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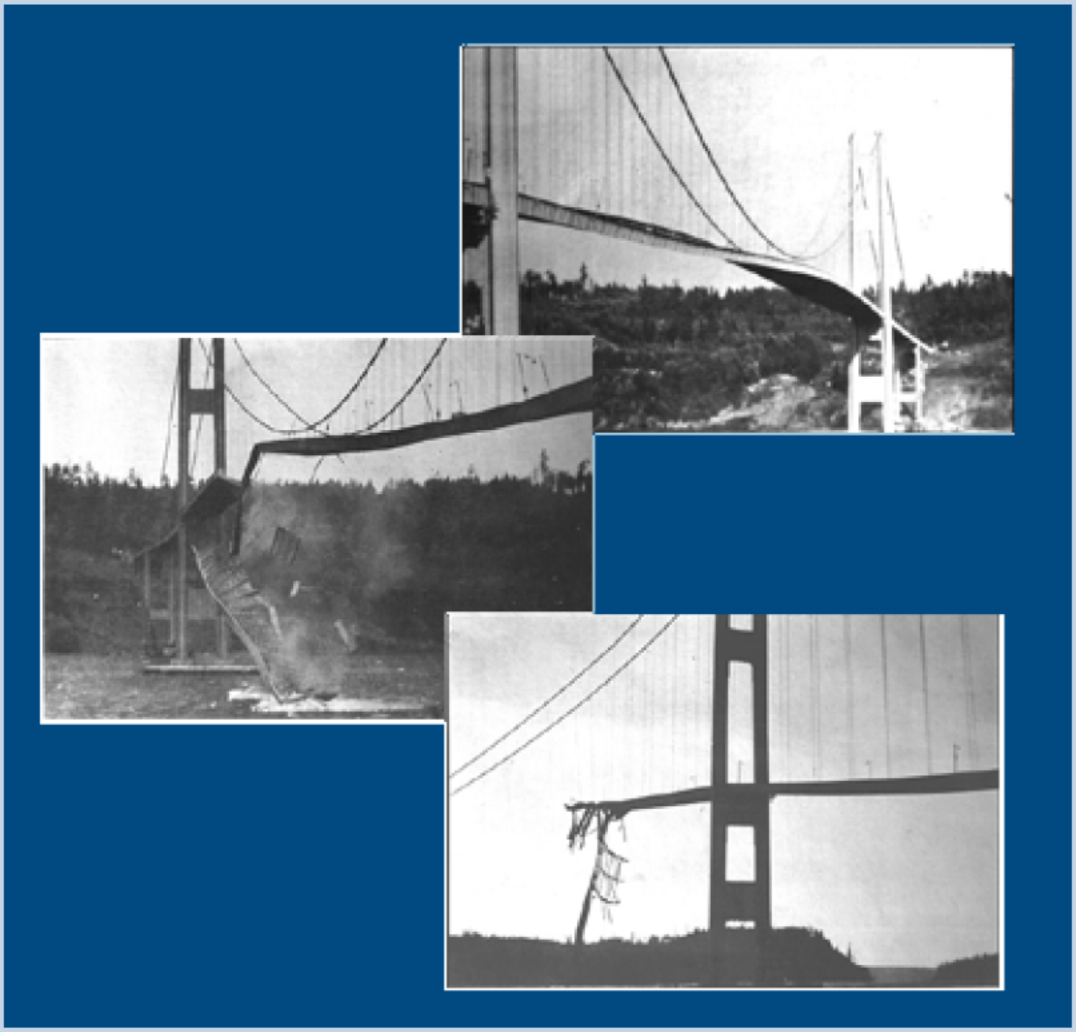
The Collapse of the Tacoma Narrows Bridge, Evaluation of Competing Theories of its Demise, and the Effects of the Disaster of Succeeding Bridge Designs



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ABSTRACT

The Tacoma Narrows Bridge gained notoriety in the engineering and scientific communities when it collapsed on November 7, 1940. Even though the odd motions of the bridge were recorded in detail, including film footage that documented the final moments of the structure, technical experts still disagree on the exact nature of the phenomena which led to its destruction. One aspect of the failure remains quite clear, however. The Tacoma Narrows Bridge, despite the embarrassment it caused those involved with its design, has played a significant role in creating more sophisticated analytical tools for engineers to use. This document presents an evaluative review of the major theories presented about the cause of the failure, the accepted results within the engineering community, and the effects of the collapse on structural designs that followed.

INTRODUCTION

> *. . . . the Tacoma Narrows bridge failure has given us invaluable information . . . . It has shown [that] every new structure which projects into new fields of magnitude involves new problems for the solution of which neither theory nor practical experience furnish an adequate guide. It is then that we must rely largely on judgment and if, as a result, errors or failures occur, we must accept them as a price for human progress.*
>
> - Othmar Ammann, leading bridge designer and member of the Federal Works Agency Commission investigating the collapse of the Tacoma Narrows Bridge

The first Tacoma Narrows Bridge (TNB), destroyed over fifty years ago, has continued to elicit many references in scientific and engineering journals, as well as the popular scientific press. Perhaps much of this attention stems from the fact that the noticeable vertical undulations of the bridge had been witnessed from the early days of construction, and as a result, were being documented with photographs and film footage. On November 7, 1940, these oscillations became sufficiently large to snap a support cable at mid-span, producing an unbalanced loading condition that created severe torsional oscillations which eventually led to the bridge's collapse. During its use, the bridge's harmless vertical motions drew the interest of both the engineering profession and the public; the latter to experience the rollercoaster-like thrill of crossing 'Galloping Gertie,' the sobriquet given to the bridge. It is the engineering interest in this particular structural failure that is the focus of this report. The TNB failed, after only four months of operation, because of its interaction with the moderate winds that were funneled down the canyon-like narrows of Puget Sound. In the aftermath of the failure, many people asked why such an apparently well thought out design could have failed so completely.

