Engineering: Still Twisting
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Still Twisting

Henry Petroski

The dramatic collapse of the Tacoma Narrows Bridge in 1940 was recorded on film, in large part because the new structure had been exhibiting large oscillations for months and was being watched closely by engineers and nonengineers alike. Its two-lane roadway stretched more than half a mile between towers, and the bridge had an especially sleek and modern look because the deck rested on solid girders only eight feet deep, rather than the more conventional 20- or 30-foot-deep trusswork employed in contemporary suspension bridges such as the Golden Gate. The first sinuous motions of the bridge had actually made several construction workers seasick and raised serious concern about its safety, but the dynamic behavior was declared structurally benign and the bridge was opened to traffic. Drivers crossing the Tacoma Narrows would see cars in front of them alternately rising and falling into and out of view with the moving peaks and valleys of the roadway. The public had come to call the bridge by the affectionate nickname Galloping Gertie, and many flocked to it as to an amusement park. Some, however, drove out of their way to avoid it.

Until the morning of November 7, 1940, the motion of the Tacoma Narrows deck had always been symmetric about the solid center line that separated the two lanes of traffic. The roadway had sometimes assumed the undulating form of a sine wave, but from side to side it had remained flat and never banked. On each of the bridge's sidewalks, the lamp posts had remained in the vertical plane of the suspension cable as they rose and fell and tilted back and forth between the bridge towers. This pattern continued until about 10 o'clock that morning, but as the vertical motion grew larger it suddenly took a novel twist. The large motions of the bridge apparently caused a cable band to loosen and slip out of place, introducing an asymmetry into the forces acting on the deck. The bridge began to execute asymmetric oscillations, with the deck twisting about the centerline, as if the roadway were an aircraft alternately banking left and right; the lamp posts now swayed in and out of the vertical plane of the cable stays that connected the bridge deck to the main cables. The bridge was closed to traffic, and Professor Burt Farquharson, who had been watching the behavior of the real bridge in conjunction with his experiments on a model at the University of Washington, reportedly rushed to a camera shop to borrow the equipment that recorded the bridge's final minutes.

A lone automobile remained stalled on the twisting bridge, abandoned by a reporter who may have been trying to drive across the moving roadway to get a unique story. In the film the car is on the wrong side of the road, where it was thrown after its engine stalled. The unwilling pedestrian was reported to have clung to the curb until he could begin to crawl to safety during a lull in the bridge's motion. Professor Farquharson himself was also captured on the film, at times walking a bit like a drunken sailor along the relatively steady centerline, which effectively remained a motionless nodal line during the twisting. He is said to have risked his life trying unsuccessfully to rescue a small dog trapped in the stalled car; the canine became the only life lost when the bridge twisted itself apart and collapsed. The final minutes of the writhing of the Tacoma Narrows Bridge have become *the* classic film of structural failure. Its scenes, as one reporter put it, "rank among the most dramatic and widely known images in science and engineering."

For half a century the film of the bridge's collapse has gotten mixed reviews from engineers. Although it provides a rare glimpse of a full-scale structure exhibiting the extent of its flexibility, the film also provides incontrovertible evidence that engineers can make colossal mistakes—something of which few need to be reminded. Physicists, on the other hand, seem to have no reservations about replaying the film, for it not only provides a visual real-world example of a dramatic mechanical phenomenon but also gives them an opportunity to show how their theories can explain and predict behavior of which at least some engineers 50 years ago were so clearly ignorant. It is perhaps no accident that the famous film of the Tacoma Narrows collapse is distributed not by an engineering organization but by the American Association of Physics Teachers. The visual evidence of the colossal design blunder is now available in video tape, accompanied by a paper titled "The Puzzle of the Tacoma Narrows Bridge Collapse."

