Collapse of Tacoma Narrows Bridge

November 7, 1940 in Tacoma, Washington, USA

Masayuki Nakao (Institute of Engineering Innovation, School of Engineering, The University of Tokyo)

The Tacoma Narrows Bridge in the state of Washington was completed and opened to traffic on July 1, 1940. The bridge was the first of its type to employ plate girders to support the roadbed. Shortly after its construction, the bridge was discovered to sway and buckle dangerously in windy conditions. On November 7, just four months after the opening, it collapsed due to wind-induced oscillations (19 m/sec of wind velocity). No human life was lost in the collapse of the bridge.

1. Event

The Tacoma Narrows Bridge at Puget Sound in the state of Washington was completed and opened to traffic on July 1, 1940. On November 7, just four months after the opening, it collapsed due to wind-induced oscillations. No human life was lost in the accident.

2. Course

The Tacoma Narrows Bridge was completed and opened to traffic on July 1, 1940. It stretched like a steel ribbon across the Tacoma Narrows in Puget Sound near the city of Tacoma, Washington (Figure 1). It was the third longest suspension bridge of its time with a center span of 853 meters, and had sleek appearance with its length in comparison to its width and thickness of 11.9-meter wide road bed providing two traffic lanes and sidewalks (Figure 2). It was a narrow bridge for its long length.

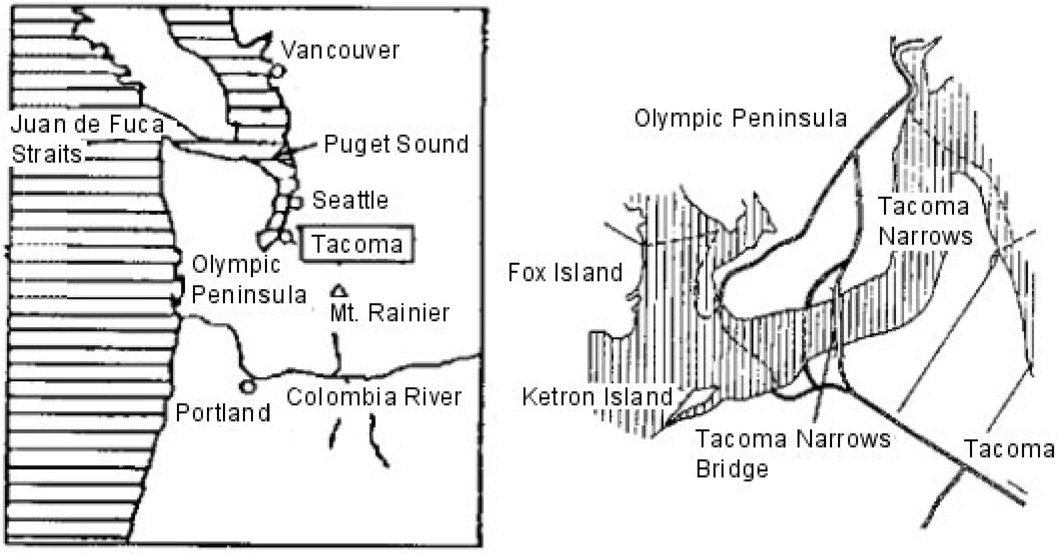


Figure 1. Location of Tacoma Narrows Bridge [1]

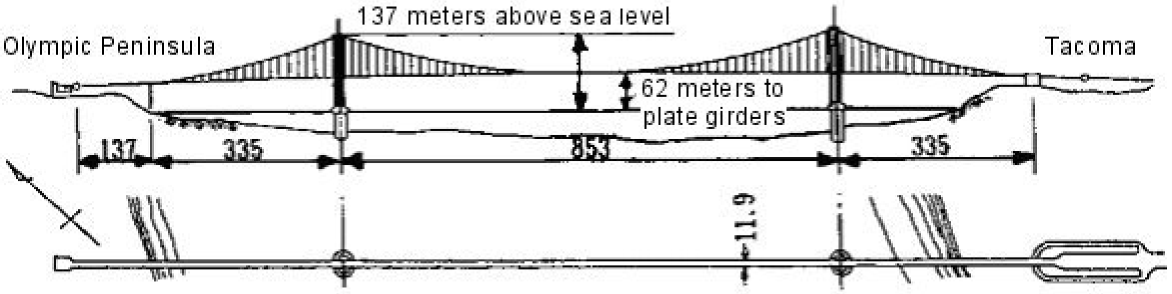


Figure 2. Structure of Tacoma Narrows Bridge [1]

