PDHonline Course R134W (2 PDH)

Ethical Issues from the Tacoma Narrows Bridge Collapse (Live Webinar)

Instructor: J. Paul Guyer, P.E., R.A., Fellow ASCE, Fellow AEI

2012

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INTRODUCTION
Here are the ethical issues we will address....

- Theoretical and experiential knowledge as a basis for design
- Adequacy of theoretical and experiential knowledge for this project
- Supplementing experiential knowledge
- Commercial interests that may force design proposals

Paul Guyer, P.E., R.A.

The Tacoma Narrows Bridge (all reference here is to the original bridge, not its subsequent replacement, which is in service today) was in Washington State. It was constructed to cross the Tacoma Narrows, part of Puget Sound, between the city of Tacoma and the Kitsap Peninsula. It was the third longest suspension bridge in the world at the time. Construction was completed in July 1940, and in November of the same year it collapse.

Paul Guyer 2010

Paul Guyer, P.E., R.A.

Paul Guyer is a registered Civil Engineer, Mechanical Engineer, Fire Protection Engineer and Architect with 35 years experience designing buildings and related infrastructure. For an additional 9 years he was a principal staff advisor to the California Legislature on infrastructure and capital outlay issues. He is a graduate of Stanford University and a Fellow of the American Society of Civil Engineers and the Architectural Engineering Institute.

Paul Guyer 2010

Location of the Tacoma Narrows Bridge

Paul Guyer 2010
INTRODUCTION

Driving Distances and Time Via and Around 1940 Narrows Bridge

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INTRODUCTION

The Tacoma Narrows today

The Tacoma Narrows today

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HISTORY

Interest in construction of a bridge across the Tacoma Narrows developed as early as the 1880s when the Northern Pacific railroad proposed construction of a trestle bridge to carry railroad traffic. Nothing substantive was achieved by this early effort and, with the coming of the automobile, interest shifted to a bridge that would carry automobile traffic. In the 1920s business and government interests in the Tacoma area began to develop plans to seek financing for the project. Bridge engineers David Steinman and Joseph Strauss were consulted and in 1929 Steinman presented a specific proposal for design and construction of a suspension bridge. In 1931, however, Steinman’s contract with the Tacoma chamber of commerce was terminated because of a feeling that he was ineffective at raising funding for the project.

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Funding: Tolls

Proponents of a Narrows Bridge rationalized spending millions of dollars for such a project by explaining that the cost could be repaid by tolls. But, the Peninsula had a small population. Demand for travel to and from the area did not offer a very strong incentive until after the mid-1930s. Even then, federal officials doubted the numbers presented by Tacoma and Peninsula promoters. With the onset of the Great Depression after 1929, the hard times of the 1930s proved an even more difficult hurdle for bridge enthusiasts.
A Rock in the Road: The Ferry Concession

An existing ferry service presented a serious issue that delayed realization of a Narrows Bridge. The Washington Navigation Company held an exclusive concession to operate a ferry service across the Narrows. The concession agreement, awarded in 1926, promised the company “no competition.” This franchise agreement would not expire until 1936. Also, federal officials believed that Washington Navigation Company ferries met local travel and commerce demands. Any bridge deal had to include funds to buy out the Washington Navigation Company agreement.

The Funding Issue Improved in 1936

The end of 1936 brought renewed hope to Tacoma and Peninsula bridge promoters. The Washington Navigation Company’s ferry contract ended. Also, increased funding for public works projects under the federal government’s “New Deal” held new promise for finding the money to build a Tacoma Narrows Bridge.

The Military Necessity

The 1940 Narrows Bridge was built “primarily as a military necessity” to link McChord Air Field south of Tacoma and the Puget Sound Navy Shipyard in Bremerton. Successful funding for a Tacoma Narrows Bridge was closely linked with the nation’s defense strategy in the late 1930s. In particular, McChord Air Base became a catalyst and ally in the fight to get a Narrows span. Now, Narrows Bridge proponents had strong support from the United States Navy, because of its shipyard in Bremerton, and the Army, because of its installations at McChord Field and Fort Lewis. War and worries of war after 1935 played a role in the climate that helped create funding for the Narrows Bridge. With the bridge connecting the field and Ft. Lewis with the Bremerton Naval Shipyard, the nation’s defenses were an important step closer to being prepared for war.

