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

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

ETHICAL ISSUES FROM THE TACOMA NARROWS BRIDGE COLLAPSE

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

 1

INTRODUCTION

Here is what we will talk about today….

- •**History of the project**
- •**Design proposals**
- •**The design**
- •**Oscillation observed**
- •**Mitigation efforts**
- •**The collapse**
- •**The investigation**
- •**The ethical issues**
- •**Lessons learned**
- •**Aftermath and the replacement bridge**

Paul Guyer 2010 2

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 2010 3

INTRODUCTION

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.

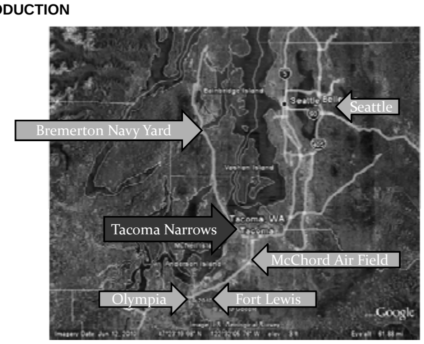
Paul Guyer 2010 4

INTRODUCTION

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 5

INTRODUCTION



Location of the Tacoma Narrows Bridge

Paul Guyer 2010 6

INTRODUCTION

DRIVING DISTANCES AND TIME VIA AND AROUND 1940 NARROWS BRIDGE		
Route	via Olympia	via Narrows Bridge
Tacoma to Gig Harbor	107 miles	8 miles
	2 hours 10 minutes	17 minutes
Bremerton Naval Shipyard to McChord Air Base	79 miles	39 miles
	1 hour 50 minutes	55 minutes
Tacoma to Port Orchard	91 miles	21 miles
	2 hours	30 minutes
Tacoma to Bremerton	90 miles	30 miles
	2 hours	40 minutes
Tacoma to Port Angeles	152 miles	115 miles
	3 hours 25 minutes	2 hours 33 minutes

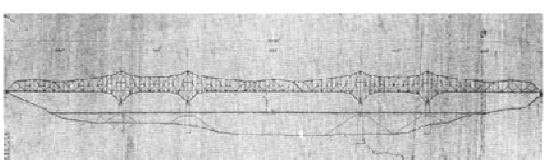
INTRODUCTION

The Tacoma Narrows today

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.

1929 Proposal by David Steinman for a Tacoma Narrows Suspension Bridge



1931 proposal by the Tacoma City Engineer for a Tacoma Narrows Cantilever Bridge

HISTORY

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.

HISTORY

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.

Paul Guyer 2010 13

HISTORY

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.

Paul Guyer 2010 14

HISTORY

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.

Paul Guyer 2010 15

DESIGN PROPOSALS

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 convention 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 (Authority) submitted the Eldridge design to the federal Public Works Administration (PWA) with a request for $11 million.

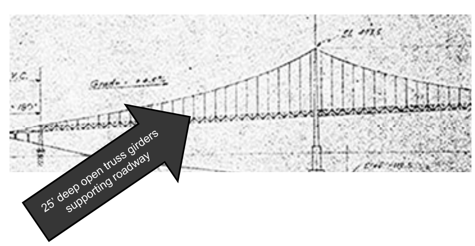
Paul Guyer 2010 16

DESIGN PROPOSALS

Clark Eldridge
Project Engineer
WA State Toll Bridge Authority

Paul Guyer 2010 17

DESIGN PROPOSALS



The Washington State DOH (Eldridge) proposal for a suspension bridge with the roadway supported on 25-feet deep truss girders

Paul Guyer 2010 18

DESIGN PROPOSALS

The Competition Heats Up

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."

DESIGN PROPOSALS

The Competition Heats Up

The State Toll Bridge Authority reluctantly agreed. Leon Moisseiff of New York became the consultant hired to design the superstructure (towers, cables, etc.). The firm of Moran & Proctor of New York became the consultants hired to design the substructure (piers).