The TNB, the third longest suspension span in the world at the time, cost $6,559,000, a relative bargain for a structure of its magnitude [Goller, 1965]. This particular design was the culmination of a style in the 1920s and 30s to 'streamline' products, including the construction of slender, graceful bridge spans. By using shallow plate girders instead of traditional deep stiffening trusses, the TNB was able to economize on material as well as providing a slim, elegant aesthetic form. The use of trusses for strength was being considered less of a factor in the 1930s when railroad expansion was slowing and new bridges were being constructed to take the much lighter loads of automotive traffic. What was unknown to the designer of the TNB, was that trusses effectively damped out aerodynamic forces on structures by their sheer weight. Because bridges constructed with these trusses showed little sign of vibration in the wind, designers of the early 20th century considered aerodynamic failure a remote possibility.

The TNB was certainly not the first bridge to manifest aerodynamic instability. Indeed, reports dating as far back as 1818 with the Dryburgh Abbey Bridge in Scotland had indicated the susceptibility of long, slender spans to wind loading that created large vertical and destructive torsional oscillation. Prior to the TNB accident, the most notable suspension bridge failure in the U.S. was that of the Ohio River Bridge at Wheeling, West Virginia in 1854. This bridge, built in 1847, had a span of 1010 ft. which held the record in length for 20 years. Several of the TNB's contemporaries including the Thousand Islands Bridge in New York (1938), the Deer Isle Bridge in Maine (1939), and the Bronx-Whitestone Bridge in New York (1939) had reported wind-induced vibration that called for additional structural support to reduce the motions. Like the TNB, all of these bridges were stiffened by plate girders [Goller, 1965]. Even the Golden Gate Bridge in San Francisco (1937), designed with conventional truss supports, exhibited some danger signs of aerodynamic instability due to its very long span of 4200 ft. Seemingly unaware of these problems, the designer of the TNB extrapolated the practice of constructing slender spans one step too far, setting the scene for the spectacular collapse of the bridge.

This report will include the history of problems specific to the TNB and how careful study of its failure has influenced other suspension bridge designs. Recognizing that the specific reasons for the bridge's destruction are still being debated today, emphasis will be placed on evaluating the major theories published on the suspected cause(s), and the challenges that this pivotal design presents to the scientific community in understanding the aerodynamic behavior of large, static structures. The review of the TNB failure will conclude with a look at how that incident affected the future of bridge design and the development of advanced scientific methods for predicting similar phenomena. Background information as to the construction of competing bridge designs (cantilever, arch, etc.) will not be discussed, except where design details provide solutions to the types of problems inherent to suspension bridges like the TNB. For information regarding the soundness of the unique design of the Tacoma Narrows Bridge, and the engineering profession's view of the designer of the structure, see Appendix A.

The purpose of this report is to make engineers aware of the dangers of exceeding a design paradigm, and by recognizing the trend, to prevent similar disasters in the future. The first section of the paper briefly accounts the history of the TNB and the logic that went into its design. The report will point out notable gaps in understanding aerodynamic loading that occurred in all stages of the bridge's brief existence, from planning through construction and 'stop-gap' measures taken to control the oscillations of the structure. Accepted practice that was considered state of the art in 1938 for design of suspension bridges will be addressed in connection with the TNB design.

Once the background has been presented on the characteristics of the TNB, the report will discuss the theories that have been proposed about the true cause to the bridge's collapse. The theories are presented in chronological order to help illustrate the importance of an increasing engineering and scientific knowledge base on the understanding of aerodynamic instability. Finally, the currently accepted explanation of the events at Tacoma Narrows will be used to show how the collapse of this particular structure led to many advances in the engineering profession in the years since 1940.

Design Of The Tacoma Narrows Bridge

Suspension bridges work on essentially the same principle as a clothsline. This type of bridge fundamentally consists of cables anchored to the earth at their ends and supported by towers at intermediate points. From these cables a floor or 'deck' is suspended. Thus, a suspension bridge creates its load-carrying capability through a balance of opposites, with the cables always in tension and the towers in compression [Paine, et. al., 1941]. These basic components alone, when correctly designed, will susccessfully resist the dead load of the structure. In general, however, a suspension bridge not properly braced is too flexible to be useful. Though in a structural sense the excessive flexibility may have no harmful effects, it is doubtful that travelers who cross the structure will accept the potentially large undulations without reservation. With this in mind, stiffening trusses are usually added to reduce and control the vertical and torsional motions that can result from an eccentrically placed live load or from overturning moments produced by the wind. Suspension bridges are, however, very flexible as compared with other types of bridges, the maximum motions being many times greater. Because of the continuity provided by the main cables, interaction exists in all parts of the structure, so that design changes in one part of the structure must involve a study of all parts. For a pictorial respresentation of the major components of the TNB, see Appendix B.

