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A CRITICAL ANALYSIS OF THE SAINT ANTHONY FALLS (I-35W) BRIDGE, MINNEAPOLIS

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Abstract: This conference paper will introduce the Saint Anthony Falls (I-35W) Bridge in Minneapolis, USA. The paper will take an in-depth critical analysis into a variety of aspects related to the bridge and also the previous bridge which collapsed catastrophically. This will include the bridge's aesthetics, strength, serviceability, durability, foundations and construction. There will also be analysis into the potential load cases that the bridge will experience in its life-time such as the dead load, wind load, traffic and temperature effects.

Keywords: *Reinforced Concrete Box Girder, Smart-bridge, Design-Build, Collapse, Saint Anthony Falls*

1 Introduction

On August 1st 2007 at 6.05pm the original I-35W Mississippi River Bridge suddenly collapsed severing a key highway link to downtown Minneapolis, the University of Minnesota, area businesses and north suburban destinations, killing 13 people and injuring over a hundred more. The impact of the collapse was catastrophic to the businesses and residents of the Minneapolis area costing an estimated $43 million loss to the economy during the down time between the collapse and the opening of the new bridge. It was therefore absolutely vital that a new bridge was erected in its place, and that it was done so in the quickest possible time. The result was a record-breaking design-build project that saw its completion within a year after it began, opening to the public on September 18th 2008.

Figure 1: Saint Anthony Falls Bridge

Named after the only natural major waterfall on the Upper Mississippi River, the Saint Anthony Falls Bridge represents a master class in civil engineering. The speed and precision of the design and construction led to a modern day smart-bridge telling the tale of its time.

1.1 Previous Bridge Collapse

Figure 2: Bridge 9340 before its collapse

Before its collapse the original I-35W bridge, officially known as Bridge 9340, represented one of the most important and busiest bridges in all Minnesota carrying 140,000 vehicles a day at its peak. The bridge collapsed suddenly and catastrophically with the centre span of the bridge giving way in a matter of seconds, followed by the adjoining spans. Victims caught in the collapse describe seeing the "concrete rolling like a wave."

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The original bridge measured 570m long and 35m tall, with a total of 8 lanes for highway traffic. Completed in 1967, with a design life of 40 years, the bridge structure consisted of three main spans, made up from a deck truss with eleven approach spans using steel multi-girder construction.

The bridge was consistently inspected by the Minnesota Department of Transport (Mn/DOT) since 1993, however, due to construction work on the bridge no inspections were carried out in the year of the collapse. During this time there were actually a number of problems that were found with the bridge structure. These included significant corrosion in its bearings and cracking in the cross girders. Although temporary solutions were found there was still a huge concern with the fracture critical design of the bridge, meaning that this lack of redundancy could see the entire bridge collapse in the event of any one single structural failure.

At the end of 2006 there were even plans for a steel reinforcement project for the bridge to increase the safety but these were axed a month later in favour of more periodic safety inspections, mainly due to findings that stated the drilling for the retrofitting of the project would in fact weaken the bridge. Finally, in August 2007 taking recommendation from the U.S Department of Transportation's National Bridge Inventory the governor at the time, Governor Pawlenty, announced that the bridge was to be replaced in 2020. Unfortunately, this proved far too late a date.

Figure 3: Bridge 9340 immediately after its collapse

The National Transportation Safety Board began an immediate comprehensive investigation into the collapse and Ref. [1] is taken from their official report into the collapse citing two key reasons for the collapse of the bridge.

The first reason was due to a design fault of a number of the specified steel gussets plates used to connect the girders together in the truss structure. The gusset plates were undersized to 0.5 inches thick as opposed to the 1 inch design requirement making them inadequate to support the increased load on the bridge. The second reason was an increased loading on the bridge on the day of collapse. Firstly, the bridge was initially designed to cope with a projected 66,000 cars per day in comparison to the much larger number of 140,000 that it eventually received. Combined with this was an upgrade to the pavement and the presence of 575,000 pounds of construction equipment occupying 4 whole lanes of the bridge, all ultimately leading to the collapse of the bridge.

2 Aesthetics

When analysing the aesthetics of any bridge there are a number of methods that can be adopted to give a comprehensive overview of the entire bridge. This paper will utilise Fritz Leonhardt's technique of evaluating how a bridge is designed in comparison to ten areas of aesthetics taken from pages (pp.) 28-43 of Ref. [7].

It is vitally important that any bridge establishes a sense of stability in its function, imparting a feeling of safety and satisfaction on the people who will use the bridge. This was exceedingly important when designing the Saint Anthony Falls Bridge due to the collapse of the previous bridge. The function is clearly represented with the use of three large curved piers at either side of the river, visible from afar as well as closes up due to two viewing platforms set up around the base of two of the piers. From these platforms it is also easy to see the four box girders that make up the deck span further fulfilling the functional requirements of the aesthetics.

