ASSESSMENT OF THE SAN FRANCISCO – OAKLAND BAY BRIDGE (1933 – 1936)

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Abstract: This article assesses the aesthetics of the bridge, the construction of the bridge, the structural background of the bridge. Spanning the Bay Area was once thought to have been impossible. However, the construction of the San Francisco – Oakland Bay Bridge (SFOBB) or Bay Bridge began in 1933. It linked the bay area to the first transcontinental railway, a major economical benefit therefore. The Bay Bridge was the longest bridge in the world when it was completed, running a staggering 7km. However, it should be noted that this bridge consists of two crossings and an island in between, were each crossing has numerous structural systems including steel suspension bridges, cantilever truss, through trusses and deck trusses. The Bay Bridge was designed with three considerations always present: cost, structural integrity and aesthetics. These factors dictated every part of the design.

Keywords: Aesthetics, Bridge details, Loading, Serviceability and Other considerations

1 Aesthetics
The bridge was designed using the three main considerations of cost, structural integrity and aesthetics; of which aesthetics was the easiest to compromise. The reason for this was because that the bridge was built during America’s great depression and cost had to be kept low. Structural integrity cannot be sacrificed as it and unsafe bridge is just not feasible. However the designers maintained to make the best looking bridge possible.

1.1 Analysis of Aesthetics
It is hard to analyze how beautiful a bridge is to analyze, but Fritz Leonhardts ten golden rules are widely respected across the industry.

1.1.1 Fulfillment of function
I believe that this bridge fails this rule because of the shear complexity of the design. The many types of bridge confuse the onlooker. A bridge in my opinion if it is to pass this rule should be easy to the eye, easy to understand and also give a sense of stability.
Under assessment I believe that the bridge should be split up into the two crossings because that is probably how the public would view it.

The west bay crossing, Fig. 1, is clearly more pleasing to the eye than the east bay crossing, Fig. 2. It is obvious how the loads travel throughout the suspension bridge to most members of the public. There is a sense of stability from the double height deck, which looks very deep in elevation and therefore confidence inspiring. The main cable is also large 0.75m in diameter, making the onlooker aware of the strength of this massive engineering effort. The size of the central anchorage (51.8m) also reinforces the confidence of the user when using this bridge.

The east bay crossing is a whole concoction of different systems; this is quite unpleasing to the eye and is quite confusing. Although it may be ugly, the structural reasons behind the choice are logical.

The soil is very weak so a conscious effort was made to reduce the weight of the piers and also to lower the loads that are taken through to the ground by having more spans.

The deck trusses across the whole bridge provide a simple method of increasing the traffic capacity of the bridge, with six lanes of traffic on two different levels.

Suitable replacements for this bridge would be a cable stayed bridge or a suspension bridge with post tensioned decks.

1.1.2 Proportions

The west bay suspension bridges are very well proportioned; the spans are well sized with the central spans twice the size of the side spans for both suspension systems. The central anchorage is positioned very close to the centre of the bay this is good as symmetry reflects simplicity.

The main cable has a larger cross-section than the vertical hangers because the forces are clearly higher in the main cable. The proportions seem to be correct i.e. the hangers aren’t too thin or the cable is not oversized.

When moving your eye along the bridge your eye is attracted to the central anchorage due to its size (51.8m). This is a bad attribute because your eye should be able to flow along the bridge. I believe that the designers have sacrificed the aesthetics of the bridge due the massive forces that this central anchorage is undertaking. It is after all the world’s first anchorage connecting two back-to-back suspension bridges.

The east bay crossing is very complex and difficult to analyze. If this bridge were built now then it quite simply wouldn’t have been designed like this. However at the time I do believe they achieved the best looking bridge they could with the structural and geotechnical difficulties they had to overcome.

One of the most beautiful structural aspects of the bridge is the member sizing because they used bars for tensile members and box sections for compression members. So the onlooker can understand how the bridge works.

1.1.3 Order

From a distance I believe that the west bay crossing uses repetition beautifully and your eyes flows reasonably undisturbed along the main cable.

When you are close to the bridge then I believe you start to see some flaws, the connections between the hangers and the decks stick out too much. A solution to this could have been to place the connections behind the horizontal members of the deck.

