A CRITICAL ANALYSIS OF THE DESIGN AND CONSTRUCTION OF THE SYDNEY HARBOUR BRIDGE

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Abstract: This paper analyse the Sydney Harbour Bridge in Sydney, Australia. There is a brief history of the bridge. Other areas covered are the aesthetics, the design and construction, the maintenance, serviceability and durability of the bridge. Also it is checked if it fulfils the nowadays standards for dead and live loads and for wind and temperature effects.

Keywords: Sydney Harbour Bridge, steel arch

Figure 1: The Sydney Harbour Bridge in Sydney Australia
1 Introduction

There are only few bridges around the world so famous that the city is recognised by them. One of these landmarks is Sydney Harbour Bridge (fig. 1). An arch bridge made of steel. It is located in Sydney, Australia and crosses port Jackson. The locals had also nicknamed it as The Coathanger because of its shape.

The idea of connecting the Sydney central business district and the north shore was dated back to 1815 when firstly Francis Greenway proposed it. But nothing happened until after a century when, in 1912, John Bradfield was appointed as the chief engineer of the bridge project. Unfortunately, the World War I postponed the construction. Finally, in November 1922, the needed laws for the construction of the bridge were voted by the New South Wales parliament. The competition for construction tenders took place the same year and the British firm Dorman Long and Co Ltd, Middlesbrough won it the next year with the design of an arch bridge. The bridge finished and opened ten years later, in 19 March 1932.

The original designer of the bridge is John Job Crew Bradfield. But it was Sir Ralph Freeman who was appointed by the company to design the model in further detail. In fact, there was an argument between them for who actually designed it. Also Arthur Plunkett proposed three different schemes to the company. The engineer of the project was Gilbert Roberts and the consulting engineer was Georges Camille Imbault.

It was constructed to hold six lanes of traffic, two lanes for trains, two lanes for trams and two footpaths. Its deck is still the widest for a long span bridge (according to Guinness World records) and tallest steel arch bridge. It was also the tallest structure in Sydney until 1967.

2. Aesthetics

As a landmark, Sydney Harbour Bridge is widely accepted as a beautiful structure. So in this paragraph will not be checked if it is nice in aesthetic way but the reasons behind this acceptance. The fact that the designer really considered the aesthetics in his design is the pylons at the end of the bridge which they were constructor mainly for the beauty of the structure.

From the first time, a viewer sees the bridge can understand the way it works. The arch was a shape widely used for bridges from the roman times. The difference is that the arch instead of being under the deck, it is coming over it. The reason is clearly structural. The deck does not have to be in the level of the top of the arch. The arch can have a larger span, with the top height up to several meters and the deck can be at the level of the banks in each side. This principal is used in rivers where the end of the arch can not be under the sea level.

The huge amount of steel in the arch makes the bridge look more stable (fig. 2). Also the complexity and the big steel parts make the arch look like solid from every angle. The small depth of the deck is helping as the arch seems that it doesn’t hold a heavy weight. But at the same time the whole shape looks really simple. The eye is concentrating in the arch instead of the deck and keeps in mind the shape of the arch with a nice uniform ending under it from the deck.

The shape of the bridge is totally symmetrical. The pylons at the ends make the bridge look smaller than its actual size. They also show like they are holding the bridge in place (Fig. 3).
The colour of the bridge is grey fitting to the urban environment. Also grey is the colour of the steel, making understandable the materials used and looking more natural. Finally, grey absorbs all the shadows from the huge arch.

In conclusion, the bridge fulfils all the aspects of aesthetics. In some of them, it can be considered as an exceptional example. Even in those that it is inferior, they are over average.

3. Rational behind the Design

In 1890, a royal commission determined that there was a heavy traffic of ferries in the harbour. The construction of a huge bridge between the two banks was the only solution. Even when some smaller bridges were constructed they could not solve the problem of the traffic jam. From 1900, designs and proposals were requested for the bridge but all of them were not accepted. In 1912, John Bradfield was appointed as the chief engineer of the bridge project and he traveled the world looking between a numerous designs for the appropriate one. He concluded to the New York City's Hell Gate Bridge (Fig. 4).

