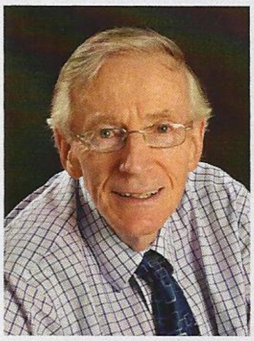
The legacy of the Tay Rail Bridge Collapse

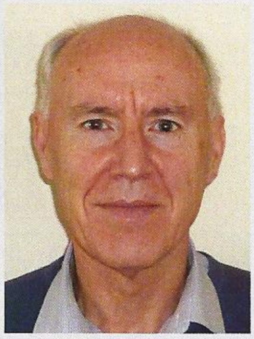
Iain MacLeod, Tom Martin

Abstract

In terms of loss of life, the Tay Rail Bridge collapse in 1879 may have been the most serious peacetime structural failure in the UK in the last 200 years. The event continues to hold fascination. While much has been written about the reasons for the collapse (reference 1 is recommended as the best general account of the event), the paper focuses on what can be learned from it. It is concluded that the designer of the bridge, Thomas Bouch, was negligent in relation to the design of the connections of the ties to the columns of the piers. The paper discusses strategies that may be used to avoid such events.



Iain MacLeod



Tom Martin

The event

29th November 1879, at about 7.15 pm, a train was on the navigation spans i.e. those with higher clearance for shipping of the Tay Bridge as it approached Dundee. The navigation section of the bridge, buffeted by a high wind with very strong gusts, collapsed. The girders, the train, the crew and the passengers plunged into the water. There were 59 named victims - no survivors.

The Bridge

The North British Railway Company commissioned Sir Thomas Bouch to design and supervise the construction of the bridge. He was an independent consultant with a very good reputation for delivering fit for purpose railways at competitive costs.

A site investigation contractor reported that, for most of the proposed line of the bridge, below about 6m of sand, lay bedrock. The initial design was therefore based on high foundation pressures and a contract was let for the piers to be in brickwork with the girders that spanned between them in wrought iron.

The completed bridge had 85 spans of which 13 were navigation spans - Figure 1. The navigation spans were 'through' girders, i.e. the girders were above deck level so as to provide maximum clearance for navigation. The piers were supported on caissons founded on the 'rock'.

Soon after construction began, it became evident that what had been identified as rock was in many places a thin layer of gravel over clay. The bearing pressures assumed at the bases of the caissons had therefore to be significantly reduced. This meant either increasing the diameter of the caissons or reducing the load on them. Bouch sought to do both and it is here that the seeds of the disaster started to be sown.

Figure 1. The original bridge

To reduce the loading, he re-designed the piers as cast iron columns braced by wrought iron ties -Figure 2. This could have worked well but Bouch made several errors in specifying the new arrangement as discussed in the section that follows.