The east bay crossing is a fine example of poor order. There are so many members in the cantilever truss, which in turn leads to confusion.

The revealed underside of each deck takes away some of the beauty of the bridge. This is because the soffit is broken up into the structural elements. However this minimized weight and cost.

1.1.4 Refinements

One of the most ingenious subtleties of this design is that the batter-leg steel towers taper so that the cables are centred over the truss. This also prevents the optical illusion of the columns appearing wider at the top than the base.

The X-braced steel towers support the trussed deck. There is a large enough distance between the towers to allow for an ever-present view under the bridge, regardless of position.

The designers opted to choose for a groundbreaking centre anchorage, Fig. 1, which connects two suspension bridges instead of carrying the load across the bay or constructing two central anchorages. I believe this not only to be a positive step forward in engineering of the time but also adds to the beauty of the bridge.

Each anchorage has encased the post-tensioned eye-bars and other steel members in concrete. The connection therefore seems to be a lot simpler than it actually is.

Using steel for the bridge is an obvious choice when self-weight had to be kept to a minimum so the foundations were sound.

The suspender rope sits in a cable band on the main cable in such a way that you cannot see the join. This allows your eye to easily run along the main cable. If the designers had specified a larger connection then for every suspender rope there would be an interruption along the main cable. The suspender ropes on each side have two hangers placed with a small gap in between them. This is very clever because from a distance the hangers will look a lot bizzier than they are, Fig. 3.

![Figure 3: Hanger connections](image)

The travellers on the lower deck have to endure the unsightly soffit, Fig.4, of the upper deck for the whole length of the bridge. I find this understandable in terms of...
The idea of a suspension bridge across a large span of water is the correct choice. Most other types of bridge would not have been feasible to use to cross this stretch of water.

The east bay crossing look slightly peculiar but it actually is the perfect way to cross the water, due to the weak ground conditions.

If a suspension bridge was used then the forces would have been too great and the bridge would have not have been able to stand up. The Bay Bridge uses depth of members to provide confidence for the general public. The stiffened deck truss is 8m deep this depth achieves this confidence in abundance.

The bridge was constructed in a seismic zone so there design was highly influenced by the certainty of an earthquake occurring in its lifetime.

1.1.4 Texture
The concrete anchorages and piers have a matt finish as the general rule states.

This rule has been taken a step further by even allow the concrete pours to be evident when close by. This is a wonderful way of making sure that the passer-by knows exactly how the pier was constructed.

The steel members also have a matt finish coating but the fasteners are easily seen the whole length of the bridge. I believe that this takes away from the beauty of driving across the bridge. However from a distance this goes unnoticed and is a success.

1.1.5 Colour
The west bay crossing steel suspension bridges fit into the surroundings exceptionally well. They are painted the perfect colour; a greyish blue, this allows the vertical hangers disappear in the sky in such a way that the bridge looks so simple and elegant.

The east bay crossing is coloured the same way the members are not hidden, due to the member sizes.

1.1.6 Character
This bridge I believe has a lot of character because it makes the public ask themselves why there are two completely different kinds of bridge system either side of Yerba Buena Island. This is a good thing because people will take interest in the bridge. However, if it was possible I believe that if suspension bridges either side of the island may have been even more spectacular than the Golden Gate Bridge.

1.1.7 Complexity
The Bay Bridge is a fantastically odd bridge because each side tells a different story. The west bay crossing is simple and beautiful with hidden genius and the east bay crossing is logical, complex and slightly chaotic. However, it is intriguing.

I believe the designers have made the bridge with aesthetics further back in their mind than cost and structural integrity but they certainly have achieved a fascinating bridge with a lot of interesting facts.

1.1.8 Nature
I believe that the designers of this bridge felt that at the time nature was not a major consideration when designing a bridge. However it should fit comfortably into its environment. Steel was the only choice of material that could be used for this bridge to be a success.

2 Bridge Details
2.1 Brief outline
The west bay crossing, Fig 1, contains two standard suspension bridge systems with the main cable and hangers in tension and the towers in compression supporting a double height warren deck truss. However the designers were innovative in their design because the suspension bridge at the time could not span the whole crossing they decided to build two back-to-back suspension bridges that anchor into a central anchorage.

