Why Things Break

Henry Petroski

There is nothing new about things breaking. Sticks and stones have always broken bones, and knappers learned long ago how to fracture stones to make flint knives and arrowheads. Galileo used Renaissance experience with broken-stone obelisks and wooden ships to motivate his research into the strength of materials. But it was the widespread industrial application of iron in the development of the railroads that brought the growth of cracks and the fracture of parts containing them to the attention of engineers. When an axle, rail, wheel, beam or bridge broke spontaneously, the result was often a spectacular accident accompanied by loss of life. It was important to understand the ultimate cause of such failures in order to build reliable railroad systems.

Among the early investigators of the fracture of railway axles was the Scottish civil engineer and physicist William John Macquorn Rankine. In 1843, while still in his early twenties, he presented a paper at a meeting of the Institution of Civil Engineers titled, "On the causes of the unexpected breakage of the Journals of Railway Axles and on the means of preventing such accidents by observing the Law of Continuity in their Construction." It was a model of practical analysis within the context of a paucity of theory. In his paper, Rankine cited the prevailing hypothesis that metal deteriorated over the course of repeated use when "the fibrous texture of malleable iron assumes gradually a crystallized structure, which being weaker in a longitudinal direction, gives way under a shock that the same iron when in its fibrous state would have sustained without injury." Rankine contended that this was a difficult hypothesis to prove, since the crystalline texture may have existed in the new axle. He proposed making axles not with the conventional abrupt steps in profile but with gradual changes in diameter, so that the metal's "fibre shall be continuous throughout." In other words, he recognized the deleterious effect of abrupt changes in geometry.

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Metal fatigue has long posed a challenge to engineers

Trains Outrun Technology

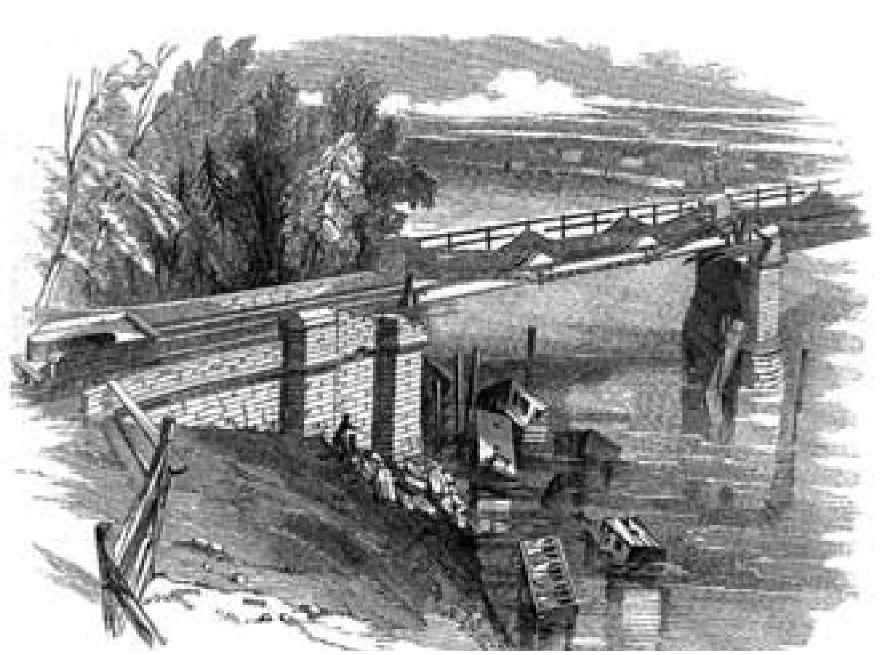
In spite of Rankine's skepticism, the crystallization of iron under repeated loading prevailed for the rest of the century as the conventional technical wisdom in explaining brittle fractures—that is, those unaccompanied by any significant distortion of the metal in the vicinity of the break. One such failure took place in 1847 under the weight of a train traversing a span of the railroad bridge over the River Dee at Chester, England. This was a critical crossing in the famous London-to-Holyhead route that provided a vital and strategic communications link between England and Ireland, via Wales and the Irish Sea.

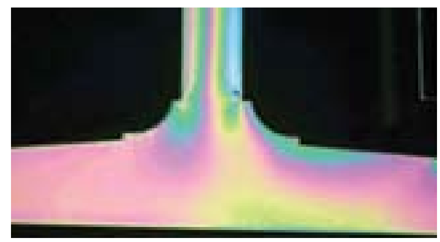
The Dee Bridge was a hybrid or composite design, with cast-iron sections trussed together with wrought-iron rods. Since cast-iron beams were generally limited in length to about 35 feet, the almost 100-foot girders of the Dee were made up of three cast-iron beams arranged end-to-end, with wrought-iron rods keeping the assembly clamped together so that cracks could not open up between or within the beams. The wrought iron also served to keep the bridge from suffering total collapse should the cast iron fracture. Bridges of similar design had been used on railroads since about 1830, and because they had provided reliable service over the years, they had come to be used for longer and longer spans with lower and lower factors of safety—a natural evolutionary trend for structures of all kinds. The Dee was the longest bridge of its type ever made.