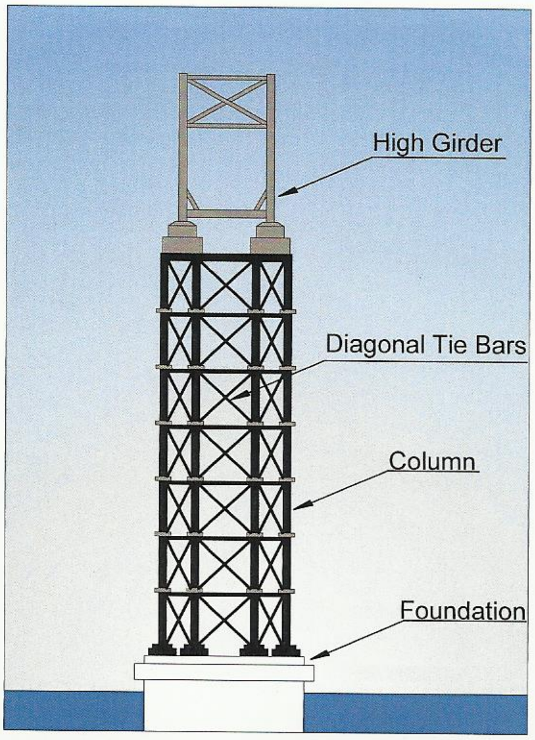


Figure 2. Elevation of a pier

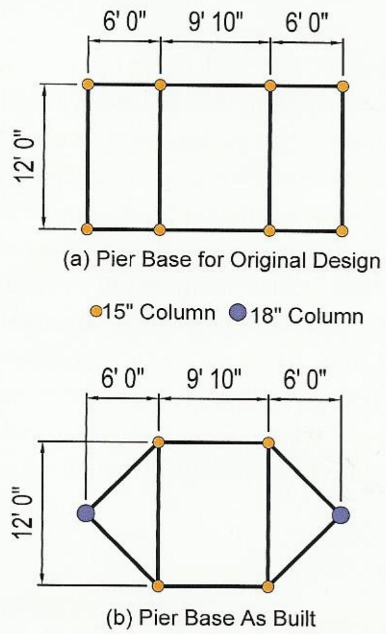


Figure 3. Layouts of columns for a pier

Seeds of disaster

Layout of cast iron columns in the piers

For an early design of the bridge, Bouch used an 8 column layout - Figure 3(a) - but in order to reduce the diameter of the caissons, and hence reduce the cost, he chose the 6 column layout with only single columns in the outer rows - Figure 3(b). For a layout of this type under lateral load, the outer columns take the highest stresses and therefore the 8 column arrangement is significantly stronger and provides more stability. That would have been a much better choice.

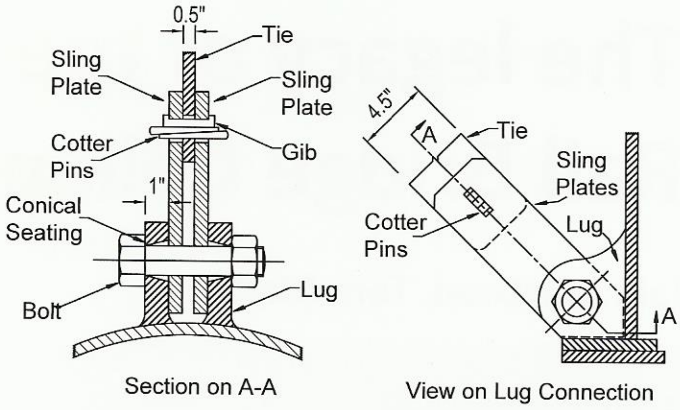


Figure 4. Tie bar connection

Bracing assembly

The diagonal bracing between the columns had a critical role in stabilising the piers but Bouch's design for them had a number of serious defects:

- The diagonal tie bars were connected to the columns by lugs that were cast with the columns - Figure 4. The bearing surfaces for the bolts on the lugs were as cast and were therefore uneven. There was no specification to ensure that these bearing surfaces were smooth. This was the most serious defect in the tie assembly. One does not need to be an engineer to understand that having an uneven bearing surface will increase the bearing stress.
- The stresses in the cast iron lugs were tensile. The tensile strength of cast iron is significantly lower than its compressive strength and the material is brittle. Wrought iron would have been a much more suitable material for making the connections to the columns.
- The strength of the ties themselves was less than that required by the calculations.
- A mechanism for tightening the ties used a cotter arrangement that did not allow the ties to be adequately tightened and tended to work loose.

Lengths of the navigation spans

To reduce the number of expensive foundations, the number of navigation spans was reduced from 14 to 13. This reduced cost but increased the loads on the piers.

Estimates of wind loading

When Bouch was carrying out the re-design for the Tay Bridge, he was also working on the design of a much longer span bridge across the River Forth. In relation to the Forth Bridge design, he received a copy of a report from George Airy, the Astronomer Royal that stated:

"We know that upon very limited surfaces and for very limited times, the pressure of the wind does amount to sometimes 40 pounds per square foot, or in Scotland to probably more. However, I think that the greatest wind pressure to which a plane surface like that of the bridge will be subjected to over its whole extent will be 10 pounds per square foot."

At the Court of Inquiry for the Tay Bridge Disaster[2], Bouch, stated that he had not made any allowance for wind pressure in the design of the bridge presumably based on Airy's report. However, his assistants, William Pole and Allan Stewart, who carried out calculations for the Tay Bridge for him, stated in a report that they had used a wind pressure of 20 lb/sqft. 10 lb/sqft would only have had a minor effect on the stresses in the bridge. 20 lb/sqft was better but still inadequate.

Sir George Stokes, Professor of Mathematics at Cambridge University and a world expert on fluid dynamics, giving evidence at the Inquiry into the collapse, stated that in wind speeds of 90 miles per hour, the wind pressure could be 50 pounds per square foot and that gusts of only short duration should not be assumed.

It seems likely that Airy's advice was to Bouch's liking. Catering for significant wind loading would have increased the cost.

Here is a conversation between Bouch and Airy that we can be certain did not occur:

Bouch: 'On what data do you base your recommendation?'

Airy: 'We measured the wind force on 2 foot square plate outside the Royal Observatory at Greenwich. There was a fresh breeze - about Force 5. The main finding from our experiments was that the forces in the gusts were of very short duration.'

Bouch: 'If the gust force might be greater in Scotland might not the force over the whole of the bridge also be greater in Scotland.'

