Past and Future Failures

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Literary history would hardly seem to have much in common with structural engineering. Still, a recent development in the study of literature has revealed temporal patterns in the rise and fall of literary genres surprisingly similar to those related to the success and failure of large bridge types. For some years now, the literary scholar Franco Moretti has been applying quantitative methods to the study of the novel. In the recently published first in a series of three projected articles, he has proposed that the genre has had not a single rise but rather that different forms of it have developed, evolved and disappeared in a repeating manner. In fact, according to Moretti, different novel types—picaresque, gothic, domestic *et cetera*—appear to have experienced roughly 30-year periods of rising and falling popularity, indicating that there are forces at work that transcend any given literary movement or fashion. Such forces also appear to be at work in structural engineering, where cycles of a similar duration and patterns of success and failure apply across a wide variety of bridge types.

It is now more than 10 years since I described in these pages ("Predicting Disaster," March–April 1993) the study of historic bridges carried out by Paul Sibly in his 1977 doctoral thesis, *The Prediction of Structural Failures.* Sibly's research was "mainly concerned with the prediction of one class of structural failure, namely that due to the extrapolation of existing design or construction procedures to fit new situations." He considered four types of large metal bridges that ended in dramatic collapses. In a subsequent article he and his advisor, A. C. Walker, pointed out that the failures followed a temporal pattern: They had occurred at roughly 30-year intervals.

The cycle that Sibly described continued beyond the cases that he initially studied, which led me to speculate that a dramatic bridge failure might be expected to take place sometime around the year 2000. In the early 1990s, the bridge type whose evolution appeared most closely to be following the pattern that emerged from Sibly's work was the cable-stayed bridge. Though cable-stayed bridges have become notorious for the unwanted motion of their cables, no dramatic catastrophic failure has yet occurred in a completed bridge, so it is reasonable to ask why not. Furthermore, it is also reasonable to ask whether in the past few years any other bridge type did suffer an instability significant enough to continue the cycle identified by Sibly. First, however, it is be helpful to review the historic bridge failures that establish the pattern and bring thinking about them up to date.

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Four Times Thirty

In the 1840s, at the height of the British expansion of the railroads known as "railway mania," the state of the art in iron-bridge building was to use cast iron. Since casting beams longer than about 30 feet was not common, longer distances were spanned by attaching beams end to end and employing wrought-iron trussing as a sort of belts-and-suspenders safety measure. The longest bridge of this type (spanning almost 100 feet) was constructed across the River Dee on the Chester & Holyhead Railway and was passed in 1846 by the Inspector General to the Board of Trade. According to James Sutherland, "he was opposed to this form of iron trussing and virtually admitted that he had approved the bridge because of the number of apparently successful ones already built."

The Dee Bridge collapsed suddenly in 1847, just after a load of gravel had been added to its roadbed, and this "first serious structural collapse on the railway network" was the subject of an inquest. This in turn prompted the subsequent appointment of a royal commission charged with looking into the use of iron in railway bridges. The bridge had been designed and constructed under the supervision of the eminent engineer Robert Stephenson, who was exonerated. Landmark failures like that of the Dee seem never to be fully put to rest, however, and the design of the bridge is looked at afresh in a recent biography of Stephenson. According to James Sutherland, "It would be wrong to blame a single individual for the misconception over

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Figure 1. Since the collapse of the Dee Bridge in 1847, bridge failures appear to recur at approximately 30-year intervals. This suggests that a failure should have been due around the year 2000, 30 years after the Milford Haven Bridge collapsed during construction. Although no bridge fell at the changing of the millennium, several footbridges exhibited severe problems, including this one, the Passerelle Solferino in Paris.

the behavior of these girders. This was a case of group myopia suffered by a large tranche of the most distinguished engineers of the day." Such collective nearsightedness is responsible for most colossal failures.

The Tay Bridge, completed in 1878, was built to carry the North British Railway over the wide estuary at Dundee, Scotland. Although it was overall the longest bridge in the world when completed, none of the Tay's many individual spans exceeded contemporary experience. In late December 1879, during a storm, the bridge's highest and longest girders, along with a train with 75 passengers, were blown into the river. A court of inquiry found that, "The fall of the bridge was occasioned by the insufficiency of the cross bracing and its fastenings to sustain the force of the gale." The engineer, Thomas Bouch, had assumed that the maximum wind force would be barely one-fifth what it might have been that night.

