ANALYSIS OF THE SECOND TACOMA SUSPENSION BRIDGE

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Abstract: The second Tacoma Narrows Bridge has been used for public traffic for more than 26 years, its design which influences all the suspension bridge afterward. Although its predecessor which was Tacoma Narrows Bridge, was failure in 1940 but the engineer found the reason though the research. It is the first bridge considering the wind action after failure. There are many unique features we can find in this special bridge. We will focus on the aesthetics, loading, strength, serviceability, construction, temperature, creep, wind, durability, susceptibility and future improvement.

Keywords: Bridges, suspension, Tacoma, wind action, failure, construction, improvement, future,

Introduction

The Second Tacoma Narrows Bridge which totally cost $14,000,000 for the whole project, opened to traffic on October 14, 1950. The Tacoma Narrows Bridge was the third longest suspension span in the world in 1950 and the fifth longest span in North America in 1991. It played an important role for the bridge design because of its numerous unique design features. It was the first time we used a research program to investigate the effects of wind acting upon a bridge in aerodynamic area and used wind tunnel tests to determine the behavior and stability of a physical model of a bridge in the structural design. Because of the new method using in this project which had been never done before, it gave important information and set a good example for the case studies. All suspension bridge designs followed the basic design of considering the effect of wind action. There are many unique features in the construction:

- Open steel grid slots,
- Great ratio of the depth of stiffening truss to span length,
- The double lateral system
- The hydraulic energy absorbing and damping devices
- The record depth below water when caissons were submerged

The bridge had received much nation-wide attention due to the failure of the first Tacoma Narrows Bridge. In addition, it is one the most important transportation corridors between the mainland with the Kitsap and Olympic peninsulas in Washington State.

Figure 1 Location of Second Tacoma Suspension Bridge
The failure of its predecessor

The design of the suspension bridge was slightly different to the other suspension bridge at the time. For example, Golden Gate Bridge in San Francisco, its deck was built with stiffening trusses, but for Tacoma Narrows its deck was built with shallow plate girders. This was designed to economize on material. They limited the width of the bridge with the same reasons, also taking into account the light traffic loads that they expected. Even though Tacoma Narrows has the third longest span of suspension bridges at the time, but its depth and width of deck were 8 and 39 feet respectively. The two-lane bridge was extremely narrow relative to its length. As a result, the Tacoma Narrows experienced rolling undulations, which were driven by the wind making the roadway prone to oscillate. It vibrated rather strongly whenever there was a little wind. Crossing it was like a roller-coaster ride so that it acquired the nickname “Galloping Gertie”. The major weakness in the Tacoma Narrows was its flexibility, both vertically and in torsion. One reason for this was that the ratio between the depths of the girders to the span of the bridge was very large, over twice that of the Golden Gate bridge. Another reason was the high ratio between the width and the span of the bridge. Though in a structural sense the excessive flexibility may have no harmful effects, but it is doubtful that travelers who cross the structure will accept the potentially large undulations without reservation. Stiffening trusses are usually added to reduce and control the vertical and torsional motions. This can damp out any aerodynamic forces on the structure by their sheer weight and overturn any moments produced by the wind. When a moderate wind storm stroke the bridge in the morning of 7th November 1940, 4 months after it opened for the traffic, the Tacoma Narrows collapsed. Initially, winds at 35 mile per hour excited the bridge's transverse vibration mode, with an amplitude of 1.5 feet. The wind then increased to 42 miles per hour. A support cable at mid-span suddenly came loose and the roadway began to twist back and forth in increasingly violent fashion. This resulted in an unbalanced loading condition. The bridge was quickly closed to traffic. The bridge response thus changed to a 0.2 Hz torsional vibration mode, with an amplitude up to 28 feet. There are three theories that likely causing collapse of the bridge:

- Random turbulence
- Periodic vortex shedding
- Aerodynamic instability

The wind pressure simply excited at the natural frequencies of the bridge. This condition is called "resonance". This steadily increasing the amplitude of its oscillations until the span was ripped apart. The problem with this theory is that resonance is a very precise phenomenon, requiring the driving force frequency to be at, or near, and the natural frequencies of the system in order to produce large oscillations. The turbulent wind pressure, however, would have varied randomly with time. Therefore turbulence would seem unlikely to have driven the observed steady oscillation of the bridge. The collapse of the original Tacoma Narrows bridge has taught engineers a valuable lesson. After its failure, engineers learned a lot about how aerodynamic forces begin to affect a structure, and how it is dangerous to exceed design parameter without fully understanding all the forces acting on the structure. After the collapse Federal Works Agency reported that the bridge construction was the most suitable for its uses, economics, and location. Therefore, the engineers should not be blamed for the failure, since their understanding was incomplete. Even during the construction the structure was experiencing small oscillation.
The design consideration

