The **American Association of Physics Teachers**

presents

The Tacoma Narrows Bridge Collapse

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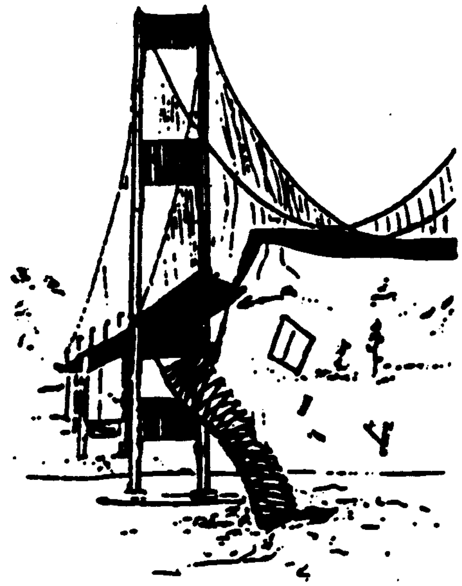
THE PUZZLE OF THE TACOMA NARROWS BRIDGE COLLAPSE



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Tacoma Narrows Bridge History

The first Tacoma Narrows Bridge was built between November 23, 1938 and July 1, 1940 at a cost of approximately $6,400,000. The physical properties of the bridge included:

total length: 1524 meters (5000 ft)
length of center span: 854 meters (2800 ft)
width: 11.9 meters (39 ft - two lanes of traffic)
height of side girders: 2.4 meters (8 ft)

This bridge exhibited large vertical oscillations even during construction. Shortly after it was opened to traffic the bridge was christened "Galloping Gertie" by the people of the Tacoma area.

After the various studies of the collapse, a new suspension bridge was constructed at the same location. The new bridge is four lanes wide and has open grid sides instead of solid I-beams. It was opened on October 14, 1950 and has not displayed any of the interesting oscillatory properties of the first bridge.

CAST OF CHARACTERS

Critical decisions such as the length of the main span and use of plate girders were made upon the recommendation of L. S. Moisseiff, consulting engineer from New York. By the time of its collapse F. B. Farquharson, Professor of Civil Engineering, University of Washington, had been retained as a consulting engineer and was attempting to stop the bridge's oscillations. Professor Farquharson took some of the film which appears on this disc. The script of the opening segment is taken in part from the formal statements given by Prof. Farquharson and Ken Arkin, chairperson of the Washington Toll-Bridge Authority, during the investigation of the collapse.

Leonard Coatsworth, a reporter for the Tacoma News-Tribune, drove the last car onto the Bridge and reported his experiences in the newspaper. His words begin and end the opening sequence on the disc.

One other person played a very important role in the material which is used for the opening sequence of the bridge. Barney Elliott, proprietor of The Camera Shop in Tacoma, and his co-workers shot the color film of the construction and collapse of the first Tacoma Narrows Bridge.

Suggested Readings

ORIGINAL REPORTS AND SUBSEQUENT ANALYSES

"*The Failure of the Tacoma Narrows Bridge: A Reprint of Original Reports*," Texas Engineering Experiment Station, Bulletin No. 78, College Station, Texas, 1944.

"*Aerodynamic Stability of Suspension Bridges with Special Reference to the Tacoma Narrows Bridge*," University of Washington Experiment Station, Bulletin No. 116, parts 1-4, Seattle, 1949.

Steinman, D. B., "*Suspension Bridges: The Aerodynamic Problem and Its Solution*," American Scientist 42, 397 (1954).

ENGINEERING TEXTS

A fine introductory reference book for the treatment of this extremely complex phenomena is:

Houghton, E. L. and N. B. Carruthers, *Wind Forces on Buildings and Structures: An Introduction*, Halsted Press Div., John Wiley and Sons, Inc., New York, 1976.

More advanced engineering texts are available such as:

Gould, P. L., and S. H. Abu-Sitta, *Dynamic Response of Structures to Wind and Earthquake Loading*, John Wiley & Sons, New York, 1980.

Sachs, P., *Wind Forces in Engineering*, 2nd Ed., Pergamon Press, Oxford, 1978.

Simiu, E., and R. H. Scanlan, *Wind Effects on Structures*, John Wiley & Sons, New York, 1978.

Thompson, J. M. T., *Instabilities and Catastrophes in Science and Engineering*, John Wiley & Sons, New York, 1982.

POPULAR TEXTS

Andrew, Charles E., *Final Report on the Tacoma Narrows Bridge*, Washington Toll Bridge Authority, Olympia, Washington, 1952. (This is a report on the new bridge.)

