Bridge Collapse Cases/Tacoma Narrows

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Tacoma Narrows Bridge Collapse

Only three months after the Tacoma Narrows bridge opened in 1940, tie-down cables intended to stiffen the bridge snapped during a windstorm. The cables had been anchored into the ground and attached to the parts of the bridge deck that were moving the most. The cables were replaced. The bridge became notorious for large movements during high winds. On 7 November 1940, with a wind velocity of about 60 kph, the bridge began twisting and oscillating violently. The bridge was twisting about 45 degrees in two waves, and oscillating up and down one meter in nine waves. The oscillations reached 8 meters as the bridge tore itself apart (Levy and Salvadori, 1992, Feld and Carper, 1997).

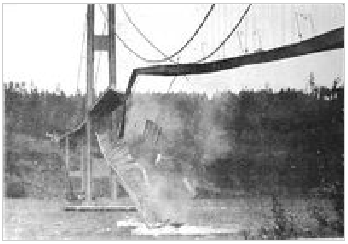
The mathematics involved in the oscillations of a slender bridge are difficult, and were not well understood in 1940. However, suspension bridges had failed in the 18th and 19th centuries. The Tacoma Narrows bridge was three times more flexible than the Golden Gate or George Washington bridges. Like the Bronx-Whitestone Bridge, it used a damper, but the damper failed almost immediately. The other bridges had a much greater stiffness and mass moment of inertia, and were less prone to wind-induced accelerations (Levy and Salvadori, 1992). The replacement bridge, which is still in use, had four lanes rather than two and 10 m deep stiffening trusses in place of the original 2.4 m trusses (Feld and Carper, 1997). The resistance to the vertical oscillation is proportional to the mass of the bridge, which is doubled in the replacement design.

Should more attention have been paid to the causes of the tie-down cable failure ? Is the occasional failure of a ground-breaking structure part of the cost of doing business ?

References:

- Shepherd and Frost, 1995, p. 40
- Wearne, 2000, Chapter 2 - "Suspension Bridges: Galloping Gertie and the Point Pleasant Bridge"

Rachel Martin's Case Study - originally developed for the UAB REU Site, 1999



Collapse of the Tacoma Narrows Bridge

Tacoma Narrows Bridge Collapse

Tacoma, Washington

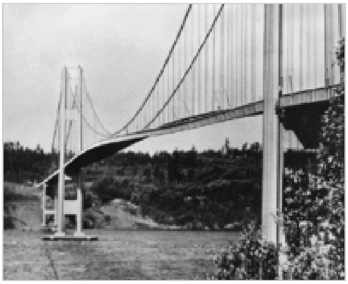
November 7, 1940

by Rachel Martin

Design and Construction

On July 1, 1940, the Tacoma Narrows Bridge, connecting Seattle to Tacoma with nearby Puget Sound Navy Yard, opened to the public after two years of design and construction. Its 2,800-ft. mainspan connected two 420-ft. towers from which cables were draped (Levy and Salvadori, 1992).

Even though it was the third longest bridge in the world, Tacoma Narrows was much narrower, lighter, and more flexible than any other bridge of its time. With a 39-ft wide and 8-ft deep concrete deck, it accommodated two lanes of traffic quite comfortably while maintaining a sleek appearance. This appearance was so important to the bridge's designer, Leon Moisseiff, that he designed it without the use of stiffening trusses, leaving Tacoma Narrows with 1/3 the stiffness of the Golden Gate and George Washington bridges. Tacoma Narrows light appearance, however, was no illusion. Its dead load was 1/10 of that of any other major suspension bridge. These unique characteristics coupled with its low dampening ability caused large vertical oscillations in even the most moderate of winds. This soon earned it the nickname, "Galloping Gertie," and attracted thrill seekers from all over (Feld and Carper, 1997). **Table-1** compares the properties and deflections of the five long suspension bridges in 1941.



Tacoma Narrows Bridge

While these undulations could be quite unnerving to motorists, no one questioned the structural integrity of the bridge. Leon Moisseiff was a highly qualified and well-respected engineer. Not only had he been the consulting engineer for the Golden Gate, Bronx-Whitestone, and San Francisco-Oakland Bay bridges, but he had also developed the methods used to calculate forces acting on suspension bridges (Levy and Salvadori, 1992). Even though the Tacoma Narrows Bridge adhered to all of the safety standards and its oscillations were not considered a threat, Prof. F. B. Farquharson began researching ways to reduce its motion at the University of Washington. By studying how different winds affected a highly accurate model of the Tacoma Narrows Bridge and testing new devices on it, Farquharson was able to propose helpful modifications to the bridge. After proving successful on the model, 1 9/16 -in. steel cables attached a point on each side span to 50-yd concrete anchors in the ground. Unfortunately these cables snapped a few weeks later proving to be an ineffective solution (Ross, 1984). They, however, were reinstalled in a matter of days. In addition to these cables, center stays and inclined cables, which connected the main cables to the stiffening girder, were installed. Finally, an untuned dynamic damper, similar to the one that had proved quite successful in curtailing the torsional vibrations of the Bronx-Whitestone Bridge, failed immediately after its installation in the Tacoma Narrows Bridge. It was discovered that the leather used in this device was destroyed during the sandblasting of the steel girders before they were painted rendering it useless (Levy and Salvadori, 1992). Farquharson also discovered that proper streamlining would almost completely stop the bridges disturbing movements. The bridge collapsed before this knowledge could be applied (Ross, 1984).

