Aesthetics versus function: the fall of the Dee bridge, 1847

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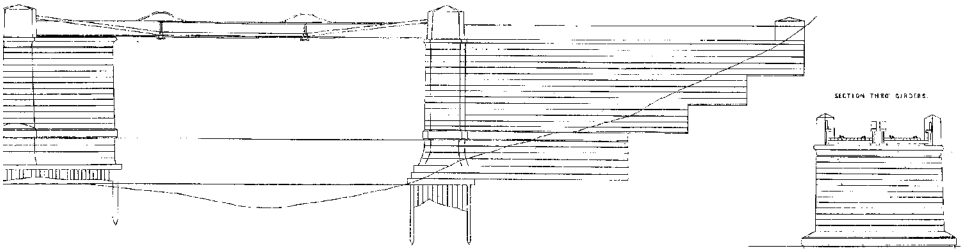
Numerous new bridges were needed when the railway line from London to Holyhead in Wales was built in the 1840s. The project's chief engineer, Robert Stephenson, chose a cast iron girder design to cross the river Dee just outside Chester, and the bridge was finished in November 1846. About six months later, on 24 May 1847, a local train was crossing the final span when one of the girders failed suddenly, sending most of the train crashing into the river below. Five lives were lost. The accident created a national furore, and Stephenson came close to being accused of manslaughter for the design. We have reviewed the witness evidence and concluded that the bridge probably failed by fatigue due to a defect at a sharp corner in a flange on a girder. The corner was present in a cavetto moulding, which had presumably been added as an artistic flourish.

The London to Holyhead railway line was one of those great Victorian projects which emerged from the frantic construction of a national rail network in the UK in the 1840s. The period became known as 'railway mania', and has distant similarities to the 'dotcom bubble' of our own times. Robert Stephenson was one of the principal pioneers of the rail network, in particular making the final link in the Holyhead line with his spectacular Britannia Bridge over the Menai Straits to Anglesey. The river Dee just outside Chester presented another challenge as it is about two hundred and fifty feet wide and is subject to the scouring action of ebb and flow from the tide. The first design was for a bridge of five arches with individual spans of sixty feet. However the foundations were thought to be insecure for a heavy masonry structure, and there were objections from river users to the proposal. Instead Stephenson opted for just two masonry piers in the river bed to be bridged by iron girders. He had recently used cast iron girders reinforced by wrought iron trusses in smaller spans elsewhere with some success, as had other engineers of the day.[1]

The approach to the bridge across the flood plain was constructed in the conventional way with brick piers and arches, the present bridge adopting the same course as the first structure. In addition, a cutting was needed where the line met the other, much higher bank of the river. The line met the river at an angle of about fifty degrees just by Chester racecourse, and then curved away to Saltney station about half a mile away. The bridge was built during 1846, and formed by laying cast iron girders across each opening of about a hundred feet between masonry piers. Each track (an up line and a down line) was supported by separate girders, so twelve were needed in all. Each girder was made by bolting together three smaller castings of roughly equal length, which were reinforced by wrought iron trusses running the entire length of each composite structure (Fig. 1). The line itself was laid on thick oak beams which were supported at each end on the lower flanges of the I section cast iron girders.

DOI 10.1179/030801804225012563

 Published by Maney for the Institute of Materials, Minerals and Mining



1 Section of composite girder, shown straddling stone piers, with transverse section at right: the span seems to be supported over much of the length of the first casting, but this is a false perspective owing to the angle of the track

The Dee bridge was opened to local freight traffic on 4 November 1846, after inspection and approval by the Board of Trade inspector Major-General Pasley (see table). In the early days, large deflections of several inches were observed by painters working on the structure when trains passed over. Such observations seem not to have been communicated to Stephenson or his staff, but emerged later at the inquest. A short time before the bridge was opened to the public, a small fracture was seen in one of the cast iron girders near a joint, and it had to be replaced by a new casting. Stephenson thought the fracture had been caused by a casting defect, and the girder had to be supported by piles while the new casting was made. On 24 May 1847, another girder failed suddenly when a train was passing, and five people were killed.

Our interest in the accident arose during reinvestigation of the Tay Bridge disaster of 1879, where a major cause lay in the poor design of cast iron columns used to support the wrought iron girders which carried the track. The piers were braced by wrought iron tie bars linked to the columns by lugs cast integrally with the columns. The lugs were much weaker than expected owing to their tapering section and the inevitable stress raising effect of the bolt holes required to attach the tie bars.[2]

