Ethical Issues from the Tacoma Narrows Bridge Collapse

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1. INTRODUCTION

The original Tacoma Narrows Bridge (all references made here are related to the original bridge, not its subsequent replacement which is in service today) was built 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.

Figure 1

Opening Ceremonies for the Tacoma Narrows Bridge in 1940
(University of Washington Libraries. Special Collections Division, PH Coll. 290.25)

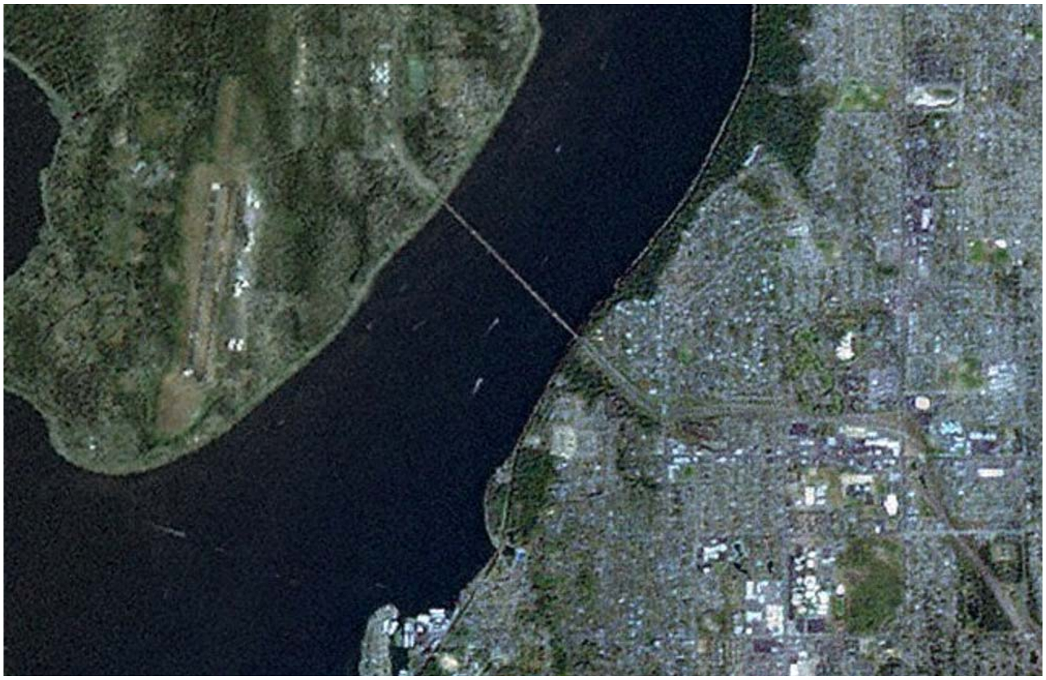

Figure 2

The Tacoma Narrows Bridge today

2. HISTORY

Interest in the 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. In 1937 interest was revived when the state of Washington created the Washington State Toll Bridge Authority (Authority). In response to a request from the city of Tacoma and others, the

Authority initiated a study of the feasibility of financing a Tacoma Narrows bridge from toll revenue. This study concluded that toll revenue would not be sufficient to fund the design and construction.

In the national security environment of the late 1930s, however, the U.S. military had a strong interest in seeing the bridge built because of the need for a direct route between the Puget Sound Naval Shipyard in Bremerton on the Pierce County side of the Narrows and the Army's McChord Field and Fort Lewis on the Tacoma side. In addition, federal stimulus policies to bring the country out of the Great Depression looked favorably on public works projects to create jobs. 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.

