Patterns of Failure

Structural failures occur in part because the design process is subject to all the flaws and failings of human intelligence and human nature.

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ENGINEERING DISASTERS ARE NOT A MODERN PHENOMENON, NOR IS THE INTERPLAY BETWEEN SUCCESS AND FAILURE. The success of the Meidum pyramid, which rose at a steeper angle than any of its predecessors, appears to have emboldened the Egyptians to build the pyramid at Dahshur at a still steeper angle. The great masses of debris at the base of this structure, combined with the fact that its angle changes from 54º to a more conservative 43º about halfway up, suggest that a spectacular failure during construction led to a rethinking of the pyramid's profile.[1]

Over two millennia ago, Vitruvius recounted incidents of success and failure in engineering, including the case of Paconius and the stone pedestal for a statue of Apollo. Ingenious schemes for moving heavy stone building components had been devised by the Greeks, who had to transport large cylindrical shapes for columns and large prismatic shapes for architraves from the quarry to temples' construction sites. Paconius, faced with the somewhat unusual problem of transporting a large block of stone intended to replace the deteriorating base beneath the statue of Apollo through narrow spaces, modified a previously successful scheme used for architraves into one suited to his circumstances. According to Vitruvius, Paconius's scheme failed miserably because of unanticipated behavior and because the contractor went bankrupt.[2]

Failures have persisted…because the design process remains fundamentally one carried out by a human mind in a human context.

In the Middle Ages, the design and construction of Gothic cathedrals followed the familiar pattern. As daring cathedrals were successfully erected, even more daring ones were attempted—until the thirteenth-century collapse of the cathedral at Beauvais defined a turning point in the climb to heaven.[3] This situation had not changed by the Renaissance, and Galileo opens his *Dialogues Concerning Two New Sciences* with anecdotes of the spontaneous breaking up of large ships and obelisks that had been carefully scaled up geometrically from smaller, successful structures.[4] During World War II, welded steel Liberty ships (and other similarly fabricated structures) broke up spontaneously in situations that would not have threatened their riveted predecessors.[5]

A major bridge failure occurred about once every 30 years between the middle of the 19th century and 1970, a pattern first noted by Paul Sibly.[6] If there was any underlying principle establishing this pattern, another bridge failure should have occurred around the year 2000. And if this historic pattern had any predictive power, then the type of bridge that should have been at risk would have been one that had an established period of success and that had been designed according to the state of the art. At the end of the 20th century, at least two types of bridges fell into this category—footbridges and cable-stayed bridges.

Footbridges

Footbridges are the oldest kinds of bridges, but they seemed to have been experiencing a resurgence in new materials and forms at the end of the millennium. Not surprisingly, footbridges of exceptional span and modern aesthetic were being designed and constructed, but they were not without new problems. Among the most surprising was the movement of the bridges under crowd traffic. This in itself was not a new phenomenon. The collapse of suspension bridges under marching soldiers has long been known—some bridges still carry signs warning crossing soldiers to break step. As a result, pedestrian bridges have been designed to handle repetitive, up-and-down lock-step or marching motion in the frequency range expected of pedestrians.

London's Millennium Bridge, a pedestrian bridge across the River Thames, was designed in this way. However, just three days after this much-anticipated suspension bridge was opened to foot traffic in 2000, it was closed. Unexpectedly large side-to-side movements of the bridge were causing people to grasp the side rails, and it was feared that someone might get seriously hurt.

The design of the bridge was carried out by an interdisciplinary team consisting of an architect, a sculptor, and a structural engineer and should have been more or less routine—save for the bridge's abnormally shallow profile. However, as with all bridge types that are known to have failed, some basic assumptions about footbridges were not reexamined. In particular, the people walking on the structure were assumed to load it vertically but not horizontally. There is a sidewise horizontal component to a walker's gait, and in the case of the Millennium Bridge previously unobserved effects of this component proved to dominate the bridge's structural response.[7] The bridge remained closed for about three years while it was reanalyzed and retrofitted with dampers and other devices designed to mitigate the effects of pedestrians.[8]

Although the Millennium Bridge did not collapse, it revealed a previously unacknowledged failure mode, and its sudden closure could be interpreted as a major bridge failure, which fits into the pattern that persisted for over a century and a half. If this is the case, the question that then arises is: What kind of bridge might be susceptible to the next major failure, which could be expected to occur around the year 2030? Or is there another bridge failure yet to happen—rather than the Millennium Bridge—that may be a bit late in the approximate 30-year cycle?