The TNB was designed with a new method of calculating stresses in the bridge structure that allowed lighter, less expensive designs to be constructed. Known as the 'deflection theory,' this method made it possible for designers to distribute part of the shear and bending moment loads to the main cables, rather than relying completely on stiffening trusses below the bridge deck to support the loads. Due to the light traffic expected to cross the structure, the bridge was designed for one lane of traffic each way, giving the bridge a width between cable centers of only 39 ft. The large, unsupported span length of 2,800 ft. was made necessary by the poor bottom conditions and swift currents in the Narrows. The TNB was designed with cables that were fixed to flexible towers, which by 'deflection theory' standards were better able to deal with the continous variations in cable pull than were the conventional massive towers and cables that moved across the tower tops on rolling saddles [Goller, 1965]. The tower and cable stresses are primarily a result of the dead load, while the stresses in the stiffening girders are almost entirely due to the live loading imposed on the structure. The stiffening girders used on the TNB were unusually shallow, only 8 ft. deep, in comparison with their length. This depth-to-span ratio of 1:350 (over twice that of the Golden Gate Bridge) made the TNB by far the most flexible design of its time. Figures 1 and 2 illustrate, on the basis of dead loading, the comparitive vertical and torsional rigidities of five suspension bridges built during the 1930s.

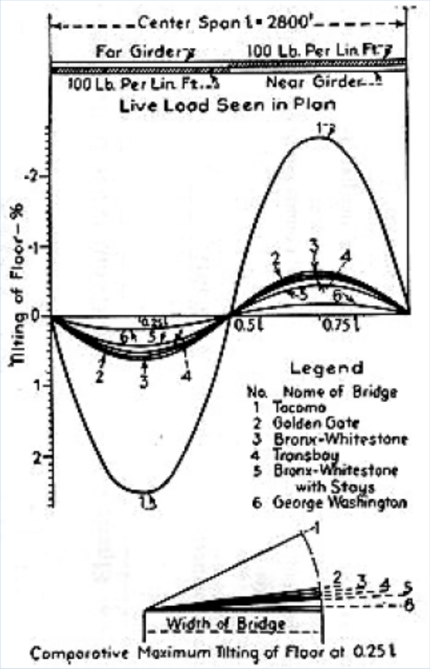

Figure 1. Comparative vertical deflections of the five longest suspension bridges [FWA report, 1940]

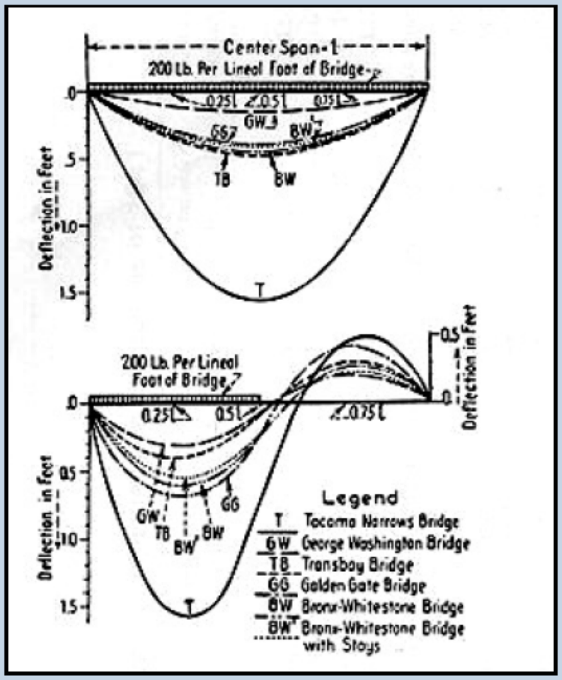

Figure 2. Comparative torsional deflections of the five longest suspension bridges [FWA report, 1940]

All bridges are subject to forces which cause torsion or lateral tilting of the deck. In the case of suspension bridges with ample width and vertical rigidity, such torsional forces are usually of small consequence [FWA report, 1940]. The TNB design depended largely on the stabilizing effect of the dead load for its rigidity and as a consequence, there was comparatively little structural damping in the system.

Immediately following the destruction of the TNB, The Federal Works Agency (FWA) established a commission to determine the cause of the collapse. Included on the commission were Othmar Ammann, one of the world's leading bridge engineers, and Theodore von Karman, the famous aeronautical engineer [Ross, 1984]. In its review of the TNB design, the commission observed that the design had several shortcomings that, while obvious in hindsight, met all criteria for acceptable practice at the time. The review of the static strength of the structure was based on an assumed live load of 1500 pounds per linear foot, one-and-a-half times greater than the load used for the actual design. Even with the higher loading, the commission found that all stresses were within safe limits. The commission did note, however, that when the load was distributed in such a fashion as to produce maximum torsional deflection, the inherent lack of stiffness of the design became evident. Under the severe dynamic loading that occurred on November 7, the main cables, cable hangers, towers, and various members of the bridge deck were subjected to stresses well above the design limits of these components; at several locations, subject to stress levels at which failure had to occur. Where failure did occur, it was determined that the steel members had reached yield stress, indicating not only a properly designed static structure, but confirming that there were no flaws in the material used or defects created during assembly [Ross, 1984]. All experts agree that the TNB's transition from (relatively) safe vertical motion to destructive torsional motion occurred as a result of the slipping of the cable band on the north side of the bridge to which the center cable stays were attached. Due to the action of the severe torsional motions, the concrete roadway experienced torsional stresses that exceeded the ultimate strength of the material. The breaks in the roadbed were near the centerline of the roadbed, where the maximum torsional stresses were to be expected. The collapse of the center span left the towers with severe unbalanced loading, supporting the full weight of the side spans on their shoreward sides, without the balance of a center span. As a result, the shoreward deflection of the towers at their tops was 12 feet, over 12 times the design maximum deflection. The side spans, though remaining essentially intact, were left sagging over 60 feet at their centers as a result of the tower deflection.

