

TAP 307- 12: Tacoma Narrows: re - evaluating the evidence:

Text to read

This reading is adapted from 'The collapse of the Tacoma Narrows bridge, evaluation of competing theories of its demise and the effects of the disaster on succeeding bridge designs' by James Koughan of the Department of Mechanical Engineering, University of Texas at Austin.

It takes further the analysis of what has become a classic example of resonance, found in almost every physics textbook. As recent reinterpretations show, the cause of this famous collapse remains a live controversy in the world of civil engineering.

The facts of the matter

The dramatic end to the Tacoma Narrows Bridge, Washington, has been a standard example of resonance used by teachers and book writers almost since the day it collapsed. Before challenging what has become accepted theory, what are the facts behind this most famous of disasters?

The Tacoma Narrows Bridge was the third longest suspension bridge in the world when it was opened in 1940. It was not a radically new design, but incorporated ideas of bridge design that had been developed over the previous ten years. The central span was 853 metres long and only 12 metres wide between the cable stays. A new method of calculating stresses (known as 'deflection theory') was used which allowed lighter, less expensive designs. Shallow plate girders were used on the decking instead of more traditional deep, stiffening trusses. The cables that supported the deck were attached to flexible towers which were more able to deal with changing loads than earlier designs using massive towers. All in all, the design was light, flexible and used the latest technology available.

This extreme flexibility proved to be the weakness in the design of the bridge. The vertical oscillations of the deck began soon after construction. The motion was generally considered fairly harmless and became a draw, as people came to ride the bridge. It was affectionately dubbed 'Galloping Gertie' as a result. On the 7 November 1940, some four months after the bridge was built, the vertical oscillations became so large that a supporting cable at mid-span snapped. The unbalanced loading created severe torsional oscillation which led to the collapse of the bridge.

The enquiry that followed the collapse decreed that the design of the bridge had been acceptable, apart from the width to length ratio. It was proposed that a replacement should be wider, despite the additional costs that would be incurred. All experts agreed that the transition from a (relatively) safe vertical motion to the destructive twisting motion was due to the slipping of a cable band to which the centre cable stays were attached. The torsional motions caused the concrete roadway to crack apart. The 'deflection theory' had to be addressed further with a view to examining loadings under different and dynamic as well as static conditions.

Why did the bridge collapse?

(i) The standard solution

The source of the motion of the bridge was always known to be the wind. The building up of the oscillations is seen as being due to resonance. In order for the bridge to undergo resonance, there must be a force causing the bridge to move which is periodic, regular and which matches the natural frequency of oscillation of the bridge. This effectively means that any thoughts of gusting winds being responsible can be disregarded. The gusts would have had to be very regular and this phenomenon, apart from being unlikely, was not witnessed.

The long standing theory behind the collapse of the bridge was proposed by the leading aeronautical engineer Theodore von Kármán, who was on the committee set up to study the disaster. He was convinced that the oscillations were due to the shedding of vortices from the bridge. As air flows round an object, swirls of air, called vortices, are carried away by the wind. This is due to air at different speeds combining. Consider a car with the wheels on one side driving faster than the other. The result would be the car would turn with the faster wheels on the outside of the 'bend'. It is a common and recognised phenomena that with non-streamlined objects the vortices are shed from one side, then the other of the object (see below).



The vortices generate alternating high and low-pressure regions on the downwind side of the body, in this case the bridge. Such vortices are called Strouhal vortices and are shed at a rate determined by the equation

$$f_s = SU / D$$

where f_s is the frequency of vortex shedding, S is the Strouhal number (a constant for a given body shape), U is the velocity of the air flow and D is a characteristic dimension of the body (usually the width).

The characteristic dimension of the bridge was the thickness of the deck, which was 2.44 m. On the day of the collapse the wind speed was 68 km h^{-1} which, with an appropriate Strouhal number (developed by wind tunnel testing of many shapes over many years) gives a shedding frequency of about 1 Hz. A secondary effect would also have developed whereby the motion of the bridge would in turn generate vortices which would therefore be shed in time with the oscillations. This phenomenon is called 'lock on'. This is the generally accepted view of how the bridge came to shake itself to pieces.

