However, despite these low values, and although extra metal has been provided in the enlarged eyes, forge-welded to the ends of links, there are still relatively high stress concentrations adjacent to the pin-hole.

76. Fig. 14 shows that the eyes at the saddles do not have the shoulders which were provided on all the links across the span. A temporary yoke could be fitted to allow either a pin to be taken out, or a chain link to be extracted in the event of

Fig. 13

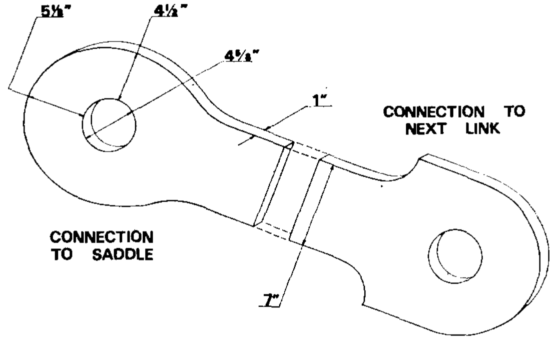

Fig. 14. Enlarged eyes for end link connecting chain to saddle

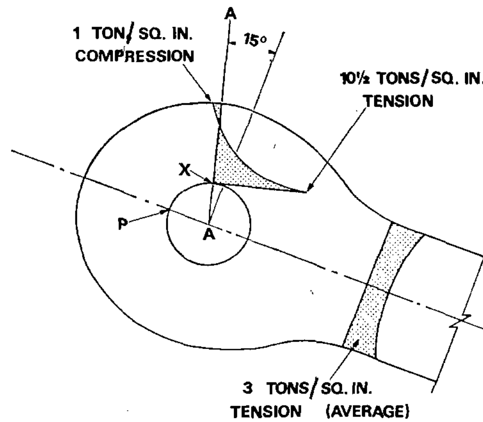

Fig. 15 Distribution of principal stresses for dead load condition

damage. This does not apply to saddles where, presumably, Brunel expected that he could make some other connexion behind the saddles. Illustrating my reference to 'extra metal' being provided, there are two legs of 4½ in. each, giving 9 in. of metal compared with the section at the main shank of only 7 in.

77. Fig. 15 shows the distribution of stress for dead load only, applied axially at point P as determined by finite element analysis and checked on a full size model. The radial section A–A passes through point X at the surface of the pin hole where the greatest stress concentration occurs. Of course it is well known that links of this type show such stress concentrations, but because the end eyes of the chains rotate on their pins in the saddles, and because this might cause significant stress fluctuations, a study was carried out with Dr Cullimore using the testing facilities at Bristol University. This study took into account the proof loading which Barlow tells us was applied to all the links, including those brought from the Hungerford footbridge.

78. Because the proof load of 10 ton/sq. in. in the shank was more than three times the dead load which gave the stresses shown in Fig. 15, considerable yielding occurred in the area around point X. On unloading there were substantial residual compressive stresses at this point. Even when combined with the dead load stresses applied when the links were erected in the bridge, these residual stresses greatly reduced any chance of fatigue in regions with stress concentrations, such as point X.

79. This brings me to the question that I should like to ask: did Brunel know that by proof loading the links he would leave residual stresses which are beneficial

in reducing the risk of fatigue? Indeed, did he know of the possibility of fatigue in wrought iron? Or did he, as I am inclined to believe, only regard the proof loading as a test of the qualities of the materials and workmanship employed?

Dr M. S. G. Cullimore, Civil Engineering Department, University of Bristol

A good deal of the Paper is devoted to the chains, and in particular to the design of the lugs at the ends of the links. The strength of these is of great importance, as is the strength of the welds which were made to join them to the flat bar forming the shank of the link. The proof loading, which Mr Thorpe has discussed in relation to the stress distribution it produces in the eye, was not, however, a severe test of the welds, as it would have produced visible distress only in cases of very inferior welds.