At either end of this crossing the cables anchor into gravity anchorages. This means that the weight of the anchorages transfer the loads from the bridge into the ground by means of shear mass of the concrete.

The east bay crossing, Fig.2, consists of a Cantilever Truss, 5 Through Trusses, 14 Deck Truss spans and three girder spans. The cantilever truss bridge works like the Fig.6.
The top members (arms) are in tension and the bottom members are in compression in order to lift the central span (or the man). If the man on the left’s right arm was not restrained the middleman would fall down, and if the man’s arms were a rigid system his arms would move up. So the anchorage either side has to be built to hold this uplift force.

The through truss works as a warren truss with high tensile steel on the bottom chords to resist the tension and box sections making up the nearly the rest of the truss.

The deck truss has a continuous top and bottom chord separated only by necessary expansion joints.

### 2.2 Suspension bridge systems

The back-to-back suspension bridges main structural system is two main cables, 730mm in diameter and 20m apart. The cables run over the towers and are anchored into a massive gravity anchorage on the San Francisco side, an anchorage on Yerba Buena, which relies on the strength of the rock to hold the main cables down, and finally the main cables of each suspension system anchor into a single central anchorage, which is large in size. This was the first time back-to-back suspension bridges had been anchored together.

The hangers (57mm diameter) hold up the deck truss, which carries 6 lanes of traffic on two decks. The hangers and the truss members are spaced the same distance apart so that the hangers are initially vertical. The deck trusses hold the double height lanes of traffic. The traffic is supported on a 135mm reinforced concrete slab, which in turn rests on stringers (parallel to the truss), which sit on floor beams. The deck is then stiffened up to take lateral loads with horizontal chevron bracing spanning between the floor beams, seen in Fig. 7.

The towers support the main cables, which run over the top of them, this allows for thermal expansion to take place without exerting high forces into the systems by allowing movement. The towers are cross-braced so that when lateral loads occur the towers don’t twist as much.

#### 2.2.1 Installing the foundations

The two foundations adjacent to the San Francisco anchorage were constructed of reinforced concrete, cast in place in open cofferdams made of sheet piling. The pier furthest west is built on reclaimed land so was easily constructed. The next pier was in the water and therefore needed a slightly different approach. This pier used a steamboat as a platform to work from. A timber frame was floated out and sunk using weights. The sheet piling was driven around the frame to reach the bedrock not too far from the surface. The sand and mud was excavated allowing for a workable surface for the concrete.

The water was pumped out of the sealed cofferdam and the concrete was allowed to cure.

For the rest of the piers a cellular caisson was floated out to see and then sank by pouring concrete around the cylinders. Once the caisson reached the bottom the mud was removed using clamshell buckets then the concrete was poured to the base of the excavation. Anchorages for the steel towers were also installed to connect to.

#### 2.2.2 Constructing the towers

The towers consist of two columns connected by horizontal and diagonal bracing. The columns were built from a series of steel cells that taper as you increase in height due to varying width of steel in the boxes. This design was chosen for construction reasons. The hollow section allows for a derrick to be situated at the towers lower levels. The derricks can then be operated from the tower and used raise new parts. As the tower went up the bracing was placed in between the columns. If this was not done at the same time it would have been more difficult to install them once the towers had been built.

#### 2.2.3 Constructing the Anchorages

The San Francisco anchorage, Fig. 8, relies on its weight to hold the cables down. This massive concrete structure is 56.2m long and 32m wide and stands 45m above the streets. The anchorage is 263m away from the end of the suspension bridge were the soil conditions are better. This results in a cheaper and logical foundation system.

The concrete was poured in three major steps. The first step encased the steel girders and the first set of eyebar chains. This allowed movement during cable spinning. This structure contains 68000 cubic yards of concrete and 1200 tons of steel.

The next pour is made after cable spinning to give the bridge the strength to take the loads from the deck.