At the same period, a whole system of underground railways was constructed at the Sydney’s central business district. The bridge was supposed to carry both the road traffic and trains.

4. Construction

The competition for the construction tenders started in 1922 either with an arch or a cantilever design (Fig. 5). The British firm Dorman Long and Co Ltd, Middlesbrough won it the next year with a design similar to the New York City's Hell Gate Bridge (fig. 7). Many people disappointed because a foreign firm was chosen so the firm assured that the entire workforce for the construction would be Australians.
Small-scale models were made of a number of girders for testing to destruction, in order to check the design. But the actual size of the bridge was too big so even these models were 15 meters long. At that time there wasn’t any machine big enough to test them. So the firm made a new one in its headquarters in Middlesbrough. The results from these testing were extremely helpful and information about the strength of the bridge was obtained from the tests.

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Figure 7. The seven suggestion that was given by the British firm Dorman Long and Co Ltd, Middlesbrough which finally won the contest.

The construction began with a demolition of 800 homes in 1923. The excavation was 12.2 meters deep (and 30 meters long by 13 meters wide) in a variable yellow stone with horizontal seams of clay and shale. After it was filled with special reinforced high-grade concrete laid in hexagonal formations.

The bridge is mainly constructed by steel. About 79% came from Middlesbrough in the North East of England (traveling from the other end of the world) and the rest was Australian-made (only 21%). But it was fabricated in Sydney, in new workshops, specially built and equipped for the project. In those workshops 800 men were employed. The total steel used in the project was 38,390 tons for the arches and 52,800 tons in total.

The arch was not manufactured as whole. Each half of the arch was constructed in each bank of the harbour. The upper chords of the arch were held by 128 steel wire ropes (7 cm each in diameter and 365 meters long) in both sides. The ropes were passing down to the ground and round an inclined U-shaped tunnel cut 30 meters deep in the rock. The total length of cable used was 93.5 km. Hence, each half could not fall unless the steel ropes or their connections would break or the rock above the tunnel would fail. (Fig. 8)

Figure 8. The temporary cables securing each half of the arch until the completion.

The steel members of the arch were lifted from water and placed from two cranes, each one at the top of the constructed half. Each crane was capable of lifting weights up to 120 tons.

When the construction of the two half finished, the bridge passed its most difficult test. A strong wind blew full on the side of the bridge. Fortunately, the steel ropes were strong enough to support the construction. After that, the cables were taken off one by one until the two parts joined. The process should finish fast enough so the effect from temperature difference between day and night would not affect the construction.

At the same time, there was also the construction of the four pylons in process. The granite used at the face of them (about 17,000 cubic meters) was quarried near Moruya (about 250 km south of Sydney), where about 250 Australian, Scottish and Italian stonemasons and their families lived in a temporary settlement. For the transportation of the granite, three ships were specifically built to carry it. The inside of the pylons is made by concrete and their height is 89 meters. Even though, they don’t have any structural usage but constructed for aesthetical purposes only.

All the parts were connected by rivets as it was the most common technique for metal framed structures. They were also used in the Eiffel Tower. The total number of rivets used in the construction was about 6 millions.

The bridge is pinned and each of the four pins is 4.2 meters long and 368 millimeters in diameter.

After the construction of the arch, the construction of the deck was the easy part. The cranes that were used to lift the arch members, they also used for the lifting of the deck members (figs. 9,10).
Unfortunately, during the construction, the standards of industrial safety were not as high as today. The result was the death of 16 people and the injury of many more. Also a lot of workers were suffering of deafness several years after the finishing of the works.

The bridge was opened on 19 March 1932, almost eight years since the contract was signed (March 1924). The total financial cost of the bridge was £10,057,171. That was way too higher (more than double) than the estimated one when the contract was let to the British firm 8 years earlier for the sum of £4,218,000. The cost covered by loans which they finally paid off 56 years later (in 1988).
5. Maintenance

As any other major bridge, Sydney Harbour Bridge is inspected frequently from specialists. The inspection is extremely detailed and they are checking every centimeter of the bridge. If any bolt or rivet loosens, it is changed. Also they check all the steel parts for cracks or beginning to buckle.