81. If one was wishing to make an assessment of the reserve of strength in the structure as it exists today, it would be desirable to know something about the strength of these welds. It would be possible to remove a link from the chain for testing, but this would be a costly and probably unacceptable proposition. However, welding was also used to attach the eyes and the threaded ends to the suspender rods. These rods have an eye at one end and a threaded portion at the other. Fortunately, some of these rods were available for testing, as in 1923 three rods were removed from the more heavily stressed parts of the bridge and replaced by new specially made wrought iron ones.

82. One short rod was tested by Merrs Kirkaldy in London. The load was applied by a pin through the eye, so simulating the actual working conditions at the bridge. The weld at the screwed end fractured at a mean stress on the weld of 18·8 ton/sq. in. The remainder of the rod was then pulled and broke at a stress of 21·9 ton/sq. in. (quite a normal value), giving a fracture surface with the usual fibrous appearance. The strength of the weld was thus 86% of that of the rod, a satisfactory figure.

83. At the same time, tension tests were made at Bristol University which showed the strength of the weld as 18·6 ton/sq. in., 84% of the strength of the rod adjacent to the weld which came out at 22·1 ton/sq. in. A round machined specimen 1 in. in diameter was made and tested and, as might be expected, gave a slightly higher strength of 22·7 ton/sq. in. The average of the extensions over all these tests was about

Fig. 16 Macro-etchings of weld sections

13%, indicating there had been no loss of ductility with age. It was concluded at the time that there was no cause for uneasiness so far as the rods were concerned. More recently, an examination of the weld at the eye end of the suspender road has been made, on a rod which was acquired from the bridge store. I am not certain of the history of this rod, but it is one of the genuine rods from the bridge.

84. The material from the weld area gave an ultimate tensile strength of 22·2 ton/sq. in., compared with 23·7 ton/sq. in. from the rod adjacent to the weld. The weld strength here is proportionately larger than in the earlier tests, and this is to be expected because the small section of the test piece (¼ sq. in.) contained none of the flaws and surface defects which were present in the full sized weld. A metallurgical examination was also made of the weld.

85. Figure 16 shows macro-etchings of sections of the weld. The top one is the transverse section and the bottom one is the longitudinal section showing the line of the scarf. The material on the right hand side is the suspender rod and on the left hand side the eye. The dark lines in the etched surfaces represent carbon rich zones and help to demonstrate the distortion suffered by the iron in the welding process.

86. The metallurgical examination showed that there was no sharp demarcation in the weld, demonstrating the soundness and effectiveness with which the welding operation had been carried out. Apart from some slag inclusions, trapped near the surface of the weld, the weld is a very good piece of work. It would be very interesting to know if Dr Porter Goff has found any records of the manufacture of the suspension rods which might indicate whether the quality of the welds in the suspender rods was typical of contemporary workmanship, and that similar strengths might therefore be expected from the welds in the chain links.

Mr H. J. Wadsworth, Rendel, Palmer & Tritton

I have found the Paper of particular interest because I have been involved in the reconstruction of two other suspension bridges, albeit of smaller dimensions: the Marlow Suspension Bridge, built in about 1830, and the current partial reconstruction of the Hammersmith Bridge, which was built about 1890.

88. One must agree that the increased dip relative to span shown in Fig. 6 makes for lighter chains, but this increases the tower height and probably the proportions of the tower at the same time, and it increases the length of the suspender rods. So possibly the balance is not correct at the suggested 1 in 10. As a point of interest, both the Marlow Bridge and the reconstructed Hammersmith Bridge have a dip/span ratio of 1:12. So far as the chains are concerned, the Marlow chains had links 2¼ in. square in cross-section, and I agree that this makes a cumbersome chain joint. When the bridge was reconstructed these were replaced by links about 3½ in. deep which made a more efficient section.

89. In Fig. 8 (b) it is possible to see a weakness in Telford's design and Mr Thorpe has already made this point very clear. The area of the eye behind the pin is only half the area through the pin; in other words, there is no reinforcement of the end of the eye, and good practice in eye bar design dictates that there should be two-thirds of the area across the eye provided behind. This apparently was not realized in Brunel's case, but he came close to it.