![Figure 7: Lateral stiffening in the west span](image)

![Figure 8: San Francisco anchorage](image)
The Yerba Buena anchorage, Fig. 9, was constructed by excavating a 52m tunnel in the rock placing the steel girders and the eyebars in position and then filling the tunnel with concrete stopping just before the final set of eye bars. This permits movement during cable spinning, after cable spinning the tunnel is filled leaving the strand shows uncovered.

Figure 9: Yerba Buena anchorage

The centre anchorage, Fig. 10, appears as one anchorage but it acts as two, connecting the two suspension bridges to a foundation. Basically the two anchorages pull against each other and are held in place by a steel box, called an “A frame”, see Fig. 10, encased in concrete.

Figure 10: Central anchorage

Again the anchorage contains 5 rows of inclined steel girders in order to hold down the eyebars. The eyebars were tensioned using jacks. This was critical because if they were not tensioned then they would have to be able to take compression and tension.

2.2.4 Spinning the cables

After the anchorages, piers and towers had all been completed the main cables were spun using standard methods. A catwalk had to be constructed to act as a safe working platform and also transfer some of the materials. The cables were carried across the bay by barges on sets of coils. When the coils reached a pier they were connected to a cable saddle and lifted to the top of the towers one at a time. When raised the catwalk was completed with floor beams. The spinning wheels were then placed in the tram cable and span the wires at 365 metres per minute. The through the tops of the towers and down again. The wire is held in place by steel shoes in the anchorages.

2.2.5 Lifting the suspended deck

The deck trusses were then hoisted from a barge using motors and a set of lifting struts positioned along the main cable. This part of the construction was probably the most difficult because if the trusses were raised from west to east then you would expect to cause high forces in the main cable and also high strains at the anchorage. What was necessary for this bridge to be built was a balance of forces.

The trusses are secured to the hangers by connecting the hanger to a socket using molten zinc and then secured inside steel plate anchorages.

2.2.6 Comments on the west construction

I believe that this is the correct method of construction for this type of bridge. However I do believe that using chains for the eyebars in the anchorage is a mistake. If a link in a chain fails then the bridge fails.

2.3 The East bay crossing

This crossing contains three major types of bridge system; cantilever truss, through trusses and deck trusses. There is a perfect reasoning for this, weak soil. A suspension bridge was just not feasible due to the foundations that would accompany this. The changing ground profile also dictates the types of foundation used in this bridge.

2.3.1 Installing the foundations

Two types of foundations were used on the east bay crossing, piles and reinforced concrete caissons. The pier on the western side of the most western anchor arm was built into the bedrock of the island using conventional methods and designed to resist the uplift forces from the cantilever arm. The next pier was also easily constructed this is because of the depth that need to be overcome. The problems arise for the piers where the bedrock is far below the surface. The eastern crossing has the deepest pier in the whole bridge including the western foundations. At the time this was the deepest pier in the world reaching 74m.

The caissons were floated out and then sunk by pouring concrete in the voids. After excavation of the mud concrete is poured below the edges of the caisson.

The remaining pile foundations were designed to lower the cost of the build. The piles were not driven to bedrock; they rested on a load-bearing layer of sand and clay. All steel cofferdams were pounded into the ground to the desired depth. Then the timber piles were driven into the mud. The water inside the cofferdam was then pumped out. The cofferdam was sealed and then dewatered for the rest of the structure to be completed.
2.3.2 Construction of the cantilever truss

The cantilever truss, Fig.11, was separated into two simultaneous jobs, which meet in the middle.

![Figure 11: Cantilever truss](image)

Temporary bents were installed under the anchor arm. Two guy derricks sit on top of a track. The derrick hoists the truss elements into position where they are connected to the top and bottom chords of the previous segment. The upper deck was stiffened up using temporary props during construction.

2.3.3 Construction of the deck and through trusses

Both of these systems were constructed in the same manner. A boat with a crane on top acted as a working platform.

The towers were constructed first followed by temporary supports and each connection joint of the truss. These props reduced the stresses that each segment would feel. The deck segments were raised into place using the cranes and then they were fastened together using rivets. Then the floor systems were set in place.