In the immediate wake of the accident, which claimed five lives, the railway commissioners called for an investigation. It was found that one of the cast-iron girders had fractured in two locations. In an attempt to better understand what had happened, a series of tests were conducted by driving a locomotive over the remaining spans and noting how much they deflected under it. The deflection was less than when the train was just standing on the girder, but as the train passed over the span there were noticeable vibrations set up in the supporting structure. Among the conclusions of the investigation were that under the action of heavy and repeated loads, "girders of cast iron suffer injury, and their strength becomes reduced." This was a primitive description of what is today known as metal fatigue.

Because people were killed when the train carriages fell with the broken bridge span, an inquest was also conducted. Painters who had worked on the bridge testified that it had indeed deflected considerably under passing trains, and the amount of deflection depended on the speed of the train. One painter used his ruler to measure a deflection of 5-1/2 inches in a girder that later broke and was replaced. Testimony was also taken from several engineers, including Robert Stephenson, the bridge's designer. He had designed many shorter bridges of the same type and insisted that the structure was not at fault. According to Stephenson, the accident on the Dee was initiated by a derailment, whereby the train stuck the girder sideways and broke it. This explanation was contradicted by eyewitnesses.

The coroner preempted the jury from finding Stephenson negligent, but invited it to comment on the failed bridge's design. The jury found 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." The jury further asserted 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 feared that the hundred or so bridges similar in design to the Dee "all are unsafe." The jury's recommendation was that the government institute an inquiry to determine whether such bridges were safe. If they were not, they should all be condemned; if they were, the public should be so assured. A royal commission was established to look into the use of iron in railway structures. It conducted full-scale tests on cast-iron girders and confirmed that repeated loading decreased their strength. According to the commission's report, which was published in 1849, the broken beams showed "a peculiar crystalline fracture and loss of tenacity," which reinforced the idea that Rankine had expressed six years earlier.





Dee Bridge, at Chester, England, collapsed in 1847 as a train passed over it. Five people were killed. Peter Lewis, of the Open University, thinks that stress concentration at an ornamental cavetto molding *(see simulation, at right)* led to fatigue-crack growth and ultimately failure of a cast-iron beam. (Image at top from the *Illustrated London News;* simulation courtesy of Peter Lewis.)

Hypotheses on Hypotheses

Strictly speaking, failure analyses are hypotheses heaped on hypotheses. How the bridge was designed, constructed and maintained can predispose it to failure, and official and anecdotal records can provide grist for imaginative scenarios. Generally speaking, the nature of the fracture surfaces of broken parts can provide valuable clues as to how a fracture proceeded, but they can be but one investigator's reading of the artifacts. Failure hypotheses can seldom be proven with certainty because the structure no longer stands to be tested, and evidence is usually either incomplete or tainted. In the case of the Dee Bridge, parts of the fractured girder were lost in the river. Even when all fragments can be recovered, the fracture surfaces can be altered as the failure proceeds or be mishandled in the process of recovery, thereby making conclusions drawn from them suspect. As a result, incidents like the Dee Bridge failure can be revisited and reinterpreted for years, decades and even centuries.

Just before the Dee Bridge collapsed, five inches of ballast were added to its roadway to keep embers that spewed from passing locomotives from starting fires in the wooden deck. This added dead weight prompted the hypothesis that the fatal train was the load that broke the camel-like girder's back. Another hypothesis related to the fact that the wooden planking was supported by the inner flange of the cast-iron beams, thus producing an asymmetrical load on the structure and causing it to twist under a passing train. This twisting may have initiated an instability that caused the girder to buckle and consequently fracture. This was the prevailing explanation in recent decades.

The most recent hypothesis has been advanced by Peter Lewis, who is with the Open University and is coauthor of, among many other publications, *Forensic Materials Engineering Case Studies.* According to Lewis, the ultimate cause of the failure of the Dee Bridge may be traced to an aesthetic flourish that was cast into the beams, thus introducing a location where there were concentrations of stress that could have precipitated the growth of cracks from any tiny flaws in the casting. The idea that the seemingly innocuous desire to make a functional structure a bit more attractive can be the root cause of a failure is not far-fetched. The design of the infamous Tacoma Narrows Bridge was driven at least in part by the aesthetic goal of producing a long, slender structure. That slenderness proved to be the structure's Achilles heel.

