Forensic engineering: a reappraisal of the Tay Bridge disaster

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The Tay Bridge disaster of 1879 shocked the world and led to important changes in bridge design, construction, and inspection. The Court of Inquiry produced its final report in six months, and condemned the structure for its design and materials defects. However, the court did not specify exactly how the final collapse of the 'high girders' section occurred on the night of the accident. By reexamining the wealth of evidence surviving from the time, in particular the photographic archive and the court proceedings, we have looked again at the causes of the disaster. Our reappraisal confirms the conclusions of the original inquiry, but it also extends them by suggesting that lateral oscillations were induced in the high girders section of the bridge by trains passing over a slight misalignment in the track. The amplitude of these oscillations grew with time, because joints holding the bridge together were defective, and this in turn resulted in fatigue cracks being induced in the cast iron lugs, which reached criticality on the night of the disaster. Numerous east–west lugs fractured when a local train passed over the bridge in a westerly gale on the evening of 28 December 1879. The express train which followed was much heavier, and the towers in the high girders collapsed progressively as the train was part way over the section. Although wind loads contributed to the disaster, the bridge was already severely defective owing to failure of its most important stabilising elements.

From the early days of the Open University we have used case studies of disasters (such as the Markham Colliery incident of 1973, in which eighteen miners died when a brake rod failed, causing a pit cage to fall to the bottom of a shaft) to demonstrate the importance of fatigue.[1] In our new course on forensic engineering,[2] the block on catastrophic failures follows earlier blocks which present case studies of more recent product failures on a much smaller scale. We use our own published papers as the basis for student analysis, and expand the text where necessary to explain the underlying principles.[3]

The forensic tools used to analyse disasters are identical to those used for troubleshooting routine production or failure problems, photographic evidence being a core tool. Simple mechanical analysis using reasonable estimates of key variables allows hypotheses to be tested against the witness evidence. Elementary chemistry may also enter the analysis in considering stress corrosion cracking problems. Whatever survives is the most likely scenario which caused the accident. Determining the precise cause or causes of a product failure is vital for making better products, and if the cause is misinterpreted, further failures may be expected.

The skills needed to solve problems in forensic engineering are not easily developed, because there are so many factors to be overcome. Bias for or against a particular theory can be a formidable obstacle in approaching the truth, often encouraging selection of the facts to bolster a particular viewpoint without the wider picture being examined. Appreciation of the approach of different disciplines is vital to most product failures, and all assumptions made must be explicitly stated and justified. This last is not a luxury item, but a necessary precondition in expert evidence used, for example, in the UK courts. Failure will always occur at the weakest part of a structure, and can result in a chain reaction if not checked (the collapse of the World Trade Centre on 11 September 2001 is a good example). Computer analysis can thus seriously overestimate the ultimate strength of a structure, and must surely be used with caution. Bias will be familiar to all forensic engineers who have entered litigation. Sometimes it is produced by preferential inspection of evidence not yet available to the other side. When this happens, however, most cases are quickly settled as the whole picture soon emerges. In other cases there is an inbuilt bias to the client who is paying the fee. Interpretation of the evidence is then twisted or ignored, ultimately at the expense of the client, should the facts be against them.

In the Tay Bridge disaster of 1879, the focus of this paper, the bridge designer Sir Thomas Bouch quickly raised the defence that the wind blew the train from the track into the bridge, and that the shock caused the lugs on the nearest tower to break, so causing the collapse. His theory receives support from some local Dundee people,[4] however it fails to explain why all twelve towers collapsed and not just the one nearest the point on the high girders which the train allegedly hit. In fact, there is little real evidence in support of this theory. Only the guard's van and one passenger carriage showed anything like the serious damage that would be expected if they had come off the track. Traces of glancing damage

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above the track discussed at the inquiry were too high to have been caused by the train toppling over in the wind. Even if it had occurred, why did *all* the high girders collapse so catastrophically? The answer must be that they were either all intrinsically weak, or had been seriously weakened by 28 December 1879 by extensive generic flaws. The 1880 inquiry came to the conclusion that the bridge's 'downfall was due to inherent defects which must sooner or later have brought it down'.[5] Steady deterioration occurred by slackening of joints and fatigue crack propagation caused by trains passing over the structure. In our analysis of the photographs taken after the disaster, some of which are published here for the first time, we show just what the flaws were that caused the collapse of the high girders, and how they weakened the structure. Our reappraisal of the evidence still available confirms and extends the findings of the original Court of Inquiry.

The Tay Bridge disaster

The collapse of the Tay Bridge on 28 December 1879 was the worst structural failure to have occurred in Britain at the time, and in terms of both lives lost and the size of the failed structure it still retains this dubious distinction. Unlike many other disasters, it has retained its hold on the public imagination, perhaps because it involved both a railway and a bridge failure, perhaps because of the scale of the accident in terms of lives lost and the extent of devastation.

Several popular books have been written on the disaster, including John Prebble's 'The high girders' from 1955 (the oldest),[6] a book from the early 1970s by John Thomas,[7] and the most recent by David Swinfen.[8] A recent engineering analysis has also been carried out by D. R. H. Jones of Cambridge University.[9] The report of the Court of Inquiry is available in the parliamentary archives, together with several key expert reports, numerous line diagrams describing the remains of the collapse, and the two final reports.[10] Most interesting of all, the scene was photographed about a week after the collapse by a local firm, Valentines of Dundee; the main archive lies in Dundee City Library, and other photographs are kept at the University of St Andrews. The witness statements are preserved in the Scottish National Archive in Edinburgh, and the library of the Institution of Civil Engineers in London holds detailed plans of the structure.

It is clear from modern accounts that the causes of the disaster are still controversial. The view that wind loading alone toppled the bridge is still held by some, and is argued most strongly by Martin and Macleod,[11] whilst others argue that the train derailed and hit the bridge, thus bringing it down.[12] These views reflect some of the contemporary opinions considered by the original inquiry. However, the President of the Court, Henry Rothery, condemned the construction of the bridge in no uncertain terms, describing it as 'badly designed, badly constructed, and badly maintained'. Whatever conclusions we come to in our reanalysis are therefore bound to be controversial, and a stimulant to exponents of all theories to justify their arguments. For our students, this helps them appreciate how evidence is sifted by forensic engineers in arriving at reasonably coherent conclusions.