Geis, J., *Bridges and Men*, Doubleday, Garden City, New York, 1963.

Steinman, D. B., and S. R. Watson, *Bridges and Builders*, Dover Publications, New York, 1957.

This documentary is taken from the complete videodisc authored by R.G. Fuller, D.A. Zollman and T.C. Campbell and published in 1982. The videodisc, The Puzzle of the Tacoma Narrows Bridge Collapse, is available from John Wiley & Sons, Inc. 605 Third Avenue, New York, NY 10158. Additional copies of this videocassette are available from Physics (Video-Images), Box H, 110 Ferguson Hall, University of Nebraska-Lincoln, Lincoln, NE 68588-0116.

Preliminary Version, May, 1987

The Physics of the Tacoma Narrows Bridge Collapse

by
Robert G. Fuller and Dean A. Zollman

INTRODUCTION

No film of physics phenomena is more interesting to students than the single concept film of the collapse of the Tacoma Narrows Bridge. We have lost track of the number of copies that have been worn out or destroyed in our film loop projectors. Because of the great amount of student interest in the Tacoma Narrows Bridge Collapse we selected that film as the basis for our first videodisc, The Puzzle of the Tacoma Narrows Bridge Collapse.[1] During the development of the materials for videodisc, we learned much about its collapse and about bridge resonances in general. In this paper we review the available information and translate from the language of engineers to that of physicists.

BACKGROUND

The Tacoma Narrows Bridge was not the first suspension bridge to collapse. In fact, a survey of the history of suspension bridges shows that several were destroyed by wind or other oscillating forces (See Table 1):

Collapsed Suspension Bridges

Bridge	Designer	Span Length (ft)	Failure date
Dryburgh (Scotland)	J. and W. Smith	260	1818
Union (England)	Sir Samuel Brown	449	1821
Nassau (Germany)	L. and W.	245	1834
Brighton(England)	Sir Samuel Brown	255	1836
Montrose (Scotland)	Sir Samuel Brown	432	1838
Menai (Wales)	T. Telford	580	1839
Roche (France)	LeBlanc	641	1852
Wheeling (USA)	C. Ellet	1010	1854
Niagara (USA)	E. Serrell	1041	1864
Niagara (USA)	S. Keefer	1260	1889
Tacoma Narrows	L. Moisseff	2800	1940

-Table 1 -

However, the Tacoma Narrows Bridge was, by far, the longest and most expensive suspension bridge to collapse due to interaction with the wind. Perhaps because nearly 50 years had elapsed since the previous collapse of a bridge, this collapse seemed so striking. Or perhaps Barney Elliott's memorable motion pictures of the torsional vibration mode of this bridge made it famous. For whatever reason, it is an event never to be forgotten in the annuals of bridge construction. The work of Sir Samuel Brown should not be overlooked. You will notice that he had a rash of bridge collapses in the 19th century. In addition, it has been reported that one of his bridges actually collapsed when a battalion of soldiers marched across it, lending support to the warning given each semester by physics teachers to their students.

PHYSICS PRINCIPLES

In this paper we will summarize the physics involved in the collapse of the Tacoma Narrows Bridge. While we frequently tell our students that the collapse of the Bridge was a resonant effect, we seldom discuss the details . This is not surprising because the physics is neither trivial nor obvious. Furthermore, many aspects of the application of physics to the collapse have been disputed from the the days of the beginning of the vibrations. In Table 2 six different explanations of why the Tacoma Narrows Bridge collapsed are presented. Each presents as slightly different view of the role of design factors and wind factors in the collapse. However, none is given in the language of physics.

Why Did The Tacoma Narrows Bridge Collapse?

"It is very improbable that resonance with alternating vortices plays an important role in the oscillations of suspension bridges. First, it was found that there is no sharp correlation between wind velocity and oscillation frequency such as is required in case of resonance with vortices whose frequency depends on the wind velocity. Secondly, there is no evidence for the formation of alternating vortices at a cross section similar to that used in the Tacoma Bridge, at least as long as the structure is not oscillating. It seems that it is more correct to say that the vortex formation and frequency is determined by the oscillation of the structure than that the oscillatory motion is induced by the vortex-formation. " A Report to the Honorable John M. Carmody, Administrator, Federal Works Agency,Washington, D.C. March 28, 1941.