The fundamental weakness of the TNB was its extreme flexibility, both vertically and in torsion. The bridge's narrowness, based of economic factors and transportation studies, made the structure extremely sensitive to torsional motions created by aerodynamic forces. Several methods were employed to reduce the motions of the TNB during its short life. The first solution involved the attachment of tie-down cables to the plate girders and anchoring them to fifty-ton concrete blocks on the shore. This measure proved ineffectual as the cables snapped shortly after installation. A second approach was attempted by adding a pair of inclined cable stays that connected the main cables to the bridge deck at mid-span. These remained in place until the collapse but were also ineffectual at reducing the structural vibrations. Finally, the bridge was equipped with hydraulic buffers installed between the towers and the floor system of the deck to damp longitudinal motion of the main span. The effectiveness of the hydraulic dampers was nullified when it was discovered that the seals of the unit were damaged when the bridge was sandblasted prior to being painted [Schlager, 1994].

In their exoneration of those involved with the design, the FWA admitted that the criteria used for considering rigidity against static forces do not necessarily apply to dynamic forces. In addition, the report concluded that the choice of a suspension type bridge was the most suitable and economical that could have been selected and that a more satisfactory location for the bridge could not have been chosen. The commission report was vague about what had truly caused the destruction of the TNB, leaving the door open to years of interpretation of the events of November 7, 1940. During the next forty-five years, engineers and scientists would debate the cause in both technical journals and the popular press. Two of the more prominent theories are compared in the following section.

WHY THE BRIDGE COLLAPSED, COMPETING THEORIES

Initial suggestions as to the cause of the TNB collapse came from the FWA commission. Without drawing any definitive conclusions, the commission explored three possible sources of dynamic action; aerodynamic instability (negative damping) producing self-induced vibrations in the structure; eddy formations which might be periodic in nature; and the random effects of turbulence, that is, the random fluctuations in velocity and direction of the wind. Each source was considered separately in seeking the causes of the vertical and torsional oscillations. The commission appeared to have identified the leading possible contributors to the destructive oscillation, since all competing theories which followed to date fit into one of the above categories.

The standard textbook explanation for the collapse attributes the cause of the failure to the phenomenon of resonance. Like a mass hanging from a spring, a suspension bridge's deck hanging from its cables oscillates at a natural frequency, or more than likely being multi-modal, has several natural frequencies. In order for a resonant phenomenon to exist, the driving force would have to be periodic, that is, varying regularly with respect to time. The mathematical model that most simply illustrates this type of behavior is represented by the following differential equation:

$$m\ddot{x} + b\dot{x} + kx = F\cos\omega_f t \tag{1.1}$$

where m = *mass* of the system
b = *damping* coefficient of the system
k = *stiffness* of the system
ω_f = radian *frequency* of the exciting (input) force
F = *amplitude* of the exciting force
x = characteristic (output) *motion* of the system

This model, known as a single-degree-of-freedom oscillator, characterizes the motion of a system (the TNB in this case) based on an input force that varies with time explicitly. With this model, resonance, or maximum response amplitude, occurs when the external forcing frequency, omega-subscript f, approaches the square root of k/m, representing the system natural frequency. When resonance occurs, a small input force can produce large deflections in a system. Several proposed solutions to the TNB problem build their theoretical foundation on this concept.

According to several accounts [Billah and Scanlan, 1991], the turbulent wind blowing over the bridge deck produced a fluctuating force 'in tune' with one of the structure's natural frequencies, steadily increasing the amplitude of its oscillations until the structure was ripped apart. The specific characteristics of the 42 mph wind that blew over the bridge on November 7 were not recorded in the same detail as the collapse, and much speculation has accompanied the nature of the flow [Peterson, 1990]. Allowing for periodic wind gusts, the turbulent conditions that were created could produce a flow pattern whose time-varying pressure matched a natural frequency of the structure. This explanation of the disaster appears to fundamentally flawed, however. Resonance is a very precise phenomenon, requiring the frequency of the driving force to be near one of the system natural frequencies in order to create large oscillations. A steady wind still has enough variability in its motion that many find it difficult to accept the idea of the wind alone having the periodicity needed to set up resonance in the structure. Applied mathematician P. Joseph McKenna of the University of Connecticut in Storrs notes that the elegance of this explanation is too simplistic:

> *This explanation has enormous appeal in the mathematical and scientific community. It is plausible, remarkably easy to understand, and makes a nice example in a differential equations class....It is hard to imagine that such precise, steady conditions existed during the powerful storm that hit the bridge.*

.

Von Karman was convinced that the oscillations that contributed to the failure were due to the shedding of turbulent vortices in a periodic manner. This vortex shedding has the potential to produce the necessary periodicity to establish a resonant condition. Through experimental observations, von Karman and others had shown that bluff (blunt) bodies like bridge decks do in fact shed periodic vortices in their wake . Figure 3 illustrates this type of flow pattern around a spherical body.