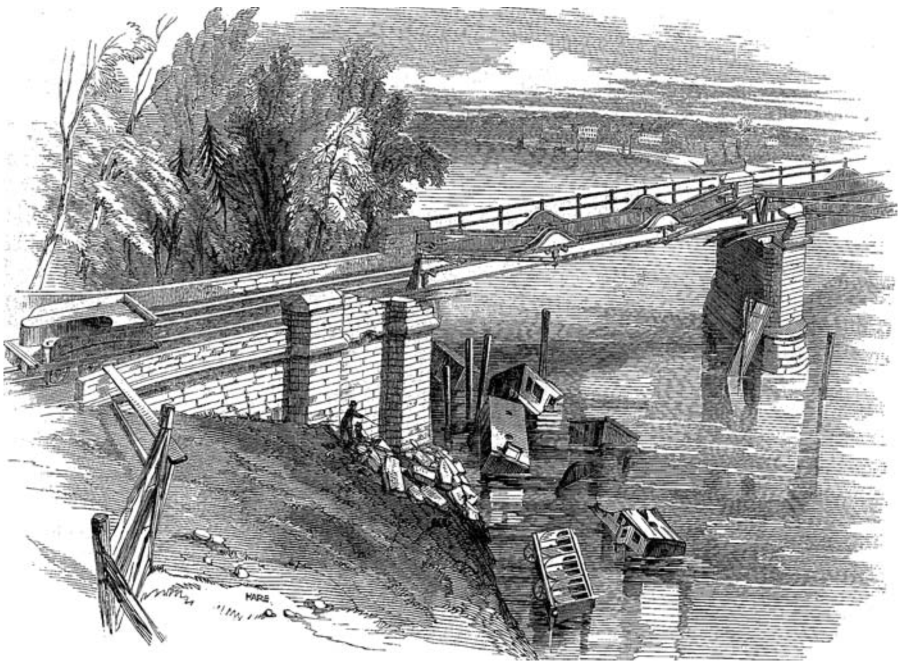
Chronology of events surrounding fall of Dee railway bridge, May 1847

September 1846	Completion of bridge by Robert Stephenson
4 October	Inspection and approval of bridge by Major-General Pasley
4 November	Bridge opens to traffic
April/May 1847	Painting of bridge
24 May	am/pm: six trains pass over safely
	pm: Stephenson orders ballast to be laid on track bed
	c. 6.15 pm: local train falls through final span
27 May	Captain Simmons inspects fallen bridge
28 May	Simmons examines broken parts and conducts various tests
29 May	Dismissal of Pasley
31 May	Stephenson writes to Directors of Chester & Holyhead Railway, attempting to show that train derailed and caused crash
4 June	Inquest at Chester Town Hall opens
15 June	Publication of Simmons' report
29 June	Commissioners of Railways minute to HM Government requesting Royal Commission on use of cast iron in railway bridges
27 August	Royal Commission into Application of Iron to Railway Structures
26 July 1849	Final report of Royal Commission

THE ACCIDENT

On the morning of 24 May 1847, six trains had passed over the bridge without problems. The new bridge was inspected by Stephenson that same day. He was worried about the exposure of bare wood to sparks and ash from passing trains, especially as this had recently destroyed a bridge on the Great Western Railway. He personally ordered a local contractor to lay five inches of ballast over the timbers, apparently equivalent to an extra load of about eighteen tons imposed uniformly on each span of the bridge. The extra dead load on one girder would thus have been about nine tons. The ballast was laid in the afternoon, the next train after the operation leaving Chester at 6.15 pm. The train weighed about sixty tons and was travelling at about thirty miles per hour towards the bridge, according to an estimate made later by Captain Simmons, one of the accident investigators (see table).

The train never reached its destination. As it was passing over the final span, the outer girder cracked and the carriages fell through the gap into the river below. The driver described how he felt the train sinking beneath him, so he put on full steam and just reached the far bank with the tender. However, all the carriages fell with the bridge almost forty feet to the surface of the water, killing four passengers and injuring many more. The stoker was killed when he was thrown off the tender, which was derailed and struck the stone parapet of the bridge. It was left standing about fifty feet from the water's edge, and three feet off the rails.[3] An engraving published in the *Illustrated London News* two weeks later shows the accident scene in some detail (Fig. 2), but no photographs (calotypes or daguerreotypes) appear to have been taken, or if they were, to have survived. There are



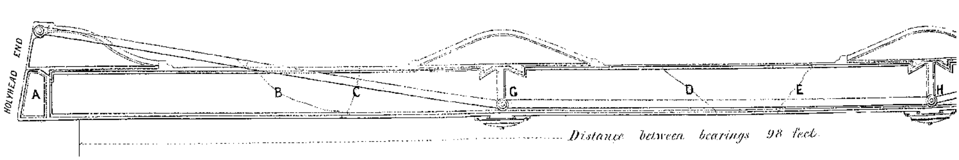
2 View of disaster site in etching from *Illustrated London News* of 12 June 1847: the view is from the south bank of the Dee looking north west along the river, with the tender at extreme left and the damage to the abutment visible at centre some spurious additions, such as the fanciful backdrop showing berthed schooners and other ships, an impossible vista from the position taken by the artist.[4] However, the foreground bears close comparison with the known facts as surveyed by the accident investigators. The driver (Clayton) was the only uninjured survivor, and with great presence of mind he drove the locomotive another half mile to Saltney station, where he raised the alarm. He then crossed over onto the opposite track, and courageously recrossed the bridge so that he could warn other trains of the danger. Fortunately there were many locals who had seen the accident, and the survivors were soon rescued from the river.