When designing a bridge the proportions play a key role in establishing a relationship between the masses and the voids. Spanning over 300 metres (m) over the Mississippi River it was important that the bridge did not draw too much attention from the water and therefore by leaving a complete uninterrupted view down the river it enabled the bridge to have the perfect mix between light and shadow. Another area in which the bridge excels in its proportions was the way in which it utilises a dominant curve shape along the length of the deck, tapering from 9 m above the piers to a much more slender 3 m at the mid span.

By creating a clear order to the bridge, using a symmetrical nature across the river and a set of only two main rows of piers, the aesthetics reduces the number of edges and struts to the design. This eradicates the potential for any mental disquiet to the design as well as continuing the simplicity of the bridge.

A number of refinements were used in the design as well. The most noticeable is using much smaller spans as the bridge approaches the abutments. It is also the first bridge in the interstate highway system to use LED lighting for its lampposts. However, being part of the interstate highway system it was required to have a number of large signs along its deck, reducing the aesthetical appeal of the design.

One of the key design themes that the designers tried to carry through as much as possible was an "Arches, Water, Reflection" theme in an attempt to integrate the bridge in with the environment and utilise nature. The curved piers are the first place in which this is achieved, as the curve continues directly into the superstructure from the ground framing the river whilst drawing the eye to and from the water very well. Aside from the Saint Anthony Falls Bridge there are also a number of other historical influences in the nearby area such as a stone arch bridge, Mill Ruins Park and the 10th Avenue Arch Bridge. It was therefore important that the bridge did not overpower these, and the use of a simplistic modern design achieves this perfectly.

The colour and texture of the bridge are both very simple but at the same time create quite a striking structure over the river. During the design, consultation with the local residents over the colour was always at the fore-front of the process in an attempt to make sure that the people who will see the bridge the most were appeased. The piers and deck use a “Snowbound” white coloured matt finish all over in keeping with the modern aspect of the bridge. The bridge also uses local stone to face the retaining walls at either end of the bridge. Tall wavy sculptures are featured at both ends of the bridge, utilising a special mix of concrete that maintain their gleaming white finish by scrubbing stain-causing pollutants from the air.

After the collapse it was important that the new bridge acted as a monument to those that lost their lives. So in this instance the bridge already had a huge amount of character even before it was designed, and by running continuing construction tours to the public it meant that the public felt part of the process. However, it was still key that the design developed its own character at the same time putting its own stamp on Mississippi River, which it does so with its simple modern elegancy.

The final area that Leonhardt talks about is complexity, stating that it is possible to be visually stimulated with a certain amount of complexity in a bridge. This is obviously one area in which the Saint Anthony Falls Bridge decidedly opted to ignore choosing to keep the design simple, which in terms of the site location suits the design much better.

2.1 Summary of Aesthetics

The Saint Anthony Falls Bridge establishes itself over the Mississippi River as a simple, elegant and functional bridge. Whilst it may not be as aesthetically striking as other landmark bridges in the world, the fact that the bridge was built on a design-build basis with the key driving force behind the bridge being a quick construction process to restart transportation; the final aesthetics can be seen as a success for the design team.

3 Structure

The bridge structure is a long-span reinforced concrete box-girder with a design life of 100 years separated into two independent bridges stood next to each other. Each structure is made up of two side-by-side box girders supported on a series of concrete piers and abutments. Each of the main piers has three large disc bearings on which the superstructure rests with a service load capacity of 2500kN protected by concrete extensions.

With the previous bridge suffering from its fracture critical design the Saint Anthony Falls Bridge is designed with multiple levels of redundancy. Initially achieved in the separation of the box girders, this is continued into the internal structure with the deck connected together using multiple steel tendons. Each steel tendon used in the deck consists of 19 high strength steel strands, which in turn consist of seven steel “ropes.” By using multiple tendons this helps create multiple levels of redundancy in the structure. All in all there is close to a thousand miles of these strands in the bridge, encased in grout, pipes and concrete to provide more protection.

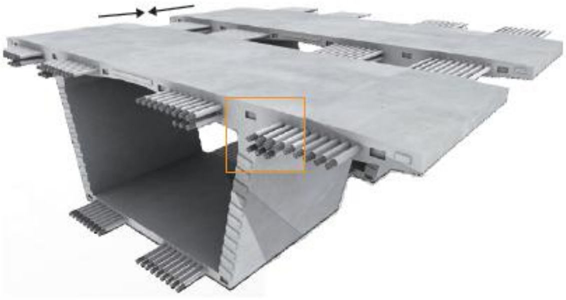


Figure 4: Post-tensioning steel tendons

The loads are transferred through the box girders to the piers with the drilled shaft foundations located directly underneath them leading to a highly beneficial direct load path.