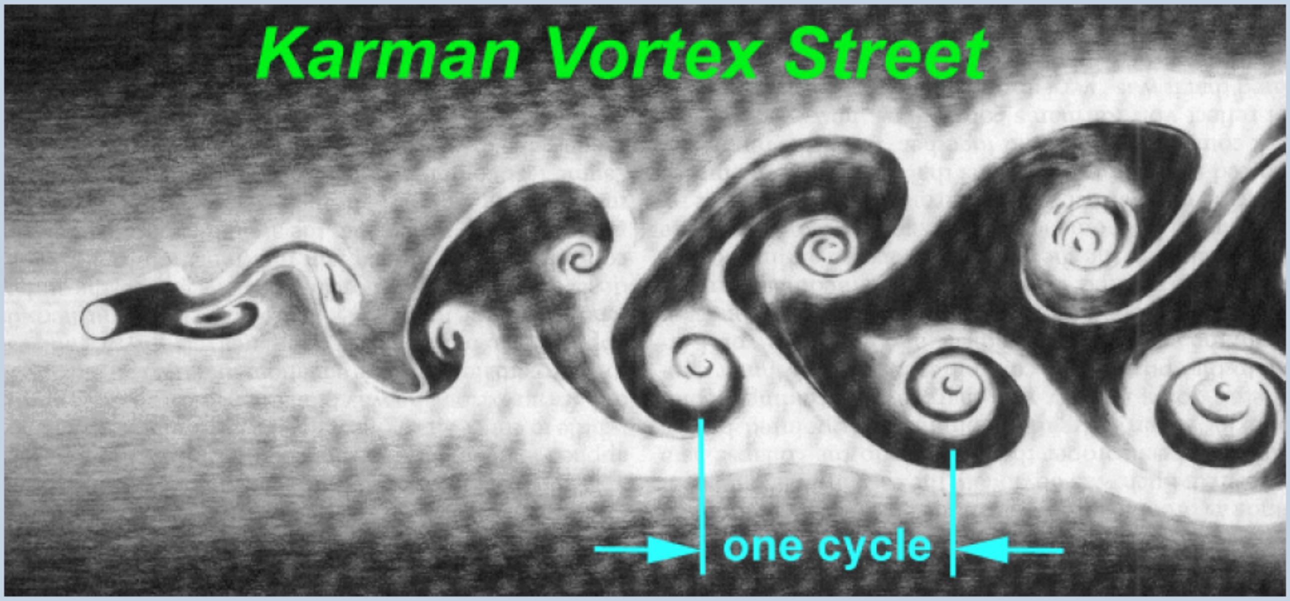

Figure 3. Natural vortex shedding off a smooth, non-streamlined body suggestedas the source of periodicity responsible for the collapse of the Tacoma Narrows Bridge [Petroski, 1991].

These vortices generate alternating high and low pressure regions on the lee side of the body, which resonates in consequence. Vortices produced in this manner are termed Strouhal vortices and the rate at which they are shed off the body in question is governed by the following relation:

$$f_s = \frac{S * U}{D} \qquad (1.2)$$

where f_s = *Frequency* of *vortex* formation
S = Strouhal number (a constant for a given body shape)
U = Velocity of the flow over the body
D = Characteristic dimension of the body

For the case of the TNB, the characteristic dimension, that is, the dimension directly associated with the vortex formation, was 8 feet, the depth of the side plate girders and the main obstruction to smooth flow over the bridge deck. Noting that the wind speed was 42 mph on the morning of the collapse, this relation dictates a vortex shedding frequency of about 1 Hz (cycle/sec). According to several sources [Petroski, 1991], the wake region reinforced structural oscillations that grew until the bridge deck could no longer hold itself together. How this would occur is fairly simple. Natural vortex shedding can create a phenomenon known as 'lock-on'. When the frequency of vortices being generated around the body closely matches one of the resonant frequencies of the structure, the driving force feeds off of the structure's motion and vortex-induced vibration can occur that can build to destructive amplitudes. This explanation goes a long way in describing the events that took place in the destruction of the TNB. One of the questionable aspects of this solution, however, is that as the amplitude of structural motion increases, the local fluid boundary conditions are modified in such a way as to generate compensating, self-limiting forces [Scanlan and Billah, 1991]. Figure 4 depicts the various modes that existed for the TNB structure. In all modes except one, the production of self-limiting forces is evidenced by an increase in amplitude up to a specific wind velocity for each mode, followed by a decline in amplitude prior to the manifestation of the next mode. Because of these structural characteristics, the motion of the TNB was restricted to fairly benign amplitudes during its lifetime. The slipping of the cable band on November 7, however, created an unbalanced loading condition that, married with the unstable torsional mode shown in Figure 4, allowed the twisting motions of the bridge to increase steadily to failure. The 'lock-on' theory proposed by von Karman does not appear to account for the fact that observations made at the scene of the accident show that the oscillation frequency of the torsional mode was only around 0.2 Hz, substantially different than the Strouhal frequency of 1 Hz. Thus, it does not seem likely that the power behind the destruction of the TNB can be wholly attributed to the natural vortex shedding of the structure. Even the Federal Works Administration report of the investigation concluded that "It is very improbable that resonance with alternating vortices plays an important role in the oscillations of suspension bridges" [Ross, 1984]. With portions of the natural vortex shedding theory in doubt, a more recent theory was published that disputes the idea that the TNB failure was a case of simple forced resonance.

Robert H. Scanlan, a professor of Civil Engineering at Johns Hopkins University believes that the forces at work behind the collapse of the TNB were highly interactive ones. In a paper published in the American Journal of Physics in 1991, Messrs. Scanlan and K. Yusuf Billah attribute the behavior of the bridge to a phenomenon known as self-excitation. This concept differs from the above theory of vortex-induced vibration in the fact that the driving force for oscillation is not purely a function of time, as described by Equation (1.1), but is rather a function of bridge angle during torsional oscillation and the rate of change of that angle. For torsional motion, the behavior is described mathematically by the relationship:

$$I * \left[\ddot{\alpha} + 2\zeta\omega\dot{\alpha} + \alpha 2\alpha\right] = F(\alpha, \dot{\alpha}) \qquad (1.3)$$

where I = *inertia* of the system
ζ = *damping* ratio of the system
ω = natural *frequency* of the system
α = angle of *torsion* deflection (twist)

According to this theory, the motions of the TNB built 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 [Billah and Scanlan, 1991].