THE INVESTIGATION

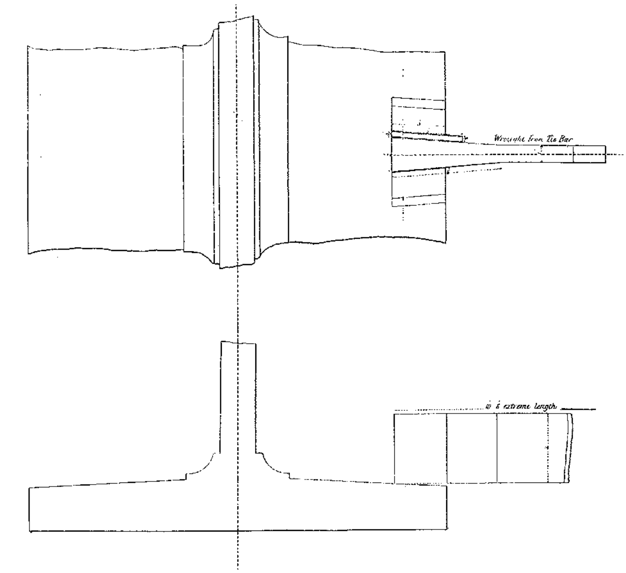
The Railway Commissioners asked Captain Simmons RE of the Railway Inspectorate to investigate the disaster. He was helped by James Walker, a civil engineer, and they produced a report in the remarkably fast time of around three weeks. Simmons made two visits to the site, presenting a description of the original design, a detailed inspection of the broken parts and extensive tests on the girders still intact on the bridge. Their joint report provides very detailed drawings of the design as well as the remains left after the disaster.[5]

The three castings were bolted together to form the composite span of ninety-eight feet, and were tied together at the joints by massive semicircular castings at the top of each joint (Figs. 1 and 2). Each girder was reinforced by longitudinal wrought iron tension bars attached to the girder at end flanges, at some distance above the main axis of the ends as well as at several points along the axis. The tension bars were provided in the form of a chain, as the elevation of one of the girders shows (Fig. 3). They were also tied together laterally by wrought iron tie bars attached to dovetail sockets cast into the structures (upper plan in Fig. 4). The large oak joists (ten by ten inches) were laid loose onto the lower flanges of the girders, and supported four inch planks onto which the rails were laid (Fig. 5). Inside the main rail was a duplicate set, which acted as a guard rail to prevent sideways toppling.

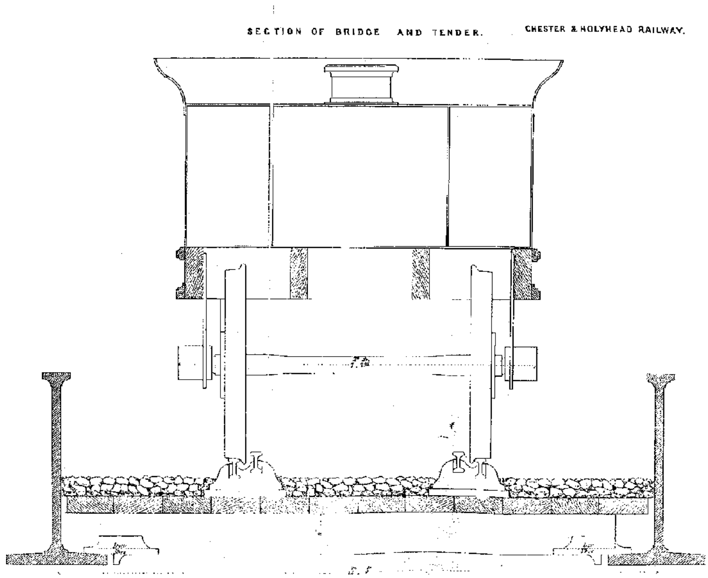
Simmons found the girder broken in two places, one near the centre of the middle casting , the other the abutment girder near one of the joints (Fig. 3). The form of each break appears, on the evidence of the contemporary drawings, to be similar. However, his description notes several differences. The fractures on the abutment girder led down to the lower flange, which was broken in one place only. The fracture in the centre girder was more complex, he states, consisting of several pieces, some of which were still in the river at the time his report was written. No detailed drawings of the fractures appear to survive. Simmons attributed the damage to the stone abutment to the derailment of the tender (Fig. 2).



3 Section of broken girder from accident site showing two main fracture zones, BC on the casting nearest the Holyhead end of the girder and DE on the centre casting (from Simmons' report)



4 Plan and section of cast iron flange of single casting: plan (above) shows the dovetail joint with lateral wrought iron tie bar which held the parallel girders together; below is a section of the flange with an oak beam at right



5 Full section showing how track was supported on the Dee bridge, with oak joists on which the sleepers were laid and the double track with guard rail: the oak joists were laid on the inner flanges of the cast iron girders; also shown is the ballast laid on Stephenson's orders on the day of the accident

Captain Simmons also conducted a series of experiments on the surviving girders and track with a locomotive to see how the girders responded to both static and live loads. He used a train of total weight forty-eight tons, giving a distributed load of twenty-four tons on each girder. Using a theodolite he observed a mean deflection of 2.36 inches at the centre of an intact girder with the train at rest . The top flange moved inwards by about half an inch, the lower flange moving outwards owing to the asymmetric loading on the girder (Fig. 5). He repeated the measurements with the train moving at around twenty miles per hour, the deflection decreasing to about one and five eighths inches. More significantly, he felt the bridge oscillating beneath him as the train moved across.