4 Serviceability

Serviceability is a key part of the Saint Anthony

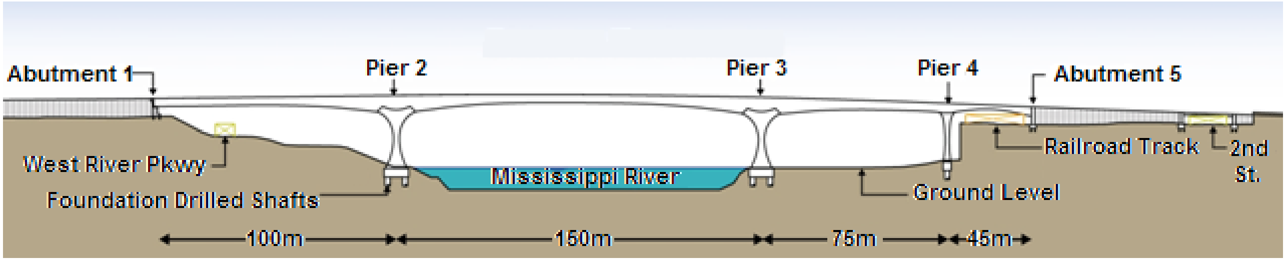


Figure 5: Bridge elevation

Falls Bridge and it was the serviceability part of Figg Engineering's design pitch that actually won them the contract in the first place. The reason for this was that they were the only engineers to include the use of sensors in the bridge. All in all there are close to 350 state-of-the-art sensors contained in the bridge making it into a 'Smart Bridge' as well as fulfilling the long-term serviceability role. The total cost of the entire bridge sensor networks only cost around $1 million that's less than 0.5% of the total project.

5 different sensor types are utilised in the bridge to help with serviceability, starting with strain measurement devices that measure the shortening or stretching in the deck and piers. With a number of expansion joints, movement is also be tracked due to temperature changes in the bridge. Combined with this there are also separate gauges that measure the temperature in the concrete itself correlating it to changes in curvature. In case the bridge does experience any corrosion, metal pieces are embedded in the deck able to pick up warning signs before the reinforcing steel starts to corrode. Finally, accelerometers note vibrations that could indicate damage to the bridge.

However, it should be mentioned that as "smart" as the designers promote this bridge as being with the use of these sensors, new designs into wireless sensors have been introduced that in theory will pave the way for bridges to affordably introduce thousands of these sensors into their structure.

5 Foundations and geology

The first work on the Saint Anthony Falls Bridge began with the design and construction of the foundations.

The geology of the Mississippi River at the location of the bridge consists of around 15m of glacial till and deposits above a layer of sand stone. Although there was State provided information in the form of foundation boring logs from the previous bridge almost 40 years of weathering, erosion, scour, and human activity may have altered the conditions of the geology. Due to this fact, a number of test shafts were also drilled near the in-place south abutments with hollow stem augers and diamond core drills.

A combination of 2.1m and 2.4m diameter shafts were chosen to be drilled into the sand stone to form the main bridge foundations. By using a large diameter for the shafts it reduced the number of construction operations necessary for each foundation as well as working within the site constraints. In total 40 shafts were drilled using four drill rigs up to a depth of 29m socketed into the rock to support the main bridge piers. As well as this, another 69 1.2m diameter shafts up to 8m long were used to support the north abutment and the 2nd Street overpass.

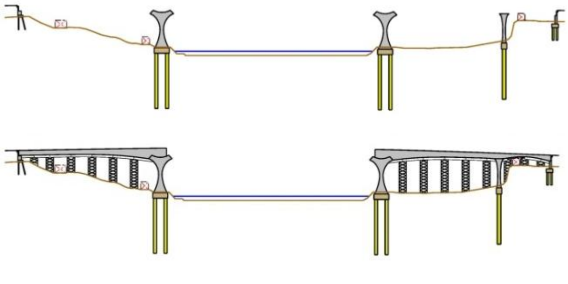
With emphasis placed on the quick tempo of the construction a monolithic, high-quality, self consolidating concrete (SCC) was used in the shafts. This SCC concrete mix was designed to comply with the design specified compressive strength of 5000 psi. However, the concrete bypassed this requirement by a considerable margin achieving a strength of 9890 psi by the 56th day of curing.

The final aspect of the foundations is the rectangular footings at the base of the main piers. Each footing supports two of the 21m tall concrete piers, which in turn support two of the concrete box girders. The four main footings vary in length from 10m to 13m, in width from 24m to 34m, and in depth from 4m to 5m. With a number of site constraints in place such as the remaining unused foundations from the original bridge and large drainage tunnels the footings were designed to span over these. During the curing process the concrete had to be maintained as close to 33 degrees as possible so temperature became a critical factor. Sensors were used to observe any changes, with blankets utilised to make sure the concrete remained in a hot environment, and cooling tubes used to make sure that any chemical reactions that occurred did not cause the concrete to overheat.

6 Construction

The construction process for the Saint Anthony Falls Bridge was a huge part of delivering the bridge in the record-breaking time that it was constructed. Mn/DOT took the decision to use a design-build process as opposed to the more traditional design-bid-build process in order to get the bridge, and therefore the Minnesota economy, back up and running to full capacity. Further emphasis on finishing the bridge on time was introduced in the form of a $200,000 a day fine after the deadline. By bringing the designers and contractors together much earlier it meant that construction could begin after only a portion of the final detailed design had been completed. It also meant that there was a much greater innovation and flexibility in selecting the design, materials and construction methods, as well as an accelerated response time and dispute resolution.