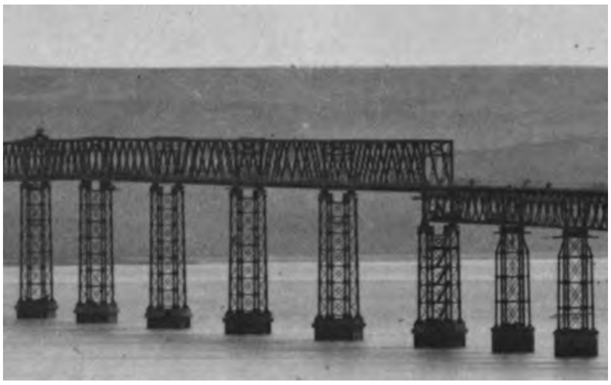
Contemporary evidence

Where to start research? It seemed to us that the best *de novo* starting points were the 1880 report of the inquiry, and the photographic collection in Dundee. They were both primary evidence, and so of greater significance than all the secondary and tertiary information. The report was photocopied from the microfiche, and the photographs scanned to produce high resolution tiff files. Both were significant exercises: the report runs to over seven hundred pages, and the archive stands at over fifty images. In the form of tiff files, the pictures could be enlarged up to about ten times to examine the points of detail which the court discussed at some length. They say a picture is worth a thousand words, and the dictum proved very apt in this case. The photographic archive proved invaluable because the pictures had been recorded with a plate camera of low aperture, and using a fine emulsion at long exposures in sunny weather, judging by the resolution we obtained from the enlargements. Indeed by their clarity and crispness they gave a real immediacy to our research. In the absence of key material remains (particularly the cast iron columns which supported the bridge – but see Note 13), they were the most important element in the reinvestigation. Although parts of the high girders are preserved in the Royal Scottish Museum in Edinburgh, numerous cast iron exhibits from the inquiry were lost in the London Blitz of 1940.

The best approach then was to read the report, for the witness evidence it contained, in conjunction with the pictures – in effect working as the court worked, since the pictures were used directly in evidence to the court. Owing to the scale of the disaster, the starting point would be the shots taken from a distance: Fig. 1 shows the new bridge as seen from Dundee, and a closeup of the high girders section is shown in Fig. 2. The second set of pictures shows the bridge after the accident, seen from the south side of the estuary: here Fig. 3 demonstrates the extent of the devastation, with ten piers swept totally clear of the towers which once stood upon them (Fig. 4).

The Tay Bridge was at the time the longest in the world, spanning about two miles across the Tay estuary. It was the central part, the so called high girders, which collapsed completely on the night of 28 December 1879, leaving a gap of well over half a mile (almost exactly a kilometre). The collapse took with it the express train from Edinburgh and a total of seventy-five victims, twenty-nine of whom were never found. When boats approached at first light next

1 The Tay Bridge just after completion, showing the centre or 'high girders' section needed to allow passage of high masted sailing ships upstream along the river to Perth (clearance was about eighty-eight feet at high tide). Some finishing work was still being performed on the bridge, judging by the staging and ladders seen at various points



2 Closeup of the join between the high girders at left and the low girders at right on the Dundee side of the bridge. The centre of each high tower shows the diagonal tie bars and horizontal struts which united the two sub-towers. Unlike the low towers at extreme right, the tops of the high towers are not reinforced by complete girders

4 Closeup of the join between the low and high sections of the bridge showing partly intact tiers on two piers. The boat in the foreground is searching for survivors in the girders, which are just visible in front of the third fallen pier, poking above the waterline. Numerous tie bar breaks can be seen in the centre of the last standing tower

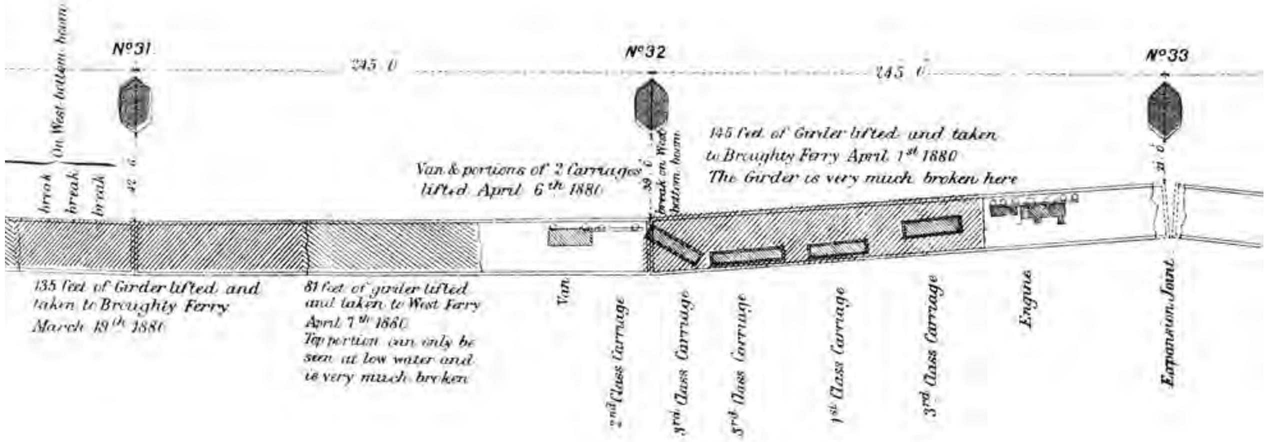
day, they found no survivors or bodies. The high girders were resting on the estuary bed, in a remarkably intact state and partly exposed at low tide (Fig. 5). Divers later found the train resting between the fourth and fifth piers, relatively little damaged except for the guard's van and the final passenger carriage (Fig. 6). The locomotive (a new 4–4–0 engine) had only superficial damage, and would later be restored to a long working life.

The events of the night of 28 December 1879

So what happened that night? From eyewitness evidence to the court, a rather confused picture of events emerged. A strong gale was blowing, the sky partly cloudy, partly lit by a full moon. A local train had been seen crossing at a quarter past six, although the journey across had been difficult, and sparks flew from the wheels of the carriages as the wind tilted the carriages against the guard rail. Bridges were routinely fitted with such rails to prevent toppling in just such circumstances. The worried passengers and guards later described the shaking of the carriages,

3 Long shot of the collapsed high girders section of the bridge, with twelve pier platforms almost completely swept off their high towers

5 Side of the high girders seen at low tide. The girders were found almost intact close to the pier bases, and laid out in a wave form alongside the high section of the bridge



6 **Plan of the section of the high girders between the fourth (no. 32) and fifth (no. 33) piers, showing the nearly intact train with the 4–4–0 locomotive at the front**

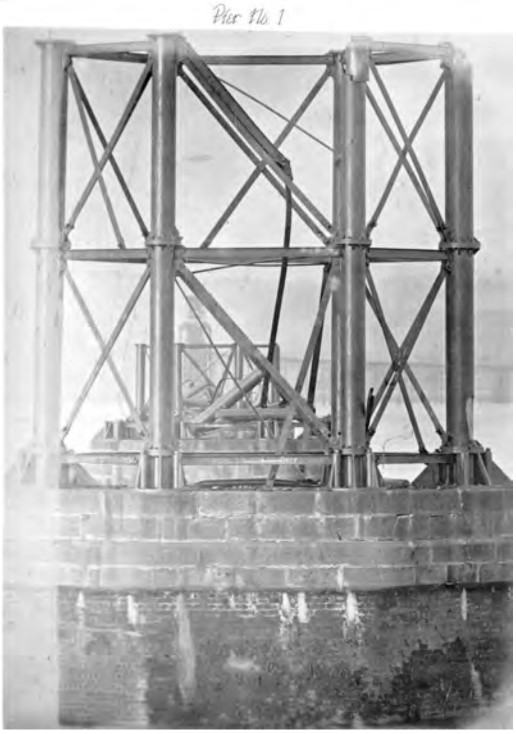
although the driver and stoker were entirely unaware of the problem because of the greater weight of the locomotive.