"The primary cause of the collapse lies in the general proportions of the bridge and the type of stiffening girders and floor. The ratio of the width of the bridge to the length of the main span was so much smaller and the vertical stiffness was so much less than those of previously constructed bridges that forces heretofore not considered became dominant. " Board of Investigation, Tacoma Narrows Bridge, L.J.Sverdrup, Chairman June 26, 1941.

"Once any small undulation of the bridge is started, the resultant effect of a wind tends to cause a building up of vertical undulations. There is a tendency for the undulations to change to a twisting motion, until the torsional oscillations reach destructive proportions." Bridges and Their Builders , D. Steinman and S. Watson, Putnam's sons, N.Y. 1941.

"The experimental results described in a (1942) report indicated rather definitely that the motions were a result of vortex shedding." University of Washington Engineering Experiment Station Bulletin No. 116, 1952.

"Summing up the whole bizarre accident, Galloping Gertie tore itself to pieces, because of two characteristics: 1. It was a long, narrow, shallow, and therefore very flexible structure standing in a wind ridden valley; 2. Its stiffening support was a solid girder, which, combined with a solid floor, produced a cross section peculiarly vulnerable to aerodynamic effects." Bridges and Men , J. Gies, Doubleday and Co., 1963.

"Aerodynamic instability was responsible for the failure of the Tacoma Narrows Bridge in 1940. The magnitude of the oscillations depends on the structure shape , natural frequency, a, natural frequency, and damping. The oscillations are caused by the periodic shedding of vortices on the leeward side of the structure, a vortex being shed first from the upper section and then the lower section." Wind Forces on Buildings and Structures , E. Houghton and N. Carruthers, J. Wiley & Sons, N.Y. 1976.

Table 2

There are a variety of levels at which we teach physics. We need to be prepared to explain the collapse of the Tacoma Narrows Bridge at a number of different levels. Here we present three different levels of explanation - a conceptual level which is most appropriate for nonscience students, a somewhat more advanced level mathematically which we call the causality level and then the full quantitative level. For students at all levels the most striking visual images are those of this massive long concrete steel bridge wiggling about in the wind as if it were a piece of spaghetti. (Figure 1) The only differences are in the ways in which they can understand the physics.

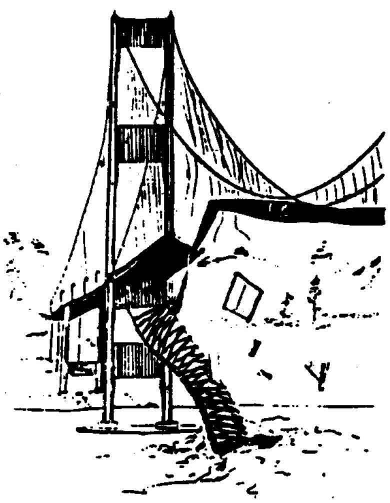

Figure 1.

CONCEPTUAL LEVEL

Students who are not able to follow a mathematical analysis of the bridge and its interaction with the wind are best served by a conceptual approach to the application of physics to the collapse of the bridge. We believe at this level the most satisfying explanation for the students is the idea of sympathetic vibrations. Every system has a natural fundamental vibration frequency. If forces are exerted on that system at the right frequency and phase then sympathetic vibrations can be excited. Oscillating forces at the right frequency and phase can cause sympathetic vibrations of catastrophic proportions. The forces applied to the bridge by the wind were applied at a natural frequency of the bridge. Thus, the amplitude of the bridge's oscillations increased until the steel and concrete could no longer stand the stress. (As we shall see before long a correct wording of the statements emphasize the oscillations of the forces applied by the wind and not oscillations of the wind itself.)

CAUSALITY LEVEL

The next level of presentation, which we call the causality level, is directed to students who hear the conceptual level explanation and ask the question: But how does the fluctuating force of just the right frequency arise on the bridge by the wind blowing across it? The first idea that comes to mind is that the gusty wind had pulses striking the bridge at just the appropriate frequency to cause the large oscillations. Closer examination of this explanation shows it cannot be right. While all winds have fluctuations in their wind speeds, these tend to be random in phase and variable in frequency. The gusts of the wind are not an appropriate explanation. Furthermore, the kinds of forces that need to be exerted on the bridge are up and down forces - transverse to the direction of the wind. The wind was blowing across the bridge from one side to another and the forces on the bridge were acting up and down. An explanation for these oscillating vertical forces lies in a concept called vortex shedding. When a wind which exceeds a minimum speed blows around any object, vortices will be formed on the back side of that object. (Figure 2)