A one-directional cantilevered construction process was adopted for the main span between the piers, with the approach spans cast in place on formwork. Along with the construction of the 6 piers and foundations the construction process is shown in figure (fig.) 6.



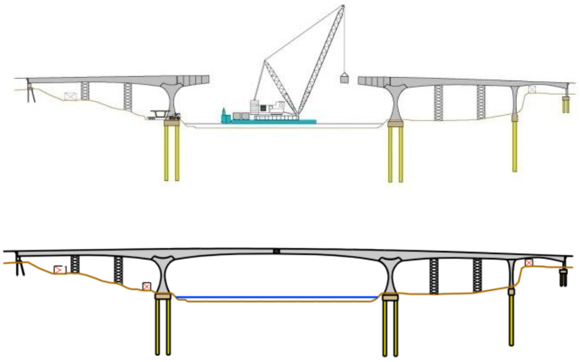


Figure 6: Construction process

As covered in the previous section the first stage of construction was the laying of the foundations. Once these were ready to bear weight the 8 main piers were constructed in a similar fashion, with temporary formwork being erected allowing them to be cast-in-place.

Whilst this was all going on and in order to accommodate for the construction of the main centre span, eight casting beds each approximately 75m long were used, set up on the then unused existing I-35W roadway to the south of the bridge. A grand total of 120 segments were pre-cast in this make shift yard, with each weighing in the region of 150-200 tonnes. With the deck exhibiting quite a predominant curve along its length the segments varied from 3.3m to 7.5m tall. It was vital that the formwork used to create the segments, shown in fig. 7, were made with the most upmost precision due to only as much as 1/8th of an inch in alignment error creating considerable unalignment at the centre. This was achieved by utilising rolling heated structures moving along with the segments as they were cast in an attempt to provide reliable working and curing condition, especially during the harsh winter months.

Figure 7: One of the 120 concrete pre-cast segments

Whilst the segments were being pre-cast away from the main site, work was also being carried out on constructing the side spans connecting the bridge superstructure back to the land. The concrete deck was cast in place on temporary formwork set on the land either side of the river. Once the side spans had been erected each side was post-tensioned in order to take the extreme loadings they would be subjected to during the cantilevered construction. Steel tendons were used to lock the side spans into the foundations on either hill side. A high specification hydraulic jack pulled the tendons to the specified force, close to a million pounds. This method of post tensioning was then carried out throughout the entire deck pulling the strands through each new segment as it was put in place.

Once the side spans were completed the cantilevered construction could begin on the main span and the existing road could be enhanced with alignment geometry. The segments first needed to be transported from the casting yard to where they needed to be installed. This on its own was no easy task considering the sheer size and weight of each segment and the unaccommodating layout of the Minneapolis streets. The segments were individually loaded onto a trailer and transported over a mile through the streets down to the banks of the Mississippi River. From here the segments were hoisted into a river barge by a crane named “Bohemian Blue” and moved a further ¼ mile upstream to their final location in between the two rows of piers. Once in position the segments could be lifted into position using a floating crane called “Big Ben,” as shown in fig. 8.

Figure 8: Cantilevered construction

Extreme precision was once again required to make sure that the pre-cast keys in each segment lined up exactly as needed. This was achieved by initially using a 0.45m wide concrete closure pour and continual monitoring using 3d surveying monitors to optimize precise geometric set-up, and within 32 weeks after construction began the first piece was already put in place. Before the post-tensioning tendons were installed the segments were first tied to the previous segments by high strength post-tensioning bars in the longitudinal and transverse direction. The joints between each segment were further enhanced by a high epoxy resin, enabling the joints to become seamless as well as having a waterproof seam. The final action was to cast in place the closure joint between the two cantilevering spans, overall this measured 7 foot across.

The entire cantilevered construction process for the main span took only 47 days from start to finish. This is despite having to cope with extremely harsh conditions, including a localised tornado that struck out of no wear whilst one of the segments was being lifted into position by the floating crane. Luckily enough, the strength of the crane was able to resist the 40mph gusts.

Once the main superstructure construction was completed, the only remaining work to finish was adding the minor finishes to the bridge such as the signage, railings and the observation decks.

The construction process can be seen as an absolute success in every single way. The entire process lasted under a year, from October 2007 to September 2008 finishing 3 months ahead of schedule earning the builders a bonus of $25 million.

7 Design loading

The Saint Anthony Falls Bridge was designed in accordance with the LRFD Bridge Design Specifications, however, for the purposes of this paper, in which these were unavailable, the bridge will be analysed in accordance with BS 5400-2: 2006. Although this is not the analysis used during the original design it will still prove a more than adequate assessment.

Nominal loads are achieved from the various loadings by multiplying by two partial factors; γ_{fl} and γ_{f3}. γ_{fl} represents the partial load factor and the relevant values for this conference paper are shown in table 1, and γ_{f3} is a further factor introduced to allow for possible inaccuracy with it taking a value of 1.10 for concrete bridges at the ultimate limit state (ULS).