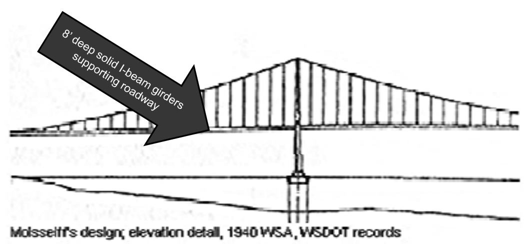
When Moisseiff's design arrived at the Washington State Highway Department in Olympia, the agency's engineers protested. The state's experts called Moisseiff's plan "fundamentally unsound." The design made the Narrows Bridge lighter and narrower than any bridge ever built, they said, "in the interests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

DESIGN PROPOSALS

Leon Moisseiff

DESIGN PROPOSALS



The Moisseiff proposal for a suspension bridge with the roadway supported on 8-feet deep solid I-beam girders

THE DESIGN

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

Based upon this theory Moisseiff proposed stiffening the bridge with a set of eight-foot-deep plate girders rather than the 25 feet deep trusses proposed by the Washington Department of Highways. This change contributed substantially to the difference in the estimated cost of the project.

Additionally, because fairly light traffic was projected, the bridge was designed with only two opposing lanes and total width was only 39 feet. This was narrow relative to its length. With only the 8 feet-deep plate girders providing depth the bridge's roadway section was substantially reduced.

THE DESIGN

1940 Tacoma Narrows Bridge and Contemporaries				
	George Washington	Golden Gate	Bronx/ Whitestone	Tacoma Narrows
Year completed	1935	1937	1939	1940
Cost ($ millions)	59.5	35.0	19.7	6.4
Length of center span (feet)	3500	4200	2300	2800
Girder depth (feet)	36	25	11	8
Width (feet)	106	90	74	39
Ratio of girder depth to length of center span	1:120	1:168	1:209	1:350
Ratio of width to length of center span	1:33	1:47	1:31	1:72

Paul Guyer 2010 25

THE DESIGN

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.

Paul Guyer 2010 26

THE DESIGN

Tacoma Narrows Bridge Under Construction
(University of Washington Libraries, Special Collections, PH Coll. 11.19)

Paul Guyer 2010 27

THE DESIGN

Tacoma Narrows Bridge Under Construction
(University of Washington Libraries, Special Collections, PI-20789)

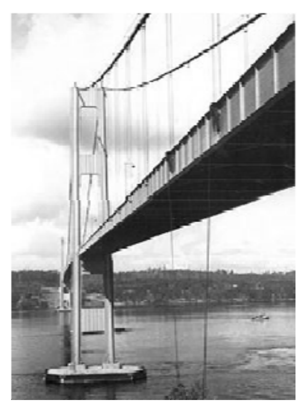
Paul Guyer 2010 28

THE DESIGN

Tacoma Narrows Bridge Completed
(University of Washington Libraries. Special Collections Division, PH Coll. 290.24)

Paul Guyer 2010 29

THE DESIGN



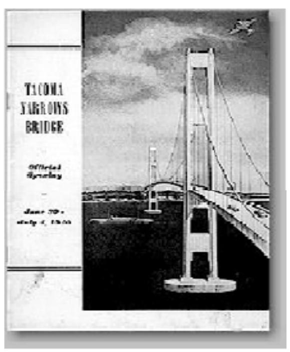
Paul Guyer 2010 30

THE DESIGN

THE DESIGN

Opening Ceremonies for the Tacoma Narrows Bridge in 1940

THE DESIGN



Opening Ceremonies for the Tacoma Narrows Bridge in 1940

OSCILLATION OBSERVED

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.

OSCILLATION OBSERVED

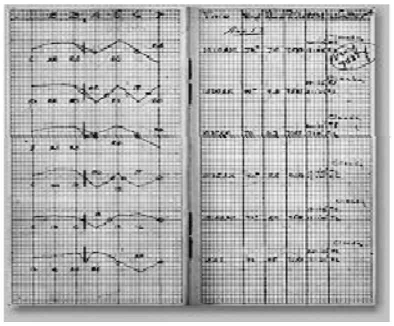
The bridge became something of a tourist attraction. Cars often made trips specifically to 'ride' the bridge. Engineers at the time believed that the structure was safe, but in late July 1940 the University of Washington, under the direction of Professor F.B. Farquharson, began filming the bridge's movement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

OSCILLATION OBSERVED

Transit and Motion Picture Camera mounted on Tacoma Narrows Bridge Tollhouse. PH Coll. 290.26 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 Records, Acc. No. 06-034, Bridge Movement Data Logbooks. University of Washington Libraries. Manuscripts, Special Collections, University Archives Division.