The Tay disaster continues to be the focus of attention. In the most recent study, researchers scanned archival photos of the accident scene and used modern digital photography tools to enhance the photos and inspect the record of remains. What they found was evidence of numerous broken tie-bar lugs, strongly suggesting that the bridge structure was loosely held together and racked excessively under crossing trains, which caused the lugs to fail under the repeated action, a phenomenon known as metal fatigue. The analysis was confirmed by contemporary comments of the president of the court of inquiry, who described the structure as "badly designed, badly constructed, and badly maintained." Truss bridges did not cease to be built after the Tay collapse, but they were constructed with more attention to detail and to resist much stronger winds. The Tay itself was rebuilt as a truss bridge, and its more substantial appearance is testament to the natural response to failure.

When the Tay Bridge failed, Bouch was in the process of building another bridge on the North British line, one across the Firth of Forth near Edinburgh, but that commission was understandably taken from him. Instead of the flimsy suspension bridge he had planned, the new engineers John Fowler and Benjamin Baker designed a massive cantilever structure, then a relatively unfamiliar bridge type. The Forth Bridge was intended to restore confidence in the railroad not only by its striking difference from anything designed by Bouch but also in its own right by looking like it could take anything nature could throw at it.

The immediate success of the Forth Bridge prompted engineers around the world to emulate it, and for many of them the cantilever became the bridge type of choice to carry heavy railroad trains across wide rivers, gorges and valleys. One example under construction in the early 20th century was the bridge to carry the Canadian transcontinental line over the St. Lawrence River near Quebec. With an 1,800-foot main span, the Quebec Bridge was to be the longest cantilever in the world, bettering the Forth Bridge by almost 100 feet. The bridge was under construction in 1907 when it collapsed with 86 workers present. Only 11 survived.

A royal commission found that the bridge's design and construction were carried out in a disorganized manner, and with an inadequate respect for the magnitude of the structure. The principal consulting engineer, Theodore Cooper, who was *de facto* also the chief engineer, oversaw the project from a distance, not once visiting the construction site. The principal design engineer, Peter Szlapka, was without field experience and so was in no position to interpret warning signs when he did visit the site. After the collapse of the Quebec Bridge, the cantilever no longer challenged the suspension bridge as the form of choice for the longest spans.

Modern suspension bridges date from the early 19th century, but they fell out of fashion especially in Britain when several collapsed under marching soldiers or were destroyed in the wind. Indeed, it was these failures that John Roebling systematically reviewed before designing his own suspension bridges, apologizing somewhat for his focus on failures: "In speaking of the weak points of the system, I have only intended to show how much caution is necessary in planning and executing a suspension bridge in order to insure perfect safety." He saw wind as the greatest enemy of such bridges, and his signature stay cables were intended to check any motion that might be initiated by it.

Twentieth-century suspension bridge designers considered Roebling's diagonal cables redundant and did not include them. Furthermore, throughout the 1930s suspension bridges became increasingly more slender, not only in depth but also in width, as more bridges were built in remote areas, where two narrow traffic lanes sufficed. By the end of the decade, the roadways of a number of these bridges were exhibiting unexpected motion. Engineers retrofitted their designs with cables, but there was not even agreement on whether the auxiliary cables should stretch from the bottom of the tower to the main suspension cables or from the top of the tower to the bridge deck, since the behavior of the structures was not fully understood. The culmination came with the collapse of the Tacoma Narrows Bridge in 1940 in a wind of 42 miles per hour.

The aerodynamic phenomenon that had brought the bridge down was simply not taken into account in designing suspension bridges, and the full implications of that omission were not evident until the extremely narrow and slender Tacoma Narrows, the third longest suspended span at the time, revealed the consequences. As with the other failures described above, the Tacoma Narrows continues to be the subject of inquiry.

Continuing Pattern?

Sibly's thesis focused on the design climate in which these four major bridge failures occurred. He speculated on how such accidents might be predicted, while admitting that the amount of data collection and analysis necessary to do so would involve considerable effort. His concluding remarks include a brief discussion of the 1970 failure of the Milford Haven Bridge, in Wales, a steel box-girder structure that collapsed while still under construction. A similar accident that same year befell the West Gate Bridge under construction in Melbourne, Australia.

It was this reinforcement of the 30-year cycle that contributed to the speculation that a major bridge failure might be expected around the year 2000. Looking at the kinds of bridges being built and designed in the early 1990s, it appeared that the cable-stayed was the most likely candidate. After all, the cable-stayed bridge type was being extended to span lengths not imagined by its early developers, and several incidents had already pointed to an incomplete understanding of the type's behavior.