At about 7.13 pm, an express train drawn by a much larger and heavier locomotive left the south end of the bridge and was seen by witnesses in Dundee passing over the southern part, again with some difficulty and with sparks flying from the wheels. One witness thought he saw the lights on the bridge shake at about this time. An especially severe gust was felt on land just as the train was passing through the high girders at about 7.20 pm, and several observers saw what appeared to be flashes of light coming from the metalwork of the bridge. Some claimed to have seen the girders fall, starting at the south end, but others thought the collapse had started from the north. The nearest observers were about a mile from the train when it fell (Fig. 1 shows the view of some of them) and were scattered at various quite different locations, so it is not difficult to appreciate why accounts of the disaster varied.

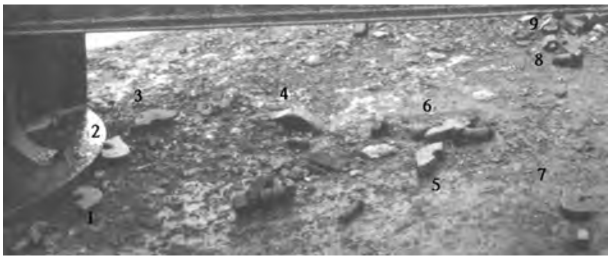
The Court of Inquiry

Acting rapidly, the court assembled within five days at Dundee to take direct witness evidence. The three judges also commissioned the photographic survey, and themselves visited the site of the fall by boat and inspected numerous wrecked piers. Just two of the twelve towers survived with intact tiers, the first next to the standing pier of the low section shown in Fig. 7.

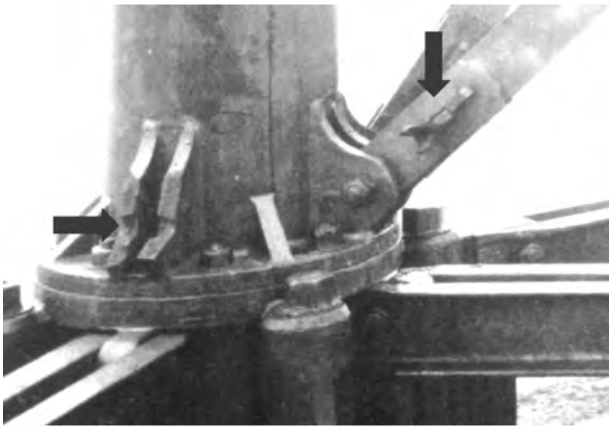
What we found most revealing was the nature of the debris on these two partly standing piers. Because most of the superstructure had been swept away, the stone platforms were relatively clear of debris, apart from fractured wrought iron bolts and broken pieces of cast iron of almost identical shape (Fig. 8). It turned out that these lumps of cast iron were the outside edges of the lugs holding bracing bars for each column (Fig. 9). There are nine such lug ends shown in Fig. 8, and while some may have come from adjacent broken tie bars (Fig. 10), the rest must have come from the missing higher tiers. Moreover, the two partly standing piers showed that the centre bracing bars facing east were most likely broken (Fig. 7). A similar pattern appears on the two fully



7 **Two partly intact tiers on the first pier, photographed from the south looking north. East facing tie bars have all broken on the centre cells, while the west facing tie bars are intact. Breakage has occurred consistently at the lower lugs**



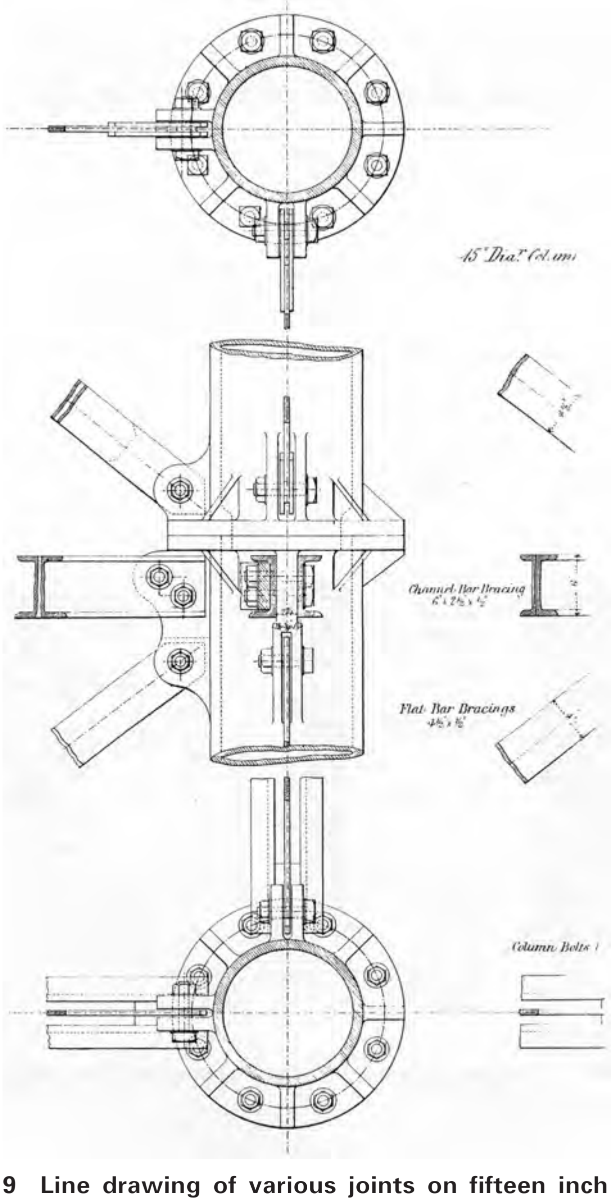
8 Debris field with nine lug ends plus nuts and bolts on the platform of the third pier (looking east). Base of fifteen inch column at left showing structure of cottered joint



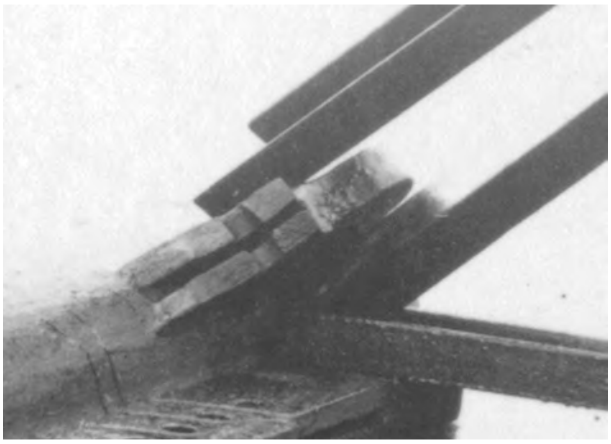
10 Broken lower lug on third pier (looking west), showing conical taper on bearing surface for one and an eighth inch bolt (lefthand arrow). The narrowest part of the hole is an inch and a quarter in diameter, so producing a large stress concentration at the contact zone. Joint at right shows gap between cotter and slot, allowing loosening with time (righthand arrow)

standing towers of the low sections, although some of the west facing bars were also fractured at their lug attachments (Fig. 4).