In their joint report, Walker and Simmons thought that the wrought iron chain gave little or no reinforcement to the cast iron girders since the ends of the chain were tied to the cast iron itself (Fig. 3). The girder had been underdesigned by Stephenson, although at the foundry the deflection under a static load of twenty-five tons was two and a half inches, in rough agreement with Simmons' observations. However, the foundry test did not replicate service conditions by loading the flange, as emerged from evidence given to the inquest by the manager of the Horseley ironworks where the castings had been made. Walker and Simmons noted that the bridge had experienced heavier loading than the train which fell, for example when three locomotives linked together passed over in October 1846 in proof testing the structure. It had also experienced heavy loading since opening. So what had caused the failure? Their inspection of both types of ironwork showed that the cast iron was sound, and contained no voids or blowholes (in particular in the fracture surfaces). Likewise the wrought iron was of good quality. However, they thought that the vibrations induced by trains might weaken the materials:

> … when a weight, partly permanent and partly passing, but together forming a very considerable proportion of the breaking weight of the girder, is in continuing operation, flat girders of cast iron suffer injury, and their strength becomes reduced …

This comment by Simmons is one of the earliest references to the problem of metal fatigue, where a component fails well below its rated strength owing to crack formation and growth by repeated loading cycles. Adding the extra load of ballast just before the accident must have contributed to the failure by increasing the static load supported by the girders.

THE INQUEST

The formal legal investigation opened at Chester Town Hall on 4 June, just ten days after the accident.[6] The first witnesses were painters who had been employed in April and May 1847, immediately before the accident. They had seen substantial deflections on the girders when trains passed over, the first witness describing deflections of up to two inches on both tracks. This witness, William Clegg, went on:

> … I observed it also when the passenger trains went over; they went faster than the ballast trains considerably; the extent of the deflections was 3 1/2 to 4 inches; I got my rule and put it under the bridge and noticed how much it went down …

The next painter to give evidence (William Clarke) went further, since he had observed a critical girder himself:

> … when passenger trains have gone over the deflection was according to the speed; in one instance it was 5 1/2 inches; it was the outside girder in the middle arch, which afterwards broke and had to be replaced; I measured it with my rule …

The deflection was downwards, but also the base was seen to 'elbow outward' while the top moved inwards. Clarke is presumably referring to the girder replaced by Stephenson before the accident. The evidence of the painters corroborated Walker and Simmons' observations.

There were also eyewitnesses of the accident who saw the bridge fall, and described very vividly the sequence of events:

> . . . I was on the Saltney side; I was from fifty to one hundred yards above the bridge: I saw the train come up about half way on to the middle arch; I saw it on the last arch; there was a tremendous crash; a large piece of girder fell from the middle buttress; also a lot of rubbish and the carriages; the last carriage dropped first, and the rest followed . . . (Thomas Frith)

> I was mending nets at the time of the accident on the marsh below the Dee bridge, about four hundred yards from the railway bridge; I was on the west side; I saw the train coming; I saw it on the last arch, when it all went down, except the engine and the tender . . . (Thomas Barlow)

> I am a publican and milkman in Chester; I was on the Grosvenor bridge at the time of the accident; I saw the train at the ship yard; I put my milk cans down and watched it across the bridge; when the train got on the furthest arch on the Saltney side, I observed a crack open in the middle of the girder; the train and tender were about the centre; the crack opened from the bottom; the engine had passed the crack, and the tender was right upon it; the engine and tender went on, and I saw the tender give a rise up; the carriages gave a jump and fell backward; the last carriage went down first according to my judgment; the next I saw was the large stones fall off the wall on the Saltney side; I heard a crash when they fell; I am certain the girder opened up from the bottom . . . (Thomas Jones)

The testimony of Thomas Jones was heard late in the proceedings, and although he was much further away from the other eyewitnesses (about seven hundred yards), it was very strong evidence for the course of events. Captain Simmons presented his and Walker's conclusions towards the end of the inquest, and they were to be crucial to the jury.

The most serious objections to simple failure in the middle of the centre girder were presented by Robert Stephenson, and he was supported by an array of distinguished engineers, Locke, Vignoles and Thomas Gooch. Stephenson claimed that the bridge failed when the train derailed and struck the inner side of the bridge, and fracture followed. This derailment theory was not supported by the eyewitnesses, and is remarkable for having been discussed at all given the flimsy nature of the case Stephenson presented. The tender had derailed (Fig. 2), but the witnesses clearly said this had occurred *after* the initial break in the centre girder, and not before. The remains of the train were scoured for any support for the theory, but very little could be produced. A single broken wheel, for example, was claimed as strong evidence for derailment of one of the carriages, but eyewitnesses said that the wheel had been broken deliberately to rescue the injured. Those passengers who were fit to give evidence concurred: the carriages had not derailed in the accident, a conclusion supported by Clayton, the driver. The jury themselves visited the scene of the accident, and were able to dismiss much of the scanty evidence said to support the derailment theory.

THE JURY'S DECISION

In his summing up for the jury, the coroner went out of his way to exclude negligence by Stephenson, let alone the possibility of manslaughter. On the other hand, it seemed clear to him that Stephenson's derailment theory was not a credible explanation for the collapse. If they so wished, then the jury should comment on the design of the bridge.

The jury agreed. They were unequivocal in their own view of the causes of the accident, stating first that all of the victims had died accidentally. Their unanimous opinion was that

... the girder did not break from any lateral blow from the engine, tender, carriage or van, or from any fault or defect in the masonry of the piers or abutments; but from its being made of a strength insufficient to bear the pressure of quick trains passing over it.