![Figure 5 Illustration of basic suspension bridge](image)

Arch bridge, beam bridge, cable-stayed bridge, cantilever bridge and suspension bridge are the main type of the bridges in the world. A typical suspension bridge, the cables must be anchored at each end of the bridge so that the load could be transformed into a tension in these main cables. There is a continuous girder with one or more towers erected above piers in the middle of the span. There are some features comparing to other type of bridges.

- Long in proportion to the materials required for long span.
- Being flexible under wind and seismic conditions,
- Less weight and bulk in the same strength and stability of other design schemes
- Less expensive to construct and maintain.

However, there are some advantages of suspension bridges.

- Unusable in strong wind conditions because of lacking stiffness.
- Being flexible not used for heavy rail crossings
- Require expensive foundation work when building on soft ground.

When a bridge is designed, there are many impacts need to consider such as aesthetics, loading, strength, serviceability, construction, temperature, creep, wind, durability, susceptibility and future improvement.

Aesthetics

There are ten areas of bridge we need to consider in aesthetics, according the Fritz Leonhardt[1].

1. Fulfilment of function
2. Proportions of the bridge.
3. Order within the structure.
4. Refinement of design.
5. Integration into the environment.
7. Colour of components.
8. Character.
9. Complexity in variety.
10. Incorporation of nature.

![Figure 6 The aesthetics of the bridge](image)

The new Tacoma Narrows Bridge is quite different from its predecessor which was failure in 1940. When entering the pre-war period, the design of suspension bridge had been changed not only in structure, but also the aesthetics. The bridge also represented the aesthetic sense of that generation and the expression of American culture. It showed the wisdom and beauty of American design. Standardization and pre-fabricated parts had become more and more important in construction methods comparing the modern design during Second World War era. Because of the vibration in wind, the suspension bridge is like a guitar string which could make a sound, normally the sound is not inaudible. One of the remarkably feature is the "X" cross-brace which is designed between tower piers. The "X" cross-brace is also the main design element in aesthetic and it expresses conveys strength, power, and solidity in graph. The whole bridge is painted with green colour which is called Narrows Green. The design gives us chances to overlook from the bridge and to find remain tower which was undamaged in 1940, became a part of the new bridge.

![Figure 7 The view of the bridge](image)
From remain tower, we can image the old one which was described as the most beautiful bridge in the world during that period. [2]

**Piers**

Foundation is one of the most important factor to be considered in bridge design. The piers carry the weight of the traffic and suspended structure, which were steady during environmental hazard. The piers were designed by Clark Eldridge, which stood ready to support the new span's towers. The twin steel legs of each tower were 60 feet apart, center-to-center. Because of the narrow and close to the water in the original pedestals, the new pedestals were 18 feet in order to keep the tower legs safe from salt spray (corrosion). The height of the towers on the new span was 58 feet higher than those on the 1940 Narrows Bridge. It was better when gave 1.6 times the load which carried by the original piers. It distributed more evenly by the greater width between tower legs. Another feature was the dead load pressure which was increased on the piers by only 6 percent. We found that the cells in the footing had been full of water. The weight of the water was more than we expected. We should build higher height of piers if we considered these at the beginning.

**Towers**

![Figure 8 Towers with catwalks, 1949](image)

Towers are influence by both vertical applied load and eccentricity from the top of the tower. Because of supporting the main cables, the dead load mostly affects on tower. For this reason, an increase in live load does not greatly affect the axial load of towers. However, the cable system is distorted by the application of live load. The $P$-$d$ effects are acting on a tower where $P$ is the axial force and $d$ is the eccentricity of its application. $P$ is little affected by live load, compared to $d$. [3]. Tower erection used A "crawler crane," is used for tower erection, which was convenience for workers to complete each tower leg.

The vertical legs of tower were made of hollow steel cells which is designed four columns to form a hollow core in the center. Each section is 32 feet long and weighs 27 tons. Viewed in cross-section, the four cells in each leg form a cross shape. Temporary "outriggers" were added into construction in order to keep the tower stable. The "outriggers" was used until the cables and deck trusses could be completed. When the top cross bracing was completed, the 28-ton cast-steel cable saddles were constructed and place at the top of each leg. 36 bolts were used to secure the cable saddles.