The Washington State DOH Design

With the prospect of federal funding now in view, the Washington Department of Highways, under the direction of engineer Clark Eldridge, prepared plans for a suspension bridge using conventional suspension bridge design practices as they were known at that time...specifically, the roadway deck was supported by deep (25-feet) truss girders to stiffen it. The Washington State Toll Bridge Authority submitted the Eldridge design to the federal Public Works Administration (PWA) with a request for $11 million.

Clark Eldridge
Project Engineer
WA State Toll Bridge Authority

The Washington State DOH (Eldridge) proposal for a suspension bridge with the roadway supported on 25-feet deep truss girders
According to Clark Eldridge, "eastern consulting engineers" went to the PWA and Reconstruction Finance Corporation (RFC) and said that the bridge could be built for $8 million, much less than the $11 million Eldridge's design would cost. By "eastern consulting engineers," Eldridge meant the prominent New York bridge engineer Leon Moisseiff. The message fell on willing ears. Most of the cost saving was due to Moisseiff's replacement of the 25-feet deep roadway support truss girders with 8-feet deep plate girders. This was unquestionably a more elegant and slender design, but greatly reduced the stiffness of the bridge.

Federal authorities made the award, but the money was less than the $11 million requested by the Authority. Only $6.4 million was granted. And, it came with strings attached. They required the State Toll Bridge Authority to hire outside consultants for the bridge design. Those outside consultants, Clark Eldridge later claimed, were mandated by the Public Works Administration. He put it in simple words. "We were told we couldn't have the necessary money without using plans furnished by an eastern firm of engineers, chosen by the money lenders."

When Moisseiff's design arrived at the Washington State Highway Department in Olympia, the agency's engineers protested. The state's experts called Moisseiff's plan "fundamentally unsound." The design made the Narrows Bridge lighter and narrower than any bridge ever built, they said, "in the interests of economy and cheapness."

Thus the economic and political forces were set in motion that in an indirect but meaningful way led to the collapse of the Tacoma Narrows bridge. Specifically, a strong political push for a bridge, but one that was going to have a tight budget because of low toll revenue projections.

The Moisseiff proposal for a suspension bridge with the roadway supported on 8-feet deep solid I-beam girders. The bridge's main span was 2,800 feet, making it the third-longest suspension bridge in the world at the time. The theoretical underpinning of the Moisseiff design was a paper published in 1933 by Moisseiff and Fred Lienhard, a Port of New York Authority engineer, (Leon S. Moisseiff and Frederick Lienhard. "Suspension Bridges Under the Action of Lateral Forces," with discussion. Transactions of the American Society of Civil Engineers, No. 98, 1933, pp. 1080–1095, 1096–1141). In this paper a theory of elastic distribution was presented which went beyond the deflection theory that was developed by Josef Melan, an Austrian engineer, to horizontal bending under static wind load. This paper theorized that the stiffness of the main cables (via the suspenders) would absorb up to one-half of the static wind pressure pushing a suspended structure laterally. This energy would then be transmitted to the anchorages and towers.
### The Design

<table>
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<tr>
<th>Washington</th>
<th>Golden Gate</th>
<th>Bronx Whitestone</th>
<th>Tacoma Narrows</th>
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<tbody>
<tr>
<td>Year completed</td>
<td>1935</td>
<td>1937</td>
<td>1939</td>
</tr>
<tr>
<td>Cost ($ millions)</td>
<td>59.5</td>
<td>35.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Length of center span (feet)</td>
<td>3000</td>
<td>4300</td>
<td>2500</td>
</tr>
<tr>
<td>Girder depth (feet)</td>
<td>36</td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td>Width (feet)</td>
<td>106</td>
<td>50</td>
<td>74</td>
</tr>
<tr>
<td>Ratio of girder depth to length of center span</td>
<td>1:120</td>
<td>1:108</td>
<td>1:209</td>
</tr>
<tr>
<td>Ratio of width to length of center span</td>
<td>1:33</td>
<td>1:47</td>
<td>1:31</td>
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The use of such shallow and narrow girders proved to be the undoing of the bridge. With such thin roadway support girders, the deck of the bridge was insufficiently rigid and was easily moved about by winds.