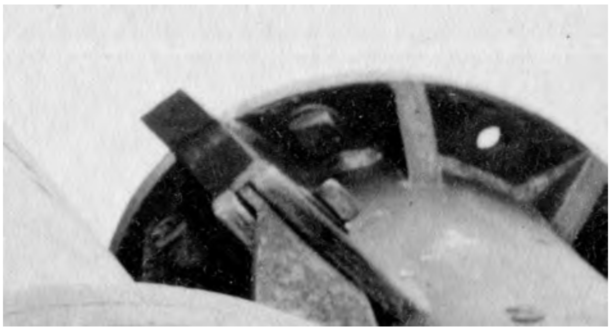
The discovery of the lug ends in abundance on pier platforms suggested that the collapse occurred by loss of the vital east–west tie bars which braced the columns together and were held by the lugs. It clearly demanded cross-examination of foundrymen still resident in the area at the time of the original inquiry. All the cast iron was made at the local Wormit foundry, but their evidence proved contradictory. The suggestion that there were ‘cold shut lines’ on the lugs, for example, is not borne out by our direct inspection of enlargements of the lugs (such as that shown in Fig. 10). These defects occur where the metal parts at a hole and then recombines at the other side. If the metal is too cool, a shut line forms and is a clear weakness in the lug. Moreover, close inspection of the fractures showed that the bolt holes were not drilled out to give a parallel bearing surface for the bolts. On the contrary, the holes were cast as one with the lug and column, and given a taper. This was a serious design defect because it produced a severe stress concentration, over and above that caused by the hole, when the bolt was stressed during straining of the bracing bars. The effect must have been to raise the stress at the outer edge of the hole by well over three times the nominal applied stress. In addition, it was observed by Henry Law, expert adviser to the inquiry team, that the bolt diameter was one and an eighth inches to fit the narrowest part of the tapered hole of an inch and a quarter. The bolts were thus a very loose fit, inducing another stress raising factor into the equation. Our inspection of the photographs revealed that *all* connection holes in the structure were tapered, apart from the flange holes in the cast iron eighteen inch columns, which were drilled. Figure 11 shows the bolt holes on an upper lug, whilst Fig. 12 shows an example on a strut joint. Cross-examination of the foundrymen showed that the lugs were a problem from the start, with many breaking in the yard from impacts. Attempts



9 Line drawing of various joints on fifteen inch diameter column, including upper and lower lugs, strut, and flange, all cast as one with the column (Institution of Civil Engineers)



11 Conical taper on broken upper lug. The column shows part of a lifting wing used during construction of the bridge



12 Conical taper on broken strut lug with intact upper lug joint in foreground

had been made to ‘burn’ them back on, with mixed success. If such repaired lugs had been used in the bridge, further weakness would have been introduced.

Although only a very small proportion of the tower parts lay on the pier platforms, attention was also drawn to fitment defects exposed in the broken parts. However, such defects were rather intermittent according to testimony, a feature we have confirmed by inspection of the photographs. What were far more serious were the many design defects present in the high girders section (see table). These included the taper section lugs, ill fitting bolts (Fig. 10), and the lack of a continuous connection at the head of the column where the high girder was supported by the pier. In effect, each tower consisted of two separate subtowers connected solely by the bracing bars and struts lying on an east–west axis (Fig. 2). That each subtower fell separately was suggested by the remains at the fifth pier, where the east tower lay under the high girder and the west on top. This observation was made by John Cochrane, an engineer called by Sir Thomas Bouch.

Design defects found in the high girders section of the old Tay Bridge

Defect	Prevalence
Lugs of low strength	All
Bolt holes with conical sections, so bolts acting only against short length of hole	All
1⅛ inch bolts for tie bars fitted to 1¼ inch bolt holes in lugs and flanges	All
Strut not abutting column wall	All
Strut bolts difficult to tighten	All
No spigots on column ends, allowing lateral movement of columns	Some
L girders not continuous across pier head	All
Pier base too small	All
Batter on eighteen inch columns too low	All
Girders resting freely on piers	Most
Girder not centred on pier; deviation at joint between high and low girders	One

Materials testing

The suspicions about the design of the lugs, especially the lower lugs on each column, led the inquiry to commission extensive materials tests on intact surviving columns and their bracing bars, which must have been taken from the intact parts available from the first and third piers (Fig. 7). They turned to David Kirkaldy, a well known engineer and owner of one of the first commercial laboratories equipped with a three hundred ton capacity hydraulic tensometer for mechanical testing purposes. He tested the complete bracing bar structure to destruction, although at a very slow rate of test, an inevitable result of the way strain was recorded at numerous datum points during the test.[14]

Kirkaldy’s results were not available till near the end of the inquiry (which by then had been transferred to Westminster, where the expert evidence was heard). His data confirmed early suspicions about the bracing system for the cast iron towers. The lug holes were the weakest link in the chain, breaking from the edges in just the same way as found on the piers, and the lower lugs were weakest of all, possessing a strength only about a third that of solid cast iron (tested separately from samples machined from the columns)! However, even these results were probably optimistic because they did not allow for fast loading conditions, as occurred on the night of the disaster. Those conditions would have produced the much higher stress concentration expected of a loose tapered bolt hole, and thus a much reduced strength. Under slow testing what happened was that the tough wrought iron bolts bent into the taper, and so increased the strength by spreading the load.[15] Indeed, such bolt bending probably occurred extensively through the structure during initial fitting of the tie bars, judging by the number of bent bolts seen in the pictures. This would also explain why the joints worked loose with time. The wrought iron tie bars proved to be very tough, none of the bracing bars or the struts in the photographs being broken. Most were however grossly deformed by the collapse of the towers.

Theoretical analysis

Both the experts employed by the inquiry and Sir Thomas Bouch produced very similar analyses of the stability of the structure when loaded by a lateral wind. They applied a quasi static analysis to determine what wind magnitude would topple an individual tower into the estuary, assuming that each bracing element was loaded uniformly. They estimated the area exposed to the wind by the structure and then added the effect of the solid train when on the tower. The open lattice of the tower actually has a relatively small exposed area, and the train was thus a significant contributor to the turning moment. The experts calculated that a wind pressure of about thirty-five pounds per square foot (psf) would topple a tower in the high girders section of the bridge. There being no anemometers in general use, evidence of wind force to produce such a pressure came from observers' estimates using the Beaufort scale. The general consensus was a wind force of ten or eleven (storm to violent storm), which on the scale is equivalent to a wind speed of fifty-nine to sixty-eight miles per hour, producing a pressure of ten and a half to fourteen psf. Benjamin Baker (appearing as an expert witness for Bouch) made a meticulous survey of damage to walls and buildings such as signal boxes, and even examined the condition of the ballast on the track. He concluded that pressures were no greater than fifteen psf on the night of the disaster. Such a figure is far below the predicted toppling pressure, so what explanation could there be for the collapse?