Cable-Stayed Bridges

Cable-stayed bridges are sometimes confused with suspension bridges, but they are a distinct genre. The modern cable-stayed bridge was introduced in Europe after World War II, when the design concept was used to rebuild structures lost in the war. Cable-stayed designs were intended to be mid-span bridges, with span lengths not to exceed 1,200'. The genuine suspension bridge was still thought to be the only option for truly long spans. By the 1980s, however, cable-stayed bridges exceeding 1,500' were being designed and built. Spans were approaching 3,000' in the 1990s, and today's designs exceed that. In other words, the evolution of cable-stayed bridges was following a pattern similar to that which had been observed in the case histories of failures.[9]

Before the end of the century, there were increasing indications that the construction of cable-stayed bridges was not without problems. The cables of many such bridges were vibrating unexpectedly in the wind, often when it was raining. These unexpected behaviors were dealt with ad hoc, by tying cables together and by installing devices like shock absorbers and tuned-mass dampers. Roadways that were exhibiting equally unexpected behavior were likewise retrofitted with dampers. Not infrequently, these retrofits ruined the clean lines that had been such strong selling points for the signature bridges in the first place.[10]

Cable-stayed bridges of record span continued to be proposed, designed, and built in spite of indications that there was something inherent to the cable-stayed design that was strikingly reminiscent of the problems experienced by suspension bridges in the years before the 1940 Tacoma Narrows collapse. It was this situation that caused this author to predict as early as 1993 that the cable-stayed genre was a most likely candidate to experience the next major bridge failure.[11] Since the millennium was approaching, it seemed there was a good chance that such a failure would be the next to continue the pattern. The instability of the Millennium Bridge may have fulfilled that role, but the cable-stayed bridge remains a likely genre to reinforce and continue the pattern further.

Failures have persisted, as case histories of 19th- and 20th-century bridges demonstrate and the 30-year pattern memorializes. This seems to be the case because the design process remains fundamentally one carried out by a human mind in a human context, even as theories of structures and tools of analysis have become increasingly sophisticated. Therefore, it is subject to all the flaws and failings of human intelligence and human nature, the latter of which has evidently not changed in any fundamental way since ancient times and probably not since prehistoric times. Human beings always have been, are, and likely always will be subject to the flaws of hubris and complacency. On one hand this drives progress. On the other hand it trips it up, and in the case of large bridges perhaps in a historically cyclic fashion.

Bridge failures, or any other kinds of failure, cannot be expected to be eliminated by the development of all-encompassing theories or more refined computational models. In the end, it is the human drive to build on success and to strive for ever longer, taller, more massive, and more economical structures—and the hubris and complacency that accompany prolonged success—that inevitably lead to the setback of failure. Some engineers have even argued that we should not wish it to be any other way: If there never were any structural failures we would be overly conservative in our efforts, wasting resources that might better be applied elsewhere in society.[12] MSC

References

[1]See, e.g., Henry Petroski, *To Engineer Is Human: The Role of Failure in Successful Design* (New York, 1985), pp. 54-55.

[2]Vitruvius, pp. 288-89. See also, Henry Petroski, *Design Paradigms: Case Histories of Error and Judgment in Engineering* (New York, 1994), pp. 15-26.

[3]See, e.g., *To Engineer Is Human*, pp. 56-57.

[4]Galileo, pp. 1-6. See also, *Design Paradigms*, 29-46.

[5]See, e.g., Great Britain, Navy Department, Advisory Committee on Structural Steels, *Brittle Fracture in Steel Structures* (London, 1970); K. G. Richards, *Brittle Fracture of Welded Structures* (Cambridgeshire, 1971).

[6]Paul Sibly, *The Prediction of Structural Failures.* Ph.D. thesis, University of London, 1977.

[7]For a look at the Millennium Bridge from several points of view, see *Blade of Light: The Story of London's Millennium Bridge* (London, 2001).

[8]Ibid., pp. 85-87.

[9]See Henry Petroski, "Predicting Disaster," *American Scientist* 81 (March-April 1993): 110-113. See especially p. 112, Fig. 3.

[10]See, e.g., Henry Petroski, "Le Pont de Normandie," *American Scientist* 83 (September-October 1995): 415-419.

[11]Petroski, "Predicting Disaster."

[12]Sir Alfred Pugsley, *The Theory of Suspension Bridges* (London, 1968).