Construction began in September 1938 and the bridge was completed and open to traffic in July 1940.
Opening Ceremonies for the Tacoma Narrows Bridge in 1940

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The bridge became known for its movement immediately. A modest wind could cause alternate halves of the center span to visibly rise and fall several feet over four- to five-second intervals. This flexibility was experienced by the builders and workmen during construction, which led some of the workers to christen the bridge “Galloping Gertie.” The nickname soon stuck, and even the public felt these motions on the day that the bridge opened on July 1, 1940.

The bridge became something of a tourist attraction. Cars often made trips specifically to ‘ride’ the bridge. Engineers at the time believed that the structure was safe, but in late July 1940 the University of Washington, under the direction of Professor F.B. Farquharson, began filming the bridge’s movement and conducting a series of experiments to devise methods to limit the movement.

Transit and Motion Picture Camera mounted on Tacoma Narrows Bridge Tollhouse, PH Coll. 206.26 University of Washington Libraries, Special Collections Division.
OSCILLATION OBSERVED

Logbook entry of the motion on the Tacoma Narrows Bridge, recorded by Farquharson on August 12, 1940. UW Engineering Experiment Station. Logbooks, University of Washington Libraries, Manuscripts, Special Collections, University Archives Division.

MITIGATION EFFORTS

The oscillations observed during construction prompted proposals to reduce the motion of the bridge. Proposals that were implemented were:
• attaching tie-down cables to the plate girders which were then anchored to 50-ton concrete blocks on the shore. This measure proved ineffective, as the cables snapped shortly after installation.
• the addition of a pair of inclined cable stays to connect the main cables to the bridge deck at mid-span. These remained in place until the collapse but were ineffective at reducing the oscillations.
• the structure 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, however, because the seals of the units were damaged when the bridge was sand-blasted before being painted.

MITIGATION EFFORTS

The Washington Toll Bridge Authority hired engineering Professor Frederick Burt Farquharson from the University of Washington, to undertake wind-tunnel tests and develop solutions to reduce the oscillations of the bridge. Professor Farquharson and his students built a 1:200-scale model of the bridge and a 1:20-scale model of a section of the deck. The first studies concluded on November 2, 1940—five days before the bridge collapse on November 7. He proposed two solutions:
• To drill holes in the lateral girders and along the deck so that the air flow could circulate through them, thereby reducing lift forces.
• To give a more aerodynamic shape to the transverse section of the deck by adding fairings or deflector vanes along the deck, attached to the girder fascia.

The first option was not favored because of its irreversible nature. The second option was the chosen one; but it was not carried out, because the bridge collapsed five days after the studies were concluded.

MITIGATION EFFORTS

Stiffening trusses added in 1946
Streamlining fairing added in 2004

THE COLLAPSE

On the morning of November 7, 1940 the wind was blowing through the Narrows at a steady speed of about 42 miles per hour. At 10 AM the bridge began to oscillate severely in the torsional mode and the bridge was closed to traffic. At 11:10 AM the center span collapsed.

This is a link to a video clip showing the collapse:
http://www.youtube.com/watch?v=3mdp9IqmcCs
With the exception of a small dog, there was no loss of life or injuries as a result of the collapse.

The investigation was undertaken by a commission formed by the Federal Works Agency. The commission suggested three possible causes of the failure:

- Random fluctuations in velocity and direction of the wind
- Fluctuating eddy currents formed as the wind passed around the plate girders, that is, vortex shedding
- Self-induced vibrations caused by wind fluctuation near the natural frequency of the bridge, that is, resonance

The commission did not conclude which of these possible causes was predominantly to blame for the bridge's collapse, but other early investigations tended to conclude that the probable cause was self-induced vibrations driven by vortex shedding as the wind passed around the solid plate girders. Subsequent opinions tended to attribute the collapse to aeroelastic flutter.
THE INVESTIGATION

Earlier suspension bridge designs typically had open lattice beam trusses supporting the roadbed. The Tacoma Narrows bridge was the first suspension bridge to use solid I-beams to support the roadbed. With earlier designs wind would pass through the truss and have minimal effect on the structure. With the Tacoma Narrows bridge design the wind would impact the solid girders directly and be diverted above and below the solid girders. After construction finished in June 1940 June it was observed that the bridge would sway dangerously in relatively mild wind conditions. This vibration of the roadbed was transverse, that is, "up-and-down" like a sinusoidal wave.