Airy: 'That could be so.'

Bouch: 'I would like a second opinion. Who else might I consult.'

Airy: 'I think that George Stokes at Cambridge might have better knowledge about this than me.'

Bouch: 'Many thanks for that advice. I will consult with Professor Stokes.'

It is easy with hindsight to postulate such a conversation. One would expect that Bouch would not challenge a member of the Great and Good of British science in this way and that Airy might not be pleased to be challenged. However, Bouch should have adopted the principles that (a) he should use the best advice that he could obtain despite such advice having the potential to push up the project cost and that (b) since he was working with a safety critical issue about which there was much uncertainty he should play it safe. Neglecting the wind pressure was not playing safe.

We have no information about the data used by Airy. We do know that the 10 lb/sq ft was much too low a pressure and that if Stokes had been consulted and his advice taken, it is very likely that the bridge would have survived the storm.

Inadequate supervision of the construction

There were faults in the construction of the bridge. For example, imperfections in the cast iron columns were patched up.

The role of the client

The client, the North British Railway Company, put pressure on Bouch to keep the cost down and get the work finished as quickly as possible. There is no evidence that they considered safety issues. This was unsatisfactory client behaviour.

Site investigation

The integrity of the results of the site investigation was a key issue in the events leading to the failure. Some reflective questions should have been posed. 'How far into the rock did you drill?' 'Are the cores that you obtained available for inspection?' 'When will you drill the next hole so that I can be there to observe?'

It may have been that the site investigation contractor was under pressure to keep the cost down and get on with the job.

Why did the collapse occur?

Attributions for the cause of the collapse have included:

- That the train went off the rails as it traversed the navigation spans causing high lateral loads on the girders[3]
- Dynamic oscillations leading to fatigue in the cast iron columns of the piers resulting in their failure[4]

While these effects may have been present, our analysis[5,6] indicates that they are not needed to explain the failure.

Due to the low level of design wind pressure, the piers did not have adequate resistance to the storm force winds acting on the structure and on the train when it was on the navigation spans. Under the wind strength experienced at the time of collapse, there would have been uplift on the windward columns but this was not catered for in the design. The design of the tie assembly had serious faults and the trigger for the collapse is likely to have been failure of the lugs on the columns. In a strong gust, the bracing ties of one of the piers progressively failed from bottom to top. That pier lurched sideways putting extra lateral load on the other piers. The structure toppled.

Culpability

Figure 5 shows culpability paths for the two major faults of low wind force allowance and unsatisfactory specification of the lug detail.

Wind loading path culpability path - blue dashed line, Figure 5 That wind loading might be important was recognised but no design rules were available. Bouch's action to mitigate this risk was inadequate. He was dealing with a safety critical issue about which there was much uncertainty. He should have sought to err on the safe side but he did not. Therefore, one could infer that he steered a course towards being negligent but did not cross the line.

Design of the bracing assembly (red dotted line, Figure 5) That the ties were understrength and that the cotter arrangement was unsatisfactory may have been due to errors of judgement or of commission but culpability for the errors in the design of the cast iron lugs on the columns was at a different level.

At the Court of Inquiry for the collapse, it was observed that Bouch had previously used much better specifications for similar connections for the Belah Viaduct in Yorkshire. The ties specified for that bridge were connected via wrought iron bands on the columns rather than by cast iron lugs

W H Barlow, one of the Commissioners at the Court of Inquiry, and Bouch had the following dialogue at the Inquiry:

Barlow: 'Why did you depart from that type of construction (used for the Belah viaduct)?'

Bouch: 'I can only tell you this, that I had a different idea of the force of the wind at that time before I got the report of the Forth Bridge.'

Barlow: 'Is that the only reason why you did away with those ties?'

Bouch: 'They were so much more expensive: this was a saving of money'