Movement of the bridge piers

Critical evidence of the state of the bridge a few months before the accident came from the crew working on repainting the bridge. They had experienced severe vibrations on the piers when a train passed over (without any wind blowing). Here is the testimony of one of the painters:

> 4916. Did the passing of the trains have any effect on the bridge? – Very much.
> 4917. What was its effect? – Oscillation, I would term it first, side to side movement.
> 4918. Was there any other movement? – Yes.
> 4919. What? – Vertical movement.
> 4920. With regard to the oscillation or lateral movement, was that severe? – Yes, it was very severe.
> […]
> 4940. What effect did you see the motion thus produced have on anything that was placed on the bridge? – I have seen the spilling of a pail of water a long while before the train approached. You could feel the oscillation half a mile off.
> 4941. But you have seen a pail of water upset? – No, not upset, only the water oscillating and spilling over the side.
> 4942. Had it any effect on the paint-pots? – We always secured them with every passing train.
> […]
> 4953. Were both those movements greatest inside or outside of the high girders? – Inside, about the centre.

This evidence was corroborated by eight other workmen who had been on the piers during the summer of 1879. The extent of lateral movement of the bridge appears from their evidence to have been between two and three inches at the top of a tower. Further support for dangerous vibrations from passing trains was provided by many passengers, especially those travelling from south to north. These included the Provost of Dundee, who had complained to the local stationmaster of the alarming vibrations he and others had felt. Nothing was done to allay their fears.

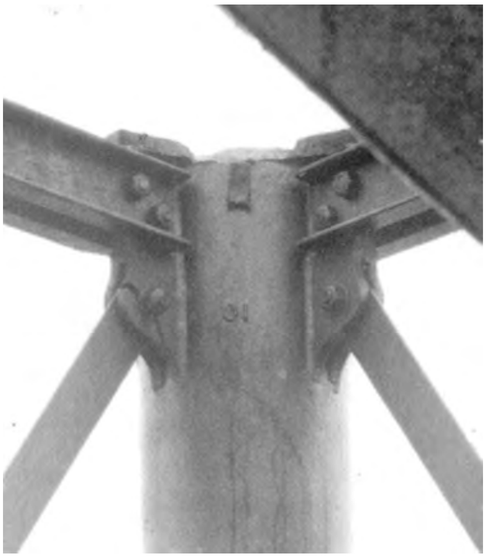
But movement of a different kind had been observed much earlier. After completion of the bridge in the spring of 1878, an inspector was appointed to maintain the structure, a Mr Noble. In fact he spent most of his time worrying about the problem of scour around the bases of the masonry piers, dumping large amounts of rock to inhibit the problem. While near one of the pier platforms in October 1878, he heard a rattling noise when a train passed overhead. In his own words to the court:

> 11404. Leaving the foundations, let us go up a little bit. Did you discover whether any of the ironwork of the bridge was getting unstable or loose? – In taking those soundings that I have spoken of, I noticed or heard a chattering of the bars.
> 11405. You heard them moving or shaking? – Yes.
> […]
> 11409. Did you examine the bars in order to see what was the matter with them, or whether they needed any repairs? – Yes.
> 11410. Tell me what it was you found to be wrong with the bars on your examination of them? – I do not know whether I can explain it to you. I found that the cotters in coming together had got a little loose – there was not a sufficient width to get a good grip, and they had got a little loose.
> […]
> 11416. How loose were they? – Had they been loose of course they would have been found at sight. We had to go and find out where this chattering motion took place, and then through the cotters to see which was loose, which showed me that they must have been just about as tight as this. In sounding them with a hammer we found that they were not tightened up sufficiently. In driving them home we found that they were scarcely wide enough to get a tight grip.
> […]
> 11425. Did you report what you had found to anybody? – No.
> 11426. Why? – Because I thought I could remedy it.

Such was the dramatic testimony of defective joints in the towers in the high girders section of the bridge. Unfortunately, Mr Noble did not pass the news on to Bouch, but decided to fix the problem himself. He purchased lengths of wrought iron bar (a half by a quarter of an inch in section), and cut them to make shims.[16] He hammered them into loose joints to stop the chattering, but by so doing he jammed the joints into a fixed state bearing little or no strain from the tie bars. Each tie bar was meant to be strained on fitment by knocking the cotters together, the tie bars then acting to stabilise the towers. It was reckoned afterwards that he might have treated some hundred and fifty joints in this way.

Taken together, the evidence of the painters and Mr Noble pointed towards serious deterioration of

13 Closeup of three broken lugs from twelfth pier. The centre sample shows numerous crack arrest lines with a small blowhole on the lefthand wing of the lug, probably indicating intermittent crack growth (fatigue)



14 Closeup of fractured lug on third pier (looking west). Only one wing of the lefthand lug has broken, suggesting cyclic loading during or before the accident and collapse of the tower. There are no washers on the strut bolts, and these appear to be tightened by different amounts (judging by differing thread heights above the nuts)

the towers of the high girders section after the bridge had been tested by the Board of Trade in February 1878. The tests involved running six heavy locomotives (total weight of well over four hundred tons) at high speed (forty miles per hour) over the bridge and observing the effect on the pier towers. The Board of Trade inspector, Major-General Hutchinson, measured little effect on the structure.[17] However, by October of that year joints were coming loose, probably as a result of high frequency vibrations from passing trains. Hammering shims into the gaps may have stopped the joints rattling, but it also meant that they were no longer effective. That steady cumulative loosening of the structure on all of the towers allowed the lateral movement felt by the workmen on the bridge in 1879.

The implications of the movements of the bridge were fully appreciated by the court, who referred to the 'racking' of the east–west braces of the towers. However, the court failed to take the further step of pointing out the problem to which movement could give rise. Fatigue was known at the time (cyclic testing of rail axles having been pioneered by Wöhler in Germany), but testing had been conducted for hundreds of thousands or millions of cycles, rather than the much smaller number to which the bridge was exposed by passing trains. (Britain was to rediscover the problem of low cycle fatigue cracking during the investigation into the Comet airliner failures in the early 1950s.) The joints most at risk would be those which were still tensioned, essentially because the imposed loads from passing trains would be transferred from the loose to the tight joints. Fatigue cracks thus probably grew in a proportion of the joints, relieving the loads but allowing greater movement.