However, two researchers by the names of Scanlan and Billah pointed out in 1991 that, as the amplitude of the motion of the bridge built up, other changes to the airflow over the bridge would produce compensating, self-limiting forces. In addition, the twisting motion that, it is accepted, caused the bridge to collapse was at a frequency of around 0.2 Hz. Therefore, the collapse cannot be wholly attributed to the natural vortex shedding of the bridge structure.

Why did the bridge collapse?

(ii) New ideas

Robert Scanlan of Johns Hopkins University believes that the forces that caused the collapse were highly interactive. He claimed, in 1991, that the driving force for the oscillations was not just a function of time, as would be the case with simple vortex shedding, but was also a function of bridge angle during the oscillation. This leads to a phenomenon known as self-excitation.

According to this theory, the motion of the bridge built up to destructive amplitudes based on an intimate interaction of the wind and the structure – the wind supplying the power needed for movement and the movement supplying the power-tapping mechanism. Simply, the twisting of the bridge caused the shedding of vortices which cannot be predicted using the earlier method (the Strouhal frequency). The new flow pattern further excites the torsional mode of oscillation. The aerodynamic forces cannot affect the basic response frequencies of a massive structure like a bridge, but they can affect the damping. This resulted in the increasing amplitudes and the final destruction of the bridge.

Conclusion

As an example of resonance, the destruction of the Tacoma Narrows Bridge remains a firm favourite with educators and hopefully students at all levels. What recent studies show is that the motion of the bridge cannot be simply explained like a resonance experiment in a school laboratory. The interactions of forces, especially in a dynamic situation, become a great deal more complex. It was this that was not foreseen by the designers of the bridge in their use of new methods for lighter, flexible bridge design. However, the fact that it has been some 50 years until a more convincing theory as to the destruction of the bridge has been developed goes some way to exonerating the original designers and gives plenty of food for thought for bridge designers in the future.

Practical advice

This is a more demanding reading on the Tacoma Narrows Bridge collapse. The development of ideas concerning the subtle interactions of forces, especially in dynamic situations, may provoke discussion. Alternatively, the simple, older ideas behind the collapse of the bridge make for a straightforward resonance example. Video footage of the collapse is easily found and some measurement of frequencies, tied in to data and equations presented may be useful.

Pictures and a short video clip are available at:

<http://www.enm.bris.ac.uk/research/nonlinear/tacoma/tacoma.html#file> (as at September 2005)

Alternative approaches

There are many video clips showing the bridge in resonant oscillation, and the eventual collapse. One source is the Mechanics in Action video produced by the project team of the same name based at Leeds University.

Social and human context

The Tacoma Bridge disaster did not result in the loss of life, but a similar collapse could easily do so. The idea of the advancement of engineering and science through pushing designs to the limit and beyond is a sometimes visited concept. The impact on bridge design after the disaster may warrant further research.

Location of resources

Adapted from Koughan J 1996 The collapse of the Tacoma Narrows bridge, evaluation of competing theories of its demise and the effects of the disaster on succeeding bridge designs (Department of Mechanical Engineering, University of Texas at Austin).

Teachers may wish to look the at the Scanlan and Billah article from the American Journal of Physics Volume 59 No.2 February 1991: <http://www.engsoc.org/~leito/Billah-Scanlan.pdf> . It is not suggested that this article is for students, unless they are interested.

Teachers may also like to consider the London Millenium Bridge

(These sites were available September 2005)

See:

<http://www.arup.com/MillenniumBridge/>

<http://www.urban75.org/london/millennium.html>

http://en.wikipedia.org/wiki/London_Millennium_Bridge

<http://www.ice.org.uk/downloads//Millennium%20Bridge%20Report.pdf>