![Figure 9 Main Tower Elevation and Side view](image)
Anchorages

The new bridge had a much bigger cable load, increased from the original 28 million pounds to 36 million pounds. Because of this, the modification of 1940’s bridge anchorages was needed. The new anchorages were 60-foot spacing between cables. The original structures became the cores of the new, choosing the heavier and wider anchor blocks which were 54,000-ton. The There are 62-foot long eye-bars constructed in the anchorages which embedded into the new concrete.

Figure 10 Anchorage construction, 1948

Cables

Once the towers and cable saddles were finish, the 20-1/4 inch diameter main suspension cables started to construct. The cables are spaced 60 feet separately, each cable contained 19 strands of 458 No.6 gauge wires. A continuous cable from anchorage to anchorage was form by the strands looped. When each section of the deck was assembled, all workers hung the suspender cables. Each set of two cables, looped over the main cable appears to be four wires. These 1-3/8 inch diameter wire cables were attached to the deck at 32-foot intervals by zinc.

Figure 11 Anchorage view with cable and eye-bars, 1949

Deck

The 33-foot deep Warren stiffening truss system was assembled to support the deck. Four rolling derricks moved each way from the tower. There are four riveting crews and traveler operators. Two worked from the tower piers to the center of the main span, while two other from the piers to the shore. Firstly the top and bottom chords and their diagonal bracing were placed. Secondly, the workmen placed the floor beams between the chords. Then, the workmen laid the deck stringers lengthways on top of the beams. Finally, the members were pinned in place and finished the process. The deck was 46 feet 9 inches (curb-to-curb) for the 4 traffic lanes, and two sidewalks 2 feet 9 inches wide. Steel reinforcing rods were placed in the roadway. Then, workmen placed the deck slab, a light-weight concrete 5-3/4 inches thick with a 5/8-inch asphalt riding surface (used to lessen the load on the piers). The open steel wind grates were installed between driving lanes and at the curbs.

Figure 12 Deck cross-section, Current Narrows Bridge

WSA
**Stiffening System**

Stiffening system was used in the bridge design in order to spread out the live load to avoid “kinking” the main cable when the point loads are applied. Stiffening is provided by steel trusses in older bridges and steel box girders in newer bridges. The stiffening system is no stresses under dead load; however, stresses can be high when live loads are applied. An increase in live load will have a direct and an almost proportional effect on the stiffening system.

In suspension bridges, floor beams is used for connecting the stiffening trusses and supports the roadway deck. In the Tacoma Narrows Bridge, the floor beams are trusses.
Parallel Bridge

The Washington State Department of Transportation starts to plan to construct a second bridge after a half century. Because of the increasing traffic and reducing the stresses of the old bridge, the new bridge would be built in very close to the existing one. It cost over $800 million. Traffic would flow one way on the new bridge and the other way on the existing one. The design of two bridges would introduce the possibility of aerodynamic interaction between the two structures. Some open gratings would be covered in plan. These gratings had been incorporated into the existing bridge for aerodynamic reasons.

Figure 16 Truss decks of the Parallel Tacoma Bridges

Figure 17 the view of new bridge

Before the new bridge was designed, the wind climate analysis should be done.

Wind climate analysis including the effects of local terrain.
- Sectional model tests, addressing the aerodynamic interactions between the two decks.
- Full-scale measurements of the frequencies and damping of the existing bridge.
- Full aeroelastic models of both bridges to study in depth the interaction effects.
- Derivation of equivalent static wind loads for structural design.
- A study of the new bridge’s stability and wind loading during construction.
- Sectional model studies of future modifications to the new bridge involving the addition of a lower-level deck.
- A study of possible wind-induced vibrations for the new bridge’s hangers.

Calculation
Consider the load
I. Dead Load (DL)
II. Super Impose Load (SDL)
III. Live Traffic Load (LL)
IV. Wind Load (WL)
V. Temperature Effect (TE)

Therefore, consider
Combinations 1(DL+SDL+LL)
Combinations 2(DL+SDL+LL+WL)
Combinations 3(DL+SDL+LL+TE)

Loading
There are several different types of loads, each with its own effects.

Dead Load
Dead load refers to the permanent weight of the bridge. Where permanent partitions are indicated, their actual weights are included in the dead load. Clearly, there will be increases if lanes are added or widened or if existing decks are strengthened to support heavier loads. The cables, towers, foundations, and anchorages of a suspension bridge will be affected by increasing dead load, so it is necessary to minimize any increases.