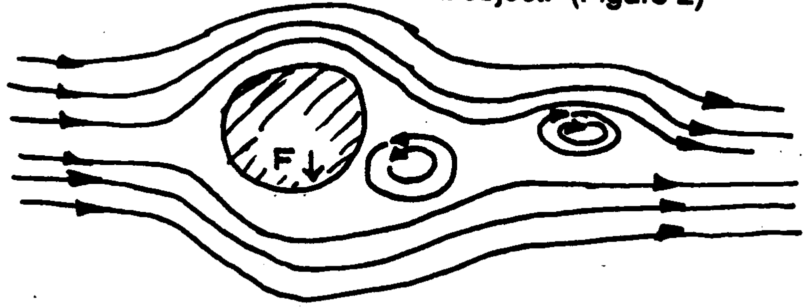

Fig. 2. Vortices down wind of a cylinder

As the wind increases in speed, the vortices form on alternate sides of the down-wind side of the object, break loose and flow downstream. At the time a vortex breaks loose from the backside of the object a transverse force is exerted on the object. The frequency of these fluctuating eddies is about 20% of the ratio of the velocity of the wind to the width of the object. These lateral forces can be as much as twice as large as the drag forces. Then, vortex shedding allows us to understand the exerting of fluctuating vertical forces on the Tacoma Narrows Bridge even though the wind was blowing across it in a transverse, horizontal direction.

QUANTITATIVE LEVEL

For students with good quanitative and mathematical skills the explanation can be presented in terms of the bridge's normal modes, both vertical and torsional. At this level we create a model of the Tacoma Narrows Bridge and treat it as if it were suspended by two springs with equal force constants. In Figure 3 a cross sectional view of this model is shown.

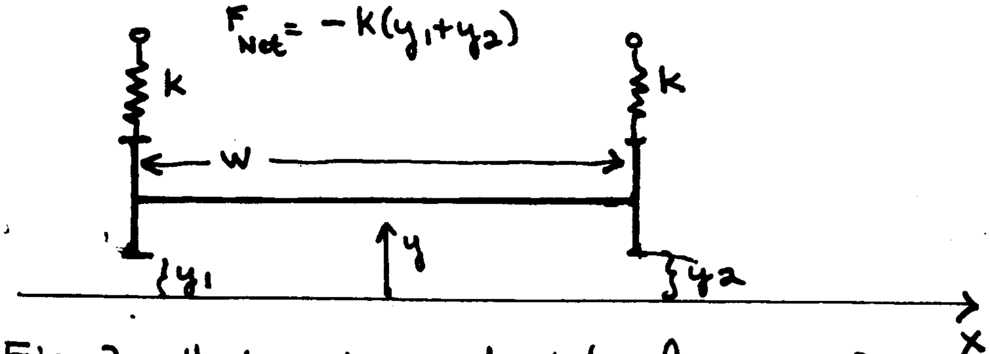

Fig. 3 Hooke's Law Model for the Bridge
Consider a unit length of mass M, moment of inertia I, and width W.

We can then write down the equations of motion using Newton's Second Law for translation (Equation 1) and for rotation (Equation 2).

$$-k(y_1+y_2)=ma \qquad \text{(Eq. 1)}$$

$$-K\left(\frac{W}{2}\right)(y_1-y_2)=I\alpha \qquad \text{(Eq. 2)}$$

We then make a small angle approximation (Equation 3)

$$\theta=\frac{y_2-y_1}{W} \qquad \text{(Eq. 3)}$$

and assume simple harmonic motion forms for the solutions to the simultaneous equations. Thus, we can write the solutions as:

$y_1 = A_1 \sin \omega_1 t$ and $y_2 = A_2 \sin \omega_2 t$.

We can write down in a standard way the two normal mode solutions for this cross section of the bridge. The vertical motion in which the amplitudes of oscillation of the two sides are equal in magnitude and direction has a frequency, ω_1,

$$\omega_1^2 = 2k/M \qquad \text{(Eq. 4)}$$

The torsional motion in which the amplitudes of the two sides are equal in magnitude but opposite in direction and has a frequency ω_2 where ω_2 is given by

$$\omega_2^2=\frac{kW^2}{2I} \qquad \text{(Eq. 5)}$$

This latter frequency describes the twisting motion of the bridge which ultimately caused it to fall down. Of course, the exact values for these oscillation frequencies depend on the characteristics of the bridge. On the basis of the physical properties of the first Tacoma Narrows Bridge, we find that the values appropriate for this analysis are: mass per unit length = 4.3×10^3 kg per meter, width of the bridge = 12 meters, radius of gyration of the bridge = 4.8 meters, effective spring constant = 1.5×10^3 N per meter. These numerical values result in the vertical normal mode frequency of 8 cycles per minute and the torsional motion of 10 cycles per minute. The approximate equality of these two frequencies played an important role in the fate of the Tacoma Narrows bridge. As can be seen in table 3 the ratio of torsional to vertical frequencies for other, older bridges is significantly larger than the ratio for the first Tacoma Narrows Bridge.