Their conclusion implied that

... no girder bridge of so brittle and treacherous a metal as cast iron alone, even though trussed with wrought iron rods, is safe for quick or passenger trains. And we have in evidence before us, that there are upwards of one hundred bridges similar in principle and form to the late one over the river Dee ... all are unsafe.

They went on to recommend strong action:

We therefore call on Her Majesty's Government, as the Guardians of public safety, to institute such an inquiry into ... these bridges as shall either condemn the principle or establish their safety to such a degree, that passengers may rest fully satisfied there is no danger, although they deflect from 1 1/2 to 5 inches.

ROYAL COMMISSION

It was well known at the time that cast iron was a very brittle material. Indeed, the world famous bridge at Coalbrookdale built in 1789 was so designed that all structural members were in compression. The numerous road bridges built later to the same design with cast iron arches were testimony to their integrity. Failures had been caused not so much by brittle fracture of the arches, as by movement of the abutments which took the lateral pressure.[7] However, they were unsuitable for providing the flat track needed for railways, which is why engineers attempted to use straight girders.

The jury's decision was acted upon rapidly by the government, which set up a Royal Commission in August 1847 chaired by Lord Wrottesley, with many distinguished members. A report was published in July 1849 (see table above) and included the results of numerous very detailed experiments with cast and wrought iron. Full scale tests confirmed the low strength of cast iron girders and their decrease in strength with repeated flexing:

The results of these experiments were, that when the depression was equal to one third of the ultimate deflection, the bars were not weakened. This was ascertained by breaking them ... with stationary loads in the centre. When, however, the depressions produced by the machine were made equal to one-half of the ultimate deflection, the bars were actually broken by less than nine hundred depressions.[8]

Although the term was not then used, the experiments demonstrated the problem of low cycle fatigue as well as the idea of a fatigue limit. However, they also introduced the erroneous idea that the structure of the metal changed fundamentally, repeated flexure producing 'a peculiar crystalline fracture and loss of tenacity'. By performing experiments on two actual bridges, they confirmed that the downward deflection at the centre of the supporting beam did indeed increase with the speed of a passing train.

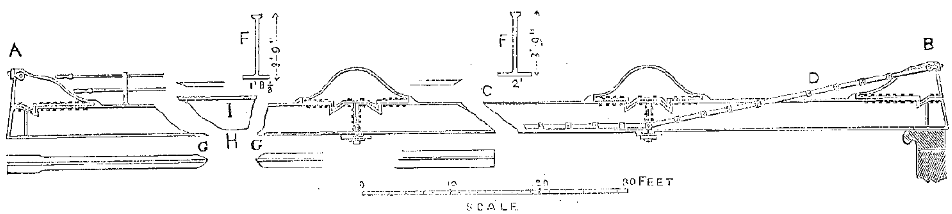
Stephenson was interrogated in detail about the Dee bridge, and it emerged that he and several other distinguished engineers had used or were planning to use the design in many other locations. Stephenson insisted that the design was not defective, which was strange given the accident on the Dee and problems with castings failing suddenly. Brunel, however, refused to use cast iron at all for structural application in bridges, although the discovery of a structure near Paddington station designed by him in 1838 shows that he did use cast iron for some of his first bridges. The design uses arches of ironwork and makes little use of bolts, the castings fitting together like the famous structure at Coalbrookdale.[9]

Fairbairn favoured his own solution of wrought iron plates riveted together to give large bridge sections, an entirely successful solution because he and Stephenson used it in the Britannia and Conway bridges built for the same railway at roughly the same time.[10] The toughness of this material provided a substantial degree of safety to the travelling public. Despite this wise decision, Stephenson still maintained that cast iron girders could be used safely, and he reinforced his existing bridges by stacking yet more girders on top of existing ones. He also made the curious suggestion that flexibility in the girders provided a degree of protection against impact or sudden loading from passing trains!

MODERN ANALYSIS

What can be said today about the causes of the Dee disaster? Modern interpretations are few and far between, but one eminent railway historian has presented an explanation not strongly supported by the original evidence. L. T. C. Rolt suggested that examination of the broken cast iron girder '. . . proved that the fracture had begun in the top flange, which had failed in compression'.[11] Walker and Simmons did not draw this conclusion at all. The suggestion was in fact first made by Henry Robertson, engineer to the Shrewsbury & Chester Railway, who during the final session of the inquest claimed that the top flange had broken in compression, although this interpretation contradicted the eyewitness evidence. Moreover, Robertson did not support his claim with any comments on the exact nature of the break.

Cast iron is much weaker in tension or bending than in compression, which is why the arch is the optimum structural form for bridges, or columns in structures which support only vertical loads. At the Tay Bridge inquiry over thirty years later, the measured compressive strength of the cast iron was about thirty-five tons per square inch, but the tensile strength only about nine, nearly four times smaller.[12] There is relatively little information in the original reports on the exact fracture paths of the broken girders (Fig. 3). Simmons admitted that fractured parts from the centre girder had been lost in the river, and neither he nor Walker identified exactly where the crack started. However, the anonymous author of the *Illustrated London News* article produced a diagram showing a fracture in the Saltney end of the casting which appears to start at or near the lower flange. This diagram (Fig. 6) shows the two main breaks, at GG and C, that at C being the first in the girder in the centre casting. It is shown as a clean angled fracture, but comparison with Simmons' diagram shows that the *ILN* artist was not aware of the second break (E in Fig. 3). The diagrams are in reasonable agreement on the crack profiles, although Fig. 6



6 Section of broken girder as shown in the *Illustrated London News* a few days after the accident: break at left is shown in great detail, perhaps because the parts had not separated; the centre break which caused the accident was more complex than shown, and several parts were lost in the river shows much more detail of the break in the abutment casting. Part of the lower flange appears to be missing, presumably lost in the river, and the profile is not inconsistent with fracture starting here and then growing into the upright web so as to eject the large fragment I. The abutment fracture was incomplete, because Simmons shows the casting intact in his plan of the accident scene.