Throughout the 1990s, cable-stayed bridges experienced ongoing cable vibration problems and were being retrofitted in a variety of ways. Among the earliest indications of problems with stay cables were observations made by the Japanese that vibration problems were aggravated in the presence of rain. Cable casings began to be fitted with raised helical strakes (ridges) to break up the rivulets that were blamed. The Pont de Normandie, which I described in these pages in September–October 1995, exhibited cable and deck vibrations significant enough to be fitted with cable ties and dampers, which altered the appearance of the structure. On a visit to Sydney, Australia, in 1998, I was driven over the new Glebe Island Bridge, whose main span is about 1,140 feet long. My host explained to me that it had recently been decided to retrofit it with dampers to check undesirable vibrations.

In spite of such examples and more, cable-stayed bridges have continued to be built with increasingly long main spans, and cable vibration problems have become commonplace. China's Dong Ting Lake Bridge, an unusual three-pylon cable-stayed structure, had its 10-inch-diameter cables vibrating side-to-side in the wind by as much as 4 feet. As a demonstration of its efficacy, a magnetorheological damper was fitted to one of the cables, which then remained dramatically stable among its swaying neighbors. Such a damper operates by relying on the rapid response to a (current-induced) magnetic field of a fluid containing iron particles, thus altering instantaneously the stiffness of the system. The technology is not new, having been applied to automobile shock absorbers, as well as to buildings subject to earthquakes and high winds. The dramatic decrease in motion of the one cable on the Dong Ting Bridge led to the installation of the dampers to the structure's hundreds of other cables.

Whether the continued reliance on retrofitting cable-stayed bridges with damping devices will prevent a colossal failure in the wind remains to be seen. What is incontrovertible is that such measures have reduced dramatically the unwanted vibration problems of these structures, checking their motion to within acceptable limits. However, such retrofitting appears to have produced a sense of confidence within the bridge-building community that if problems arise in a new bridge they can be brought under control. Until the aerodynamics of the problem are fully understood, however, there will remain a fundamental gap in the engineering science of cable-stayed structures that could be harboring an accident waiting to happen.

Another contemporary bridge type that appears to be pushing the limits of its technology is the post-tensioned concrete box girder, whose plastic material can be sculpted into graceful forms and whose method of construction has many attractive features. Most such bridges are erected in sections by means of the so-called balanced cantilever method, in which manageable segments are added alternately on either side of a bridge pier either by being cast in place or transported from a convenient yard where they are cast under controlled conditions. (As the segments are erected, they are tied together with cables located inside the box.) The new bridge across the Kennebec River at Bath, Maine ("Twin Bridges," January–February 2001) was built in the latter way; a new bridge under construction in Clearwater, Florida, employs the former method. The Bath bridge, whose 420-foot main span made it the longest cantilevered concrete span then erected by such a method in North America, has been of enormous benefit in reducing traffic congestion in the area. One proposed design for the Clearwater bridge would have employed a box beam of record width. The final design employs double box beams of proven size. Originally set to open late last year, the bridge has been plagued by construction mishaps involving buckled scaffolding, twisted and tilted spans, and cracked piers.

For all of the troubles with the construction of the Clearwater bridge, it cannot be said to have had a catastrophic failure. Nor has there been a colossal failure of a cable-stayed bridge to extend Sibly and Walker's failure cycle for another 30-year period. Was their neat cyclic pattern, which had extended over 120 years, little more than a string of coincidences? Has the lack of a dramatic failure now four years beyond the turn of the millennium made it necessary to declare the putative cycle ended? Not necessarily.

All but Failed

Another bridge type that also experienced a great spurt of development during the 1990s is the pedestrian bridge. Footbridges are nothing new, of course, having been perhaps the first bridges, and it is their very pedestrian nature that seems to have made them appear to be but modest challenges to bridge designers. Indeed, it may be precisely because of their long history and familiarity that their engineering has seldom in recent years been the focus of attention. Architecture, aesthetics and the use of new materials in footbridges have typically been much more discussed than their structural engineering.

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Figure 2. London's Millennium Bridge had to be closed three days after it first opened because of swaying. A retrofit solved the problem and the bridge reopened in February of 2002.