Figure 4. Modal response of Tacoma Narrows Bridge [Billah and Scanlan, 1991].

The distinctions made between the self-excitation theory and natural vortex shedding theory are founded in the composition of the wake region of the structure. Experimental testing has shown that bluff bodies in oscillatory motion shed vortices at both the oscillation and the Strouhal frequencies. According to Scanlan and Billah, under high amplitudes of oscillation the periodicity of the Strouhal vortices is interrupted and the vortices resulting from the periodic motion of the body predominate. With the TNB, as represented by the body shape in Figure 5, it can be seen that when the shape changes angle of attack in a fluid stream, it will shed new vorticity in its wake that cannot be described by natural vortex shedding. The motion that results from such interaction is a form of separated-flow flutter which tends to excite the torsional degree of freedom, the unstable mode for the TNB. In contrast with airfoil-type flutter, in which the high wind speeds will create aerodynamic forces that can reach magnitudes comparable to the structural inertial resistance and stiffness, bridge flutter can occur at much lower wind speeds. Because of the sheer weight of bridge structures, the aerodynamic forces that develop have little effect on the response modes or their frequencies. These wind generated forces, however, can influence the overall damping of the structure, reversing the sign of the middle term in brackets in Equation (1.3), producing a response whose solution increases without bound. For the case of the TNB the unstable torsional mode shown in Figure 4 was pushed to destructive amplitude as a result of the interactive, self-excitation phenomenon.

Figure 5. Self-excitation flow patterns around the Tacoma Narrows Bridge deck. Note that the vortexformations result from interaction with the bridge1s motion [Petroski, 1991].

The presence of contrasting theories about a structural failure that happened not only several generations ago, but that had the benefit of extensive documentation, underscores the importance that has been assigned to the TNB. In fact, the activity that has occurred in the engineering profession as a result of this specific accident has produced several important advancements in the design of similar structures.

Pinpointing the true cause(s) of the TNB collapse is more than just an academic debate. The need for practicing engineers to have a complete understanding of nature's interaction with their designs has led to new problem solving methods. Though the sensational photographs and film made the TNB an "irresistible pedagogical example," its destruction has brought many advances to the engineering community [Civil Engineering, Dec. 1990]. Now, designers look not only at static loads but also review the implications of aerodynamic effects of their structures. Few bridges, buildings or other exposed structures are currently constructed without testing a model in a wind tunnel. In fact, if a bridge is built with federal grant money, preliminary design must include at least a two-dimensional wind tunnel analysis of the structure, with a three-dimensional model that includes the surrounding terrain being preferred.

The shortcomings of the 'deflection theory' in properly compensating for the loading conditions forced engineers to advance methods that would account mathematically for stresses in all components of a structure, a process that was heretofore an extremely time consuming if not impossible task to accomplish by hand. With the advent of electronic computers after World War II, a numerical solution technique known as the finite element method was able to be routinely applied to bridge designs. This method allows a structure to be mathematically or graphically reduced to a large number of small, interconnected elements. When the overall deflections of the structure are too complex to solve for directly, the finite element method can solve for the deflections of each small piece of the structure, and then sum them up to produce the overall deflection and state of stress. With the advancement of graphics capabilities and processing speed, this testing can now done on desktop computers in any design office [Schlager, 1994].

Additionally, more complex analytical models accounting for the non-linear behavior of structures like the TNB are currently being proposed [Peterson, 1990]. McKenna is currently developing a mathematical model that will hopefully reproduce the behavior of the TNB. When designing suspension bridges in the past, engineers assumed that the cable stays would remain in tension under the bridge's weight, acting like rigid rods. This assumption allowed the designer to use relatively simple, linear differential equations to model the bridge's behavior. When a structure like the TNB starts to oscillate, the cable stays alternately lossen and tighten, producing a non-linear effect and changing the nature of the forces acting on the bridge. According to McKenna [1990], non-linear modeling of bridge behavior will provide less predictable solutions:

> *Linear theory says that if you stay away from resonance, then in order to create a large motion, you need a large push. Non-linear theory says that for a wide range of initial conditions, a given push can produce either small or large oscillations.*

In combination with other modeling techniques, accurate non-linear models will let engineers observe the response of a structure to a multitude of environmental conditions, such as those that existed during the final hours of the TNB.

Finally, the push towards wind tunnel testing bridge deck section models has led to an abundance of data on flutter response characteristics of various deck shapes [Scanlan and Jones, 1990]. These data assist in guiding a bridge designer's understanding of the general behavior of a shape under various flow conditions. In some cases, the necessity for wind tunnel testing at the initial design stages may be avoided if a sufficiently aerodynamically-similar bridge deck is used.

The theories presented in this paper represent only two of several suggestions about the behavior of the TNB on November 7, 1940. Natural vortex shedding was selected to illustrate the viewpoint of the aeronautical engineering profession in the years following the collapse. The concept of self-excitation, while not entirely new, was presented to illustrate the effect of additional years of testing and analysis on the advancement of scientific methodology.

