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Research Paper Open Access

The Tacoma Narrows Bridge: Structural Failure Research

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ABSTRACT
The Tacoma Narrows Bridge is one of the worst (and most famous) structural engineering failures. After being completed in 1940, the bridge suffered a collapse after four months due to flutter from the winds. The report covers accident causes, e.g. management causes, design and construction causes, describes the collapse mechanism, and modern technology could have prevented an accident.

Keywords: Tacoma Narrows Bridge, structural failure, aeroelastic flutter, suspension bridge, vortex shedding, finite element analysis

1. Introduction

One of the most notable badly engineered construction projects was the Tacoma Narrows Bridge, also known as Galloping Gertie. The Tacoma Narrows Bridge, or Galloping Gertie, is a bridge that crosses the Tacoma Narrows Strait in Washington State, United States. It is a suspended bridge and was completed in 1940. Unfortunately, on the day following its opening, the motion of the bridge became "unsteady and erratic" and subject to rupture as the phenomenon of aeroelas-tic flutter, set in motion by 40-knot winds. Subsequently, the Tacoma Narrows Bridge collapsed [1].

Located on State Route 16, approximately eight miles west of downtown Tacoma and forty miles south of Seattle, this city is the county seat. Situated in a spectacular setting along the banks of the Columbia River, the region features breathtaking views and scenery [2].

In 1940, the Tacoma Narrows Bridge, a slim, graceful and attractive steel ribbon that spanned Puget Sound, went into service. The world's third-longest suspension span officially opened on July 1. Within four months, the gargantuan span's brief life came to an untimely end.

2. FAILURE OVERVIEW

On the morning of November 7, 1940, a gale of 42 miles per hour caused the Tacoma Narrows Bridge to collapse. The collapse was watched by many reporters, engineers, and passersby. The sole casualty was a dog abandoned in a car on the bridge.

After completion, experts found serious trouble with the Tacoma Narrows Bridge. It began to bend and sway when the wind picked up. The winds were strong enough to create some movement of the bridge, and it made some engineers worry about it collapsing in stronger winds. To alleviate these concerns, the structural stability of the bridge against wind load has been assessed using wind tunnel test.

At approximately 70 km/h (19 m/s), the winds hitting the Tacoma Narrows Bridge that day, the bridge to collapse.

Fig. 1: Location Map of Tacoma Bridge (Source: WSDOT)

Fig. 2: Placement of Bridge (Source: WSDOT)

The centre stays of the bridges (that is, mostly at 36 cycles per minute (cpm) were producing torsional vibration at nine points respectively. As time progressed, the amplitude of the torsional vibration grew and was oscillating as the twisting one, similarly to two. The motions did not damage the bridge's central core. However, the two parts rotated towards either opposite side.

The bridge was revealed to have a severe twist with a division of two portions, which was were noticed at 14 tremors per minute. Due to the cable failure connected to the diagonal tie center on the north side of the band, the torsional motion was pronounced. Due to the suspension cables taking

Fig. 3: Tacoma Narrows Bridge, June 14, 2008 (Source: WSDOT)

Fig. 4: Iso view of Bridge, June 14, 2008 (Source: WSDOT)

alternative strains, my anchor points sagged which forced them to take up to the supporting towers of the member bridge. Before the bridge submerged, large and evident cracks began to appear on it [3].

A. How did it fail?

- Oscillations led a mid-span cable connection to slip, resulting in less severe but still significant torsional oscillations.
- Vertical hangers broke, leading the structure to collapse. The side-spans and towers sustained irreversible damage.

3. CONTRIBUTING FACTORS

A. Management & Financing issue

In 1937, the Washington State legislature created the Washington State Toll Bridge Authority and allocated 5, 000, or100,000 in today's dollars, to investigate a proposed bridge across the Narrows by Tacoma and Pierce County.

The bridge was considered not viable even before it was constructed, as projected toll revenues would not be enough to meet construction costs. Also, additional costs were caused by acquiring the ferry contract from a current private operator on

