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Abstract:

Type: Suspension bridge, Length: 1600 meters

Failure: Bridge deck collapsed damaging towers and anchors requiring complete replacement.

Failure caused by: (Mainly) - Bad aerodynamic and stability design of the bridge allowing the wind to cause **'anti-dampening'** torsional resonance causing huge stresses and deflections in the deck.

When and Where:

On the morning of November 7th, 1940, a section of the Tacoma Narrows Bridge lay tangled in the west-side of the Pugent Sound River. One of engineering's most fabled disasters unfolded that day revealing the errors in structural design that ultimately led to its dramatic collapse amid violent undulations.

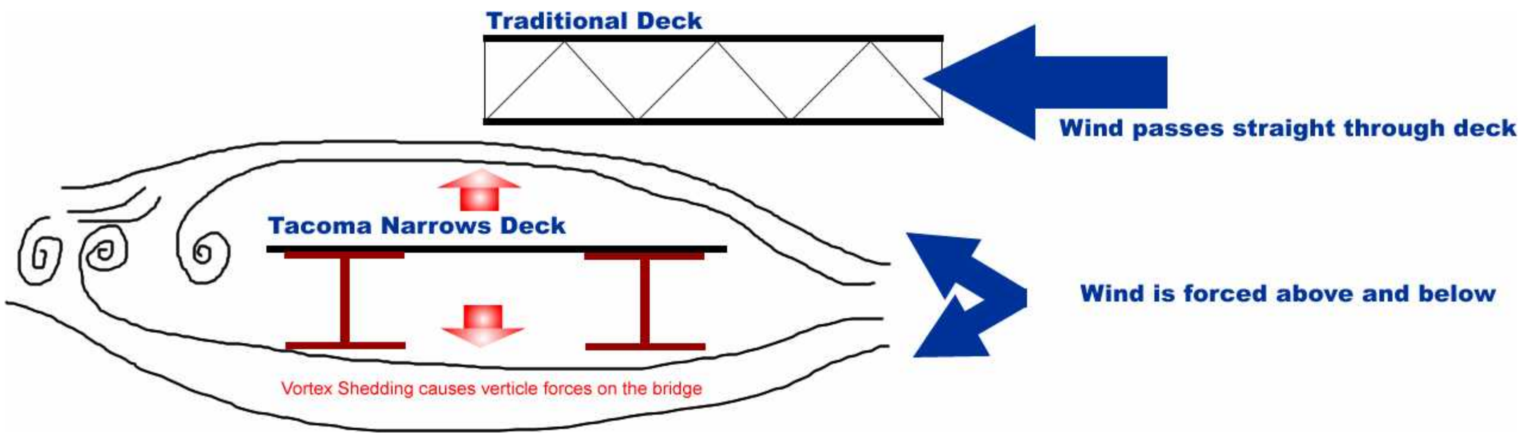
Design:

Although possessing unique structural nuances, the Tacoma Narrows Bridge realised the fundamentals of suspension bridge design. Utilising massive cables to suspend the bridge deck above the river, the bridge had a centre span of some 2800ft.

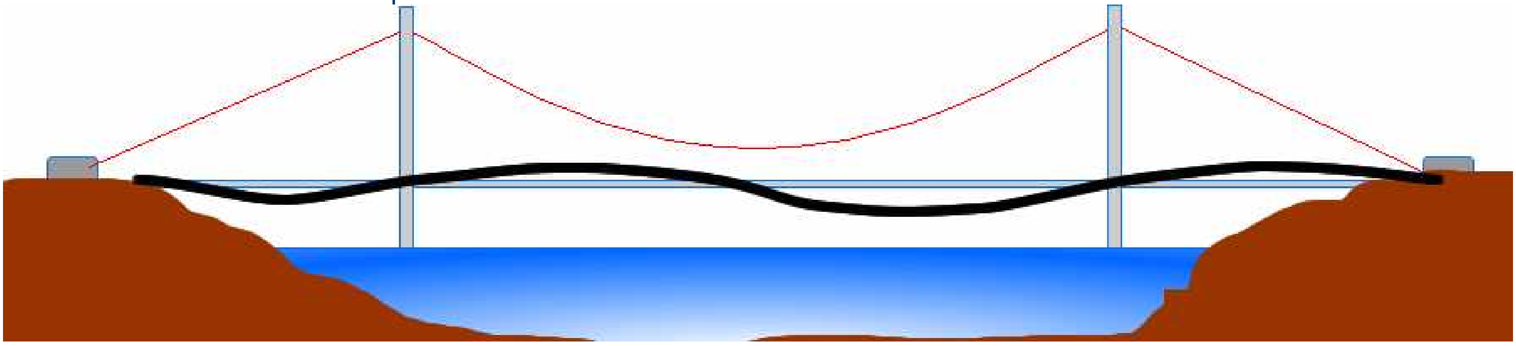
The expected demands on the bridge meant that it would only carry two lanes of traffic, thus providing a mere 39ft between the main cables and giving the Tacoma Narrows a very high width / centre span ratio of 1:72, relative to its contemporaries.