It is likely that the collapse started with fracture of the centre casting when fully loaded by the train. It deflected downwards and was also twisted slightly by the asymmetric loading conditions, with the weight of the train supported by the inner flange only. The lower part of the beam will have been in tension, the upper part compressed. Since cast iron is weaker in tension, it is thus most likely that fracture started at the lower flange, and propagated upwards until it met the free upper surface. It is also clear from the sketch of the break that there were two separate cracks growing simultaneously, since a large trapezoidal fragment was created (Fig. 3). So what was the most probable origin of the failure? Without sketches of the fracture paths it is difficult to be specific, but there are some obvious zones of weakness in the section profile as provided by Walker and Simmons (Fig. 4, lower).

STRESS CONCENTRATIONS

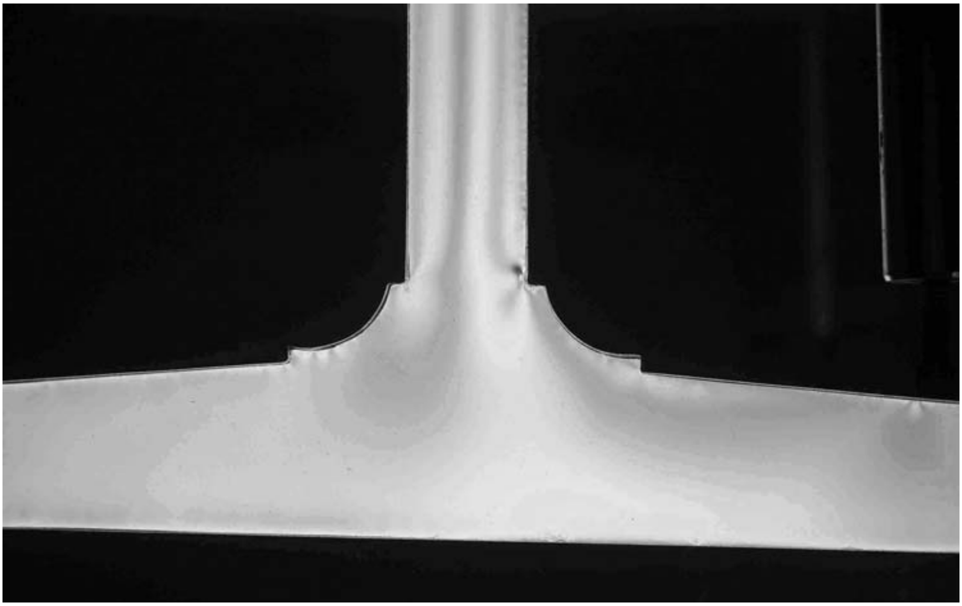
The inner corners of the girder were not smoothly rounded out, but given a curious shape more like that widely adopted by carpenters working with wooden beams. The section is known as a cavetto moulding, with two sharp corners (fillets) next to the web and flange parts and a concave surface between (Fig. 4, lower). The feature ran along the entire length of the girder on both the inner and outer sides. The fillets are very serious stress raisers, and the load imposed by the track and train will have been concentrated at the corners. Another zone of weakness is present in the lower flange at the points where the horizontal tie bars were attached (Fig. 4, upper).

The brittle cast iron will have been most vulnerable at these corners, and the corners on the cavetto moulding are the most likely origin of the brittle crack which caused the beam to fail. The crack will have run along one of the corners under tension and a small shear component, before running up the web to the free top surface of the girder. Such stress concentrating features as internal corners are well known in the modern literature.[13] They are exploited by glaziers for example, who when cutting brittle glass scribe a line in the glass surface and bend the glass about the line, so causing a crack to grow along it and separate the pane into smaller pieces.

But which of the two corners represents the most serious stress raiser? A direct experiment was attempted using polaroscopy. A scale section of the casting was machined from four millimetre thick polycarbonate sheet, a polymer with a high stress optical coefficient. The right hand flange was bent downwards in a polariscope, producing the birefringence pattern shown in Fig. 7. The upper corner of the cavetto section is where most of the applied stress is concentrated, and so where fracture will have started in the cast iron beam. By adding such a decorative feature to a structural beam, the designer unwittingly weakened it catastrophically. Aesthetic features may have been suitable on plinths for statues, but were quite inappropriate for structural components.