<table>
<thead>
<tr>
<th>Total Structure Length</th>
<th>5,979 feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension Bridge Section</td>
<td>5,000 feet</td>
</tr>
<tr>
<td>Center Span</td>
<td>2,800 feet = 850m</td>
</tr>
<tr>
<td>Shore Suspension Spans (2), each</td>
<td>1,100 feet = 340m</td>
</tr>
</tbody>
</table>

| Weight of center span | 7250 lb/ft=105kN/m |
| Width of Roadway      | 49 feet = 15m |
| Depth of girders       | 25 feet = 7.5m |
| Thickness of roadway   | 6-3/8 inch = 0.160m |

Live Loads
Live load refers to traffic, train, or pedestrian/cyclist load. There are two main live load in bridge design, super impose load and live traffic load. Increases in live load can be caused
- Increase the weights of vehicles,
- Increase the number of lanes,
- Increase the number of heavy vehicles
- Widen lanes
- Revise the original design assumptions

I. Super Impose Load (SDL)
From the table (unit weights for bridge-building materials) γ=24Kn/m³
Weight = 24*(0.160*15) = 57.6kN/m

II. Live Traffic Load (LL) (4 lanes @ 3.75m each)
There are two types of live loading, HA and HB loading. HA loading consists of a uniformly-distributed load acting over a notional lane which the numbers are 4 here. There is a knife-edge (KEL) positioned at the most adverse position, which we choose 120kN per notional lane.

HB loading represents an abnormal truck load on the bridge, for instance possibly transporting long, wide and exceptionally heavy objects. Each axle represent 10kN for each unit of HB loading.

<table>
<thead>
<tr>
<th>Loading application diagram in a bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB</td>
</tr>
<tr>
<td>HA</td>
</tr>
<tr>
<td>Central reserve no loading for global analysis</td>
</tr>
<tr>
<td>HA</td>
</tr>
<tr>
<td>HA</td>
</tr>
</tbody>
</table>

HA: HA (UDL) 9kN/m (>380 loaded length table)
Spacing: 9*3.75/380 = 0.09kN/m
HA: HA (KEL) 120kN/m (per notional lane)
Spacing: 120/380=0.32kN/m

HB: 10kN/axle which is far more than HA

Other Loads
There are other loads, such as those imposed by wind and earthquake that do not vary with traffic. For example, structural change can affect both wind force and aerodynamic stability.

III. Wind Load (WL)
In BS5400 the wind loading on bridge is derived at a height up to 10m above ground level and up to 300m above sea level. Aerodynamic effects are ignored. The formula finding the maximum wind gust value $v_c$ is below.

$$v_c = v \cdot K_1 \cdot S_1 \cdot S_2$$

where $v$ is the mean hourly wind speed, we assume $v=30m/s$ in Tacoma, Washington State. $K_1$ is a wind coefficient, we choose $K_1=1.66$ where height above ground level is 200m, $S_1$ is a funneling factor generally taken $S_1=1.00$, $S_2$ is the gust factor, we choose $S_2=1.80$ where height is 200m and horizontal wind loaded length is 850m. After calculation, $v_c=90m/s$.

The horizontal wind load, $P_t$ in N, acting at the centroid of the part of the bridge which is given the formula as below:

$$P_t = q \cdot A_1 \cdot C_D$$

where the dynamic pressure head $q$ in N/ m², the formula is as below:

$$q = 0.613 \cdot v_c^2$$

$A_1$ is the solid horizontal projected area in m² and $C_D$ is the drag coefficient which is calculated as a function of the b/d ratio.

<table>
<thead>
<tr>
<th>$v_c$ = 90m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q = 0.613 \cdot v_c^2$</td>
</tr>
<tr>
<td>$A_1 = 850*0.16 = 136m^2$</td>
</tr>
<tr>
<td>$C_D = 1.5$ from the curve where b/d = 15/8 = 1.875</td>
</tr>
<tr>
<td>$P_t = q \cdot A_1 \cdot C_D = 1020kN$</td>
</tr>
</tbody>
</table>

An important action by wind is uplift or a vertical downward force. The formula for this force is as below:
\[ P_v = q^*A_3^*C_L \]

where \( q \) is the dynamic pressure head, \( A_3 \) is the plan area and \( C_L \) is depending on the b/d ratio.

| \( q \) | 5kN/m² |
| \( A_3 \) | 850*15=12750m² |
| \( C_L \) | 0.4 (b/d=2) |
| \( P_v \) | q^*A_3^*C_L=25500kN |