2.3.4 Comments on the east construction

Due to the massive undertaking the engineers achieved a practical bridge built for a purpose. The suspended span of the cantilever system could have been improved. When the anchor arms and the cantilever arms are completed then I thought that they could use the cranes to lift the entire suspended span. This may save money because the section could be constructed on the land while other jobs were being completed. It would then be brought out to position and hoisted up.

3. Loading

This bridge is located in a windy channel with a large temperature range accompanied by seismic activity. This forces that the bridge will therefore have to resist are high. Wind and earthquakes govern the long span bridges. However, a light bridge will oscillate too much and a heavy bridge would have posed problems for the east spans due to the poor soil.

3.1 Construction loads

3.1.1 West bay crossing span

The bridge will encounter loads that it will not feel when the bridge is complete. The loads in the suspension spans during construction can be reduced if they are constructed in a logical way. The main cable and anchorages would feel high stresses if the bridge was simply built from pier to pier. If the side spans were constructed first then the horizontal reaction of the main cable in the central span would be huge. It would be the worst-case scenario for the tension in the cable.

If the central span were constructed first then huge strains would be placed on the anchorages. It is easy to appreciate that a combination is therefore required.

3.1.2 East bay crossing span

Temporary props are required when constructing the anchor span because as each segment is lifted to position the lever arm increases exerting high forces throughout the truss. The deck trusses should be able to withstand the mass of the derricks. Once the anchor span is safely secured and design to resist the uplift forces due to the suspended span lever arm then the segments can be safely hoisted into position.

It would not be economically correct to design the deck to be built using cantilever techniques because of the higher forces that it will generate in the trusses.

3.1.3 Combinations of Loads

There are five loading combinations that need to be checked for ULS and SLS design.

Load Case: 1. Permanent loads + primary live loads
   2. Load case 1 + wind + temporary loads
   3. Load case 1 + temperature + temporary loads
   4. Permanent Loads + Primary loads + secondary loads
   5. All permanent loads + frictional loads

3.2 Ultimate loads

The dead loads of the materials that have been used in the following calculations are in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ρ (kN/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced concrete</td>
<td>24</td>
</tr>
<tr>
<td>Steel</td>
<td>78.5</td>
</tr>
<tr>
<td>Cement</td>
<td>15</td>
</tr>
</tbody>
</table>

Each material has load factors, $γ_f3$ and $γ_fL$, which have to be applied in order to design out the imperfections in analysis. $γ_fL$ is taken as 1.00 for SLS and for this steel bridge $γ_f3$ equal 1.10. Values of $γ_f3$ are found in Table 2.
### Table 2: Partial load factor, $\gamma_{fl}$

<table>
<thead>
<tr>
<th>Clause</th>
<th>Load</th>
<th>Limit state</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Dead (steel)</td>
<td>ULS</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLS</td>
<td>1.00</td>
</tr>
<tr>
<td>5.2</td>
<td>Dead (concrete)</td>
<td>ULS</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLS</td>
<td>1.00</td>
</tr>
<tr>
<td>5.3</td>
<td>Superimposed dead</td>
<td>ULS</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLS</td>
<td>1.20</td>
</tr>
<tr>
<td>5.4</td>
<td>Wind</td>
<td>ULS</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLS</td>
<td>1.00</td>
</tr>
<tr>
<td>6.2</td>
<td>Temperature</td>
<td>ULS</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLS</td>
<td>1.00</td>
</tr>
<tr>
<td>6.3</td>
<td>HA loading</td>
<td>ULS</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLS</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>HB loading</td>
<td>ULS</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLS</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Due to lack of information some values have had to be assumed. The reinforced concrete slab is 20m wide and 165mm thick. The cement spans the whole deck and is 50mm thick. The trusses are very complicated so for the deck trusses an assumption that 5% of the volume of the double deck is steel. The deck is 8m high by 20m wide.

Unfactored dead loads are calculated by Eq. (1), were $A$ is the area required.

$$\text{Dead load (kN/m)} = \rho \times A \quad (1)$$

The live loads are calculated using the British Standards for the respective discipline. The traffic loads (primary loads) are calculated using BS5400. The bridge will be designed for both HA and HB loading most severe effects.