FRACTURE MECHANISM

So if one of these corners was the source of the brittle crack that destroyed the bridge, was it produced by overload or some other mechanism? The static load on the structure was



7 Section of model of girder with one flange strained by load at right, seen in polarised light, crossed so as to show internal stresses: upper corner of cavetto section is weakest part judging by high number of fringes; load concentration is seen by a similar dimple at right

increased somewhat by the addition of ballast just before the accident, but as this was distributed evenly over the whole bridge it does not explain why just one of the three spans failed. Clayton drove the train across two spans before reaching the critical one, and drove safely back across the bridge on the intact track to raise the alarm at Chester. The most credible explanation is that the fatal girder had been weakened by a fatigue crack which had grown progressively with use by passing trains. On the day of the accident, the previous six trains and the load of ballast allowed the crack to grow to a critical length, and it grew catastrophically when the 6.15 pm train entered the span. A small casting crack near the centre of the beam would have been enough to start the crack growing with passing trains. It is interesting to note that one of the painters (William Clarke), who worked on a girder which cracked before the accident, actually measured a very large deflection of five and a half inches at the centre of the span when a train was passing. If there was a growing fatigue crack, then this is just what would be expected: the remaining iron would be more greatly strained and therefore show a much greater deflection than in the unaffected girders. It is thus entirely possible that a similar effect occurred on the fatal girder, which failed catastrophically as the train passed over.

SEQUENCE OF EVENTS

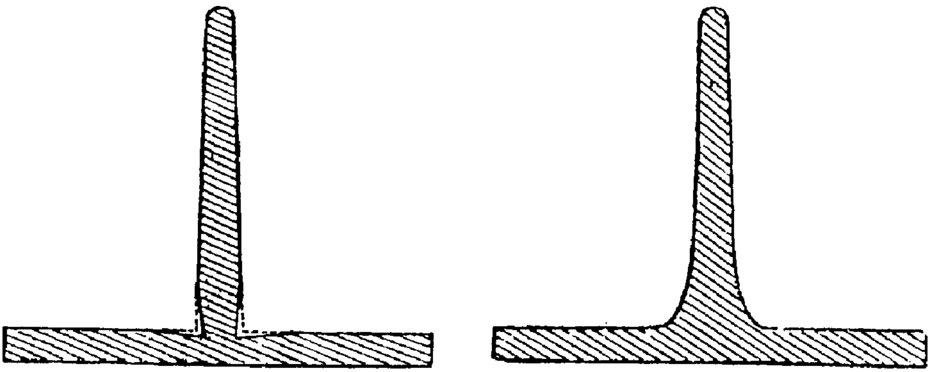
Thomas Jones's eyewitness evidence shows that the train was in the centre of the middle casting when the break occurred. Fracture of the girder occurred from a stress concentration in the lower flange. It branched and produced separation of a trapezoidal part. Although fracture will have been extremely fast, there will have been some delay on fall of the parts. All of the instantaneous load will have been immediately transferred to the wrought iron tension bars and tie bars, followed by the double rail itself. Being made of tough material, fracture will have been delayed slightly. Simmons estimated that the locomotive was travelling at about thirty miles per hour, so it would have been over the centre of the last casting in about half a second, when it too cracked in a similar way (Figs. 3 and 6). As the track sank behind the engine, its momentum carried it to the farther bank. However, the carriages behind were pulled backwards, and the coupling with the tender broke, allowing the carriages to fall into the river below. The wrench derailed the tender, and its coupling to the locomotive broke, the tender then striking the abutment and causing substantial damage.

AFTERMATH

The Dee bridge was rebuilt by creating arches below the girders, so relieving the girders of much of the load. According to John Rapley it was rebuilt again in 1870/1 using wrought iron.[14] However, further failures of the surviving girders occurred during the first rebuilding phase after the disaster. Each of the original girders was tested in a bend test and another girder failed by brittle cracking below its design strength. Yet a fourth cast iron girder was cracked by a workman in 1848 when driving a pin, requiring yet another replacement.