The Investigation

THE INVESTIGATION

THE RESONANCE HYPOTHESIS

It has been suggested that the cause of the failure of the Tacoma Narrows bridge was mechanical resonance. Resonance is when a structure oscillates at maximum amplitude at a certain frequency. This frequency is called the "natural frequency" of the structure. At this frequency small periodic driving forces can produce large amplitude vibrations because the system stores vibrational energy. The phenomenon is described by the differential equation:

$$m \ddot{x} + c \dot{x} + kx = F \sin(\omega t)$$

where $m$, $c$, and $k$ are the mass, damping coefficient and stiffness of the structure and $F$ and $\omega$ are the amplitude and the angular frequency of the exciting force. The solution of this ordinary differential equation as a function of time $t$ represents the displacement response of the structure. In this system resonance happens when $\omega$ is approximately

$$\omega_r = \left( \frac{k}{m} \right)^{1/2}$$

where $\omega_r$ is the natural (resonant) frequency of the structure.

The Investigation

THE INVESTIGATION

THE RESONANCE HYPOTHESIS

Each structure has natural frequencies. For resonance to occur, it is necessary to have periodicity in the excitation force. The suggested cause for periodicity in the wind force was vortex shedding. Non-streamlined bodies like bridge decks, in the wind shed wakes whose characteristics depend on the size and shape of the body and the properties of the air. These wakes are accompanied by alternating low-pressure vortices on the downwind side of the body. This is called the "Von Kármán vortex street". The body will try to move toward the low-pressure zone, in an oscillating movement called vortex-induced vibration. If the frequency of vortex shedding matches the resonance frequency of the structure, the structure will begin to resonate and the structure's movement can become self-sustaining.

The Investigation

THE INVESTIGATION

THE RESONANCE HYPOTHESIS

On November 7 at about 10 AM a torsional vibration mode (that is, "clockwise-counterclockwise") of the roadbed was observed for the first time. The torsional mode of vibration was the "second mode" in which the center of the span remains motionless while the two halves rotate in opposite directions. This torsional oscillation had a frequency of about 5 seconds. This torsional mode may have been triggered by transverse oscillation snapping one of the suspender cables, which created an imbalanced condition which caused aerelastic flutter.

The Investigation

THE INVESTIGATION

THE RESONANCE HYPOTHESIS

The frequency of the vortices in the von Kármán vortex street is called the Strouhal frequency $f_s$ and is given by

$$f_s = \frac{v}{d}$$

where $v$ is the wind speed and $d$ is the characteristic length of the body.
Aeroelastic flutter is a phenomenon in which several degrees of freedom of a structure become coupled in an unstable oscillation driven by the wind. This inserts energy to the bridge during each cycle so that it neutralizes the natural damping of the structure. The oscillations increase in amplitude with each cycle because the wind pumps more energy than the flexing of the structure can dissipate, and finally drives the bridge toward failure due to excessive deflection and stress. The wind speed that causes the beginning of the fluttering phenomenon is called the “flutter velocity.” Fluttering occurs even in low-velocity winds with steady flow. Hence, bridge design must ensure that flutter velocity will be higher than the maximum mean wind speed present at the site.

In the resonance hypothesis it was suggested that the Strouhal frequency was the same as the natural vibration frequency of the bridge i.e. $2\pi f = \omega$, causing resonance and therefore vortex-induced vibration. But in the case of the Tacoma Narrows Bridge, there was no resonance. According to Farquharson, one of the main investigators of the cause of the bridge collapse, the wind was steady at 42 miles per hour and the frequency of the destructive mode was 12 cycles/minute. This was neither a natural frequency mode of the structure nor the frequency of blunt-body vortex shedding of the bridge at that wind speed (which was approximately 1 Hz). Thus it is improbable that the resonance with alternating vortices played an important role in the oscillations of the bridge. There is no correlation between wind velocity and oscillation frequency as is required in case of resonance with vortices whose frequency depends on the wind velocity.

Aeroelastic flutter is a phenomenon in which several degrees of freedom of a structure become coupled in an unstable oscillation driven by the wind. This inserts energy to the bridge during each cycle so that it neutralizes the natural damping of the structure. The oscillations increase in amplitude with each cycle because the wind pumps more energy than the flexing of the structure can dissipate, and finally drives the bridge toward failure due to excessive deflection and stress. The wind speed that causes the beginning of the fluttering phenomenon is called the “flutter velocity.” Fluttering occurs even in low-velocity winds with steady flow. Hence, bridge design must ensure that flutter velocity will be higher than the maximum mean wind speed present at the site.