Table 1: Relevant partial load factors

Loading	γ_{fl}
Dead: Concrete	1.15
Super-imposed dead	1.75
Wind	1.4
Temperature	1.3
HA alone	1.5
HA and HB or HB alone	1.3
Parapet	1.25
Skidding	1.25

One thing to mention before any loads are analysed is that the bridge will be treated as two separate entities, so only one side needs to be analysed as shown in figure 9.

7.1 Dead and super-imposed dead loads

The first stage of loading analysis is to evaluate the dead and super-imposed dead loads of the bridge. The best method for this bridge is to look into the weight and amount of the box-grider segments used in the bridge as opposed to summing up the weight of the individual components. For one side of the bridge a total of 148 segments were constructed and installed. With a varying weight, due to the curve of the bridge, an average weight of 175 tonnes will be used for the individual dead weight of each segment. On top of this an assumed 100mm depth of covering asphalt is applied as a super-imposed dead load. The final factored values for the dead and super-imposed dead loads are shown in table 2.

Table 2: Dead and super-imposed dead loads

Type of load	Factored load (kN/m)
Dead	791
Super-imposed dead	110
Total	901

7.2 HA loading

HA loading is the basic vehicular live loading for heavy, fast-moving consisting of a uniformly-distributed load (UDL) acting over a notional lane combined with a single knife-edge load acting transverse to the UDL at the most adverse position. The 28m carriageway width correlates to 8 notional lanes each with a width of 3.5m, in which the HA loading is considered to act over.

The nominal UDL for loaded lengths in excess of 50m but less than 1600m is derived from the following equation:

$$w = 36\left(\frac{1}{L}\right)^{0.1}$$

$$= 36\left(\frac{1}{370}\right)^{0.1}$$

$$= 20kN/m$$

This value can then be multiplied by the corresponding γ_{fl} given in table 1 and the γ_{f3} to give a

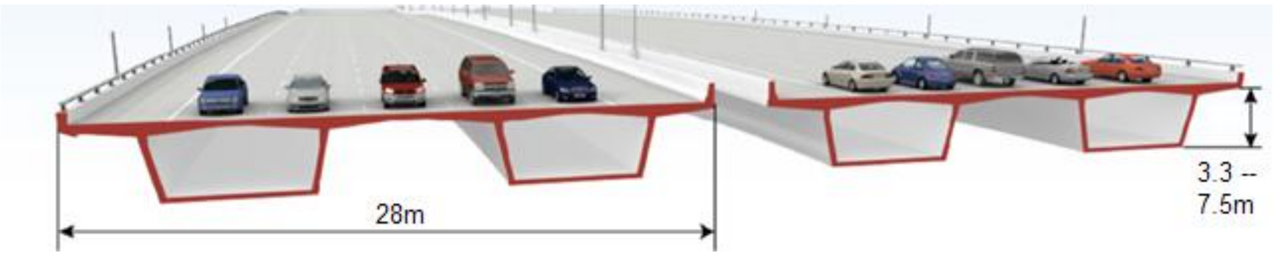


Figure 9: Bridge section

factored value of 33kN/m, also equivalent to an intensity of 9.4kN/m² by dividing through by the width of the notional lanes. The final aspect of HA loading is to add in the factored KEL of 120kN at the most adverse position on the bridge, which will be the midpoint of the 150m mid-span.

Due to the fact that the bridge is longer than 112m and contains more than 6 notional lanes from ref [8] the HA loading can be represented as shown in figure 10.

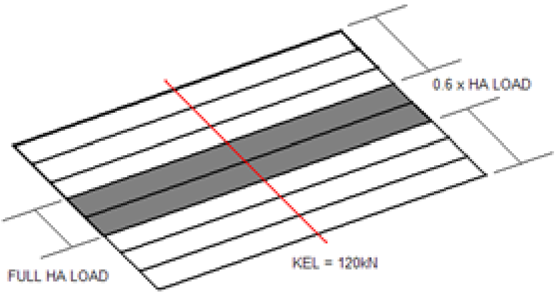


Figure 10: HA loading distribution

This arrangement of vehicular loading leads to a factored UDL for the entire width of 184.2kN/m.

7.3 HB loading

HB loading makes up the second possible live vehicular loading combination introducing an abnormal truck load on the bridge. For the most adverse effects this can be modelled as 9.6m x 3.5m long truck carrying 112.5kN for each of its 16 wheels leading to an overall load of 1800kN, applied once again at the midpoint of 150m mid-span. The relevant factored HA loadings are then added to make a new combined HA and HB loading distribution as shown in figure 11.