Pedestrian traffic subjects a bridge to quite a different kind of loading than does vehicle traffic, however. Intuition suggests it to be a lighter and gentler load, but that is not necessarily the case. In 1987, when the Golden Gate Bridge was closed to vehicles to celebrate its 50th anniversary, so many people crowded onto the structure that it was subjected to the heaviest load it had experienced in its lifetime ("Making Sure," March–April 1992). The total weight of the people has since been much discussed, along with the resultant noticeable downward deflection of the bridge's main span, but so many pedestrians also caused the bridge to swing sideways. A similar sideways motion occurred in New Zealand in 1975, when protesters took over the Auckland Harbour Bridge. But such examples of highway bridges swaying underfoot were generally considered anomalies by pedestrian-bridge engineers.

By the end of the 20th century, footbridges came to be seen as more than just pedestrian structures. The town of Gateshead ran a design competition for teams of architects and engineers to design a footbridge ("Design Competitions," November–December 1997), which resulted in the innovative Gateshead Millennium Bridge that opens for shipping along the Tyne like an eyelid to the morning light. In Japan, the structural engineer Leslie Robertson teamed up with architect I. M. Pei to produce the dramatic bridge that is part of the ceremonial entrance to the Miho Museum. In several Western countries, the engineer-architect Santiago Calatrava has designed cable-stayed footbridges dramatically supported by a single mast, such as the one that now carries people from downtown Milwaukee to the new wing of its art museum and the even newer one over the Sacramento River in Redding, California. And in London, an engineer, an architect and a sculptor teamed up to produce the Millennium Bridge linking the Tate Modern gallery to St. Paul's.

The London Millennium Bridge is, of course, famous for having been shut down just three days after its opening in June 2000, when the bridge started swaying sideways to an alarming degree ("Millennium Legacies," September–October 2001). A similar thing had happened the prior year to a footbridge in Paris. The Passerelle Solferino was designed to give pedestrians a peaceful crossing of the Seine from the Tuileries quay to the Musée d'Orsay. Although tested before opening with 150 people dancing to a beat designed to reveal dynamic susceptibilities, this technologically innovative arch bridge swayed on opening day. The 2-centimeter movement, amplified by French politics, forced the closure of the bridge that same day. Its architect-engineer, Marc Mimram, admitted that designing a footbridge "is more difficult than other bridges, with its conflicting demands of light weight and long span." Still, how could such embarrassing oversights happen, on the eve of the 21st century, when engineers were using powerful computers to design what their ancestors once sketched out only with sticks in the sand?

As with the bridge types Sibly studied, the design of footbridges had become routine. The loads considered did not include the sideways forces exerted by people walking, which have a frequency of one-half that of their vertical footfall. Historically, this had not been a problem, but the natural frequency of sideways motion of the Pont Solferino and London Millennium Bridge was close to what people walking in step would exert. Though crowds of people do not generally walk in step, when the bridges began to move sideways—for whatever reason—the people fell into step the better to keep their balance. This in turn magnified the sideways motion of the structure, and a positive feedback loop developed. The motions got so violent that public safety concerns dictated that the bridges be closed.

The Solferino and London Millennium bridges do not look anything like each other. The former is an arch and the latter a low-profile suspension bridge. Yet although they do not look similar, they shared the same design assumptions with all other footbridges, which clearly did not take into account the critical loading mode. In this sense the development of footbridges falls into the pattern pointed out by Sibly—namely, that the state of the art, which had developed out of successful experience, was finally being pushed, albeit inadvertently, into realms for which it was inadequate. By this criterion, the failure of these footbridges, in which dynamic phenomena insignificant in bridges of lesser magnitude revealed themselves to be limiting, fulfills the prediction of a bridge failure around the year 2000.

But why, if they had been under development for so long, did footbridges fall so neatly into the 30-year cycle? Apparently, major bridge failures occur once a professional generation. According to Sibly and Walker:

> 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. 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.

Sibly and Walker admitted that the 30-year return period may be coincidence, but they also speculated that there just might be "a communication gap between one generation of engineer and the next." As for why a 30-year cycle also applies for the failure of literary forms, Moretti offers a similar explanation: It is generational, but not in a strictly biological sense. Rather, the dynamic is more like the recurrent revolutions against "normal science" that Thomas Kuhn so convincingly demonstrated. Moretti posits that there is a "normal literature," manifested in a novel type, which gets replaced through some process of intellectual destabilization. But he has no good model for why such a "generational replacement" happens so regularly as every 30 or so years. The same open question remains for bridge failures, which occur in a climate of "normal engineering," and the hypothesis will again be tested around the year 2030, if not sooner.

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