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

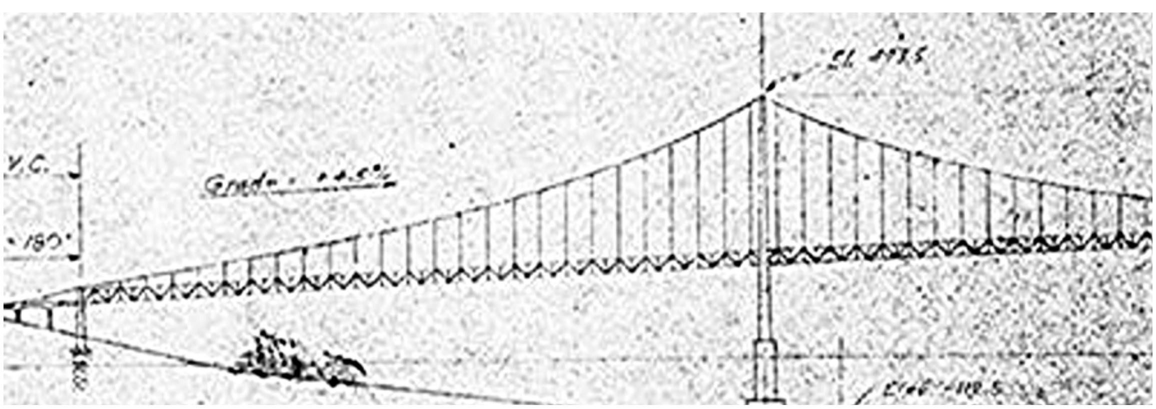

Figure 3

The Eldridge Design
(Washington State DOT records)

At this point a well known New York bridge engineer, Leon Moisseiff, submitted a proposal to the PWA and the Reconstruction Finance Corporation (RFC) to design the bridge at a cost of $8 million; a substantial saving in comparison. 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.

The combination of cost savings, Moisseiff's reputation, and the aesthetics of the slender design led to the design contract being awarded to Moisseiff and his associated engineering firm, Moran & Proctor, rather than having the design undertaken by Eldridge and the Washington Department of Highways. In June 1938 the PWA approved $6 million for the project with the remainder of the cost planned to be paid for by toll revenue. Construction began in September 1938, took only 19 months, and was completed at a cost of $6.4 million. Its main span was 2,800 feet, making it the third-longest suspension bridge in the world at the time. It was opened for traffic in July 1940 and collapsed in November of the same year.

3. DESIGN

The theoretical underpinning of the Moisseiff design was described in 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.

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 with a total width of 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.