Bridge design paradigm case studies performed by Sibly and Walker [1977] demonstrate the need for engineers to acknowledge the design history of the structures they create. By studying the temporal cycle of suspension bridge design, there was a period, in the early examples of the structural form, in which aerodynamic force analysis was of secondary importance. Over time, as designers extended the limits of this form, aerodynamic factors became of prime importance and, unheeded, led to catastrophic failure. The collapse of the TNB happened, not because the designer neglected to provide for sufficient strength as dictated by accepted practice at the time, but rather by the introduction of a new type of behavior that was not completely understood. Thus, the trend toward 'streamlining' in the 1930s took suspension bridge design away from the excessively stiff structures of the late 19th century and back to the ribbon-like decks and aerodynamic problems of a hundred years earlier.

Architects and engineers today, recognizing the importance of including a complete analysis of aerodynamic interactions with the structures they design, are able to use advanced modeling tools to assist them in their calculations. Some of these advancements grew out of the events of November 7, 1940 at Tacoma Narrows. Recognizing that scientists and engineers still argue the actual cause of the collapse shows the continued relevance of the Tacoma Narrows Bridge failure on the advancement of the 'scientific method'. This debate further underlies the fact that natural events are complex phenomena that cannot necessary be explained with simplistic equations. Hopefully, this evaluative review has offered engineers some guidance in recognizing potential lapses in their analyses of structures.

In 1950, the state of Washington opened a new 18 million dollar bridge on the site of the first Tacoma Narrows Bridge. Tested in wind tunnels at the University of Washington, the four-lane, 60 ft. wide deck and 25 ft. deep stiffening trusses form a box design that resists torsional forces. Self-excitation is controlled by hydraulic dampers at the towers and at midspan. Using the same piers as the original bridge, the new structure was evidence that the lessons learned about the collapse of 'Galloping Gertie' were being rigorously applied to new designs.

APPENDIX A

Excerpts from the report of T.L. Condron, Supervisory Engineer to the Washington Toll Bridge Authority

The following excerpt was taken from an independent review of the design of the Tacoma Narrows Bridge. The report is dated September 21, 1938, several months prior to construction of the Tacoma Narrows Bridge. The bridge would take just under two years to complete and would only survive in operation for four months before its catastrophic demise on November 7, 1940.

General Comments on Design of Super-structure

In view of Mr. Moisseiff's [designer of the Tacoma Narrows Bridge] ability and reputation, I hesitate to make any criticism of the structural design, but from a practical standpoint, I would feel that the width of this Bridge relative to the length of spans was open to criticism, particularly, since it was without precedent. The Golden Gate Bridge is the longest span bridge in the world, and the width of the structure is 1/57th of the span length. That is the highest ratio of any large bridge that has been built up to date, so far as I can learn. The proposed Tacoma Narrows Bridge has a ratio of 1/72nd. I learned that certain tests had been made on models of suspension bridge spans at the University of California, and as I could find no published report of this test, I went to Berkeley and conferred with Prof. R.E. Davis particularly with reference to horizontal and vertical deflections. Prof. Davis felt reasonably confident that the lateral deflections of the Tacoma Narrows Bridge as designed and as determined by Mr. Moisseiff, would be in no way objectionable to users of the bridge. He seemed satisfied that the theoretical determination of these lateral deflections by Mr. Moisseiff could be depended upon as representing very closely what would be experienced in the actual structure.

In the report of these tests on models published by the University of California in 1933, the following statement is made:

> *The deflection theory permits the calculation of the main cable stress without appreciable error and the calculation of vertical bending moments of the stiffening truss with a maximum error of approximately 10 per cent, occurring in the vicinity of the quarter points of the main span . . .*

In view of Mr. Moisseiff's recognized ability and reputation, and the many expressions of approval and comment of his methods of analyses of stresses and deflections in the designs of long span suspension bridges, particularly as expressed by the engineers who participated in the discussion of the paper presented before the American Society of Civil Engineers by Messrs. Moisseiff and Lienhard entitled "Expansion Bridges under the Action of Lateral Force," I feel we may rely upon his own determination of stresses and deflections.

Conclusions

I therefore feel, that with the exception of the unusual narrowness of this bridge with reference to its span length, the super-structure design is technically sound. It is probably technically sound notwithstanding its narrowness, but there are several reasons why it would be of material advantage if the bridge could be widened at a reasonable increase in the cost, and therefore, I recommend that serious consideration be given to the possible increase in the width of this structure, before the contract is let or work begun. This would undoubtedly increase the width of the anchorage blocks and the smaller piers, but it would seem reasonable to assume that the widths of the main piers would not have to be increased. Assuming it is expedient to consider changing the width of the bridge as now designed, I would suggest increasing the width of the roadway from 26 ft. to 30 ft. and making the two sidewalks each 2 ft. 9 in. clear, instead of 4 ft. 9 in. clear.

Respectfully submitted,
(Sig.) T.L. Condron
Advisory Engineer, RFC

APPENDIX B

The following figures are a geographic map of the site of the Tacoma Narrows Bridge as well as pertinent technical specifications and component drawings.