Collapse

At 7:30 A.M. on November 7, 1940, Kenneth Arkin, the chairman of the Washington State Toll Bridge Authority, arrived at the

Tacoma Narrows Bridge. While the wind was not extraordinary, the bridge was undulating noticeably and the stays on the west side of the bridge which had broken loose were flapping in the wind. Just before 10:00 A.M. after measuring the wind speed to be 42 mph, Arkin closed the bridge to all traffic due to its alarming movement, 38 oscillations/minute with an amplitude of 3 ft (Levy and Salvadori, 1992). Suddenly, the north center stay broke and the bridge began twisting violently in two parts. The bridge rotated more than 45° causing the edges of the deck to have vertical movements of 28 ft and at times exceed the acceleration of gravity (Ross, 1984). Two cars were on the bridge when this wild movement began: one with Leonard Coatsworth, a newspaper reporter, and his cocker spaniel and the other with Arthur Hagen and Judy Jacox. All three people crawled to safety (Levy and Salvadori, 1992). A couple of minutes later the stiffening girders in the middle of the bridge buckled initiating the collapse. Then the suspender cables broke and large sections of the main span dropped progressively, from the center outward, into the river below. The weight of the sagging side spans pulled the towers 12 ft towards them and the ruined bridge finally came to a rest (Feld and Carper, 1997). The bridge's only fatality was Coatsworth's cocker spaniel. Due to the fact that Prof. Farquharson was present that day studying the bridge, its collapse is well documented, photographed, and recorded on film (Levy and Salvadori, 1992).

Causes of Failure

The Federal Works Agency (FWA) investigated the collapse of the Tacoma Narrows Bridge and found the following:

- The bridge was well designed and well built. While it could safely resist all static forces, the wind caused extreme undulations which caused the bridge's failure.
- No one realized that Tacoma's exceptional flexibility coupled with its inability to absorb dynamic forces would make the wild oscillations which destroyed it possible.
- Vertical oscillations were caused by the force of the wind and caused no structural damage.
- The failure of cable band on the north end, which was connected to the center ties, probably started the twisting motion of the bridge. The twisting motion caused high stresses throughout the bridge, which lead to the failure of the suspenders and collapse of the main span.
- A suspension bridge was the most practical choice for the site.
- The supervision of and workmanship on the bridge was exceptional.
- Rigidity against static forces and rigidity against dynamic forces cannot be determined using the same methods.
- Efforts were made to control the amplitude of the bridge's oscillation.
- Subsequent studies and experiments are needed to determine the aerodynamic forces which act on suspension bridges.

In other words, the FWA concluded that because of Tacoma Narrow's extreme flexibility, narrowness, and lightness the random force of the wind that day caused the torsional oscillations which destroyed the bridge. **Table-1** compares Tacoma Narrow's flexibility, width, and weight to that of four other long suspension bridges of its time. The FWA believed that wind induced oscillations approached the natural frequencies of the structure causing resonance (the process by which the frequency on an object matches its natural frequency causing a dramatic increase in amplitude). This explains why the relatively low speed wind (42 mph) caused the spectacular oscillations and destruction of the Tacoma Narrows Bridge (Engineering News-Record, 1941). The FWA's theory, however, is not the only explanation. Many people believe that this explanation overlooks the important question as to how wind, random in nature, could produce a periodic impulse. One explanation proposed by von Kármán, an aeronautical engineer, attributed the motion of the bridge to the periodic shedding of air vortices which created a wake known as a von Kármán's street. This wake reinforced the structural oscillations eventually causing the collapse of the bridge. The problem with this theory is that the calculated frequency of a vortex caused by a 42 mph wind is 1 Hertz while the frequency of the torsional oscillations of the bridge measured by Prof. Farquharson was 0.2 Hertz (Petroski, 1991). Another explanation proposed by Billah and Scanlan admits that vortices associated with the Kármán vortex street were shed but did not affect the motion of the bridge. Another kind of vortex, one associated with the structural oscillation itself, having the same frequency as the bridge was also created. The resonance between the bridge and these vortices caused excessive motion destroying the bridge (Billah and Scanlan<u/>, 1991). While these three theories differ in their opinions as to what exactly caused the torsional oscillations of the bridge they all agree that the extreme flexibility, slenderness, and lightness of the Tacoma Narrows Bridge allowed these oscillations to grow until they destroyed it.