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Engineers are understandably reluctant to flaunt images of failure, but they do recognize that when a major suspension bridge so misbehaves that it collapses, the event stands as proof that the state of the art leaves something to be desired. Such was obviously the case in 1940, and so it may have been proper then to refer to the collapse as a "puzzle."An investigative committee appointed by the Federal Works Agency was charged with finding a solution to that puzzle. The committee included Othmar Ammann, the great bridge engineer, and Theodore von Kármán, the famous aeronautical engineer. Early on, von Kármán attributed the cause of the Tacoma Narrows Bridge failure to the shedding of vortices of air in a periodic manner, a phenomenon that created a wake known as a Kármán vortex street. In von Kármán's view, the wake reinforced structural oscillations that grew until the bridge deck could no longer hold together. The FWA report did not reflect von Kármán's convictions, however, and declared that it was "very improbable that resonance with alternating vortices plays an important role in the oscillations of suspension bridges" and that the Tacoma Narrows behavior was probably due to "forced vibrations excited by random action of turbulent wind." Such uncertainties about the cause of the collapse can be found in the literature to this day.

The 50th anniversary of the collapse of the Tacoma Narrows Bridge naturally occasioned some recountings of the event. One article in the November 1990 issue of *Construction Today* declared that "in spite of official reports and 50 years of analysis, the violent failure... is still not entirely understood." Indeed, a great deal of research, writing and debate has been focused on the cause of the Tacoma Narrows failure during the past half-century, not only among engineers and engineering scientists but also among mathematicians and physicists who are not averse to applying themselves to the study of an artifactual phenomenon. Actually, although the bridge's failure may never be "entirely understood," much progress toward an understanding has been made. The lingering confusion may reflect a breakdown in communication among fields rather than a lack of research results.

A recent example of the continuing debate is an article by two applied mathematicians that appeared in late 1990 in the *SIAM Review*, which is published by the Society for Industrial and Applied Mathematics. The mathematicians had noticed fundamental flaws in the standard explanation that the bridge was set into resonant vibration by the fluctuating force produced by a train of shed vortices. According to a report on the article in *Science News*, the pair had "spent the last six years developing an alternative mathematical model that may help elucidate the catastrophic collapse" and had obtained promising results with a model that captures the "fundamental nonlinearity" of suspension bridges.

The authors begin by writing down "the simplest nonlinear partial differential equation" that can account for the effects of slackening in the stays that connect the deck of a suspension bridge to the cable. Their analysis begins with the admitted "oversimplification" of taking the weight of the bridge to be not constant but "the first term in the eigenfunction expansion of the constant function," that is, a sinusoidal weight distribution that the authors admit "introduces an error of magnitude 10% in the loading and somewhat less in the steady-state deflection." A sinusoidal "forcing term" is also assumed, of which the authors say: "This is a peculiar term, but there is no reason why the bridge cannot have this type of forcing term."

While this may all be admirable exploratory or heuristic applied mathematics, it is not engineering science, and there is little to entice an engineer to take its results as seriously as did *Science News*. The way of mathematical analysis may be to approximate and solve equations and then go looking for applications, but in engineering analysis physics and fact tend to lead the math. The *SIAM Review* paper furthermore deals only with vertical oscillations of a bridge; the authors confess to hoping to explain the transition to a torsional mode, but they realize that the attainment of that goal "remains a long way off." In their defense, they do admit in "some last comments and some self-criticism" that their models are "painfully inadequate." I had to look elsewhere for more satisfying solutions to the "puzzle."

A cumulative index to publications of the American Society of Civil Engineers suggests that the society ignored the anniversary. However, the December issue of *Civil Engineering*, the society's general-interest magazine, did carry a news item essentially announcing that a forthcoming paper in the *American Journal of Physics* would "spread the truth" about the cause of the infamous collapse. Since the paper was written by two engineers and promised to contrast an engineering explanation with those in physics textbooks, I looked forward to the journal issue. This time I was not disappointed.

Robert Scanlan, currently professor of civil engineering at the Johns Hopkins University, has studied the dynamics of structures over a long and distinguished career. As early as 1971 he took part in investigations of similarities between flutter in airfoils and in bridge decks—research that eventually led to a clarification of the nature of the Tacoma Narrows failure. The clarification managed, however, to escape