An estimate of the free lateral movement created by the poor tolerances of the joints in the towers alone gives a sway at the top of about four inches, not dissimilar to that felt by the painters in the summer of 1879. There is evidence for fatigue cracking from some of the fracture surfaces seen in the pictures. The example in Fig. 13 shows crack arrest lines over part of the broken surface, each arrest line representing intermittent growth. There is supporting evidence for a fatigue mechanism from the several partly cracked lugs seen in the photographs. One example from about six found so far is shown in Fig. 14: one wing of the lug is broken, whilst the other is intact, suggesting at least one cycle of tensile load. Even today, hairline fatigue cracks in flake (or grey) cast iron products are very difficult to spot, and it is hardly surprising that neither the painters nor Mr Noble detected them.

Broken tie bar lugs on the two fully erect towers and the two partly standing piers support the testimony of the workmen. Both east and west facing bars are broken, confirming that the towers must have been oscillating laterally during the final collapse. The pattern of failure preserved in the four towers is more complex than indicated by simple east–west oscillation however. Lugs in the outer sets of bracing bars are also broken, despite being angled at forty-five degrees to the east–west axis. This seems to show that the vibrations in the final collapse probably had a more complex form, again confirming the testimony of the workers when they stated that the towers moved back and forth along the axis of the bridge as well as laterally and vertically. Further support for this hypothesis is provided by the fact that although a majority of columns fell to the east, some columns on some piers actually fell to the west.

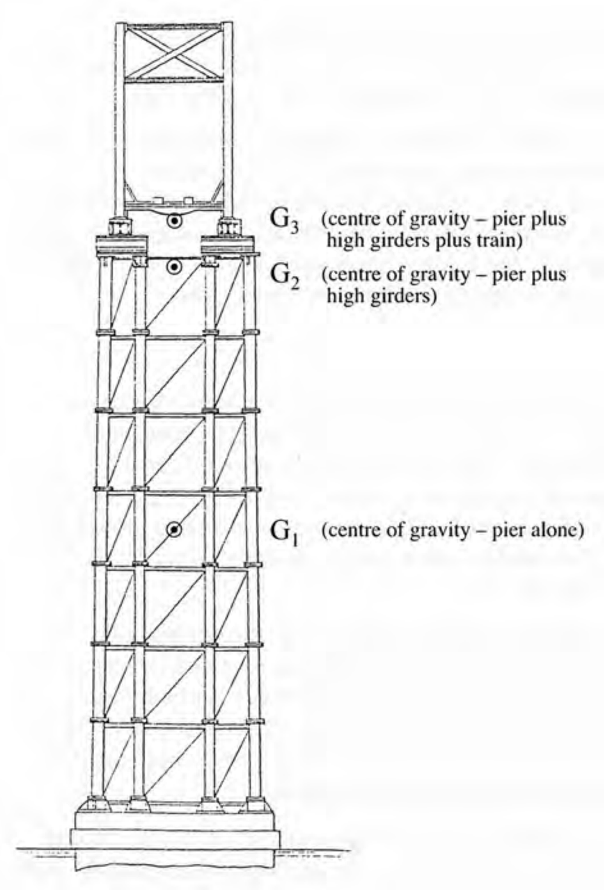
Reconstruction of events

So where does this new analysis of the collapse take us? The evidence for steady deterioration of the pier structure is convincing. It was produced by two main mechanisms, poorly designed joints in the bracing bars which allowed play to develop (chattering joints), and large stress concentrations at the bolt holes of the lugs which allowed fatigue cracks to grow. The history of the bridge from its opening to the final collapse is thus important to an understanding of why it collapsed so dramatically in the gale of 28 December 1879. In fact the bridge had been open to traffic well before its official opening in the spring of 1878, since September 1877 to be precise. It took goods traffic, trains carrying stone and ballast for completion of works in Dundee, and a growing traffic in coal from the Fife coalfields to feed the jute mills of Dundee.[18] It was heavily loaded from the outset, and traffic grew as passenger trains were added to the timetable. Such conditions led, as already described, to the loosening of joints first heard by Mr Noble in October 1878, and the swaying of the towers felt by the painters in the summer of 1879. On the day of the disaster, extra loads were added to the high girders structure by the westerly gale, especially during the passage of the six o'clock local train. The rear carriages were swaying severely enough to cause sheets of sparks from the wheels as they met the guard rail. But how much of the sway was caused by wind acting against the carriage sides, and how much by the bridge itself swaying on its joints? If joint looseness and fatigue cracking had progressed so far, then sway of the bridge itself must have been considerable. Many more tie bars must have broken and swung free during the passage of the local train, leaving the bridge in a parlous state for the following express train. None of the damage would have been seen from the land because night had already fallen.

When the express entered the high girders, the greater weight of the train (well over a hundred tons) would have produced critical movement to aid toppling of the towers over which the train passed. Each tower behaved as though composed of two separate towers linked by struts and tie bars alone. The train nearly reached the fifth tower before collapse overtook it, probably starting at the southern end and working progressively forwards until the entire high girders section had been swept away. That all the towers in the section had deteriorated is amply demonstrated by their state after the accident (Figs. 3 and 4).