The main cables were rigidly connected to two piers constructed on the east and west sides of the river allowing them to distribute the compressive load down through the piers while the cables themselves, secured deep within the anchorages on either side of the river and remained under constant tension. These rigid connections were themselves innovative, differing as they did from the rolling saddles which were normally applied to the tops of suspension bridge towers to allow the cables to move over them. They were, however in keeping with the design objectives of the Tacoma Narrows, a design which was founded on a new theory for bridge stability: *Deflection Theory.*

Expectedly, expediency and costs were powerful factors in the Tacoma Narrows project. Deflection Theory provided positives in both areas. It stressed that the flexibility of the cables and towers coupled with the structures self-weight could be used more effectively to provide stability without the need for deep stiffening trusses and bracing, thus facilitating a lighter more economical design. Stiffening trusses, the primary tool in counteracting vertical and torsional motions caused mostly by wind loading, were usually placed on the underside of a bridge deck but for the Tacoma Narrows, solid steel plate I beams were used instead. They measured only 8ft deep – extremely shallow in comparison to both their own length and to the alternative trusses employed on similar bridges. Being solid and unlike trusses, no wind could pass through the girders. Although the concrete roadway added some weight to the structure, at its opening on July 1, 1940 it remained the lightest and most flexible construction of its kind.

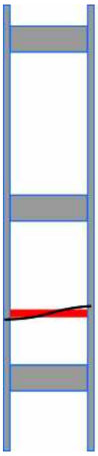


Lead up to failure:
This bridge was the first to use solid I beams to support the road; predecessors used a truss which the wind passed through. This meant that the wind had to pass above and below the deck.



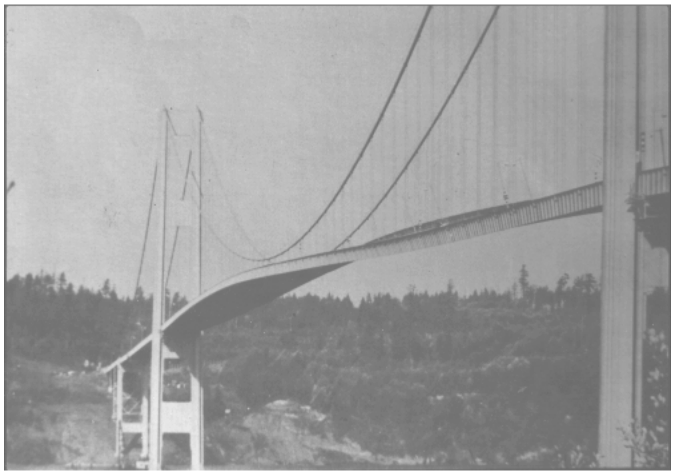
Longitudinal Resonance (above)
Shortly after its construction it was discovered that the bridge would sway and buckle dangerously in windy conditions. This resonance was longitudinal, which is shown above. This means that the road was alternatively raised and depressed in certain locations. However the mass of the deck was considered heavy enough to provide stability so it wouldn't collapse.

A new type of twisting



The failure of the bridge occurred when a new type of twisting occurred. This twisting, rather than longitudinal was torsional.

The left side would go down and the right side would rise and vice versa and the centreline of the bridge would remain steady. This is known as 'second torsional mode'



Anti Dampening (also known as positive feedback or self excitation)

- The bridge's angle of attack rose (exactly like a fin) thus giving more lift, twisting the deck even more until it aerodynamically stalls.
- The elastic energy stored in the deck returned the deck in the opposite direction.
- It now gets downwards lift and it continues to be pushed downwards until the deck stalls and the process is repeated.

BUT: With each cycle the amplitude increased because the wind added more energy than the work done in flexing the deck could dissipate. The ever increasing amplitude caused an overload to some of the suspender cables which critically weakened the bridge. Once a few of the cables broke, the weight of the deck could not be supported and it fell.

Failure:
The bridges destruction was due to a completed medley of structural and aerodynamic stability issues (mainly negative dampening). The designer failed to account for the aerodynamic forces exerted on the structure. The actual failure mode requires very complicated mathematical analysis to compute all the degrees of freedom and the set of loads imposed.

Many physicists and engineers disagreed in defining the exact theory of the cause. Subsequent wind tunnel analysis showed forced resonance did not cause the bridges failure (e.g. people walking at the same pace). - Also wind speed was constant at 67kph and vortex shedding is non linear. Some buildings react violently as their natural frequency aligns with the disturbance's frequency (seen after earthquakes, when some buildings remain standing beside others which have completely collapsed). This however, was not the case for the Tacoma narrows bridge, because the natural frequency of the isoloated structure was not near the frequency of the destructive mode.

It has been demonstrated that the ultimate failure of the bridge was in fact related to the aerodynamically induced condition of self-excitation or 'negative damping'. The 'aerolastic' phenomenon involved was an interactive one in which developed wind forces were strongly linked to structural motion and shows that forced resonance and self-excitation are fundamentally different phenomena. In this case the alternating forces that starts the motion is created and controlled by the motion itself. The wind force which acted on the large area of the 'H' shaped girders caused aerodynamic lift as pressure below the span is greater than that above the span. A moment is induced causing the twisting motion.

Preventing Similar Failure:

- Understand forces of nature
- Consider location and geography
- Understand dynamics of the structure that is being designed
- Do not design "extreme bridges", use recommended depth/length. (Tacoma narrows was 1:320 when recommended was 1:50-90). These extreme proportions resulted in vertical flexibility and instability.
- Suspension bridges should have sufficient stiffening supports.

Conclusion:

In design human error is always a factor; however a full understanding of dynamics, better materials, understanding of local conditions, and better computer modelling will all lower the probability of a major disaster.

New Design

The new Tacoma Narrows Bridge was redesigned using a more robust open truss, stiffened trusses and openings in the roadbed to allow the wind to pass through. Engineers learned vast amounts because of this failure. Many of the unknown forces which act on suspension bridges were discovered and the suitable means to resist them. Wind tunnel analysis (and a better understanding of aerodynamics) has now become vital in designing modern day suspension bridges and other important information about such bridges behaviour has been closely examined with modern technology so as to not reproduce such a catastrophe.

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