Shortly after its construction, the bridge was discovered to sway and buckle dangerously along its length in windy conditions. Engineers were conducting wind tunnel experiments on airflow characteristics around the bridge structure.

When the bridge began heaving violently on November 7, the authorities notified Professor F. B. Farquharson of the University of Washington who had been conducting wind tunnel experiments with a model of the bridge. The professor and his research team recorded the bridge with a camera.

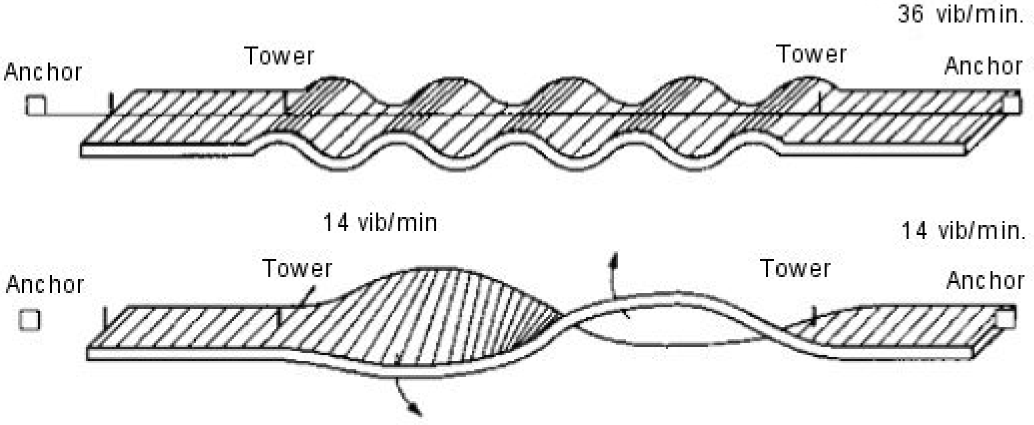
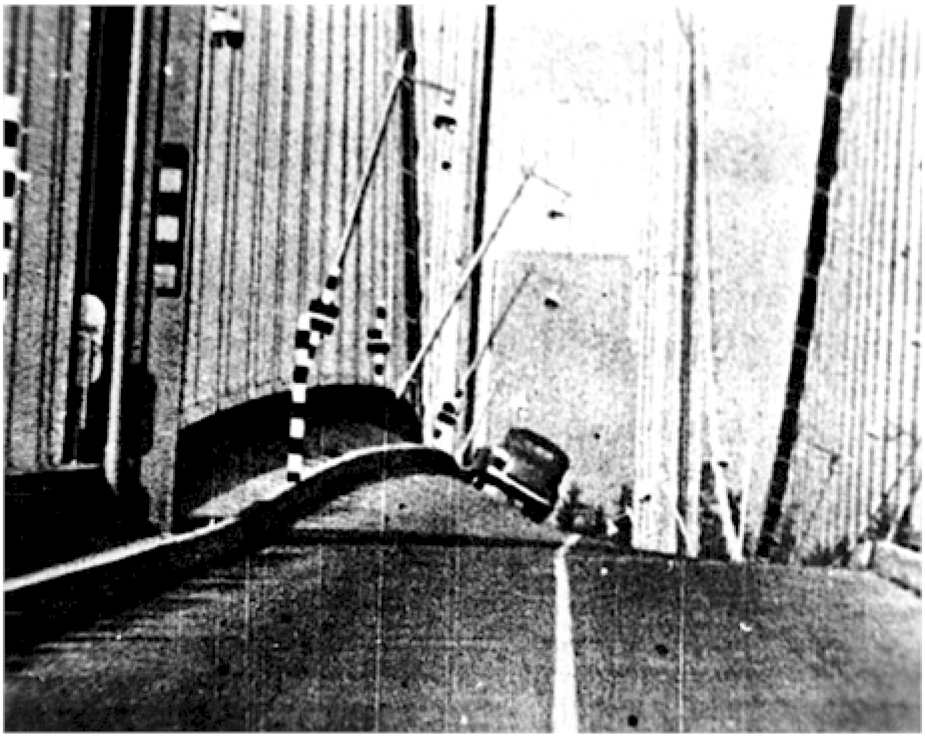