Bridge	Length	f_v	f_t	ratio f_t/f_v
Verrazano	4260	6.2	11.9	1.9
Golden Gate	4200	5.6	11.0	1.9
Severn	3240	7.7	30.6	3.9
Tacoma Narrows(1st)	2800	8.0	10.0	1.25

Table 3

Before the bridge was ever opened, the vortex shedding forces were pumping energy into the vertical motion of the bridge. Vertical oscillations were noticed early and caused many people to avoid using the bridge. However, the torsional oscillations did not occur until the day of the collapse. On that day a mechanical failure allowed the torsional oscillations to begin. Because this motion was closely coupled to the vertical motion of the bridge it quickly led to its destruction.

SUMMARY

The physics of the Tacoma Narrows Bridge Collapse involves some fairly sophisticated physics of fluid flow as well as resonant vibrations. By selecting the level of the explanation carefully students can understand some aspects of the physics as well as construct their own explanations about why the bridge collapsed. Of course, one could translate the major points of the quanitative approach into a conceptual one. However, we have found that many students are unable to comprehend that material during their first time through a conceptual or descriptive physics course.

HUMAN INTEREST ITEMS

With a disaster of the magnitude of the collapse of the Tacoma Narrows Bridge, many stories of general interest can be described to show the human as well as the physics interest. For example, a headline in the Tacoma News Tribune on July, 1940, states **Bouncing Span Will Soon Be Quieted Down.**

It continues: "What makes a bridge bounce has been asked many times in the past few weeks as the Narrows span has approached completion. Engineers declare the principal reason the span has bounced in the immediate past was because it was out of balance due to the concrete deck and walks being put in in sections. Now that the concrete work is completed and the span still has a tendency to buck under certain conditions it is because the wind, swinging the middle span to one side draws the towers toward the center, lifting the approach sections. Then the deck swings back dropping the outside sections and sending a vibration across the center section. Repeat this and you have a motion which might give you what Mark Twain called Pardonex moi, or at least the jitters. To take this tendency out of the span the engineers spent $10,000 for four hydraulic jacks which are to act as shock absorbers. If they don't take out all of the vibration what is known as storm cables will be rigged and these are certain to stop the bucking. In any case there is nothing dangerous about it and if you are riding across the span you are not likely to notice the vibrations. Only foot passengers, or autoists who stop get the effect. Some of the swinging is due to the narrowness of the span, it being the narrowest span for its length on record. It would be possible with a 100 mile wind for the span to swing sideways 20 feet but who ever saw a 100 mile wind in these parts? " (Tacoma Times,July 1, 1940)

Another interesting item was the Tacoma Times editorial on August 25, 1940 which discussed the tolls which were being charged for crossing the Tacoma Narrows Bridge. "There is no truth in the rumor that part of the Narrows Bridge toll is fo r the scenic railway effects. The charge is for crossing only and the bounce is free. " (One of the first public comments about the bounce after the bridge was opened.)

A third article explains how the cables that were to be attached to the bridge would curb its bouncing. "There is nothing unusual about the antics of the Narrows span, Eldridge states, although those of this bridge are aggravated by its slender proportions necessitated by shortage of funds with which to build it. The Narrows span is narrower in proportion to its length than any bridge in the world and at the same time the girders which would be expected to stiffen it are shallower than those of any similar structure. The Whitestone bridge, recently completed in New York has as much bounce as the Narrows bridge, according to reports, but instead of publicizing it New Yorkers have done everything they could to keep it quiet. There is nothing dangerous about the performance which in no way affects the strength or safety of the Narrows span, Mr. Eldridge states. Aside from affording a basis for tall tales of the span's cavorting the bridge's bouncing is having no real effect whatever. Motion in the span deck is caused by the center span being swung out of line by a puff of air. This draws the tops of the towers together, lifting the two outside spans. As the center span swings back the shore end spans drop, starting the wave motion which is further aggravated by swinging of the center span. As the center span is designed to raise and lower 10 feet or more, due to changes in temperature, the four foot hop of the bounce does not put any strain on it which the design does not take care of with a large factor of safety. Work on the bridge is still being done under the toll bridge authority's contract with the Pacific Bridge company, Mr. Eldridge states. Steel work will be handled by the Bethlehem Steel company, T. Martinson representing the company and concrete and other work by Woodworth & Cornell." (Tacoma News Tribune, September 5, 1940)

On November 8, 1940, the Tacoma Times reported A local bank had its billboard by the bridge which said 'as secure as the Narrows Bridge.' removed within hours of the collapse.