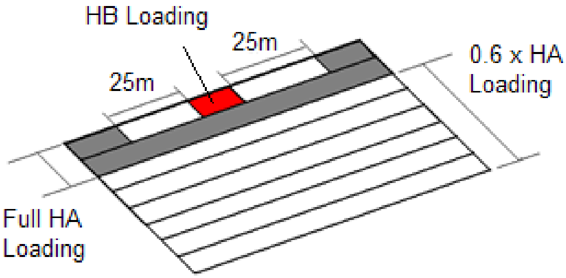


Figure 11: HA and HB loading distribution

However, with to the resultant 25m clearance in front and behind the truck the total loading on the bridge due to HA and HB loading is actually less than that of HA loading on its own.

7.4 Wind load

The main wind load is given by the maximum wind gust speed (V_d) as given in ref [8]. A design wind speed of 44m/s is given in ref [6] so it will be interesting to see if the workings from BS 5400 correlate to this in any way.

$$Vd = Sg.Vs$$

$$\begin{aligned} Vs &= Vb.Sp.Sa.Sd \\ &= 25 \times 1.05 \times (1 + 0.001 \times 250) \times 1 \end{aligned}$$

$$\begin{aligned} Sg &= Sb.Tg.S'h \\ &= (1.7 \times 0.92) \times 1 \times 1 \end{aligned}$$

$$Vd = 32 \times 1.564 = 50m/s$$

This may seem quite high in comparison to other values, but this is down to the extreme environment in Minneapolis in which tornadoes are not uncommon. Also the value obtained from the British Standards is not that far off from the given design wind speed used during the original analysis, highlighting the fact that the analysis method in this paper is sufficient.

7.4.1 Transverse wind load

Using the calculated maximum wind gust speed the transverse wind load (P_t) can be calculated, acting at the centroid of the horizontal elevation of the Saint Anthony Falls Bridge:

$$\begin{aligned} P_t &= q.A_1.C_D. \\ &= (0.613 \times 50^2) \times (5.8 \times 370) \times 1.2 \\ &= 3.94 \times 10^3 kN \; or \; 10.7 kN/m \end{aligned}$$

The wind P_t must also be derived for the two sets of main piers supporting the bridge:

$$\begin{aligned} P_t &= q.A_1.C_D \\ &= (0.613 \times 50^2) \times (5 \times 30) \times 1.9 \\ &= 437 kN \; or \; 14.6 kN/m \end{aligned}$$

7.4.2 Longitudinal wind load

The second area in which the wind load must be analysed is how it is effective in the longitudinal direction (P_L). Given as the sum of the longitudinal wind hitting the bridge itself (P_{LS}) and hitting the traffic (P_{LL}):

$$\begin{aligned} P_{LS} &= 0.25.q.A_1.C_D \\ &= 0.25 \times (0.613 \times 50^2) \times (3.3 \times 370) \times 1.2 \\ &= 5.61 \times 10^2 kN \; or \; 1.5 kN/m \end{aligned}$$

$$\begin{aligned} P_{LL} &= 0.5.q.A_1.C_D \\ &= 0.5 \times (0.613 \times 50^2) \times (2.5 \times 370) \times 1.45 \\ &= 1.03 \times 10^3 kN \; or \; 2.7 kN/m \end{aligned}$$

$$\therefore P_L = 1.6 \times 10^3 kN \; or \; 4.3 kN/m$$

7.4.3 Vertical wind load

The final wind load is a vertical force that can either be in the upward or downward direction and acts at the centroid of the bridge deck in plan. It is defined as:

$$P_v = q.A_S.C_L$$
$$= (0.613 \times 50^2) \times (28 \times 370) \times \left(0.75\left[1 - \right.\right.$$
$$2820 \times 3.31 - 0.2 \times 0$$
$$= 6.4 \times 10^3 kN \text{ or } 17.2 kN/m$$

7.4.4 Wind load combinations

The relevant wind loads are still only in their nominal values so still need to be multiplied by the relevant γ_{fl} and γ_{f3} as given in table 1. The combinations that are taken are; P_t alone, P_t in combination with ± P_v, P_L alone and $0.5P_t$ in combination with $P_L \pm 0.5 P_v$.

7.5 Secondary live loading

The final section to be considered for the design loading is secondary possible traffic loadings including braking, skidding and parapet loading.

Firstly, longitudinal loading due to severe braking of trucks is taken as resulting in a horizontal loading of 8kN/m along a single notional lane combined with a single 250kN force. When HB loading is analysed for braking loads, 25% of the HB load gets transferred over 2 axles.

Skidding is modelled as a horizontal single point load of 250kN in any direction in one notional lane only.

Finally, the bridge has two open parapets constructed of steel. These must be able to resist a collision of 25 units of HB loading

8 Temperature effects

Fluctuations in the effective temperature can cause expansions and contractions within the bridge deck introducing extra loads on the bearings that the bridge is supported on. Combined with this is the presence of more localised temperature differences between the top and bottom of the concrete box girder as it experiences heating and cooling effects from day to night. This type of localised material temperature differences can lead to induced stresses within the section.