The scenario that Lewis imagines for the Dee Bridge is as follows. The iron beams were cast with a detail known as a cavetto molding at the location where the vertical web met the horizontal bottom flange. Similar moldings were and are familiar finishing details where vertical walls meet horizontal ceilings in a house. Since carpenters would likely have been involved in making the forms for the cast-iron girders, they may well have introduced the detail as a finishing flourish, perhaps even thinking that it would produce not only a better looking beam but also a better-performing one. Unfortunately, the sharp corners of the cavetto molding provided a site for concentrating stress (much as a crevice provides one for collecting dust). If the cast beam contained any flaw at all—such as a tiny void, nick or other imperfection—it could serve as a nucleation site for a crack to grow a small amount with each passing train, a phenomenon known as fatigue-crack growth. In time, the crack would reach dangerous proportions, and the next time the beam was loaded with a passing train it would give way. Thus Lewis hypothesizes that the Dee Bridge failed because of metal fatigue initiated at the aesthetic flourish. Making things prettier should not come at the expense of making them stronger.

Further Fatigue

It was not only railway axles and bridges that had been fracturing spontaneously in the mid-19th century. In 1854, the *Minutes of the Proceedings of the Institution of Civil Engineers* carried a paper by Frederick Braithwaite, "On the fatigue and consequent fracture of metals," which bore the running head, "Fatigue of Metals." In his paper, Braithwaite recognized that "fatigue may arise from a variety of causes, such as repeated strain, blows, concussions, jerks, torsion, or tension, &c." The many mysterious accidents he believed to have been the result of metal fatigue included a cast-iron girder that broke under a beer vat that was repeatedly filled and emptied, leaking soldered joints between sections of copper pipe in another brewery and the repeated fracture of cast-iron cranks on a water pump at still another brewery. The paper was followed by discussion, in which Braithwaite credited the consulting engineer Joshua Field, who specialized in marine engines, with suggesting the term "fatigue" to characterize the "species of deterioration of metal." Among the discussants of Braithwaite's paper was Rankine, who found in it confirmation of ideas expressed in his own paper of a decade earlier. (The use of the French noun "fatigue" in the sense of structural degradation is believed to have been originated with the French mechanician Jean-Victor Poncelet, who used it in his lectures at the military engineering school at Metz and wrote in 1839 that "the most perfect springs are, in time, susceptible to fatigue.")

In a 2002 analysis Peter Lewis revisited another classic 19th-century bridge failure that over the years has been the subject of many investigations and reinvestigations. The North British Railway wished to have a bridge built across the Tay River estuary at Dundee, Scotland, so that the coastal line could be more competitive with railroads that took an inland route, where they did not encounter wide waterways that required ferries to cross. The river at Dundee was wide but relatively shallow, and so a long bridge with many spans resting on many piers had been proposed and designed by the engineer Thomas Bouch. Measuring two miles from approach to approach, the completed Tay Bridge was the longest in the world at the time of its opening at the end of May in 1878.

The bridge may have been absolutely long, but it was not especially daring in its individual truss spans, the longest of which were 245 feet—a not-uncommon length at the time. These were the so-called high girders, which were set atop the piers in order to provide maximum clearance for tall-masted sailing ships. The trains passed through the bridge structure at the high girders, rather than atop it as they did elsewhere on the bridge. The Tay Bridge carried trains across the estuary for almost a year and a half, but on the night of December 28, 1879, its high girders—which collectively amounted to over a half mile of the total bridge length—all collapsed as a train was running through them. All 75 people on board were killed.

The Board of Trade appointed a court of inquiry to look into the causes of the accident and to assign responsibility for the tragedy. There were three members of the tribunal: William Henry Barlow, who was president of the Institution of Civil Engineers; William Yolland, who was chief inspector of railways; and chairman Henry Cadogan Rothery, who was the government's wreck commissioner but not an engineer. The voluminous testimony that resulted from the inquiry provided considerable insight into the design and operation of the bridge. Among the things that it revealed was that the cast-iron piers had contained numerous imperfections, that the girders and piers had not been securely tied down against the wind, and that the bridge had exhibited considerable vibrations when trains passed over it. The members of the court, however, could not reach agreement about the absolute cause of the accident or the placement of blame.

Barlow, Yolland and Rothery agreed on what factors contributed to the failure, but the two engineers stopped short of specifying a definitive scenario, asserting that they had "no absolute knowledge of the mode in which the structure broke down." Thus, they were reluctant to place blame unambiguously on the bridge's engineer. Chairman Rothery disagreed, and thus the final report consisted of two parts, one reflecting Barlow and Yolland's conservative view and the other containing Rothery's more aggressive stance. He concluded that "the bridge was badly designed, badly constructed and badly maintained, and that its downfall was due to inherent defects in the structure, which must sooner or later have brought it down." He went on to place the blame squarely on the shoulders of the chief engineer Bouch: "For the faults of design he is entirely responsible. For those of construction, he is principally to blame in not having exercised that supervision over the work, which would have enabled him to detect and apply a remedy to them. And for the faults of maintenance he is also principally, if not entirely, to blame in having neglected to maintain such an inspection over the structure, as its character imperatively demanded." Thomas Bouch, who had been knighted upon the completion of the bridge, retreated from public view and died four months after the report was issued, a ruined 58-year-old man.