Technical Concerns

The Tacoma Narrows Bridge collapse showed engineers and the world the importance of dampening, vertical rigidity, and torsional resistance in all suspension bridges (<u>Ross, 1984). Once the threat of twisting was realized there are many ways that the disaster of Tacoma Narrows could have been averted. Making any one of the following adjustments could have prevented the collapse:

- Use open stiffening trusses which would allow the wind free passage through the bridge
- Increase the width to span ratio
- Increase the weight of the bridge
- Dampen the bridge
- Use an untuned dynamic damper to limit the motions of the bridge
- Increase the stiffness and depth of the trusses or girders
- Streamline the deck of the bridge (Levy and Salvadori, 1992)

Procedural Concerns

The Tacoma Narrows Bridge collapse highlighted the importance of failure case studies in engineering education. Between 1818 and 1889, the wind destroyed or seriously damaged ten suspension bridges (Petroski, 1994). Most of these bridges, like Tacoma Narrows, had small width to span ratios, ranging anywhere from 1/72 to 1/59. They also experienced severe twisting right before collapse as Tacoma Narrows did (Levy and Salvadori, 1992). In 1826, a hurricane partially destroyed the Menai Straits Bridge in eastern England. The deck experienced 16-ft oscillations before it broke (Feld and Carper, 1997). Thirty-eight years later in 1854, the bridge over the Ohio River at Wheeling, West Virginia also collapsed due to wind.

Many other bridges suffered a similar fate (Levy and Salvadori, 1992). In fact, it was not until the success of John Roebling's suspension bridges that they became widely accepted. Through his understanding of the importance of deck stiffness and knowledge of past failures, Roebling was able to make suspension bridges accepted as strong railway bridges (Feld and Carper, 1997). Soon, however, the success of the suspension bridges completely overshadowed the failures of the last century. Once again, suspension bridges evolved towards the longer sleeker designs forgetting the cornerstone of their success, wind resistance (Petroski, 1994).

Ethical Concerns

In the face of new technology, how do we balance public welfare and progress? If Moisseiff had designed a bridge similar to the ones which had already proven their stability, Tacoma Narrows Bridge would never have collapsed costing thousands of dollars and endangering many lives. It would also have been significantly more expensive. On the other hand, if engineers had never tried innovative techniques, suspension bridges may never have been built at all. At the time of their introduction, no one believed that a suspension bridge could safely accommodate trains. Roebling, however, took a gamble, pushed the limits of the current technology, and built a suspension bridge that he believed could safely support rail traffic. Luckily he was correct, and suspension bridges soon became widely accepted (Petroski, 1985). Moisseiff also took a gamble, trying to create a longer, sleeker, less expensive bridge, by pushing the limits of technology. He, however, was not as lucky, and what could have been a breakthrough in technology turned into a catastrophic failure. Every time engineers push the limits of technology they risk a similar loss, sometimes even a loss of life. How much is too much? When is a possible advance worth a risk to public safety? What can the engineering profession do to make the implementation of new technology safer? Do our current peer review and building code committee processes adequately protect public safety?

ASCE Code of Ethics (http://www.asce.org/Leadership-and-Management/Ethics/Code-of-Ethics/)

Links

- Tacoma Narrows Bridge (http://www.nwrain.com/%7Enewtsuit/recoveries/narrows/narrows.htm)
- The Tacoma Narrows Bridge Collapse (http://www.stkate.edu/physics/phys111/curric/tacomabr.html)

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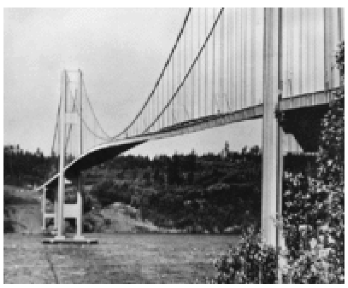
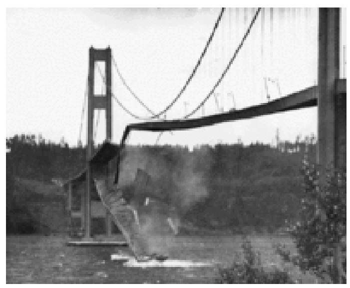


Tacoma Narrows Bridge torsional motion



Tacoma Narrows Bridge collapse

Bridge - After the Collapse (Photo from University of Washington Special Collections)

See the University of Washington Special Collections - Tacoma Narrows Series (Summary) (http://www.lib.washington.edu/specialcoll/exhibits/tnb/)
See also University of Washington Special Collections - full Tacoma Narrows Bridge collection (http://content.lib.washington.edu/farquharsonweb/)

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