The 30 year failure cycle

Could the 30 year failure cycle evident in specific bridge failures be coincidence or something more? Sean Brady looks at the technical and human aspects of this unfortunate trend.

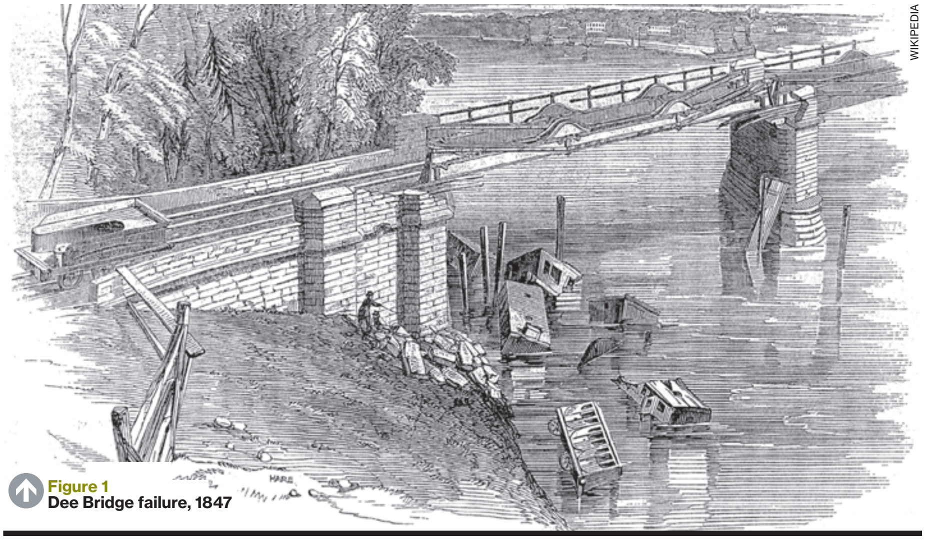

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Figure 1
Dee Bridge failure, 1847

A key aspect of failure prevention is to identify the technical and human factors that led to failures in the past – and to explore trends that may assist in anticipating future catastrophes. One such trend, discussed in a study by Sibly and Walker[1], not only highlights the lessons learned from a number of significant collapses, but also provides insight into the very nature of structural engineering design itself. The study, entitled 'Structural accidents and their causes', examined a number of prominent bridge failures and, although it was published 35 years ago, contemporary events (as highlighted in a recently published book by Henry Petroski[2]) suggest it is no less relevant today.

Sibly and Walker examined 143 accidents, and identified a trend where a weakness in a well-established form of bridge design culminated in failure. These bridge failures were the Dee Bridge (UK) in 1847 (Figure 1), the Tay Bridge (UK) in 1879, the Quebec Bridge (Canada) in 1907 (Figure 2), the Tacoma Narrows Bridge (USA) in 1940 and the box girder bridge failures circa 1970; specifically the West Gate Bridge (Australia) and the Milford Haven Bridge (UK)[1,3].

The technical causes of these failures varied. The Dee Bridge was a trussed girder bridge that collapsed due to a lateral torsional buckling failure of cast iron beams (the beams were trussed with wrought-iron ties, and while the ties were thought to provide reserve strength, they actually introduced compression and bending loads into the beams[1]). The Tay Bridge was a truss bridge that failed as a result of, among other factors, wind loading that was not sufficiently accounted for in its design[1]. The Quebec Bridge was a cantilever bridge that failed during construction due to buckling of compression members[1]. The Tacoma Narrows Bridge was a suspension bridge that collapsed as a result of dynamic wind actions[1]. The box girder bridge failures were a consequence of geometric imperfections and residual welding stresses that caused buckling instabilities in the bridges' steel plates[1].

Each of these design forms was an 'accepted design approach' at the time of their failure[3]. So why, with the profession's years of experience in each form, did these failures suddenly occur? Sibly and Walker concluded that "the accidents happened not because the engineer neglected to provide sufficient strength as prescribed by the accepted design approach, but because of the unwitting introduction of a new type of behaviour"[1].