Paul Guyer 2010 37

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.

Paul Guyer 2010 38

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.

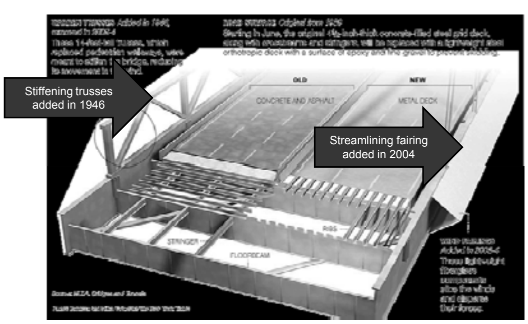
The first option was not favored because of its irreversible nature. The second option was the chosen one; but it was not carried out, because the bridge collapsed five days after the studies were concluded.

Paul Guyer 2010 39

MITIGATION EFFORTS

Paul Guyer 2010 40

MITIGATION EFFORTS



Bronx Whitestone Bridge aerodynamic fairing added in 2004

Paul Guyer 2010 41

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=3mclp9QmCGs

Paul Guyer 2010 42

THE COLLAPSE

Paul Guyer 2010 43

THE COLLAPSE

Paul Guyer 2010 44

THE COLLAPSE

Paul Guyer 2010 45

THE COLLAPSE

Paul Guyer 2010 46

THE COLLAPSE

With the exception of a small dog, there was no loss of life or injuries as a result of the collapse.

Paul Guyer 2010 47

THE INVESTIGATION

Investigation of the collapse 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.

Paul Guyer 2010 48

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

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 aeroelastic flutter.

THE INVESTIGATION

THE RESONANCE HYPOTHESIS

It has been suggest 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:

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

THE INVESTIGATION

THE RESONANCE HYPOTHESIS

where *m*, *c* and *k* are the mass, damping coefficient and stiffness of the structure and *F* and ω 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 ω is approximately

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

.

where ω_r is the natural (resonant) frequency of the structure.

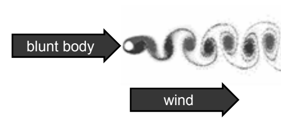
THE INVESTIGATION

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 RESONANCE HYPOTHESIS



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

THE INVESTIGATION

$$\frac{f_s D}{U} = S$$

Where U is the flow velocity, D is a characteristic length of the non-streamlined body and S is the dimensionless Strouhal number, which depends on the body in question. For Reynolds Numbers greater than 1000, the Strouhal number is approximately equal to 0.21. In the case of the Tacoma Narrows, D was approximately 8 feet and S was 0.20.

THE INVESTIGATION

In the resonance hypothesis it was suggested that the Strouhal frequency was the same as the natural vibration frequency of the bridge i.e. $2\pi f_s = \omega$, 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.

THE INVESTIGATION

AEROELASTIC FLUTTER

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 in 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.

THE INVESTIGATION

AEROELASTIC FLUTTER

Here is a generally accepted explanation of the failure mechanism. It relies on the aeroelastic flutter phenomenon driven by the vortex shedding phenomenon of the wind passing around the solid I-beam girders.

1.The bridge had relatively little resistance to torsional forces. This was because it had such a large depth-to-width ratio, 1 to 72. The bridge’s long, narrow, and shallow stiffening girder made the structure extremely flexible.

2. On November 7, 1940 shortly after 10 a.m., a critical event occurred. The cable band at mid-span on the north cable slipped. This allowed the cable to separate into two unequal segments. That contributed to the change from vertical (up-and-down) to torsional (twisting) movement of the bridge deck.

THE INVESTIGATION

AEROELASTIC FLUTTER

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 "lock-on" event.