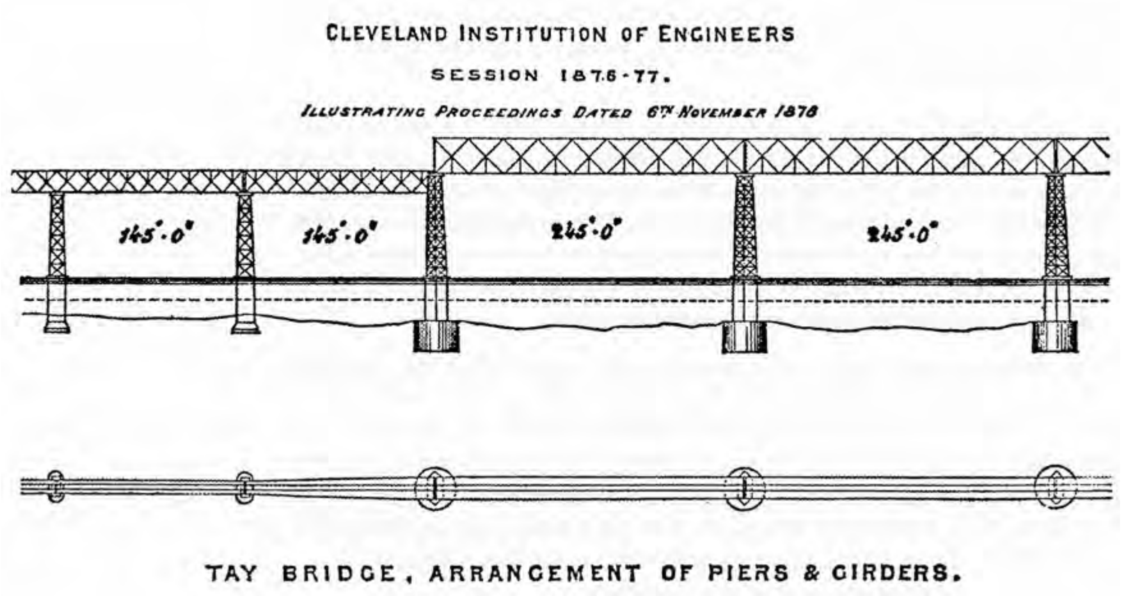
Unanswered questions

This picture of tower collapse leaves a number of undetermined issues. What caused lateral movement to develop in the first place, for example? It is interesting to observe that the design of the high girders section produced very large dead loads on each tower. Using figures estimated by the inquiry experts in 1880, we have calculated that the centre of gravity of the towers rose to just below the rail line when the train weight of well over a hundred tons is added to the weight of girder (getting on for three hundred tons), compared with the weight of a single tower of just over a hundred tons. The towers were even lighter in the original design, being completely hollow, however someone decided to fill them with Portland cement, increasing the total mass. The weight of the high girders was also increased when it was decided to cover the wooden trackway with ballast. The rise in centre of gravity is shown in Fig. 15. Thus each tower in the high girders section was very top heavy, much more so than those in the low section owing to the greater distance between piers and the heavier girders needed to span this greater distance (Fig. 16).



15 The towers in the high girders section of the bridge were top heavy, the centre of gravity lying near the the level of the track when the express train from Edinburgh crossed on the night of 28 December 1879

A clue to the lateral vibration induced by passing trains comes from evidence not presented to the original inquiry, but first revealed by John Thomas.[19] Train drivers reported a distinct sideways lurch when entering the high girders section, possibly caused by a slight misalignment of the track. This could have been enough to create a low frequency lateral wave along the entire section, a wave which grew in amplitude with time owing to progressive loosening of the joints combined with fatigue crack growth. Studies in the 1930s by Inglis showed how such waves could develop in long bridges from wheel hammer, although he only considered vertical vibratory waves.[20] Vertical movements of several inches could be induced by trains, the exact movement depending on train weight



16 The centres of gravity of the towers in the lower part of the bridge were much lower because the piers were closer together and supported smaller girders of lower weight, which helps to explain why they survived the collapse

and speed, length of girder, and so on. The position of the girder in the estuary floor is suggestive, since it adopted a wavelike form. The recent unpredicted sideways oscillation of the Millennium Bridge in London is a reminder of this problem.

Consequences

The final report of the inquiry team was delivered by 30 June 1880, a remarkably short turnaround, especially compared with present practice. Bouch himself was held personally responsible, and he died a few months later.[21] The bridge was rebuilt with a double track, using surviving girders from the low section of the old bridge, and parallel to the line of the original structure. The support piers were much wider, so giving a much higher safety factor against toppling, and upstream of the old piers, which then acted as breakwaters. The old piers remain to this day as a haunting reminder of the tragedy in 1879. Wrought iron and steel replaced cast iron in the new bridge, having been rapidly approved by the Board of Trade after the disaster. Both Bessemer and Siemens steel had been available for some time, but could not be used owing to a Board of Trade embargo. In the USA, steel had been in use for some years, and was a principal material for the Brooklyn suspension bridge, opened in the early 1880s.[22]

Tubular bridges using cast iron columns had been built elsewhere, Bouch himself having built a much shorter but higher tubular bridge at Belah in the Pennines. It survived until demolition in the 1960s, but traffic was always low, and the dead load on the towers much reduced owing to their more frequent spacing along the track. They were also given a much greater camber to resist lateral loading. Strangely enough, the joint design was quite different from that used on the old Tay Bridge, but why the design was degraded may never be known.[23] Perhaps it was a cost cutting measure – the Tay project was under severe cost constraints throughout the construction phase.

Gustave Eiffel had built many tubular bridges in the early 1870s in the Massif Central, such as the Bouble viaduct.[24] The joints were quite different in design, the tie bars being joined to gusset plates below (rather than at) the cylinder joints, and using rivets instead of bolts. All corners were given very large radii of curvature, minimising stress concentration at the joint. The towers were given curved buttresses at the base to resist side loading, reminiscent of Eiffel's later and more famous tower in Paris. Each of the Bouble towers was fitted with an internal spiral staircase for ease of inspection, unlike the old Tay Bridge, where inspection involved climbing down from the track using the struts and tie bars – a hazardous procedure at best.

Bouch had tendered for a crossing of the Forth estuary, which lapsed after the Tay Bridge inquiry. Benjamin Baker, John Fowler, and William Arrol produced the successful bid, eventually building a massive steel cantilever bridge with high resistance to wind loading. All joints were riveted using innovative methods developed by Arrol, and the bridge was subjected to a quite unprecedented level of inspection by the Board of Trade during construction. Owing to uncertainty over the effect of high winds on tall structures, a Royal Commission was set up to examine the subject, with Sir George Stokes a key member.[25] The commission recommended design guidelines on wind loadings for civil engineers, such as allowing for a maximum pressure of fifty-six psf during design of structures. Like many other distinguished scientists of the day, Stokes had given evidence to the Tay

Bridge inquiry, evidence which served to underline the problems of accurate measurement of wind speed and pressure. One of his anemometer designs is to be seen in the Science Museum today.

Victorian and modern disasters

The Tay Bridge disaster inquiry pioneered systematic investigation and recording of the evidence visible at an accident site. It was probably the first time a systematic photographic survey was made for an accident investigation, an invaluable archive which has enabled us to reexamine the disaster with the benefit of modern knowledge of likely failure modes. Other accidents of the railway age were systematically investigated before this date, for example the Dee Bridge disaster of 24 May 1847 and the Oxford disaster of Christmas Eve, 1874. However, photography was not available in 1846, and not used (as far as is known) to record the Oxford (or Shipton-on-Cherwell) disaster. On the other hand, the reports do provide copious numbers of detailed line diagrams from which much information can be distilled.[26] There are strong indications that the brittle fracture of one of the giant cast iron girders in the Dee Bridge was created by fatigue in the lower tensile side near the centre of the bridge. The design of the bridge was condemned by both the official report and the inquest, and Robert Stephenson came close to being accused of manslaughter. He abandoned this way of building bridges forever.[27] The later Oxford crash was caused by a broken wheel on an old carriage, which subsequently derailed and created a pileup when the brakes were applied. Brittle cracks from rivet holes in the wrought iron tread caused the failure, probably indicating fatigue over a long period of time.

Catastrophic railway accidents are of course not yet a thing of the past. In the UK, a train was derailed at Hatfield in October 2000 as a result of fatigue of the steel track, which led to disintegration of the track into over three hundred pieces, probably caused by rolling contact loads from passing trains. The reasons underlying the failure are still being investigated.[28] In the even more recent Potters Bar accident (10 May 2002), bolts on points near the station were left loose, the slack so created causing derailment of the last coach of a passing train.[29] Poorly assembled or maintained joints as well as fatigue are thus still serious problems facing rail engineers.