### Temperature Effects

Temperature fluctuations are an important consideration in bridge design. There are two temperature effects in bridge:

- Effective temperature
- Temperature difference

\( \sigma \) is the stress and the formula is as below:

\[ \sigma = \Delta T^*\alpha^*E \]

where \( \Delta T \) is the temperature differences \( E \) is Young's modulus, \( \alpha \) is the coefficient of thermal expansion.

| \( \Delta T \) | 30°C |
| \( \alpha \) | 12*10⁻⁶/°C |
| \( E \) | 200GPa |
| \( \sigma \) | 72MPa |

Bending moment under temperature effects, formula is shown as below:

\[ M=\sigma^*I/y \]

Where \( \sigma \) is the stress, \( I \) is the second moment, \( y \) is the length from the centroid to the edge.

### Ultimate Limit State and Serviceability Limit State

All bridges are designed according to limit state philosophy. We must check the bridge at the Ultimate Limit State (ULS), to prevent collapse, and at the serviceability Limit state (SLS), to ensure the bridge is serviceable.

#### Combinations 1(DL+SDL+LL)

The value of \( \gamma \) is taken as 1.00 for the SLS. On steel bridge, \( \gamma \) =1.10 at the ULS for all analysis techniques.

<table>
<thead>
<tr>
<th>Type</th>
<th>ULS</th>
<th>SLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL</td>
<td>121</td>
<td>105</td>
</tr>
<tr>
<td>SDL</td>
<td>110</td>
<td>69</td>
</tr>
<tr>
<td>LL</td>
<td>HA(UDL)0.1*1.25/1.5=0.08</td>
<td>1.10*1.25/1.5=0.08</td>
</tr>
<tr>
<td></td>
<td>HA(KEL)0.5*1.25/1.5=0.42</td>
<td>0.4*1.25/1.5=0.33</td>
</tr>
<tr>
<td></td>
<td>HB: 14.3*1.1/1.3=12.1</td>
<td>10.1/1.3=8.46</td>
</tr>
<tr>
<td></td>
<td>WL</td>
<td>30.1*1.0=33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4lanes of HA (USL):121+110+4*(0.08+0.42) +33 =266kN/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4lanes of HA (SLS): 105+69+4*(0.08+0.33) +30 =205.6kN/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3lanes of HA+1lane HB (USL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>121+110+3*(0.08+0.42) +12.1+33=277.6kN/m</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>105+69+3*(0.08+0.33) +8.46+30=213.7kN/m</td>
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<tr>
<td></td>
<td></td>
<td>Therefore combinations 2</td>
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<tr>
<td></td>
<td></td>
<td>ULS Load = 277.6kN/m</td>
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<td></td>
<td></td>
<td>SLS Load = 213.7kN/m</td>
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<tr>
<td></td>
<td></td>
<td>50% fixed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ULS hogging 277.6*850²/24=4.18kN/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sagging 277.6*850²[(1/8-1/12)*50%+1/12]=20.9kN/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLS hogging 4.18<em>10⁶</em>213.7/277.6=3.22*10⁶ kN/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sagging 20.9<em>10⁶</em>213.7/277.6=16.09*10⁶ kN/m</td>
</tr>
</tbody>
</table>

#### Combinations 2

1. \( P_t =1020kN \) no vertical moment
2. \( P_t \) plus or minus \( P_v \)

\[ P=25500/850=30kN/m \]

Type | ULS | SLS |
<table>
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Summary (50% fixed)
Combination ULS (10^6 kNm/m) SLS (10^6 kNm/m)
hogging sagging hogging sagging
1 3.72 14.9 2.8 14.0
2 4.18 20.9 3.22 16.09
Max  4.18 20.9 3.22 16.09

Conclusion

It is the worst case in the calculation, which is in combination 2. Comparing the deck of the bridge, the hand calculation is reasonable, although we give much assumption in values, because it has changed a lot in these 50 years such as the temperature, weather, and traffic capacity. More and more traffic loads acting on the bridge and it is necessary to increase the load capacity of the suspension bridge. It is neatly 57 since the new bridge opened to public, some expansion joint have been found during years. We must put more money in repairing the expansion joint. There are many windstorms even earthquake happened in this area, the maintenance is really important. After the parallel bridge opens to the public, the loading stress will be reduced.

References

[1] Tim Ibell, 2007, Bridge Engineering, Department of Architect and Civil Engineering, University of Bath, UK