THE INVESTIGATION

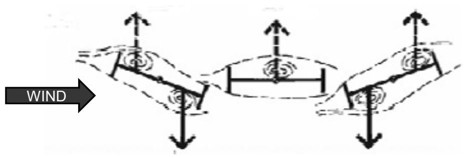
AEROELASTIC FLUTTER

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 INVESTIGATION

AEROELASTIC FLUTTER



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.

Paul Guyer 2010 61

THE INVESTIGATION

AEROELASTIC FLUTTER

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 the two were synchronized. The structure's twisting movements became self-generating. 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."

Paul Guyer 2010 62

THE INVESTIGATION

AEROELASTIC 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.

Paul Guyer 2010 63

THE ETHICAL ISSUES

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."

Paul Guyer 2010 64

THE ETHICAL ISSUES

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.

Paul Guyer 2010 65

THE ETHICAL ISSUES

THEORETICAL AND EXPERIENTIAL KNOWLEDGE.

Fundamentally, engineers employ two types of knowledge in design activities:

Theoretical Knowledge. This is the applied physics learned in engineering school. F=ma, Bernoulli's equation, Ohm's law, the Second Law of Thermodynamics, etc. In engineering practice there is no uncertainty about the correctness of these theoretically derived relationships. Engineers can confidently employ this knowledge in design activities and know that it will lead to a proper result.

Paul Guyer 2010 66

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. Sewer lines should slope 1/4 inch per foot; the location of seismic zones and their associated loads; velocities in water pipes should not exceed 10 feet per second; restrooms should be designed for 10 air changes per hour; and so forth. This knowledge can be comfortably employed by engineers *if it has an appropriate record of successful application in the past.*

THE ETHICAL ISSUES

THE TACOMA NARROWS DESIGN DILEMMA.

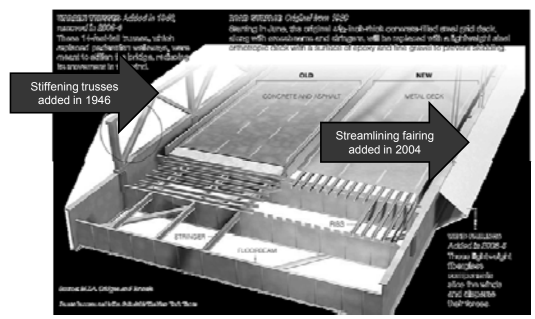
The dilemma posed in design of the Tacoma Narrows bridge was that a theoretical analysis was used as the basis for a design decision (to use the 8-feet deep solid girders) when there was inadequate recognized theory upon which to rely in design of the bridge. In the absence of adequate theoretical knowledge, then, 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, if there is a practicable way to supplement experiential knowledge it may be possible and reasonable to move the technology forward.

THE ETHICAL ISSUES

EXPAND THE EXPERIENTIAL KNOWLEDGE BASE: MODELING.

Hindsight is a great thing. Ex-post facto, the Tacoma Narrows bridge collapse taught the bridge engineering profession the importance of modeling as a tool to expand experiential knowledge. 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 Moisseiff 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.

THE ETHICAL ISSUES



Bronx Whitestone Bridge aerodynamic fairing added in 2004

THE ETHICAL ISSUES

EXPAND THE EXPERIENTIAL KNOWLEDGE BASE: MODELING.

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.

THE ETHICAL ISSUES

EXPAND THE EXPERIENTIAL KNOWLEDGE BASE: MODELING.

The "third" Carquinez Bridge
(the "first" and "second" bridges are seen beyond; the "first" was subsequently demolished)
(California Department of Transportation)

THE ETHICAL ISSUES

A LINGERING ETHICAL QUESTION.

There have been suggestions in the literature that the engineers who proposed the solid girder design to the federal Public Works Administration and the Reconstruction Finance Corporation may have been motivated to some degree by an interest in obtaining the design contract. Clearly competition for engineering contracts is a healthy thing, but care must be taken to not propose designs that cannot be delivered safely and with a reasonable expectation that they will be completed on-time and on-budget. There are more than just a few examples of architecturally exciting buildings that were proposed to owners by architects that turned out to be disastrously over budget and which presented many expensive engineering and construction challenges.