Acknowledgements

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Notes and literature cited

1. The example comes from Open University course T351, ‘Failure of stressed materials’, first presented in 1976.
2. Open University course T839, ‘Forensic engineering’, first presented in 2000, is part of an MSc programme in manufacturing. It currently attracts about a hundred mature students per year in two presentations. The course comprises written text and video programmes, one of which was recorded in 2001 and deals with the Tay Bridge disaster. It is very similar to a publicly broadcast TV programme associated with an undergraduate engineering course (T173, ‘Engineering the future’). There is an related website on the Tay Bridge disaster at www.open2.net/forensic_engineering. The only other postgraduate course in the UK with a forensic engineering component is Cranfield University’s MSc in Forensic Engineering and Science, which attracts about twenty students a year.
3. Such papers include P. R. LEWIS and G. WEIDMANN: ‘Failure of a polypropylene tank’, *Engineering Failure Analysis*, 1999, **6**, 197–232; P. R. LEWIS: ‘Degradation of an acetal plumbing fitting by chlorine’, Proc. ANTEC, Orlando, FL, USA, 2000; and C. R. GAGG: ‘Failure of stainless steel water pump couplings’, *Engineering Failure Analysis*, 2001, **8**, 189–199.
4. W. DOW: ‘The riddle of the Tay Bridge disaster’, BBC TV programme for Open University course T173, ‘Engineering the future’ (2001).
5. ‘Report of the Court of Inquiry, and report of Mr Rothery, upon the circumstances attending the fall of a portion of the Tay Bridge on the 28th December, 1879’, *Parliamentary Papers*, 1880, **LIX**.
6. JOHN PREBBLE: ‘The high girders’; 1955, Harmondsworth, Penguin.
7. JOHN THOMAS: ‘The Tay Bridge disaster: new light on the 1879 tragedy’; 1972, Newton Abbot, David & Charles.
8. DAVID SWINFEN: ‘The fall of the Tay Bridge’; 1994, Edinburgh, Mercat Press.
9. D. R. H. JONES: ‘Engineering materials 3: materials failure analysis’, chaps. 27, 28; 1993, Oxford, Pergamon.
10. ‘Report of the Court of Inquiry, and report of Mr Rothery’ (see Note 5).
11. T. MARTIN and I. MACLEOD: ‘The Tay Bridge disaster: a reappraisal based on modern analysis methods’, *Proceedings of the Institution of Civil Engineers, Civil Engineering*, 1995, **108**, 77–83; more details of their method of analysis are given in ‘Developments in structural engineering: Forth Rail Bridge centenary conference’; 1990, London, Spon.
12. W. DOW: ‘The riddle of the Tay Bridge disaster’ (see Note 4).

13. Following local publicity about our work, we received information that a cast iron column from the old Tay Bridge survived in a back garden near the site of the bridge in Fife. We and coworkers at Leicester university have examined a sample from this column, which shows a graphitic structure with few gas voids within the wall. The inner surface appears to show traces of Portland cement, whilst the outer has been painted with red lead. John Thomas states in his book (see Note 7) that red lead rather than whitewash was chosen for the painting in the summer of 1879. Pending direct inspection, the column therefore appears to be genuine.
14. Kirkaldy's London workshop at 99 Southwark Street is now run as a museum (the Kirkaldy Testing Museum, open by appointment). Operation of the tensometer was demonstrated on the BBC TV programme 'Local Heroes' (16 May 2000): the presenter, Adam Hart-Davis, included a superficial explanation of the Tay Bridge disaster using a hair dryer and a bridge of building blocks.
15. The suggestion was made during the inquiry from observation of many bent bolts on the pier platforms, and was repeated in W. G. KIRKALDY: 'Illustrations of David Kirkaldy's system of mechanical testing', 283–296; 1891, London, Sampson Low.
16. A shim is a thin strip of material used in structures, machinery, etc. to make loose parts fit; a cotter is a tapered wedge designed to secure part of a structure.
17. 'North British Railway, Tay Bridge: a report by Maj-Gen Hutchinson, March 5th, 1878', *Parliamentary Papers*, 1878, **LIX**.
18. DAVID SWINFEN: 'The fall of the Tay Bridge' (see Note 8).
19. JOHN THOMAS: 'The Tay Bridge disaster' (see Note 7).
20. C. E. INGLIS: 'A mathematical treatise on vibrations in railway bridges'; 1934, Cambridge, Cambridge University Press.
21. A direct connection was made by the public, perhaps because he was blamed so personally by the inquiry. Whilst the link cannot be proved, particularly as Bouch had suffered various bouts of illness through the latter part of his life, it cannot have been pleasant to have been so publicly rebuked by the inquiry and Parliament, and to suffer the indignity of seeing all his other bridges inspected for defects (some were reinforced, some demolished altogether), as well as losing the Forth Bridge contract.
22. M. MCCULLOUGH: 'The great bridge'; 1982, New York, NY, Simon & Schuster.
23. The plans of the Belah bridge are kept in the Public Record Office at Kew.
24. D. BECKETT: 'Bridges'; 1969, London, Hamlyn.
25. 'Report of the Committee appointed to consider the question of wind pressure on railway structures'; 1881, London, HMSO. Apart from his work on wind, Stokes will also be remembered for his famous law on the movement of spheres through viscous fluids.
26. 'Report of the Court of Inquiry into the circumstances attending the accident on the Great Western Railway at Shipton-on-Cherwell on the 24th December, 1874'; 1875, London, HMSO (also published in *Parliamentary Papers*, 1875, **LXVII**, 297) and 'Report to the Commissioners for Railways by Mr Walker and Captain Simmons RN on the fatal accident on the 24th day of May 1847, by the falling of the bridge over the River Dee, on the Chester and Holyhead Railway', June 1847 (also in *Parliamentary Papers*, 1847, **LXIII**, 186).
27. The story is told in L. T. C. Rolt's classic book 'Red for danger' (1955, London, John Lane/Bodley Head), with some more details in the same author's 'George and Robert Stephenson'; 1960, London, Longman.
27. Interim recommendations have been published by the UK Health and Safety Executive at www.hse.gov.uk/railway/hatfield/investigationb1.pdf. Four people died and seventy were injured in the derailment.
28. Information about the crash is at www.hse.gov.uk/railway/pottersbar/index.htm. On this occasion seven people died and seventy-six were injured, many seriously.

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Ken Reynolds is the son of a village blacksmith and has had a lifelong fascination with the working and heat treatment of metals. He worked initially in the quality control labs of a foundry, and later in the research division on titanium aerospace alloys. He then joined Birmingham College of Advanced Technology (now Aston University) and pioneered 'thin' four year sandwich degrees involving industrial training, and through UNESCO he also helped establish postgraduate courses in India before joining the Open University in 1971. Since his retirement as a senior lecturer he has practised as an independent forensic metallurgist, with well over a thousand expert reports to date. He has appeared in numerous court cases involving traffic accidents, personal injury, and product liability. He became involved in the Tay Bridge case study by examining and commenting upon the original photographs from 1880.