90. One disadvantage of the very deep chain which was produced by Brunel, and which has been copied in bridges like Hammersmith, is that the joints lock together because of the depth of construction, and this results in bending in the chains. There is no rotation of the joints. Bending stresses in the chains were measured at Hammersmith, and were found to be considerable.

91. It is interesting to learn (§ 43) that Brunel made an allowance for bedding in. In the case of Marlow, a 100 ft length of chain was laid in a test bed, and put under a tension which gave approximately 5 ton/sq. in. stress in the parallel bars of the chain. This created a permanent extension after it was unloaded, which gave the order of

the bedding in. The elastic extension measured gave a useful value of Young's modulus which was needed in order to work out the final shape of the chain and the size of the closing links.

92. On the question of hangers, there was a peculiar phenomenon at Hammersmith on the present bridge. The Hammersmith stiffening girders are not supported at their ends, but float freely, merely suspended by the chains. If a point load is put on the quarter point of the main span, say a bus, the chain tends to move towards that quarter point, forming a slightly V-shaped contour; the strange thing is that the stiffening girder moves in the opposite direction. I have never been able to understand this. Perhaps someone can throw some light on this. The effect is that the short hangers at the centre of the span are subject to considerable bending stresses. In the replacement work particular care has been taken to provide articulation of the short hangers, both in the longitudinal and the transverse directions because some allowance must be made for the tilting of the cross-girders due to loading on one lane and not on the other. I wonder whether Dr Porter Goff was able to find any reference to this problem by Brunel in his studies.

93. It was interesting to note from § 54 the mention of the stiffening girder. Marlow had no stiffening girder apart from the timber parapet, but there was a considerable stiffening effect from the excessive addition of dead weight in the deck surface. The bridge had been originally designed to have a tarmac surface about 3 in. thick on the timber decking which feathered out to nothing at the kerbs. By the time it had been reconstructed, the thickness had been increased to about 10 in. at the centre and 6 in. at the kerbs. This had a considerable stiffening effect and a very serious effect on the chain stresses. The dead load stresses in the chains were up to about 7 ton/sq. in. This is how it stood for years. The distribution of stress must surely have exceeded the yield point by a great deal on the inside of the eye, but presumably those links readjusted themselves since they were capable of taking this extremely heavy dead load stress.

94. It was very gratifying to all members of my firm to notice that James Meadows Rendel appeared to be the first person to introduce the stiffening girder into suspension bridge design. I wonder whether there is any mention by Brunel of whether he considered that the ends of the stiffening girders should be tied to bearings, or whether in his day they were left free. On the Hammersmith Bridge, which was not completed until nearly 1890, the ends were still left free; even at that time there was a lack of proper understanding of the real function of a stiffening girder as engineers know it now.

Sir Alfred Pugsley, Professor Emeritus, Bristol University

The University of Bristol and the Trustees of the bridge much appreciate this delving into the papers which have been gathered together at Bristol in recent years. This is just what they were collected for.

96. Dr Porter Goff has remarked on Brunel's youth. I can illustrate that by some of his difficulties with the Trustees at the time. He was a young man and progressively became very busy on other jobs. He also feared that the bridge would never be finished. His father, two years after the bridge was started, took that view. This must have tended to deter him from spending too much time on the Clifton Bridge project. As a result, there is repeated correspondence with the Trustees as to why he did not 'come down yesterday to the meeting' which he had promised to attend. This occurs time after time. He resorts to almost schoolboy excuses. At that time transport between London and Bristol was by coach, starting somewhere near Charing Cross. He was living at the time in Westminster. On one occasion, when he had been pretty well threatened by the Trustees for having let them down twice already, he still did not turn up. He explained, in effect, that he had missed the bus!