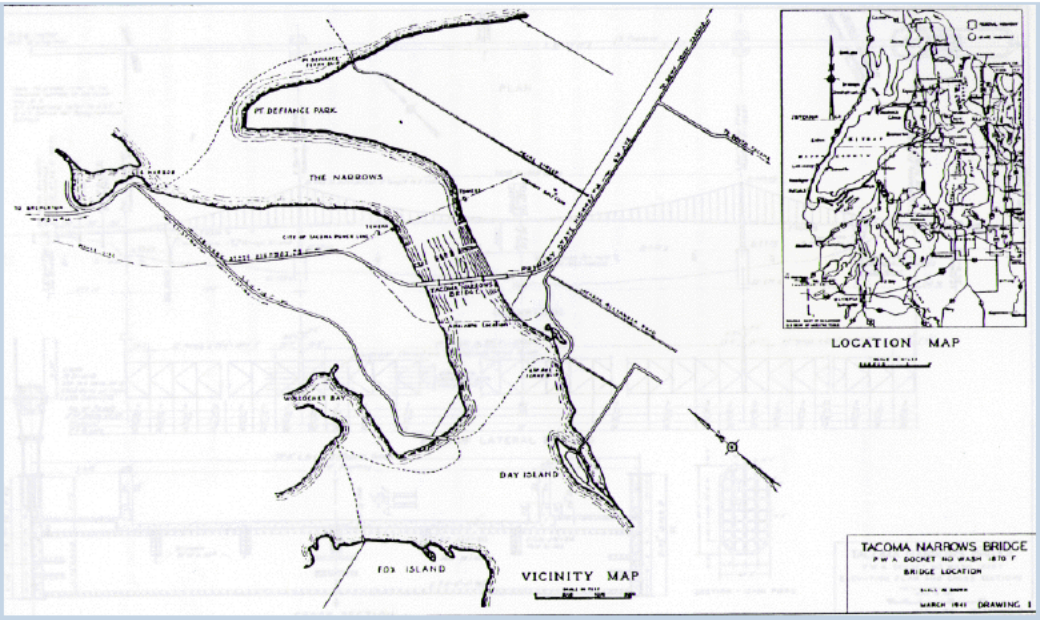

Figure B1: a geographic map of the site of the Tacoma Narrows Bridge

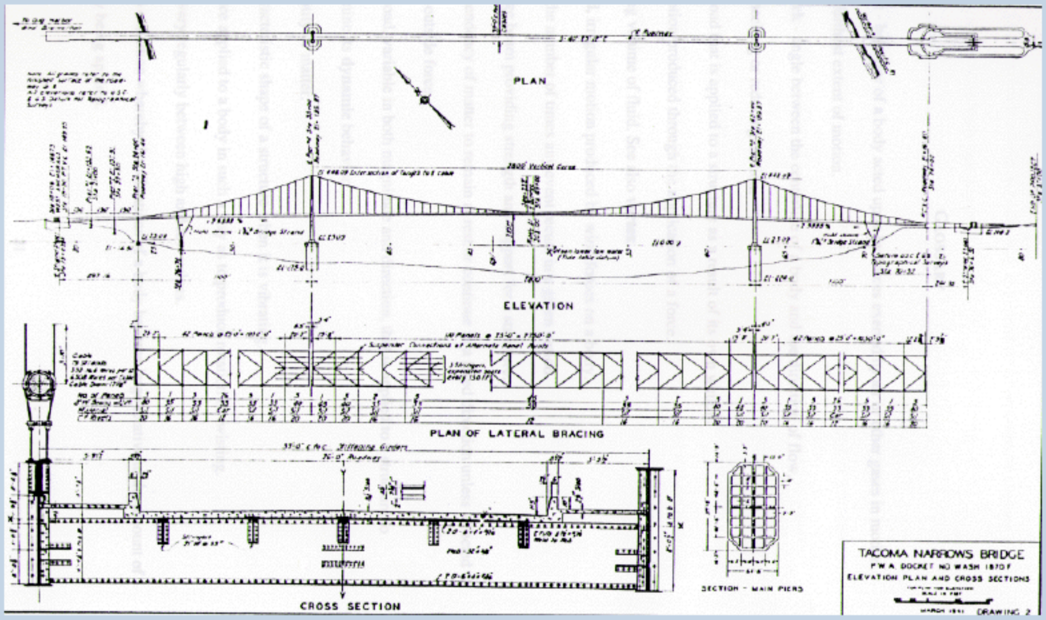

Figure B2: Technical specifications of the Tacoma Narrows Bridge and component drawings

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GLOSSARY

aerodynamic - behavior of a body acted upon by forces exerted by air or other gases in motion.

amplitude - furthest extent of motion.

angle of attack - angle between the centerline of a body and the direction of flow.

damping - checking or reducing motion.

dead load - load that is applied to a structure as a result of its own weight.

dynamic -motion produced through the application of a force.

eddy - rotating volume of fluid. See also vortex.

flutter - rapid, irregular motion produced by wind forces on a body.

frequency - the number of times any event recurs in a given period.

girder - a large beam providing strength and support for a structure.

inertia - the tendency of matter to remain at rest or continue in a fixed direction unless affected by an outside force.

live load - a load, variable in both magnitude and direction, that is applied to a structure to determine its dynamic behavior.

mass - a quantity of matter.

mode - a characteristic shape of a structure when it is vibrating.

moment - force applied to a body in such a way as to produce rotation or twisting.

oscillate - to vary regularly between high and low values.

resonance - a condition whereby the vibrations of a body become large relative to the amount of energy being applied.

shear force - force applied to a body in such a way as to produce deformation by slipping of atomic layers of the body past one another.

static - the condition of a body at rest or moving with a steady speed.

torsion - twisting motion.

truss - a framework consisting of many interconnected braces used for support of a structure.

vortex - a whirlpool-like motion of a fluid that is found in turbulent flows around immersed bodies.

wake - the region behind a body immersed in a moving fluid, or a body moving through a fluid.

yield stress - The point at which a material can no longer sustain a given load without permanent deformation.

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