Insurance companies also had their share of problems with the bridge. On the day of the collapse the Tacoma Times reported:

"BRIDGE INSURANCE WAS $5,200,000 Tacoma Narrows bridge was insured for $5,200,000 - approximately 80 per cent of its value - it was revealed in insurance circles Friday."

Over the next several months the Tacoma business community was surprised by the trial and conviction of a prominent Seattle insurance man who had collected the premium and overlooked mailing it to his insurance company: December 3, 1940.-Hallett R. French, a prominent Seattle insurance man, a general agent for Merchants Fire Assurance Co., was jailed on $2000 bond for grand larceny. He wrote an $800,000 policy on the bridge but did not notify the national office and kept the $8000 premium.

February 8, 1941 - Mr. French was sentenced to a 15 year prison term by Judge Douglas.
December, 1942 - Mr. French, who had been paroled by Gov. Langlie to work in a war industry, was working as a ship fitter.

The collapse of the Tacoma Narrows Bridge was a watershed in the design of suspension bridges. That was recognized as early as December,1940 by Walter A. Averill in the magazine **Pacific Builder and Engineer** and it seems appropriate to have a quote from him at this time:

"Of inestimable importance to the field of bridge design is the collapse of the Tacoma Narrows Bridge, third longest suspension bridge in the world. Blame for the failure is commonly placed upon cumulative undulation and twisting induced by aerodynamic forces.

Aerodynamic forces never have been taken into consideration in the design of any bridge. Heretofore bridges have been designed to withstand static stresses only. From now on, bridge designers must consider dynamic actions and aerodynamic effects. Wind tunnels, elastic models, dynamic models, and studies of aerodynamics, resonance and damping must now take their place in the design of any highly elastic bridge. "

And finally, as you might expect, the collapse of such a large structure was not without controversy among the community of civil engineers. The following quote is from an article by David Steinman that appeared in the **American Scientist** in July of 1954.

"Shortly after the Tacoma Bridge was opened and its undulatory behavior was reported in technical periodicals, I communicated with the engineers of the Tacoma span, offering to make my discoveries available. They replied that they knew all about them and that they did not need my help. Three months later the Tacoma span was wrecked by its oscillations. The amazing feature of the catastrophe was the confidence of the bridge authorities in the safety of the structure an d their failure to apply adequate corrective measures before opening the bridge to traffic. On the morning of the failure, after the oscillations had become alarming, the engineer in charge finally decided that diagonal stays were desirable; he rushed to the telephone to order the wire ropes for early installation but , when he returned to the bridge, the span was gone."

Final Comment

Regardless of the disagreements among engineers or the insurance salespeople who knew bridges didn't collapse and, thus, kept the premiums, the Collapse of the Tacoma Narrows Bridge provides a rare look at resonant behavior and can wake-up if not motivate even the least interested student. Perhaps, this idea was expressed best by one of our students who after watching the film said "I'd even pay to see that again! "

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Wind Forces on Buildings and Structures: An Introduction, by E.L. Houghton and N.B. Carruthers, Halsted Press, New York 1976.

Design of Bridge Superstructures, by C. O'Connor, John Wiley and Sons, New York, 1971.

Aerodynamic Stability of Suspension Bridges, University of Washington, Engineering Experiment Station, Bulletin No. 116, Parts I, II, III, IV and V, University of Washington Press, Seattle, 1949, 1950, 1952, and 1954.

The Failure of the Tacoma Narrows Bridge, A Reprint of Original Reports, School of Engineering, Texas Engineering Experiment Station, College Station, Texas, Bulletin No. 78, 1944.

Steinman, D.B. "Suspension Bridges: The Aerodynamic Problem and Its Solution" American Scientist, July, 1954, pp. 397-438.

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[1] Robert G. Fuller, Dean Zollman, and Thomas C. Campbell, THE PUZZLE OF THE TACOMA NARROWS BRIDGE COLLAPSE, (John Wiley & Sons, New York, 1982).