3. Contributing to the torsional motion of the bridge deck was “vortex shedding.” Shedding likely occurred as follows:

(a) Wind separated as it struck the side of the 8-foot solid plate girders. A small amount twisting occurred in the bridge deck, because steel is elastic and changes form under high stress.

(b) The twisting bridge deck caused the wind flow separation to increase. This formed a vortex, or swirling wind force, which further lifted and twisted the deck.

(c) The deck structure resisted this lifting and twisting. It had a natural tendency to return to its previous position. As it returned, its speed and direction matched the lifting force. In other words, it moved “in phase” with the vortex. Then, the wind reinforced that motion. This produced a “kick-on” event.

4. The external force of the wind alone was not sufficient to cause the severe twisting that led the Narrows Bridge to fail.

5. Now the deck movement went into “torsional flutter.” “Torsional flutter” is a complex mechanism. “Flutter” is a self-induced harmonic vibration pattern. This instability can grow to very large vibrations.
The amplitude of the motion produced by the fluttering increased beyond the strength of the suspender cables. Once several cables failed, the weight of the deck transferred to the adjacent cables that broke in turn until the central deck collapsed.

When the bridge movement changed from vertical to torsional oscillation, the structure absorbed more wind energy. The bridge deck’s twisting motion began to control the wind vortex so that the two were synchronized. In other words, the forces acting on the bridge were no longer caused by wind. The bridge deck's own motion produced the forces. Engineers call this “self-excited” motion.

It was critical that the two types of instability, vortex shedding and torsional flutter, both occurred at relatively low wind speeds. Usually, vortex shedding occurs at relatively low wind speeds, like 25 to 35 mph, and torsional flutter at high wind speeds, like 100 mph. Because of its design, and relatively weak resistance to torsional forces, from the vortex shedding instability the bridge went right into “torsional flutter.”

Now the bridge was beyond its natural ability to "damp out" the motion. Once the twisting movements began, they controlled the vortex forces. The torsional motion began small and built upon its own self-induced energy. Twisting induced more twisting, then greater and greater twisting. This increased beyond the bridge structure’s strength to resist. Failure resulted.

Othmar Ammann, a leading bridge engineer and member of the Federal Works Agency Commission investigating the collapse of the Tacoma Narrows Bridge, wrote:

"The Tacoma Narrows bridge failure has given us invaluable information... It has shown [that] every new structure [that] 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."

Which raises the question: Are "errors or failures" an acceptable price for human progress in all instances? Are they really acceptable where there is a serious risk to life and/or of great financial loss? This is the ethical issue raised by the Tacoma Narrows bridge collapse.
THE ETHICAL ISSUES
THEORETICAL AND EXPERIENTIAL KNOWLEDGE.

Experiential Knowledge. This is the body of knowledge the engineering profession has acquired by, one might say, trial-and-error. Over hundreds, if not thousands, of years engineers and their craftsmen-predecessors have tried different materials, designs and construction techniques on projects and learned what combinations produce the best result. This body of knowledge is passed from generation to generation of engineers through handbooks, codes and similar professional resources. Such knowledge can be comfortably employed by engineers if it has an appropriate record of successful application in the past.

The dilemma posed in design of the Tacoma Narrows bridge was that a theoretical analysis was used as the basis for a design decision (to use the 8-feet deep solid girders) when there was inadequate recognized theory upon which to rely in design of the bridge. In the absence of adequate theoretical knowledge, the design should have been controlled by adequate experiential knowledge. But here again, the experiential knowledge was inadequate. No suspension bridge of such length and slender proportions had ever been designed. Indeed, comparable suspension bridges that had been successfully designed and constructed up to that time had used only deep truss girders for roadway support. There was no experiential knowledge basis for the Tacoma Narrows proposal to use shallower solid I-beam girders. Did this mean the more "elegant" solution (8-feet deep I-beam roadway support girders) needed to be abandoned? Not necessarily. Absent adequate theoretical knowledge, there is a practicable way to supplement experiential knowledge it may be possible and reasonable to move the technology forward.

EXPAND THE EXPERIENTIAL KNOWLEDGE BASE: MODELING.