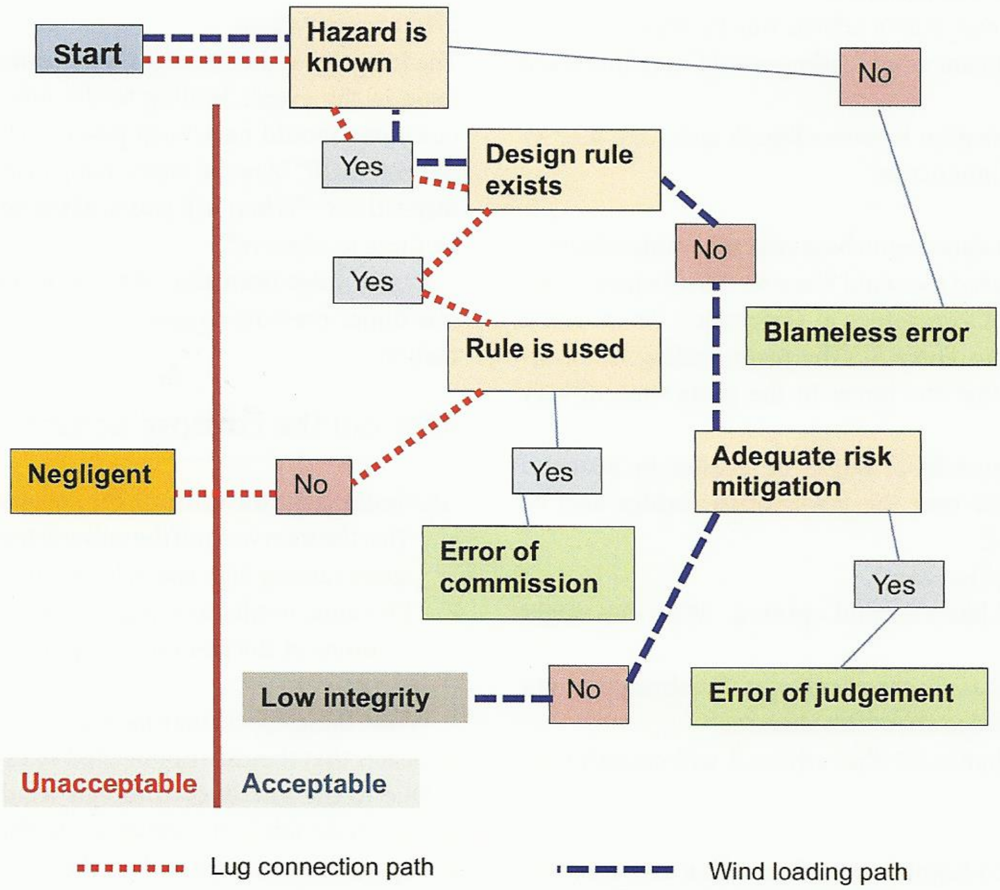


Figure 5. Design culpability

In design one often needs to make decisions that represent trade-offs among the requirements but safety issues should be treated as non-negotiable. Bouch, by his own admission and by the evidence of his previous designs, knowingly compromised safety against cost. If the tie to column connections needed to be in wrought iron for the Belah viaduct, they needed to be in wrought iron for the Tay Bridge.

It may have been that there was no formal design rule for a lug connection but Bouch knew how to specify a fit for purpose connection of this type and failed to use that knowledge. We therefore conclude that, in this respect, he crossed the line into being negligent.

Actions to prevent failures

Be a competent client

The reluctance of the client for the Tay Bridge to spend money is likely to have been a factor in the low level of supervision of the construction and maintenance work. The unsatisfactory relationship between the client and those working on the project had an important effect on the outcome. A better arrangement would been to have a adopted a 'competent client' approach where the client, via suitable representation, is an integral part of the project team seeking to control all risks. A competent client would be well aware that cutting costs for site investigation, for design checks, for site supervision or for safety in general, was inadvisable.

Adopt a safety culture

Investigations have shown that a main source of human error leading to aircraft crashes is rooted in the command structure in the cockpit. The other members of the flight crew tended not challenge the actions of the captain. Aircraft crew are now trained to pass information to the captain and the captain is required to consider such information. Everyone is working together to improve safety.

We can be confident that such a situation did not exist for the design and construction of the Tay Rail Bridge. It is likely that many people recognised the manifest faults in design and construction but were disinclined to comment on these to Bouch because they expected that he would not be receptive to such information.

The client, the designers, the contractors, all staff should feel that it is their responsibility for the goals of the project to be met with safety requirements being paramount. This situation pertained for the Queensferry Crossing (page 12). The adoption of a such a safety culture is a developing feature in engineering projects but it is not a new idea. It is likely that it was adopted, if tacitly, by great engineers of the past such as Thomas Telford.

It is likely that the failure of the Tay Rail Bridge would not have occurred if a safety culture had been adopted for the project.

Use a reflective thinking approach

In a reflective approach one asks questions, one seeks answers to them and one takes appropriate action. This is a main feature of a safety culture. We have seen how Bouch could have done this to advantage with Airy and with the site investigation contractor. Bouch should have been reflective about the detailing of the tie assembly but since he did not do that, the culture of the design team should have been such that the views of others were taken into account.

Conclusion

While there are much better checks and balances for modern infrastructure projects than for the Tay Rail Bridge, we can see from the paper on the Edinburgh schools failure (page 22) that the use of a competent client approach, a safety culture and reflective thinking still need to be strengthened in construction practice.

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