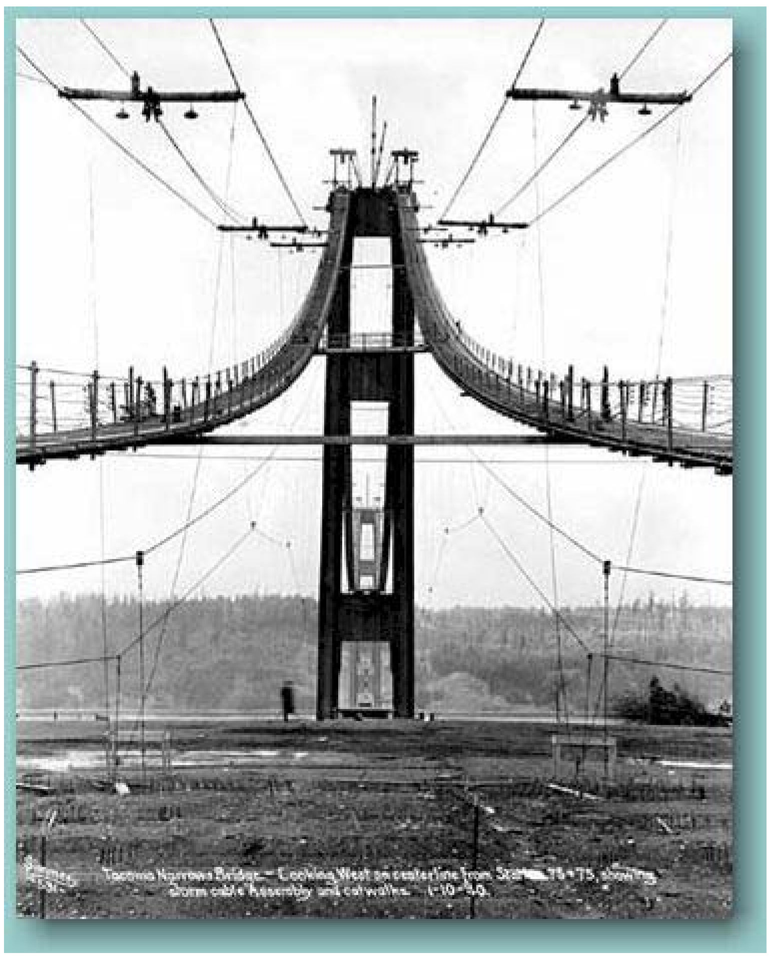

Figure 4

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

Figure 5

Tacoma Narrows Bridge under Construction
(University of Washington Libraries, Special Collections, Seattle Post-Intelligencer Collection, PI-20789. Courtesy of the Museum of History and Industry, Seattle)

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. The bridge became known for its movement. 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.

Figure 6

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

4. OSCILLATION MITIGATION EFFORTS

The oscillations observed during construction prompted proposals to reduce the motion of the bridge. Proposals that were implemented included:

- 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.

- adding 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.
- equipping the structure 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.

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.

5. 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

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

Figure 7

Collapse of the Tacoma Narrows Bridge on November 7, 1940
(University of Washington Libraries. Manuscripts, Special Collections, University Archives Division, PH Coll. 290.36)

Figure 8

Broken Cable

(PH Coll. 290.59 University of Washington Libraries. Special Collections Division, PH Coll. 290.59)

6. 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.

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, consequently, would be diverted above and below the solid girders. After construction finished in June 1940, 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.

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 causing aeroelastic flutter.

6.1 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 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.

6.2 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:

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

where *m*, *c* and *k* are the mass, damping coefficient and stiffness of the structure, respectively; and *F* and ω are the amplitude and the angular frequency of the exciting force, respectively. 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:

$$\omega_r = \sqrt{k/m}.$$

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

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.

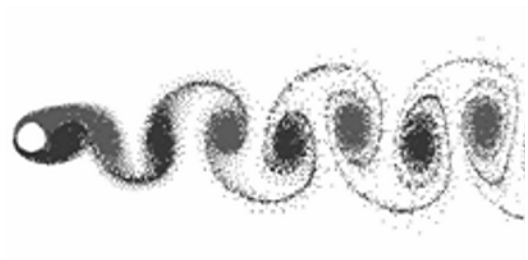

Figure 9

Vortex Shedding

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

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

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.

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.

7. 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."*

This 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.

7.1 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.

- *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.*

7.2 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.

7.3 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 2003, 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.

Figure 9

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

7.4 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.

8. 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.

9. SALVAGE EFFORTS AND THE REPLACEMENT BRIDGE. Salvage of the bridge began shortly after its collapse and continued for about three years. It was concluded by state and federal officials that repair of the bridge was not practical and it was decided the entire bridge would be dismantled and a new bridge constructed to replace it. With steel being in short supply due to World War II, steel from the bridge cables and the suspension span was sold as scrap.

The cable anchorages, tower pedestals and most of the remaining substructure were generally undamaged and were reused during construction of the replacement span that opened in 1950. The towers suffered major damage at their bases from being deflected twelve feet towards shore as a result of the collapse. They were dismantled, and the steel salvaged. The highway deck remains under water to this day.

Due to material and labor shortages as a result of World War II, it was 10 years before the bridge was replaced. The replacement bridge was completed in 1950. It is 5,979 feet long and is wider and has more lanes than the original bridge. Fifty years after its completion the rebuilt bridge was exceeding its capacity and a second parallel suspension bridge was constructed to carry eastbound traffic, with the 1950 suspension bridge reconfigured to carry westbound traffic. The new parallel bridge was completed in 2007.

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