The Minneapolis temperature range is one of the highest in all of America ranging from extremes in both regions, from a minimum of -15˚C to a maximum of 30˚C. These values can be altered slightly as outlined in ref [8] due to the type of superstructure group 4 that the Saint Anthony Falls Bridge falls into, to give a new minimum temperature of -9˚C, and a new maximum of 32˚C. It should also be noted that the base construction temperature as given in ref [6] is 8˚C so all temperature differences will be established as related to this:

$$\delta = \Delta T.\alpha.l$$

$$= -17°\text{C} \times (12 \times 10^{-6}/°\text{C}) \times 370m$$
$$= -0.075m\ (contraction)$$

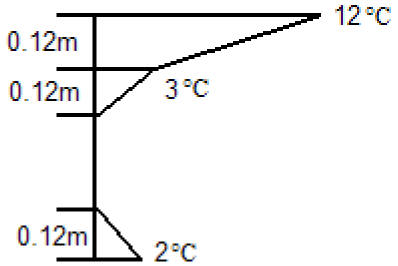
$$= +24°\text{C} \times (12 \times 10^{-6}/°\text{C}) \times 370m$$
$$= +0.11m\ (expansion)$$

As mentioned in the serviceability of the bridge; the bearings above the piers are designed to be expansion joints in an attempt to counteract this contraction and expansion. However, where the bridge meets the two abutments at either end there is no such movement designed for so it is possible that this movement may introduce stresses in the concrete section modelled as followed:

$$\sigma = \varepsilon.E$$
$$= 24 \times (12 \times 10^{-6}) \times (30 \times 10^3)$$
$$= 8.64 N/mm^2 < 30 \text{ N/mm}^2$$

The final temperature analysis to perform is to look at the localised temperature difference between the top and bottom of the 400mm concrete deck. The positive and reverse temperature differences are shown in figure 12:

Positive temperature difference:



Reverse temperature difference:

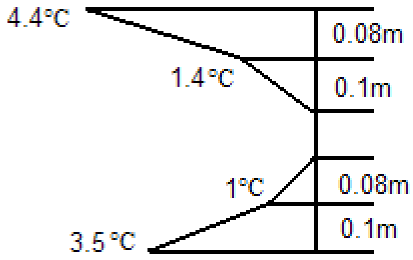


Figure 12: Localised temperature difference.

9 Natural frequency

The natural frequency of the bridge is an important value to analyse, as excessive frequencies above 75 Hertz (Hz) can cause big psychological effects to the bridge users, whereas frequencies below 5 Hz are at risk to collapse from gusting wind problems or vibrations induced from accelerations. The following equation is a simplified approach to calculating the natural frequency of the bridge using the following data; E = 30 x 10^9 N/m, I = 127.4m^4, m = 70000 kg/m and $(\beta_n \times l)^2$= 22.3733 (for clamp-clamp condition).

$$f_0 = \omega_n = (\beta_n \times l)^2 . \sqrt{EI/_{ml^4}}$$

$$= 22.3733 \times \sqrt{(30 \times 10^9 \times 127.4)/(70000 \times 150^4)}$$

$$= 7.35\ Hz$$

Although this value is within the acceptable range of 5-75 Hz, it is close to the bottom margin so is in no way comfortable in terms of natural frequency.

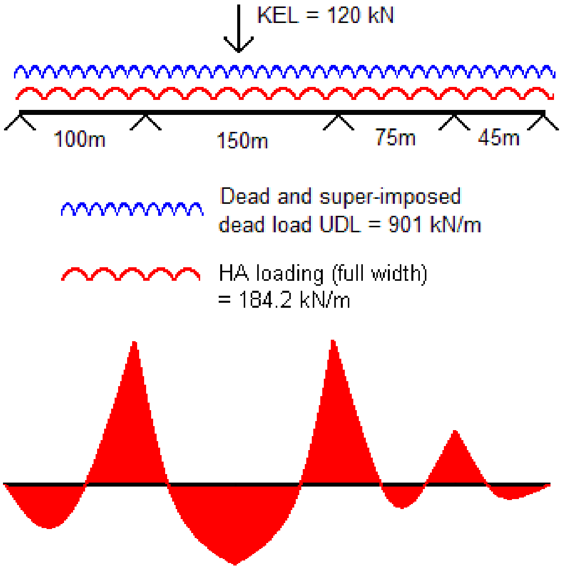
10 Strength

Now that all the relevant design loads have been assessed the Saint Anthony Falls Bridge can now being to be analysed in terms of its strength. When analysing highway bridges the following five combinations are checked at both the SLS and ULS:

Table 3: Load combinations

	Relevant design loading
1	Dead, super-imposed dead, vehicular loads.
2	Combination 1, wind, erection loads.
3	Combination 1, temperature, erection loads.
4	Permanent, secondary live, primary live loads.
5	Permanent, friction loads.