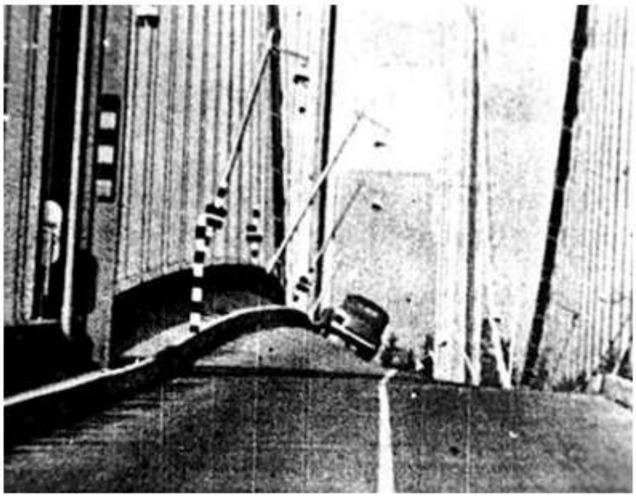

Fig. 5: Gertie twisting (Source: GHPHSM, Bashford 2784)

Fig. 6: Bridge Twisting (Source: GHPHSM, Bashford 2784)

The Narrows. Financial issues notwithstanding, the US Navy, which operates the Puget Sound Naval Shipyard in Bremerton, and the US Army, which oversees McChord Field and Fort Lewis near Tacoma, strongly backed the bridge.

The Washington State Toll Bridge Authority requested a PWA (Public Works Administration) loan of 11million(today220 million) after engineer Clark Eldridge of Washington State came up with a classic suspension bridge design. The Washington Department of Highways' early design drawings called for a series of trusses under the roadway. The depth for each truss is 25-ft (7.6-m)

Under the design by Moisseiff, the construction of the bridge began on September 27, 1938. Constructing the build-ing cost 6.4million(138.5 million today), and it was com-pleted in just nineteen months.

The Galloping Gertie Bridge was metalised on November

7 1940, stamped a disapproval on the 'deflection theory". Engineers now believed that all suspension bridges needed was reinforcement to withstand the pressure of passing cars and the "lesser" effect of wind.

Fig. 7: On November 7, 1940, the bridge's core section collapsed into the strait below. (Source: Wikipedia)

Fig. 8: Collapse complete (Source: www.structuremag.org)

The trend to design bridges lighter, more flexible and sleeker came to an end with this design. But more significantly, a whole generation of ideas and methods for bridge engineering ended [4].

B. Design & Code issue

The suspension bridge engineers, according to bridge his-torian David P. Billington, "seemed to have almost no recog-nition that wind created vertical movement at all."

Top designers of the 1930s thought that prior failures of suspension bridges were due to bad construction and high traffic. The wind was not much of a hassle. Engineers feel that stiffening trusses are critical for preventing the roads and wire from swaying sideways which is termed lateral or horizontal deflection. The temperature and traffic volume variations were most responsible for the motion; wind had little impact.

The collapse of Galloping Gertie is largely due to "torsional flutter." It is going to be useful to break this complicated chain of events down into several sections. The key points of the explanation are highlighted below.

1) Torsion forces did not pose much of a threat to the 1940 Narrows Bridge. This was owing to its exceptionally high depth-to-width ratio of 1:72. Gertie had a long, narrow, shallow stiffening girder, which provided great flexibility.

2) At ten a.m. on November 7, 1940, a major event occurred. In the middle position of the north cable, the cable band slipped. So, the wire got separated into two unequal parts. Consequently, the bridge deck twisted instead of switching as a result of vertical displacement.

3)The torsional motion of the bridge deck was influenced by "vortex shedding." In brief, the Narrows Bridge got vortex shedding as follows: The wind split when it hit the eight-foot solid plate girder supporting Galloping Gertie's deck.

- The stress caused the bridge deck to twist. Although the steel is elastic, the twisting caused a greater wind flow separation. This whirled up a vortex or wind force, raising and twisting the deck even further.
- The deck construction would not lift or twist. It was naturally tempted to revert to its original shape. It came back with the same speed and direction as the lifting force. In simple terms, it moved "in phase" with the vortex. Afterwards, the wind sped up this movement. As a result, a "lock-on" event was produced.

4) Yet, the wind's outside force was too weak to create such an excessive twist that the Narrows Bridge fell.

5) The deck exhibited the initial signs of "torsional flutter" during this period, i.e. self-induced harmonic vibrations. Vibrational forces can be large due to oscillation insta-bility.