97. I do not know whether a small technical contribution will help to answer the

question about whether Brunel knew anything about fatigue. Most engineers think of fatigue knowledge as dating from Wohler's work in Germany, which started in 1852 and was published in 1864. But of course there was earlier work by Fairbairn which he started following the Royal Commission on the use of iron in railways. The Royal Commission sat from 1847 to 1849 and did some work on repeated loading on cast iron beams. Fairbairn followed that up by work on wrought iron girders. The minutes of the Bridge Trust show that Brunel had to commit himself to the design of his chains finally in 1840, when he placed a contract with the makers of the chains in Cornwall. The chains were largely finished in 1843 when money ran out, and he was told to stop the contract. These dates are earlier than of the work by the Royal Commission, Fairbairn or Wohler, so there was not much chance of his knowing anything about fatigue in the modern sense.

98. Something of interest which is not often mentioned is that Rankine, when he was elected a member of the ICE in 1843, presented a paper on the fatigue of railway axles.[27] He did not call it fatigue, but he knew exactly what was happening. At that time, he was a young man of 23 years of age working on the railways, mainly under one of ICE's Past Presidents, in Ireland. He had noticed failures of railway wagon axles which were attributed at that time to a long-standing notion lasting through the last century, that while wrought iron started life in a fibrous condition, after use and age it became more crystalline and brittle. That produced the popular explanation of the failure of axles as due to shock on a brittle material. Rankine made it clear that he did not view that theory with any approbation whatever. He had gathered together a number of broken axles for inspection. He describes clearly the fatigue of these axles in just the way it would be done now. He noticed the 'fine fissures' moving from the outside on the shoulder towards the centre until finally the centre part failed because it could not stand the ordinary loads of use. Unfortunately, like many papers by young men to this Institution and other institutions, his paper was forgotten and I do not suppose Brunel ever heard of it. Rankine was living in the north and was not often seen in London. I have found no trace of Rankine ever talking to Brunel. My view, therefore, is that when Brunel designed the chains, he and other bridge engineers did not understand fatigue. By the time he died, he probably knew more about it. He was certainly very interested in the work of the Royal Commission.

Sir Harold Harding, Consultant

The more one reads about Brunel the nicer chap he appears. The fact he was so young was remarkable. But four years on the Thames tunnel would be enough to age anybody! As experience is measured by intensity, at the age of 24 he was probably more experienced than many people twice his age. Much is said about the Clifton Bridge, but all one ever hears about the Hungerford Bridge is that the chains were used at Clifton and the piers support the Charing Cross Bridge. There must have been some difficulty in building Hungerford Bridge. The chains must have been very good if they could be used from a footbridge to a roadbridge, even if they were stiffened.

100. There has been settlement on the piers of both London Bridge and Waterloo Bridge. The piers which Brunel built for Hungerford Bridge are sitting there happily carrying trains to and from Charing Cross. The other extremely famous gentlemen's piers have settled, but Brunel must have been a pretty good engineer, especially as the piers were built in water, whereas those at Clifton were in rock.

101. It is interesting to find that the contractors starting the foundations at Clifton were just starting the shafts for the Box Tunnel. Another point, which has nothing to do with the bridge, but which has a lot to do with Brunel, is that in dealing with the Box Tunnel, the Sapperton Tunnel and another tunnel at Bristol he writes to his directors to say that he is sinking all the shafts for the tunnels before he lets

the contract. He wanted to find out what the ground was, so that he could let a sensible contract. He was 150 years ahead of his time!

Dr R. F. Legget, Consultant, Ottawa, Canada

102. Dr Porter Goff has made an important contribution with his Paper to the limited literature on the history of early engineering works. His delineation of the development of Brunel's thinking about the Clifton Bridge design can be of real assistance to students of structural design of today.

103. Could the Author say a little bit more about 'certain members of the Institution of Civil Engineers (who) . . . formed a company to finish the bridge. . . .' Such a tribute from fellow professionals may be unique in the history of the Institution. Who were these men and who was their leader in their generous enterprise?