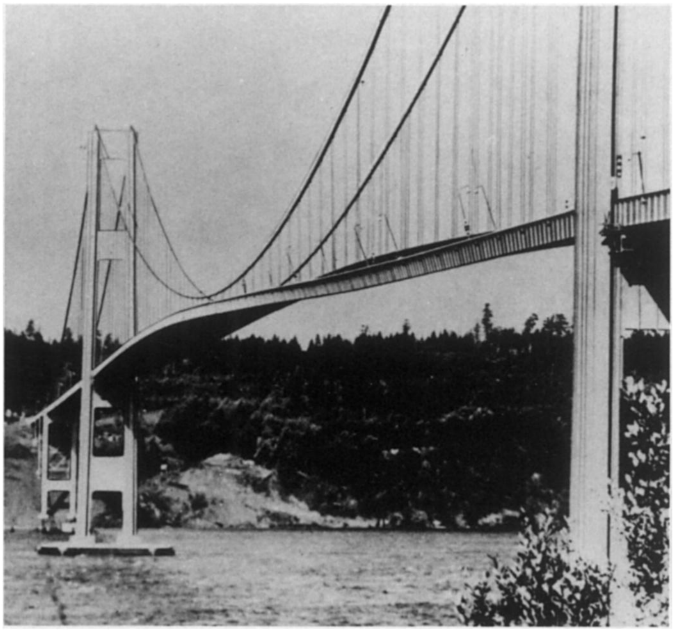

Figure 1. Burt Farquharson's classic photograph of the fatal twisting of the Tacoma Narrows Bridge under the action of wind. (Photograph courtesy of the Special Collections Division, University of Washington Libraries.)

Figure 2. Kármán vortex street, a pattern of alternating vortices created by the confrontation of a nonstreamlined body and an airstream and initially suggested as the source of the periodic impulses that drove the Tacoma Narrows Bridge to collapse.

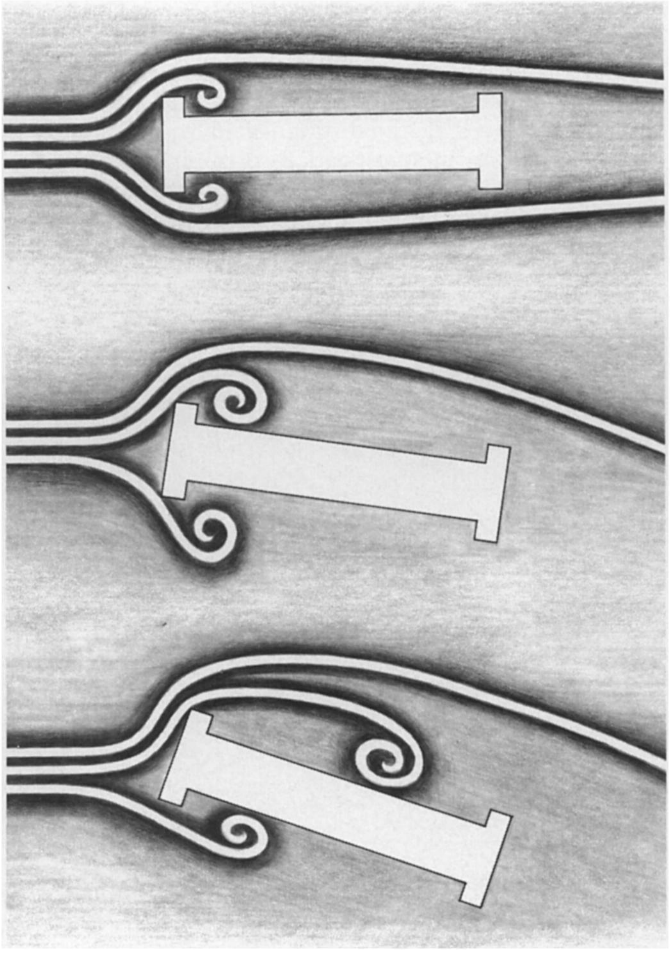

Figure 3. Motion-induced vortices over a rotating deck section, an alternative source of resonance in the bridge collapse. (From Billah and Scanlan 1991.)

widespread notice outside engineering until the review article written by Scanlan and a former student, Yusuf Billah, appeared in the physics journal this February.

The inspiration to prepare a review article on the Tacoma Narrows Bridge collapse for a physics journal came to Billah while he was browsing in a Princeton bookstore in the late 1980s. There he found himself examining "three currently used and popular [physics] textbooks [that] invoke inferences about the Tacoma Narrows episode that differ from present engineering understanding of the failure." A search of libraries and bookstores, he said, revealed the "ubiquitous presence of the Tacoma Narrows bridge failure in numerous other texts" (30 are referenced in Billah and Scanlan's article). Almost all cited the bridge's behavior as an example of resonance.