For the strength analysis in this paper the bridge will be assessed for bending and stress in the deck using the ULS and load combination 1, with the HA loading alone used for the vehicular loading as assessed in section 7.3. Figure 13 shows the longitudinal bending moment diagram for the entire bridge.



$$M_{MAX\,(SAGGING)} = \frac{(901+184.2)\times 150^2}{24} + \frac{120\times150}{8}$$

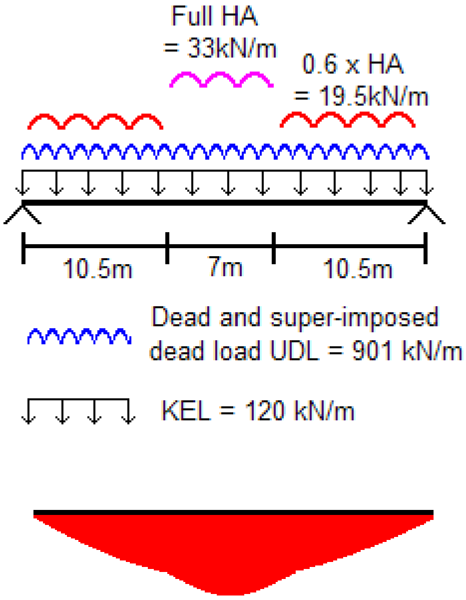
$$= 1019.6MNm$$

$$M_{MAX\,(HOGGING)} = \frac{(901+184.2)\times 150^2}{12}$$

$$= 2030MNm$$

Figure 13: Longitudinal design loading and bending moment diagram

The transverse bending moment also needs to be considered, and this is shown in figure 14.



$$M_{MAX} = \left(\frac{1041 \times 28^2}{8}\right) + \left(\frac{13.5 \times 7^2}{8}\right)$$

$$= 102MNm$$

Figure 14: Transverse design loading and bending moment diagram

From the maximum moments it is possible to evaluate the stress that is induced in cross-section of the bridge using the following formula:

$$\sigma = \frac{M.y}{I}$$

$$= \frac{(1019 \times 10^9)\times 1000}{127.4 \times 10^{12}} = 8N/mm^2\,(sagging)$$

$$= \frac{(2030 \times 10^9)\times 1000}{127.4 \times 10^{12}} = 15.9N/mm^2\,(hogging)$$

Therefore, these values for the stresses in the deck lie within the capacity of the grade C30 concrete used in the box girders so are perfectly adequate.

11 Durability & vandalism

As Minneapolis is subjective to a very bitter winter it is not uncommon for ice to form in the roads around the Saint Anthony Falls Bridge. The sensory equipment is designed to automatically trigger sprinkler systems in the pavement spreading an anti-icing solution. Although the designers tried to stay clear of the anti-icing salts, the solution will still have a deteriorating effect on the concrete. However, this should be minimal due to the 0.4m depth of micra silicate concrete used in the bridge surface. This type of concrete makes it exceedingly hard for harmful substances to penetrate the surface.

The main piers are located on the banks of the Mississippi River, so it is therefore possible that during storms or periods of high precipitation that the base of the piers may be subjected to corrosive attack from the water, so this should also be monitored.

Continuing with the durability in comparison to the climate aspect; in Minneapolis it is not uncommon for tornadoes or extreme gusts of wind to form. During these times it is unlikely to generate any structural damage but damage to relevant signage is probable, in which case it should be replaced or repaired immediately.

After the incident involving the previous bridge, Mn/DOT has pledged that the new bridge will be constantly checked to ensure that its durability is running smoothly.

Moving onto vandalism, the brand new gleaming white finish is obviously very prone to the likes of graffiti. This is heightened by the fact that there are easily accessible viewing platforms surrounding the main piers. Therefore, constant cleaning and/or repainting of any disfigured areas will be required to maintain the finish. With an abundance of signage on and around the bridge due to its use as a major interstate highway this must be monitored for any damage.

12 Future changes & suggested improvements

The main change that is in place for the Saint Anthony Falls Bridge is the introduction of a Light Rail Transit (LRT) system to operate along the bridge. Each LRT vehicle will consist of up to 3 carriages, so this will obviously introduce a new design load onto the bridge.

The entire bridge was designed very well to fulfil its required function as an Interstate highway bridge. However, one improvement that could be introduced is an element of aesthetical design, in the form of a sculptural arch for example. This could be expressed as a monument to those who lost their lives in the tragic collapse of the previous bridge.

13 Conclusion

This paper has analysed a variety of aspects of the Saint Anthony Falls Bridge in Minneapolis. This also included a brief report into history and reasons behind the catastrophic collapse that paved the way for this bridge to come about.

Without the availability of the American LRFD Bridge Design Specifications the BS 5400-2 provided the basis for a comprehensive analysis of the various design loading the bridge is subjected to. At various opportunities it was also possible to compare values obtained from the LRFD Bridge Design Manual with the calculated values from the BS 5400-2 showing a clear correlation between the two.

Overall, an in depth analysis into the aesthetics, structure and construction revealed a bridge that has made its impact on the engineering world; not through aesthetical appeal or innovation in its structural design, but instead its rapid design and construction process. The sheer pace and accuracy in which this megastructure was erected provides a precedent to any future civil engineering projects into just what is possible when put up against the clock.

14 References

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