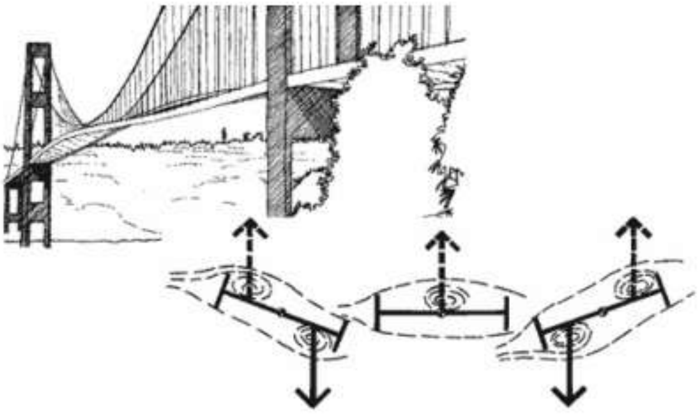

Fig. 9: Tacoma's Failure Mechanism (Source: original sketch contributed by Allan Larsen)

When the span was transferred to a torsional oscillation pattern, the resonance absorbed more wind energy. The twist-ing motion of the bridge deck controlled the wind vortex and made them synchronized. The structure began generating its own twisted motions. In other words, the wind was no longer causing the forces acting on the bridge. The bridge deck motion caused the generation of the forces. Engineers characterise it as 'self-excited' motion.

The action on the bridge could no longer be suffocated by nature. After the twisting event, they gained control of the vortex forces.

Due to its self-induced energy, this torsional motion ex-panded from its original small size. Galloping Gertie twisting more meant that the twisting had a greater twisting of its own.

This grew faster than the bridge's structural support could handle. Something went off [5].

C. Constructions & Operations issue

1) Notwithstanding the high flexibilities of the structure, it has a low capacity to absorb dynamic stresses, resulting in large oscillations in torsion and in the vertical direc-tion. Although the Tacoma Narrows Bridge had much more flexibility than any other long span suspension bridge, aerodynamic forces that had already brought down much lighter, shorter, flexible suspension bridges were not expected to bring down one as large as this.

2) The turbulent activity of the wind caused vertical oscil-lation of the Tacoma Narrows Bridge. The aerodynamic characteristic of the suspended configuration might have affected their amplitudes. Up until the present time, no evidence has been found that links the vertical oscillations to the so-called aerodynamic instability.

3) During the installation of the suspended floor, significant vertical oscillations were observed, and they sporadically continued until the day of the accident. The stiffening girders did experience considerable strains at times, but there is no evidence of structural damage. Under certain conditions, the strains conceived in the tie connecting mid-span cables to the suspended flooring became ex-tremely large.

4) Hanging structure shows indications of failure due to torsional shear action at a number of places. Since the suspenders failed, most of the hanging structure on the central span had to be removed. The unanticipated sinking of the lateral spans caused the towers and lateral configurations to bend and become overstressed.

5) The Tacoma Narrows Bridge's most pragmatic and cost-effective solution is suspension. None other types of bridges were suitable to choose.

6) The failure caused severe overstressing and deformation of tower elements. The only spot where cable breakage is noticed is at the centre of the north cable; other than that, the drooping and twisting vibrations of the side spans probably overstressed the cables. The failure did not damage the primary piers, other than possibly some localised crushing damage, and they may be able to sustain much larger reactions from the tower than from the bridge. The anchorages were unbroken and sufficiently safe to withstand stresses greater than the initial construction. [6].

4. THE DAMAGE

A. Main cables

When the collapse occurred, the main suspension cables were ejected sideways, twisted, and thrown approximately 100 feet into the air. They were released from their positions at the

Fig. 10: A bridge inspector examines Damaged cable (Source: WSDOT)

cable saddles on each tower and fell heavily on the approach spans. Due to slippage of the cable band, approximately 350 wires of the north cable at mid-span were destroyed, and other cables were found to be under significant stress and deformation. Even though the main wires were completely destroyed, recovery work took place, but they were only worth being scrap metal.

B. Suspender cables

Many suspension wires broke during the catastrophic fall. Some were ruined; others suffered heavy damage, while some were fine. They had now become aware of their scrap value.

C. Towers

All of the bracing struts were bent and twisted in addition to the main towers. When subjected to excessive stress, the metal warped and could not return. Now they comprehend that the entire scrap metal had value.

D. The deck-floor system

The steel and concrete of the central span, lying at the bottom of the Narrows, were definitely gone for good. The concrete breaking off continued on the side spans. There were areas of the floor system that twisted and overstressed. For now, they were only useful to be made into scrap metal.