Petroski explores this concept by examining the design of the Tacoma Narrows Bridge[2]. The bridge was to span more than half a mile and have a light and slender deck, a requirement of Leon Moisseiff, the bridge's designer, who was an advocate for aesthetically pleasing structures. As a consequence, the bridge was to be a significant departure from previous experience. While its span-to-depth ratio was similar to the George Washington Bridge (opened in 1931), its length-to-width ratio was 72; more than twice that of the George Washington Bridge, and its deck weight was less than 6,000 pounds per foot, significantly lighter than the 31,000 pounds per foot of the George Washington Bridge.

As is well known, the bridge collapsed. Failure was attributed to the bridge deck's response to dynamic wind action, despite the investigation concluding that the bridge was designed in accordance with the accepted practise of the day[1]. Indeed a legacy of the failure was that it served as a catalyst for the profession's research into the effects of wind dynamics on long, slender structures[1].

However, Sibly and Walker suggest that information was available prior to the design that could have alerted Moisseiff to the potential for dynamic wind induced failure in a suspension bridge with low deck stiffness. The authors cite vibration issues with a number of suspension bridges prior to Tacoma Narrows, with these vibrations "varying from small wind-induced undulations in the Golden Gate Bridge to potentially destructive oscillations in the Thousand Islands Bridge". These 'warnings' suggested that "a new form of behaviour was being encountered". Despite this information, or ignorant of it, Moisseiff pressed on with his ambitious design. Similarly, there were warnings of new types of behaviour evident in each of the design forms prior to the failures of the Dee, Tay, Quebec, and box girder bridges. These warnings also went unheeded.

Further, Sibly and Walker concluded that the new type of behaviour came about because "in early examples of the structural form, a certain factor was of secondary importance with regard to stability or strength. With increasing scale, however, this factor became of primary importance and led to failure". For example, John Roebling, the designer of the Brooklyn

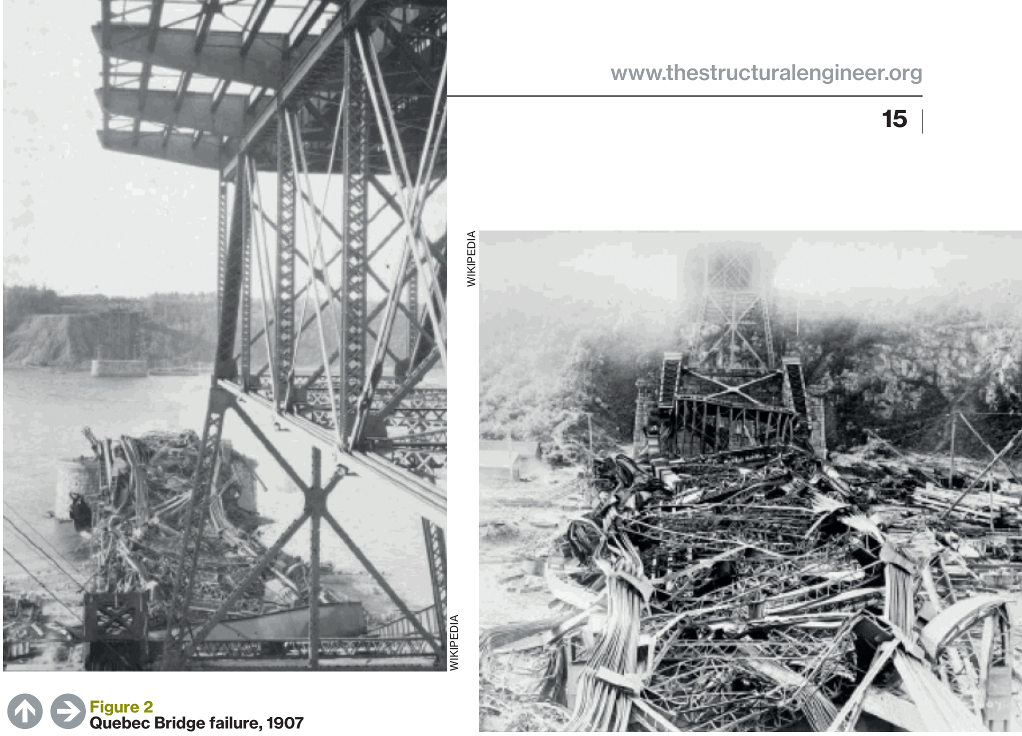
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Figure 2
Quebec Bridge failure, 1907