Figure 3. Movements of Tacoma Narrows Bridge [1]

While the wind was not extraordinary, the bridge was undulating noticeably, and the center stay was vibrating torsionally in 9 segments with a frequency 36 cycles/min. The amplitude of the torsional vibration quickly built up in an hour when the north center stay broke and the motion changed from a rhythmic rising and falling to a two-wave twisting motion. The bridge twisted violently in two parts with frequency 14 vib/min, in which the midpoint of the bridge remained motionless while the two halves of the bridge twisted in opposite directions (Figure 3). This catastrophic twisting motion was probably started by the failure of cable band on the north end, which was connected to the center diagonal ties. The twisting motion caused high stresses throughout the bridge, which lead to the failure of the suspenders and collapse of the main span (located near the vehicle in Photo 1).

The weight of the spans sagging into the river pulled the towers towards them, bridge began cracking, and the entire bridge crashed down (Photo 2).



University of Washington Libraries, Special Collections, FAR016

Photo 1. Twisting Motion of Tacoma Narrows Bridge [1]

University of Washington Libraries, Special Collections, FAR017

Photo 2. Breakdown of Tacoma Narrows Bridge [1]

3. Cause

Self-excited oscillation induced by lateral wind was responsible for the collapse. The cause was "unknown" rather than "ignorance." The self-destruction of the bridge, in fact, took place when wind tunnel experiments were underway. The Tacoma Narrows Bridge was one of the suspension bridges designed applying the "deflection theory", which had been formulated in Austria for concrete arch bridges. Leon Moisseiff, a bridge engineer and mathematician, applied the theory for suspension bridges, calculated the stresses and concluded that shear and bending loads are partly carried in the cables, rather than relying on stiffening trusses. The bridge relied on the dead load (the weight of the deck, main cables and suspender cables) for its rigidity with little inherent structural damping. This theory allowed reducing the amount of stiffening material and the construction costs. It seemed an ideal design approach for long-span suspension bridges. However, the designer extended the slender span concept too far, and the novel design caused the bridge to be excessively flexible. The girder on Tacoma-Narrow bridge then had flat H shapes as Photo 3 shows. The new bridge was redesigned and rebuilt with open trusses, stiffening struts and openings in the roadbed to let wind through, allowing less twisting than the previous design (Photo 4).