Fig. 11: View of broken wires and towers, facing west, February 1943. (Source: WSDOT)

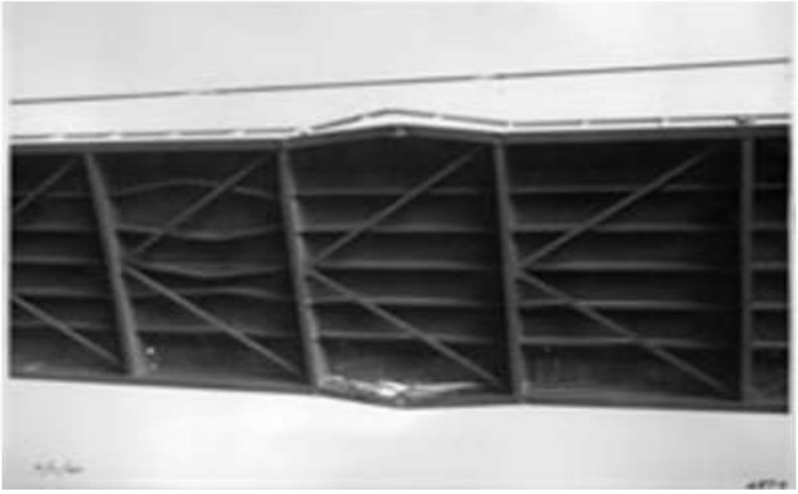

Fig. 12: View from underneath the deck of buckled steel beams. (Source: WSDOT)

E. Side spans

Substantial damage was caused by the core losing its strength first and the side spans collapsing. The events put stress and some twisting on the plate girders and floor beams. Some of them buckled beyond repair.

F. Piers

Neither West Pier No. 4 nor East Pier No. 5 suffered any kind of damage. As the centre span fell, it caused the pier tops' rivets to shear partially.

G. Anchorages

The anchorages of the main cable stood fine. Before the new main cables of a replacement bridge can spin, some concrete would need to be removed [7].

Fig. 13: M3-5: Sagging east side stretch (Source: GHM, Bashford 2795)

5. THE PHYSICS BEHIND COLLAPSE

Aeroelastic flutter caused the Tacoma Narrows Bridge to collapse, which is pretty common. The bridges have been designed so that wind can pass through them. The flow separation case in the Tacoma Narrows Bridge occurred due to an imposed action from the top and below. Certain instances cause the movement of air around the body. This will create a Ka´rma´n vortex street [8].

The Strouhal frequency (fs), which can be found by: is the vortex frequency in the Ka´rma´n vortex street.

$$f_S = \frac{S \cdot U}{D} \qquad (1)$$

where S is the Strouhal number (a dimensionless quantity), D is the characteristic length, and U is the flow velocity. As an illustration, S is 0.21 for a Reynolds number higher than 1000. Regarding the Tacoma Bridge, D measured eight feet, and S measured twenty [9].

6. ADVANCED TECHNOLOGY INTERVENTION OPTIONS & POTENTIAL IMPACTS

Following the collapse of the Tacoma Narrows Bridge in 1950, the bridge was redesigned (based on lessons learned). A bridge in open trusses was built to allow the free passage of air by opening on the roadbed. Trusses are triangular supports that strengthen struts. The new version of the bridge twists far less dramatically than before.

The US Whitestone Bridge was reinforced with trusses and the perforations beneath the road decks to decrease oscillation after the accident of Tacoma Narrows Bridge. These policies remain in effect currently. Following the incident, many began to prefer the use of dynamic and modal analysis in the design of bridges

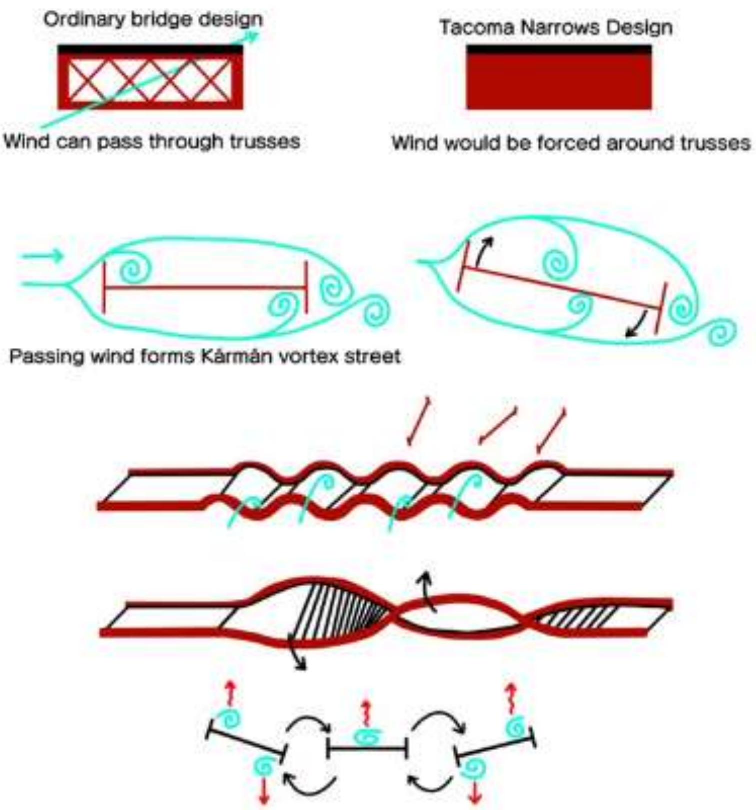

Fig. 14: A simplified illustration of the Tacoma Narrows Bridge's collapse (Source: Wikipedia)