After quoting from several texts declaring resonance to have been the culprit, Billah and Scanlan admit that the texts are qualitatively correct, but they do not properly or quantitatively identify a source of periodic impulses that could produce the resonance. The classic, linear, single-degree-of-freedom oscillator that commonly forms the basis for an explanation requires that wind itself be the forcing function, but no definite periodicity is generally associated with wind gusts or gales. Several texts actually resort to von Kármán's explanation that shed vortices created the periodic impulse that drove the bridge to destruction. To refute this, Billah and Scanlan calculate the frequency of the shed vortices in the 42-mile-per-hour wind that was blowing when the bridge collapsed. This frequency is about 1 hertz, which they note is "wholly *out of synch*" with the 0.2-hertz torsional oscillations actually observed by Professor Farquharson.

The engineers go on to reproduce a graph from a University of Washington Engineering Experimental Stations Bulletin in which Farquharson reported on the aeroelastic behavior of a full-bridge model in a wind tunnel. The graph shows that whereas the amplitude of vertical oscillation modes was self-limiting under increasing wind velocity, such was not the case for a torsional oscillation mode. (A more general treatment, including the coupling of vertical and torsional oscillations of bridge decks, is contained in *A Modern Course in Aeroelasticity*, edited by the aeroelastician Earl Dowell and written with Scanlan and others.)

According to the engineering-science model, as the Tacoma Narrows deck executed torsional oscillations, two kinds of vortices were shed. The first were those associated with the Kármán vortex street and having a frequency that did not coincide with the natural frequency of the bridge's motion. The second kind were complex vortices associated with the structural oscillation itself and having exactly its frequency—a type of vortices associated with the flutter wake that is created by a nonstreamlined body in an airstream. It was these latter motion-induced vortices, which predominate at large amplitudes of oscillation, that apparently drove the bridge to destruction. Billah and Scanlan acknowledge a "'chicken-egg' dilemma: Did the vortices cause the motion or the motion cause the vortices?" They conclude it was the latter. If there was resonance, it was complex and existed between the bridge's motion and the vortices produced by that motion.

As Billah and Scanlan report, the damping effects that would restrain oscillations in bridge decks change sign at a particular wind speed, resulting in a differential equation with "negative damping" that allows the bridge to oscillate at large amplitudes that ultimately lead to structural collapse. Evidently this self-destructive torsional mode did not occur at Tacoma Narrows until a minor structural failure created asymmetrical conditions; once it was initiated it took 45 minutes to get completely out of control.

Billah and Scanlan close their paper on the Tacoma Narrows Bridge failure by observing that the "sensational photographs have made it an irresistible pedagogical example." Furthermore, "because it lodges itself so easily in the memory, it is doubly important for educators to draw the correct lessons from this classic and sensational event." Indeed, a familiarity with case studies of failures is among the most efficacious means of avoiding similar failures in the future. However, if the explanations accompanying case studies are flawed or misleading, they have the potential for doing more harm than good.

Modern engineering rests heavily on mathematical and scientific foundations, and that is why the first two years of the engineering curriculum are dominated by mathematics and science courses. Eager and impatient engineering students often ask the relevance of those courses to real engineering, and so the discussion of real-world examples such as the oscillation and collapse of the Tacoma Narrows Bridge is especially important to receptive and impressionable students. Teachers of engineering are repeatedly reminded how difficult it is to break poor mathematics and science habits, especially those acquired in elementary courses that give preemptive explanations to dramatic engineering phenomena and failures. Yet in the Tacoma Narrows case study, mathematics and physics are clearly behind the engineering science, for which they are properly prerequisite.

The juxtaposition of a simple, albeit retrospective, physical explanation and a complex engineering error has implications far beyond mere puzzle solving, for it contrasts the omniscient mathematician/scientist and the blundering engineer. It behooves us all to avoid such oversimplification and stereotyping, whether explicit or implicit, in our textbooks and our classes. The collapse of the Tacoma Narrows Bridge will no doubt remain, as it should, an irresistible pedagogical example; it should not also remain a classic example of interdisciplinary hubris and conflict.

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