HA consists of a uniformly distributed load over a lane together with a Knife-edge load (KEL). The HA load is found from a graph which is dependent on length of bridge. The KEL is taken as 120kN per notional lane and is denoted as a red line.

HB loading is represents a police escorted special truck of a certain size with either full or partial HA loading applied to the notional lanes. Each axial of the lorry weighs 10kN per unit, where full HB loading has 45 units. The lorry is to be sized using Fig.12. The spacing of the central axis is either 6, 11, 16, 21, 26m so as to give the worst effect.

#### 3.3 Wind

Wind is often critical in long span bridges so it must be used in calculations. I have assumed to design the bridge for a level 12 wind on the Beaufort Scale ($v = 33\, \text{m/s}$). Designing for a hurricane is not only uneconomic but the cold sea conditions prevent them from reaching the coast. Dynamic pressure head, $q$ is calculated using Eq (3)

$$v_c = v \times K_1 \times S_1 \times S_2 \quad (2)$$

$$v_c = 33 \times 1.63 \times 1 \times 1.42 = 76\, \text{m/s}$$

$$q = 0.613 \times v_c^2. \quad (3)$$

$$q = 3.5\, \text{kN/m}^2.$$ A downward force, $P_v$, exerted by the wind as it passes over the deck will influence the bending in the deck. It is found using Eq. (4)

$$P_v = q \times A_3 \times C \quad (4)$$

Where $A_3$ is the plan area and $C_L$ is a lift coefficient.

#### 3.3.2 Load transfer due to wind

In the deck truss in the suspension bridge only the bottom deck is braced for lateral forces, not the upper deck. The bracing absorbs the wind energy because instead of the members undergoing added stress the bracing can deform around a pin. This is a fantastic detail in order to reduce cost but maintain structural integrity. The detail is shown below

![Fig 12: HB loading](image1)

![Fig 13: Suspension bridges lateral bracing](image2)
The added stiffness still allows for a flexible tower structure but the difference being it will move as one. The tower using box sections made up of steel plates to give the bracing compressive and tensile strength.

The eastern spans rely on bracing along the top and bottom spans to resist the wind or seismic forces. The bracings again are box sections, which are made from steel plates giving the members strength in compression and tension.

Both sides of the truss are stiffened up restraining the movement of the trusses using sway frames, Fig14.

**Fig. 14 : Sway frames**

### 3.4 Member sizing of suspension bridge

#### 3.4.1 The hangers

The hangers are spaced every 9.6m along the deck connecting at intersections on the truss, this limits bending to practically zero. To calculate the dimensions need of hangers their mass has been ignored.

The hangers will be designed for load case 2 with a superimposed load factor to the cement incase they ever plan to put another layer on top. A downward wind load will also induce more tension in the hangers. This is because any wind uplift will slacken the wires and lateral forces are assumed to have been attracted to the stiffer element in the horizontal plane.

The HB load case will be used to calculate the live load on the steel ropes. The worst-case load is found to be when the middle of an HB lorry, of length 9.6m (1.8-6-1.8 axel spacing), is aligned with the hangers. This means that one set of hangers has to support the whole lorry and the rest of the HA load.

**Fig. 15 : Upper deck loading**

The hangers support both decks and therefore traffic in both directions should be accounted for. The upper deck will be designed under HA and HB loading, Fig. 15. Whereas the lower deck will be designed just for HA loading, Fig. 16, because it is extremely unlikely and highly controllable that two police escorted lorries will pass be on the bridge at one time.

**Fig 16 : Lower deck loading**

Therefore the hangers should be designed to take one lane of HB, 3 full HA, two \( \frac{1}{3} \) HA loads, 2 KEL’s as well as twice the dead weight.