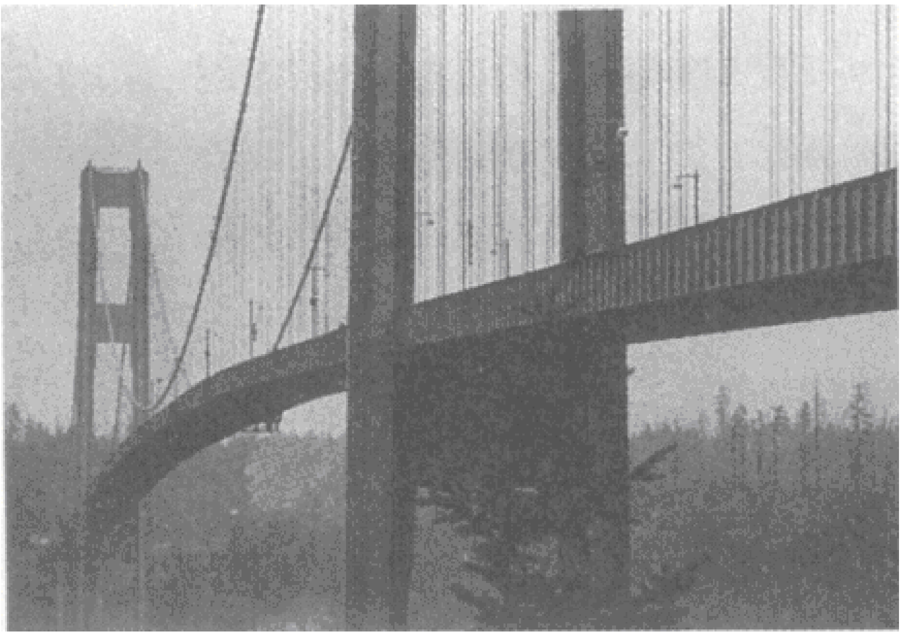


Photo 3. The former Tacoma Bridge (its bridge girder has a flat H form) [1]

The investigation of the cause of the failure and wind tunnel testing of 3-d scale model concluded that:

(1) The exceptional flexibility and small resistance against twisting of the bridge allowed it to pickup the oscillation quickly.

(2) The shape was aerodynamically unstable. The H-shaped girders allowed the air flow to easily separate at the edges, and the vortex generation happened to match the oscillation of the girders. The wind-generated vortices moved the girders that then generated new vortices. The designers were unaware of this mechanism of wind excited vibration.

4. Immediate Action

The Federal Works Agency appointed three engineers to investigate the failure: Theodore von Kármán (a hydrodynamic expert well-known for hits Von Kármán vortex), Othmar B. Ammann (the consulting engineer for the George Washington Bridge), and Glenn B. Woodruff (the consulting engineer for the Golden Gate Bridge). They issued their report in a little over four months after the collapse occurred. This report exonerated the bridge designers and engineers saying that "the Tacoma Narrows Bridge was well designed and built to resist safely all static forces, including wind, usually considered in the design of similar structures. … It was not realized that the aerodynamic forces which had proven disastrous in the past to much lighter and shorter flexible suspension bridges would affect a structure of such magnitude as the Tacoma Narrows Bridge". The report then recommend further research and testing to develop the methods used to calculate aerodynamic forces acting on suspension bridges.

5. Countermeasure

The new bridge was redesigned and rebuilt in 1960 with open trusses, stiffening struts and openings in the roadbed to let wind through, allowing less twisting than the previous design (Photo 4).

Photo 4. New Tacoma Narrows Bridge (with Open Trusses) [1]

6. Summary

The Tacoma Narrows Bridge collapsed due to wind-induced oscillations. Professor Farquharson's recordings of the collapse and wind tunnel testing conducted subsequently helped clarifying the mechanism of vibration and the importance of rigid girders. The method of dynamic analysis from the lessons gave guidelines for designing suspension bridges thereafter.

7. Knowledge

(1) Self-excited oscillation must be taken in consideration when engineering a structure. Otherwise, a bridge can fall. Self-excited oscillation is typically observed as "chatter" that occurs between the machine tool and the workpiece. This chatter can break tools and make machine tools dance during

the process.

(2) The lessons learned from failures will help advancing knowledge and technologies. Good records can turn even the worst disaster into valuable assets to technologies. The history of failures is a priceless record of human experiences.

8. Background

Leon Moisseiff who designed the Tacoma Narrows Bridge was one of the world-renowned suspension bridge engineers at that time. He implemented the deflection theory in his design to justify the substantial reduction in strengthening materials, believing that the dead weight of the bridge would suppress the vibrations caused by wind and traffic. He believed that the suspended structure would act as a counterweight and restore the bridge to equilibrium, if a bridge were designed flexible enough to bend and sway with the winds. The longer, lighter and narrower bridge design enabled to reduce the amount of steel needed to build suspension bridges. Less steel greatly reduced the cost of a bridge, which was appreciated during the Great Depression.

References

[1] Yotaro Hatamura (Editor), Jissai-no Sekkei (Practical Design) Research Foundation (1996) *Zoku-Zoku Jissai-no Sekkei (Practical Design III)*, The Nikkan Kogyo Shimbun, LTD.