Wind tunnel modeling undertaken by Farquharson after the serious oscillation condition became apparent provided an important indication that there was a serious weakness in the Moeisoff design. These model tests also suggested remedial actions (cutting holes in the girders to allow wind to flow through them, and providing streamlining fairings around the girders) that may have proven successful. For example, a suspension bridge of similar design, the Bronx Whitestone Bridge, was reinforced after the Tacoma Narrows collapse. Fourteen-foot-high steel trusses were installed on both sides of the deck in 1943 to stiffen the bridge in an effort to reduce oscillation. In 2004, the stiffening trusses were removed and aerodynamic fiberglass fairings were installed along both sides of the road deck. The aerodynamic fairings have proven successful. Regrettably, Farquharson’s model studies were completed only days before the collapse and the suggested corrective measures could not be pursued.

Today, of course, modeling studies are a primary design tool used by bridge engineer’s to design major bridges. And computers using numerical methods such as finite-elements provide a greatly enhanced modeling tool in some instances. The “third” Carquinez Bridge west of Sacramento and completed in 2003 is an example of the state of the art in suspension bridge design. Wind tunnel testing and computer modeling were important tools employed in the design process. Note the slender, solid roadway support girders, similar to those in the Tacoma Narrows Bridge design.
If the experiential knowledge base is weak or incomplete it must be supplemented by an adequate base of experiential knowledge.

• If the theoretical knowledge base underlying a design is weak or incomplete, it must be supplemented by an adequate base of experiential knowledge.

• If the experiential knowledge base is weak or incomplete it must be expanded until it is adequate. A principal way of practically doing this is through appropriate modeling. In the example of the Tacoma Narrows bridge, the modeling that might have prevented the collapse was wind tunnel model testing.

• In competing for engineering contracts, do not propose designs that are not ipso facto supported by an adequate and complete theoretical and/or experiential knowledge base.

LESSENS LEARNED

So what are the ethical lessons we learned from the Tacoma Narrows bridge collapse? This may be a way to summarize:

AFTERMATH AND THE REPLACEMENT BRIDGE

Finger-pointing

Shortly after the collapse the Tacoma newspaper reported “U. S. MONEY-LENDERS BLAMED BY ENGINEERS FOR SPAN CRASH.” Clark Eldridge, the Washington highway department’s lead engineer on the project told reporters: “The men who held the purse-strings were the whip-crackers on the entire project. We had a tried-and-true conventional bridge design. We were told we couldn’t have the necessary money without using plans furnished by an eastern firm of engineers, chosen by the money-lenders.” Eldridge and other state engineers had protested Leon Moisseiff’s design with its 8-foot solid girders, which he called “sails.” But, it was no use.

Finger-pointing

The State of Washington and the federal government appointed separate boards of engineers to investigate the collapse of the Narrows Bridge. Insurance companies that insured the project also appointed an investigative board.

The Federal Works Administration’s 3-member panel had the highest profile, consisting of prominent engineers: Othmar Amman, Dr. Theodore Von Karmen, and Glen B. Woodruff. Their report to the Administrator of the PWA, John Carmody, was called the “Carmody Board” report.
The Carmody Board refused to blame any one person. The entire engineering profession was responsible. They exonerated Leon Moisseiff. However, after the collapse his reputation was seriously diminished.

Clark Eldridge of the Washington highway department was of a different opinion. In his autobiography he said that Moisseiff and the consulting firm of Moran & Proctor, "associated themselves to secure the commission to design the Tacoma bridge. They went to Washington, called on the Public Works Administration and informed them that they could design a structure here that could be built for not more than $7,000,000.

So when Mr. Murrow [representing the State of Washington] appeared asking for $11,000,000, our estimate, he was told $7,000,000 was all they would approve. They suggested that he confer with Mr. Moisseiff and Moran & Proctor. This he did, ending up employing them to direct a new design."

In June 1941 the insurance companies informed the State that they had concluded that the piers, cables, and towers could be salvaged and reused, and they offered the State a settlement of only $1.8 million. The State counter-claimed that only the piers were salvageable and the State’s loss was estimated at almost $4.3 million.

In August 1941, the two sides agreed on a settlement of $4 million. Now the State faced the problem of replacing the Narrows Bridge. In December, however, the commencement of World War II intervened and the bridge project was put on the backburner.
The replacement bridge

Almost ten years elapsed between the collapse of the bridge in November 1940 and completion in October 1950 of its replacement. The insurance litigation, commencement of World War II, and wartime shortages of steel and wire combined to fuel the delay.