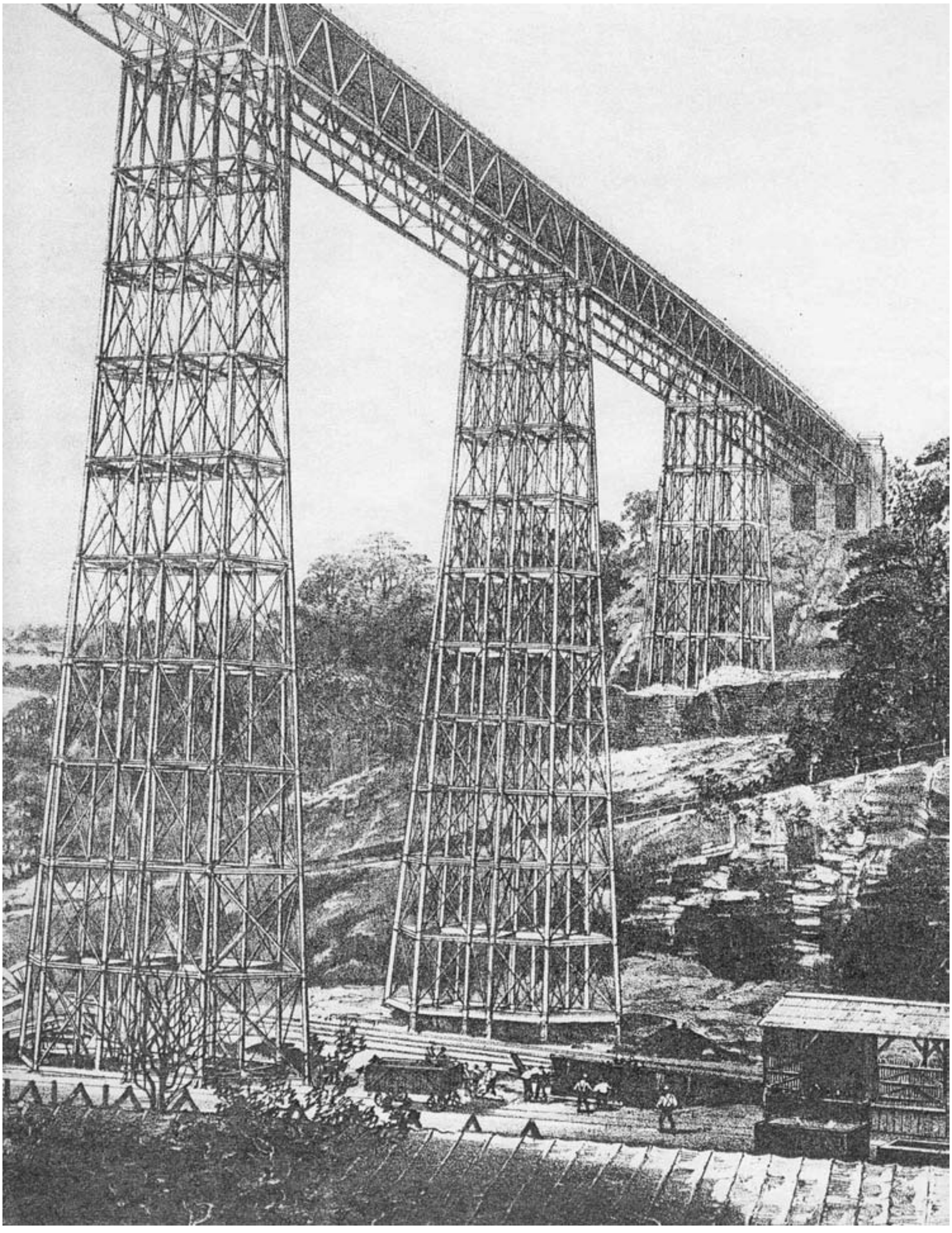
All other bridges built to the same design were either replaced by wrought iron designs or strengthened and reinforced like the Dee bridge. Stephenson himself was well advanced in his pioneering work on the Britannia Bridge across the Menai Straits using a wrought iron tube to cross the gap. He had learnt a lasting lesson from the disaster, as had other civil engineers.[15]

The final proof of the defective state of the cast iron girders is presented in a treatise published by William Humber just ten years after the disaster. The introduction to the book makes some pertinent comments on the use of cast iron girders. They should always be tested before use, but never at more than twice the design load. He then says that it is 'desirable that a girder should always be loaded in the direction of the centre line, instead of the load being supported by the bottom flange only, especially on one side'. This is a clear reference to the Dee disaster, and the way the girder was loaded asymmetrically by



8 Illustrations from William Humber's book on iron bridges and girders published in 1857. At left, defective cast iron girder with sharp corners produced by excessive shrinking of metal: Humber was unaware of the stress concentration effect of sharp corners, but did know that such girders were much weaker than expected; at right, the best form of a cast iron girder according to Humber: the corners are rounded, so reducing shrinkage, although (as we now know) amelioration of the stress raiser is much more important

Stephenson. The author goes on to talk about defects in castings, and makes very specific reference to inner corners. Indeed, his very first diagram is of the lower corners of a cast iron girder (Fig. 8, left). The diagram shows the excessive shrinkage which occurs here, and the sharp corner produced: ‘Not only is the beam weakened by this, but the grain will be found to be much closer in the angles than in the other parts of the ribs, and an unequal strain in the material itself must be the consequence.’ He then recommends a corner shape as shown in Fig. 8 (right), where the corners have been rounded to counteract



9 Frontispiece to Humber’s book showing view of Crumlin viaduct, which was begun in 1853 and opened to rail traffic in 1857: the structure was eighteen hundred feet long, stood two hundred feet above the river, and supported a double rail track the shrinkage. He says that this design modification has been proved by numerous experiments. Humber was obviously unaware that the most important effect of rounding sharp corners is to reduce the stress concentration, and so strengthen the final product.

The rest of Humber's book is devoted to detailed descriptions of the many iron bridges then built for the rail network, the most notable being the gigantic Crumlin viaduct in South Wales. By using cast iron columns as support for a wrought iron span, it made best use of the available materials, the cast iron in compression and the wrought iron in bending. The design elements are similar to those used in the brilliantly successful Crystal Palace, built in just nine months in 1851. The Crumlin viaduct was by far the largest such structure then developed for this purpose (Fig. 9), and it survived until the early 1960s when it fell victim to Dr Beeching. It inspired many similar bridges elsewhere in Britain and France, where several such structures survive to this day. Moreover, it was this design philosophy that was adopted by Bouch for his ill fated Tay Bridge.

ACKNOWLEDGEMENTS

We would like to thank John Rapley for kindly reading several drafts of this article and providing helpful criticism, and the Open University Library for help in obtaining the microfiche of the Parliamentary Papers related to the accident. The archivist and librarian of the Institution of Civil Engineers provided good quality photocopies of the Simmons report. Dr Lewis would also like to thank the members of the History Study Group of the Institution of Structural Engineers (especially Lawrance Hurst) for a stimulating discussion of the Tay and Dee bridge disasters following his lecture there in December 2003.

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