Bridge, along with his contemporaries, understood the importance of deck stiffness in suspension bridge design as far back as the 1850s - an understanding based on deflection issues due to train loading and failures due to wind loading dating back to 1818. As a consequence, Roebling's generation utilised stiffening trusses and auxiliary ties to ensure deck stability; elements which are evident on the Brooklyn Bridge today. This approach was so successful in managing wind induced dynamics, that by the 1900s, "the possibility of an aerodynamic failure seemed very remote and probably did not feature in the designer's thinking"[1]. This lack of awareness, along with a drive for more slender and aesthetic structures, resulted in the profession gradually eliminating stiffening trusses and ties, culminating in their absence from the Tacoma Narrows Bridge. Failure ensued, and in a final irony, the Tacoma Narrows was rebuilt with stiffening trusses included.

These failures provide some insight into the nature of innovative structural design. A design form evolves over time to incorporate new materials, improve structural efficiency and address more challenging requirements. Such innovation is critical for a healthy, state-of-the-art engineering profession, but once a design form has established a track record, it appears that in the absence of prudence, arrogance can sometimes replace vigilance, and the basis and assumptions of a design form can be pushed beyond their limits. For every suspension bridge design with an absence of dynamic wind issues, the profession was one step closer to the Tacoma Narrows failure.

Failure prediction?

A fascinating aspect of these failures is their regularity, with one occurring approximately every 30 years: 1847, 1879, 1907, 1940, and circa 1970. At the time of the Sibly and Walker study in 1977, its authors referred to this timing as "a point for discussion [rather] than as a serious observation". While it is quite possible that this interval is a coincidence, Petroski points to anecdotal evidence that suggests the theory has predictive merit[3].

Projecting from the box girder failures, the next failure to fit the trend should have occurred around the year 2000, and in the 1990s the cable stayed bridge was considered the most likely candidate[3]. Cable stayed bridges had been following a similar evolution to suspension bridges prior to the Tacoma Narrows failure: lengthening spans and more slender decks. In addition, prior to 2000, a number of cable stayed bridges had experienced 'warnings' in the form of vibration issues that were not anticipated[2]. Both the Anzac bridge in Australia, and the Pont de Normandie in France, experienced such issues and required retrofitting. However, despite this trend, a failure of a cable stayed bridge has not occurred. Nevertheless, Petroski still views it as the most likely candidate for a potential 2030 failure. As an aside, Petroski argues that the I-35W Minneapolis Bridge failure in 2007 does not fit the trend because it was as a result of under sized gusset plates, rather than the unwitting introduction of a new type of behaviour.

Fitting the trend

Not one, but two bridge failures are considered consistent by Petroski: the (non-catastrophic) failure of the Millennium Bridge in London in 2000 and the Passerelle Solferino in Paris in 1999. While both are pedestrian bridges, they have very different designs: the Millennium Bridge is a low profile suspension bridge, while the Passerelle Solferino is an arch bridge. Yet, both experienced vibration issues as a consequence of the horizontal loading due to people walking, a factor that had been of secondary importance in the past, but with the increasing span and slenderness of pedestrian bridges, had become of primary importance. Crucially, pedestrian bridges had been following the same evolutionary journey as the other failures in the 30 year cycle.

So what is the significance of the 30 year interval? Many authors consider this a consequence of human, rather than technical, factors. Sibly and Walker suggest that 30 years is long enough for a communication gap to develop from one engineering generation to the next. Perhaps it is also a sufficient period for the profession to lose touch with the basis of a design form, with Sibly and Walker finding that "as time passed during the period of development, the bases of the design methods were forgotten and so were their limits of validity. Following a period of successful construction, a designer, perhaps a little complacent, simply extended the design method once too often".

Put another way, Petroski suggests that structural design is about making decisions, and decisions generally involve compromises. He goes on to say that if the basis, assumptions and limitations of a design form are forgotten, an aspect that prevented a secondary factor from becoming a primary factor can unwittingly be compromised, thus introducing a new type of behaviour.

Ultimately, whether or not the 30 year cycle is a coincidence or if it assists in correctly predicting the next failure, it serves to highlight the vulnerability of the structural design process when faced with complacency, ambition, and egotism; the by-products of fallible human interaction.

Sean Brady is the managing director of Brady Heywood (www.bradyheywood.co.uk & www.bradyheywood.com.au). The firm provides forensic and investigative structural engineering services and specialises in determining the cause of engineering failure and non-performance.

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