AFTERMATH AND THE REPLACEMENT BRIDGE

The replacement bridge

In July 1941 the Toll Bridge Authority appointed Dexter Smith as chief design engineer to plan the new structure. By October, the state had a new design ready. The proposed 4-lane replacement bridge would cost about $7 million. And, it now was clear that it needed wind tunnel testing.

Wind testing of the replacement bridge was undertaken by F. B. Farquharson at the University of Washington. Between 1941 and 1947, Farquharson studied the old span and the new proposed Narrows Bridge. The tests gave the State's bridge engineers confidence in their new design. The proposed new bridge was expected to stand up to winds of 127 miles per hour.

The replacement bridge

By April 1946 revised designs for the Narrows Bridge were completed, with a projected cost of $8.5 million. But, steel was in short supply in the immediate post-WWII years. Because of post-war material shortages and difficulties in arranging for insurance coverage the State was unable to request bids for the new bridge until August 1947. By this time the estimated cost had gone up. The final construction cost estimate, made just prior to the construction bond issue, was $13,738,000.

The replacement bridge

In October 1950 opening day celebrations were held for completion of the replacement. Final cost for the bridge was $14,011,384.28.

AND NOW....

THE QUIZ
1. The Tacoma Narrows bridge was of the ________________ type.
   a. cantilever  
   b. cable-stayed  
   c. tressle  
   d. suspension  

2. The Washington Department of Highways proposed ________________ girders to support the roadway.
   a. reinforced concrete box-section  
   b. steel box-section  
   c. steel truss  
   d. steel I-beam  

3. Moisseiff proposed ________________ girders to support the roadway.
   a. reinforced concrete box-section  
   b. steel box-section  
   c. steel truss  
   d. steel I-beam  

4. The United States _______________________ strongly supported construction of the bridge.
   a. military  
   b. Bureau of Reclamation  
   c. Department of Commerce  
   d. judiciary  

5. The ________________ provided the majority of funding for the project.
   a. Washington State Toll Bridge Authority  
   b. Reconstruction Finance Corporation  
   c. Public Works Administration  
   d. design-build  

6. Prior to the day of collapse, the oscillation of the bridge that had been observed was of the ________________ type.
   a. sinusoidal  
   b. torsional  
   c. transverse  
   d. orthogonal  

7. On the day of its collapse, the oscillation of the bridge that was observed was of the ________________ type.
   a. sinusoidal  
   b. torsional  
   c. transverse  
   d. orthogonal  

8. __________________ was not one of the possible causes of the collapse identified by the Federal Works Agency in the initial investigation of the collapse.
   a. Random fluctuations in velocity and direction of the wind  
   b. Wave action  
   c. Fluctuating eddy currents  
   d. Self-induced vibrations  

9. In order to investigate the oscillation of the bridge that was observed during construction and after its completion professor Farquharson conducted wind tunnel tests on a ___________ scale model of the bridge.
   a. 1:200  
   b. 1:300  
   c. 1:400  
   d. 1:500  

10. On November 7 at about 10 AM a __________ vibration mode of the roadbed was observed for the first time.
    a. lateral  
    b. torsional  
    c. transverse  
    d. duplex  

11. With regard to aerelastic flutter, the wind speed that causes the beginning of the fluttering phenomenon is called the “_________ velocity.”
    a. primary  
    b. secondary  
    c. flutter  
    d. entrance  

12. One of the suggestions, but not the only one, for the failure of the Tacoma Narrows bridge was mechanical ___________.  
    a. coupling  
    b. forcing  
    c. reinforcement  
    d. resonance  

13. Resonance is when a structure oscillates at maximum amplitude at a certain frequency is called the "natural frequency" of the structure. The phenomenon is described by the differential equation:

\[ m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \omega^2 \sin(\omega t) \]

where \( c \) is the ___________ and stiffness of the structure and \( F \) and \( \omega \) are the amplitude and the angular frequency of the exciting force.
    a. displacement constant  
    b. acceleration constant  
    c. damping coefficient  
    d. velocity coefficient
14. In the equation below,
\[ \omega_r = (k/m)^{1/2} \]
\( \omega_r \) is the ________________ of a structure.

a. forcing frequency  
b. resonant frequency  
c. torsional frequency  
d. lateral frequency

15. In the equation below,
\[ \omega_r = (k/m)^{1/2} \]
\( k \) is the ________________ coefficient of a structure.

a. damping  
b. resonance  
c. mass  
d. lateral

That’s all folks!