**Vertical Load:**

- **slab**
  \[ 2 \times [1.1 \times 1.15 \times 0.165 \times 10 \times 24 \times 9.6] = 961 \text{kN} \]
  
- **deck truss**
  \[ 2 \times [1.1 \times 1.05 \times 2 \times 10 \times 8 \times 0.05 \times 78.5 \times 9.6] = 13900 \text{kN} \]
  
- **Superimposed cement**
  \[ 2 \times [1.1 \times 1.75 \times 0.05 \times 10 \times 15 \times 9.6] = 277 \text{kN} \]

**Live loads:**

- **KEL per lane**
  \[ 2 \times [120] = 240\text{kN} \]

- **Full HA loading**
  \[ 3 \times [1.1 \times 1.3 \times 9 \times 9.6] = 346 \text{kN} \]

- **\( \frac{1}{3} \) HA loading**
  \[ 2 \times [41] = 82 \text{kN} \]

**HB loading**

\[ 10 \times 4 \times 45 = 1800 \text{kN} \]

Using Eq. (4)

\[ P_v = 2 \times [3.5 \times 9.6 \times 10 \times 0.4] = 268 \text{kN} \]

Therefore the sum of the above values gives the axial force in the two ropes of the hanger. The rope are probably made from a high strength steel with yield stress of 760N/mm\(^2\)

**Force per rope** = 17874 kN
Area required using Eq. (5) = 175mm hanger ropes

\[ A = \frac{P}{\sigma} \]  

(5)

This appears to be considerably larger than the sections used. This probably due to the fact that some of the decks mass and the live load will be transferred through the deck and to the towers were it is then transferred to the foundations. The estimate of the dead weight of the deck was believed to be conservative. Maybe 50% of load goes through truss and the hanger ropes are actually 90mm, which is closer to the actual diameter of ropes used.

3.4.2 Main cable

There are 73 hangers across the main cable that holds up the deck. The forces in the hangers are summed up and divided by the length of the central span, l, to estimate the u.d.l. acting on it. We will assume that 50% of the load acts through the truss.

Uniformly distributed load, \( \omega = \frac{73 \times 8937}{704} = 926 \text{ kN/m} \)

The horizontal force, \( H \), in the cable can be found using Eq. (7)

\[ H = \omega \times f^2 / 8 \times f \]  

(6)

Where \( f \) is the main cable sag, which is assumed to be the height of the towers above the deck (73m)

\[ H = 926 \times 704^2 / 8 \times 73 = 785 \times 10^3 \text{ kN} \]

Using the triangle of forces between the hanger and the horizontal component the tension in the main cable, \( T \), can be calculated using Pythagoras’ theorem.

\[ T^2 = (785 \times 10^3)^2 + (4150)^2, \text{ therefore } T = 785 \times 10^3 \text{ kN} \]

The actual tension in the cable was double this than this, it was measured as 380,000kN. Again the accuracy of the assumptions should in reality properly analyzed.

4 Serviceability

The deflection of the suspension bridge is complex to calculate with out long calculations because the deck in made up of lots of components of different shapes and sizes. Any deflection that occurs is immediately transferred to the towers by axial compression. The worst case loading condition for the central deflection would most likely be Load case 2 where wind forces are included.

The deflection in the cantilever bridge may be critical but statically indeterminate virtual work would be required.

The deflection of the through trusses should be checked because they are essentially simply supported and they have no support from vertical hangers or a cantilever truss system. The internal forces are quite easily calculated, as it is determinate. Deflection could be easily calculated using virtual work equations.

5. Other considerations

5.1 Durability of the concrete

The bridge piers are situated in a very hostile environment, which could lead to high amounts of corrosion if it was not designed for. The concrete used in this construction is not known but the processes it will have to resist are predictable and I presume they have been designed for.

The concrete piers in the bay are under attack from the salt in the air and the sea and other chemicals. Chloride ions in the salt can find there way through the concrete to attack the reinforcement. This is bad because if rust forms then the concrete could spall. To prevent this occurring it is wise to choose a concrete with low permeability and a high strength.

If over time the water has seeped into the concrete then it could be susceptible to freeze thaw action where the expansion of the ice crystal will cause the concrete to break down.

The constant wave action of the San Francisco bay will eventually wear away the concrete. The reinforcing steel will become increasingly more vulnerable to attack as the concrete wears away. Abrasion wearing concrete could have been used to limit this.

5.2 Durability of the steel members

The reason why the bridge is coated in lead paint is because of moisture protection. The Bay Bridge sits in the harsh microclimate of the San Francisco bay where salty air combines with water vapour creating a mixture that can rot steel. The leads paint acts as a moisture barrier. This will prolong the steel’s life but will need reapplying.