Paul Guyer 2010 73

LESSONS LEARNED

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

- 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 practicably 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.

Paul Guyer 2010 74

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.

Paul Guyer 2010 75

AFTERMATH AND THE REPLACEMENT BRIDGE

Finger-pointing

Federal Public Works Administration officials said they knew nothing about a problem with the bridge's design. Soon, however, one of their own engineers broke the truth to the newspapers and the public. Two months after the collapse the Tacoma newspaper reported that the federal PWA's own engineer had refused to approve the bridge when it was completed in July 1940. David L. Glenn, the PWA's field engineer on site in Tacoma, submitted a report warning of faults in design and refusing to recommend acceptance of the structure. But, the PWA accepted the bridge. So did the Washington State Toll Bridge Authority. The PWA fired David Glenn two weeks after the story made headlines. Newspapers reported that he had been "relieved" of his position on January 25, 1941.

Paul Guyer 2010 76

AFTERMATH AND THE REPLACEMENT BRIDGE

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 FWA, John Carmody, was called the "Carmody Board" report.

Paul Guyer 2010 77

AFTERMATH AND THE REPLACEMENT BRIDGE

Finger-pointing

In March 1941 the Carmody Board announced its findings. Three key points stood out: (1) The principal cause of the Narrows Bridge's failure was its "flexibility;" (2) the solid plate girder and deck acted like an airfoil, creating "drag" and "lift;" and (3) aerodynamic forces were little understood and engineers needed to test all suspension bridge designs thoroughly using models in a wind tunnel.

Paul Guyer 2010 78

AFTERMATH AND THE REPLACEMENT BRIDGE

Finger-pointing

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.

AFTERMATH AND THE REPLACEMENT BRIDGE

Finger-pointing

The Carmody Board's report contained a statement by the Acting Commissioner of Public Works explaining the selection of the consulting engineers for the project. It stated: "In no instance did this Administration nominate, or express any preference for any particular individual, group or firm."

AFTERMATH AND THE REPLACEMENT BRIDGE

Finger-pointing

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."

AFTERMATH AND THE REPLACEMENT BRIDGE

Paying the bill

The bridge was insured by a collection of 22 different insurance companies. The total insured value was $5.2 million, or 80% of its full value. When the bridge collapsed, the lives of some insurance men suddenly became very interesting.

AFTERMATH AND THE REPLACEMENT BRIDGE

Paying the bill

An interesting vignette that came to light in the financial aftermath was the revelation that one insurance agent, Hallett French, had embezzled premiums on one of the State's insurance policies and never reported the transaction to his company. He subsequently went to prison.

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.

AFTERMATH AND THE REPLACEMENT BRIDGE

Paying the bill

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.

AFTERMATH AND THE REPLACEMENT BRIDGE

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.

Paul Guyer 2010 85

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.

Paul Guyer 2010 86

AFTERMATH AND THE REPLACEMENT BRIDGE

The replacement bridge

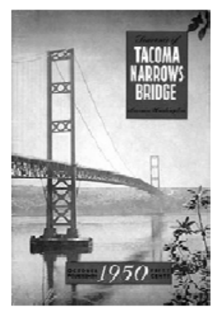
By April 1946 revised designs for the Narrows Bridge were completed, with a projected cost of $8.5 million. But, steel was in short supply in the immediate post-WWII years. Because of post-war material shortages and difficulties in arranging for insurance coverage the State was unable to request bids 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.

Paul Guyer 2010 87

AFTERMATH AND THE REPLACEMENT BRIDGE

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.



Paul Guyer 2010 88

AFTERMATH AND THE REPLACEMENT BRIDGE

The replacement bridge

Paul Guyer 2010 89

AND NOW….

THE QUIZ

Paul Guyer 2010 90

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 aeroelastic 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:

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

where c is the ________________ and stiffness of the structure and F and ω 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,

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

ω_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

Paul Guyer 2010 97

That's all folks!

Paul Guyer 2010 98