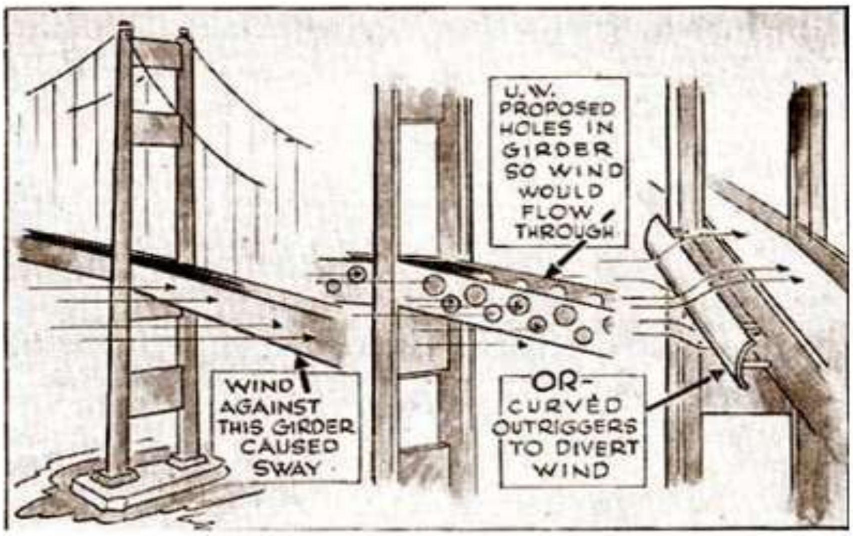

Fig. 15: Tacoma Narrows Bridge (Source: UW Libraries)

Structural engineers calculate stresses, deflections, and other data by means of complicated analytical methods. This de-flection theory is a model for these methods. Thus, finite element analysis (FEA) became a ubiquitous technique for civil engineering structures designing. [10].
Looking at this failure from a modern perspective, several factors could have resulted in a different outcome:

A. Advanced Modeling and Simulation:
Using modern technology, engineers build computer simu-lations of structures. The prediction and interpretation of the structural and environmental responses of the bridge under var-ious atmospheric conditions through simulations. The Tacoma Narrows Bridge was erected between 1932 and 1936. If these technologies had been available during the construction of the bridge, it would have been possible for the engineers to identify the bridge's emergence problems with flutter. Hence, these modifications may have been applied to mitigate flutter risk.
New developments in materials science have resulted in stronger, long-lasting materials. Modern materials could have the flexibility and stiffness necessary to resist forces applied to the Tacoma Narrows Bridge that caused its failure. The requirement could have been fulfilled with composite materials or complicated steel alloys.

B. Sensor Technology:
The structures of today are fitted with sensors on the inside of the structure to constantly monitor the integrity of the building. If engineers knew in real time how the bridge was reacting, they could've taken steps to strengthen weak points or even close the bridge temporarily during high winds until safety issues were sorted out.

C. Wind Tunnel Testing:
Through advanced testing techniques, engineers can accu-rately replicate complex wind scenarios and their impact on structures. The engineers completed wind tunnel tests of the bridge design, particularly in terms of aeroelastic flutter, antic-ipating potential problems, and made necessary modifications before critical failure occurred.

D. Advanced Construction Techniques:
With the use of prefabrication and modular construction, bridge building can happen more quickly with quality and safety in mind. It is less likely that structural defects were the cause of the crash of the Tacoma Narrows Bridge, following the controller enhancement for its virtual control and the better efficiency of its design.
Simply put, the Tacoma Narrows Bridge incident should teach us to accept better technologies and construction prac-tices to predict and avert dangers in large projects. With contemporary modelling, materials science, monitoring sys-tems, testing processes and construction techniques, engineers can minimise multi-billion dollar disasters like the Tacoma Narrows Bridge collapse and improve the strength and life of critical infrastructure assets.

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