The alternating loading that will occur quite frequently on these bridges may induce issues of fatigue. Fatigue is when a material fails below its yield point due to cyclic loading. Prolonged wind and temperature effects could attribute to this. This bridge has reduced effects of this by using an open truss. This allows the wind to travel through the bridge, so oscillations are reduced.

A sheath protected the main structural members, such as the suspenders and the main cable. The designers foresaw that if the cables were exposed to the surrounding climate then they could eventually fail.

A major issue of this bridge is that there has been little attempt to prevent collection of water in small joints. If water gets in to a gap then a chemical reaction will take place, forming rust. The diagonal members of the deck truss are a good example of this negligence. These members are constructed of a series of eyebars that are laced together. This problem could have been design out if the member was covered in some material that prevents the passage of water.

5.3 Temperature effects

The transverse deformation will not govern due to the size of the span. However, longitudinal deformation will
be significant due to the climate the bridge is in. The average temperature in summer is about 14°C and the maximum ever recorded was 45°C. The expansion of the steel will not induce any forces in the members because the bridge has been made flexible in this direction, Fig. 13. The expansion joints in the bridge are situated at either end of each span.

\[ \varepsilon = \alpha \times t \]  

(7)

where \( \varepsilon \) is strain, \( \alpha \) is the coefficient of thermal expansion \((12 \times 10^{-6}/°C)\) and \( t \) is change in temperature (°C)

using Eq. (7) for deformation of a single member

\[ \varepsilon = 31 \times 12 \times 10^{-6} = 372 \mu \varepsilon \]

So the total expansion in the central span of the bridge is shown below.

\[ \delta = 372 \times 10^{-6} \times 704 = 262 \text{mm} \]

You can imagine that if the expansion joints were not present then it would take a lot of axial force to compress the members by this much. So the member force would be high and the steel bars, designed for tension, would fail. Differential temperature in morning will lead to expansion of the top cord members. This will mean that the towers will bend in their minor axis. This was most likely to have been considered during design.

5.4 Earthquake Resistance

This bridge is infamously known due to a span collapse during the Loma Prieta earthquake. However the bridge actually performed excellently with no major structural damage except from one plate. Settlement of the piers and foundations and the lateral bracing will be critical for seismic resistance. Liquefaction could lead to catastrophic failure.

The designers ensured that the span were not too long as this would pose serious difficulties in design.

The earthquake could make the towers twist and turn, which could lead to shear failure of the deck so it is important that the lateral bracing is designed safely.

5.4 Possible changes in the future

It is likely that in the future hangers may need replace the cement course on the bridge due to wear by the vehicles. A factor has been applied incase the cement is replaced with a thick blacktop for example.

The hangers are bolted to the cable band around the main cable. If they need to be replaced some sort of temporary support may be attached to adjacent hangers to hold up the deck segment.

The bridge may in the future be used for a heavy goods railway line this would lead to higher loads. The bridge should be designed for the flexibility so the San Francisco state representatives could use the bridge for multiple functions in the future should needs be.

5.7 Intentional damage

Due to the nature of the truss system there is a high amount of redundancies, therefore this is not really an issue in these segments. The piers are protected from the boats crashing into it intentionally or not by spreading out the base with concrete and rocks.

The eyebars supporting the main cable are cast into the concrete anchorages. If these chains were vandalized then the bridge would collapse. The bridge will not have been designed for terrorism and is unlikely that it ever will need a retrofit for this.

A possible solution for this problem is to add in extra steel redundancies throughout the system.

5.8 Braking loads

The diagonal members of the deck truss withstand the shear forces of the two decks if subjected to high longitudinal loads, such as braking loads and skidding loads of heavy vehicles.

References

[1] USA Today - Daily highs and lows : National temperature extremes
URL: http://www.usatoday.com/weather/wheat7.htm

[2] Corus construction
URL: www.corusconstruction.com

[3] Bridge Engineering Tim Ibell

URL: www.concretecentre.com

URL: http://en.structurae.de/structures/data/index.cfm?ID=s000262

URL: http://memory.loc.gov/ammem/index.html