104. Although its span (of 243 ft 6 in.) does not rank it with the early suspension bridges listed in Fig. 4, the Union suspension chain bridge, built at Bytown (now Ottawa) in 1843, was another pioneering venture in view of its location deep in the virgin forests of the (then) United Province of Canada. Designed by Samuel Keefer, it was well maintained and still giving good service in 1888 when it had to be replaced by a bridge with greater capacity.

105. Dr Porter Goff pays tribute to the notebooks of Brunel. Since the writer has also had the pleasure and privilege of studying these valuable records, in the Library of Bristol University, he would like to add his tribute also. Significant in some of the notebooks is the small square of sandpaper glued to the inside cover for saving time in the sharpening of the pencils which Brunel used with such skill.

Dr Porter Goff

Mr Berridge has remarked that Brunel's bridges at Chepstow (1852) and Saltash (1859) were essentially suspension bridges, with the land ties replaced by tubular struts. There is evidence from Clifton to suggest that Brunel had been interested for some time in the concept of a hybrid structure. In July 1838 he noted down in his calculation book possible subjects for the ornamentation of the Clifton towers. Specifically he listed the designs of Telford, Rendel, Brown and Hawks—his fellow finalists in 1831—and that of William Hill. Hill's proposal survives only as a lithograph but it clearly comprised a road deck supported by both arch and chain in a single span. It appears that the Trustees did not seriously consider it.

107. **Mr Thorpe** asked whether Brunel knew of the beneficial effect of proof loading the chain links. He is probably right to suppose that the proof test was intended merely to demonstrate the integrity of the components. Telford proof loaded the chain links at Menai, and Brunel doubtless followed this sensible precedent.

108. One may, however, ask first if Brunel knew that the proof load would produce plastic deformation and residual stress in the links; and secondly whether he was aware that the residual stresses could be beneficial with regard to fatigue.

109. The earliest theoretical work on stress concentration, according to Timoshenko,[28] was by Kirsch in 1898. Brunel could therefore not have introduced the appropriate factor into his calculations, if indeed he performed any (§ 40). Experimentally, however, he was certainly aware that a lug may fail on the inside of the hole. This might have suggested to him the phenomenon of stress concentration. He would also have known that when wrought iron yielded, the majority of the yield strain remained as permanent set. One may suspect that if he had been aware of plastic deformation due to proof loading he would have altered the lug design so that it did not occur.

110. With regard to Brunel's knowledge of fatigue, **Sir Alfred Pugsley** drew attention to Rankine's paper of 1843 (§ 98). At about that time there was a growing awareness that railway axles were subject to what is now known as fatigue, although the phenomenon had not been observed in connecting rods. Even if Brunel had been

aware of the experimental evidence when designing his chain links (circa 1840), he would probably have overlooked the problem as the links were not subject to reverse bending.

111. In response to **Dr Cullimore**'s comments on the welds in the suspension rods, the Author is aware of no formal record of their manufacture—indeed by 1850 Brunel had lost some of his own Clifton papers. It may be supposed however that he would have demanded the same quality of workmanship as that achieved in the chain links that he tested (§ 40).

112. **Mr Wadsworth** refers to the need to provide articulation of suspension rods at Hammersmith. Brunel was well aware of the problem of hangar bending induced by deck movement: Telford had suffered extensively at Menai from this trouble and had modified his hanger/deck attachments accordingly. Unfortunately the Clifton project was halted before the detail design of the deck had been worked out by Brunel. We therefore do not know what his solution would have been.

113. The Author is grateful to **Sir Harold Harding** for his reference to the care Brunel took over preliminary site investigations. It underlines the impression of cautious competence in Brunel that somewhat surprisingly emerged from the Clifton study.

114. In answer to **Dr Leggett** completion of the Clifton bridge by Brunel's colleagues is well summarized by Rolt.[22] Capt. Mark Huish was Chairman of the company, G. P. Bidder (President of the Institution in 1860) and J. W. Miles (Bristol banker and sponsor of Serrell's project, § 5) were among the Directors. As Rolt remarks, 'It was a happy sequel to Brunel's tragic end that old friends and old opponents alike should thus combine in free association to do him honour'.

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