The conventional wisdom for more than a century was that the high girders of the Tay had been somehow blown over in the wind. There were reportedly strong-gale-force winds on the night of the accident, although a contemporary photograph of the destroyed bridge clearly shows a number of tall smokestacks associated with Dundee jute mills standing undamaged in the background. According to the Beaufort scale, a force-9 wind should cause light structural damage, such as broken chimney pots, and several instances of this were reported to have occurred on the night of the Tay disaster. Such a wind exerts a mean pressure of about 7.7 pounds per square foot, and in absolute terms the pressure may reach the 10 pounds per square foot that was used in designing the bridge. Nonetheless, a factor of safety would have made the bridge capable of sustaining winds several times the design load. Benjamin Baker, one of the expert witnesses for Bouch at the inquiry, surveyed damage in the area and concluded that wind pressures did not exceed 15 pounds per square foot, well below what should have been needed to topple the bridge.

Hypothesis Revisited

The photograph incidentally showing the intact smokestacks was one of a series of images captured a week after the tragedy by a local professional photographer. The photographs were ordered by the court of inquiry to provide a record of the accident scene and were used in the course of the proceedings to refresh the memories of witnesses. Among the photographs taken were those of the damaged towers that had bracketed the high-girder section of the bridge and the 12 piers in between that had supported it. In fact, most of the superstructure had gone down with the girders. The photographer captured the state of each pier and the surviving ironwork atop it from a variety of perspectives, including long shots taken from each adjacent pier and close-ups of debris taken while standing on the pier itself.

When he read the inquiry report, Peter Lewis became aware that a photographic record of the Tay Bridge remains had been made. He had known that illustrations of the accident scene showing considerable detail appeared in contemporary issues of *The Engineer,* and he knew that engravings were then commonly made from photographs. He thus wanted to find the original photographs, and he located a set of them in the Dundee City Library. From these he made high-resolution scans and studied the digitized images closely.

What he found in the photos were fractured wrought-iron bolts and broken pieces of cast iron that were identified as parts of the lugs that had been cast integrally with the columns designed to support the weight of the high girders. Lewis also found evidence in the photographs that the bolt holes were not drilled out but rather were cast directly into the lugs. Drilling would have left cylindrical holes, which would have provided relatively long parallel bearing surfaces for the bolts; the casting process left tapered holes in the lugs, thereby setting up a condition in which the bolts fit loosely and the force exerted on each lug was concentrated on a smaller surface, thereby increasing the stresses in the lug. Elevated stresses, applied each time a train passed over the bridge, accelerated the growth of any cracks that might have developed in the lugs, and when the cracks reached a critical size, the lugs failed. In other words, they failed after fatigue-crack growth. Some of the photographs confirmed this by showing characteristic patterns of incremental crack growth on the fractured surfaces.

The lugs were designed to anchor the diagonal wrought-iron bracing between the columns. The fact that the piers were littered with the remains of

Tay Bridge, at Dundee, Scotland, was also ultimately a victim of metal fatigue in cast iron, according to Peter Lewis. It collapsed in 1879, claiming 75 lives. (Photograph courtesy of Peter Lewis.)

numerous broken lugs suggests that over time much of the bracing had been lost in the support towers, rendering them more flexible and prone to a racking motion in a direction transverse to the bridge. Such flexibility would likely have increased as the structure aged, with more and more lugs fracturing and thus providing no support for the tie rods. The vibrations set up by passing trains drove the growth of fatigue cracks and the consequent failure of lugs, which in turn led to larger vibrations, which sped up the deterioration of the structure. The combination of a fast, heavy train crossing the bridge in a strong wind must have caused the towers and high girders to deflect sideways to the point of no return.

The fatigue and fracture of metals was still incompletely understood in the 1870s, but even the great advances in theory and practice that have been made in the meantime have not eliminated the dangers associated with the repeated loading of a structure. A 1998 German high-speed train accident that claimed a hundred lives was attributed to metal fatigue. And as recently as 2000, the derailment of a train in Britain was attributed to a fatigue failure in a rail that resulted in the track breaking up into hundreds of pieces. Metal fatigue is an old but not yet fully conquered cause of structural failure that is proving to be the root cause of accidents that have been debated for over a century.

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