In short periods, the bridge is painted over so the steel is prevented from corrosion. In 2002, it was decided to be repainted. Every section was sealed off and blasted to remove old paint and then extracted by vacuum. Then it was repainted. The reason for that decision was that after so many layers of paint, it was getting heavier and could have destructive results for the bridge.

6. Traffic

The bridge, originally, was built with 6 lanes for road traffic, two lanes for trams, two lanes for trains and two footpaths. As the needs for road traffic has changed through the years, in 1958, the two lanes for trams were changed and has been used for road traffic. Also one of the footpaths has changed to a lane for bicycles.

During the day, four lanes flow in each direction. But for better traffic flow, the middle lanes (3, 4 and 5) are reversible. During the rush hours, they are altered for a better flow. The bridge has a series of overhead gantries for each lane every few meters for avoiding accidents because of confusion (Figure 11). Another positive thing of the reversible lanes is changing direction is that in case of an accident, only a couple of lanes will stop working and the total weight of the vehicles is distributed more equally and they are not gathered in one end of the bridge.

Each year, about 160,000 vehicles use the bridge to pass the harbour. The maximum number was 182,000 vehicles, a year before the opening of the nearby Harbour Tunnel (it was opened in 1992).

7. Loads

The bridge is located in Australia so it should be checked by the Australian Codes. The association of state, territory and federal road and traffic authorities in Australia (Austroads) was established in 1989 to replace National Association of Australian State Road (NAASRA). The code is AS 5100-2004 with AS 5100.2-2004 for the design loads with the SM1600 designing loading.

Unfortunately, there was not free access to the public for the code and it should be purchased only from citizens live in Australia. In this paper, the British code (BS 5400) is used instead. It is one the more strict codes in the world. So if the construction passes these standards then it can pass the Australian ones too.

7.1. Dead and Super-Imposed loads

The bridge is completely balanced. The dead load is equally distributed in the four thrust bearing. Each of them can carry approximately 20,000 tones (about 200,000 kN and 800,000 kN in total). The weight of the arch is about 39,000 tones (only steel) and the total weight for steel is about 46,000 tones (it was found from the total weight of steel about 52,800 tones and the percentage of the length of arch span out of total length). So for dead load in every combination at the Ultimate Limit State (ULS) with factors of safety $\gamma_f = 1.10$ and $\gamma_f = 1.05$ then the total force is

$$460,000 \times 1.10 \times 1.05 = 531,300 \text{ kN}$$

and as the bridge is completely balanced it will be

$$531,300/4 = 132,825 \text{ kN}$$

in each thrust bearing. The bridge hasn’t got any major construction so the super-imposed loads are only the services (pipes, drainage, lights, gantries etc) which their weight is too low in comparison to the dead load.

7.2. Traffic, Pedestrians and train loads

As the bridge has already changed the two lanes from tram to traffic, in future the whole bridge could be changed into traffic which is the worst case. In this paper the bridge will be checked for all lanes used by traffic.

The width of the bridge is 49 meters. According to the British Standards each notional lane is up to 3.8 meters (the BS 5400 had width up to 22.8 meters with each notional lane 3.8 meters). So in the bridge there are 13 notional lanes.

As the loaded length is 503 meters (higher than 380 meters) the HA uniformly distributed load (UDL) is 9 kN per meter length. Two notional lanes are applied the full HA loading and the rest 11 are loaded with $1/3 \times 9 = 3 \text{ kN/m}$. So the total HA is...
2\times9\times503+11\times3\times503 = 25,653 \text{ kN.}

This is multiplied by safety factors $\gamma_D=1.10$ and $\gamma_h=1.50$ for combination 1.
The result is

25,653\times1.5\times1.1 = 42,327.45 \text{ kN.}

With the dead load is 573,627.45 kN (way less than 800,000 kN)

The BS 5400-2:2006 has changed the HA udl for highway bridges and for 503 meters (between 490 and 530 meters) is about 19.4 kN/m. With that HA and from table 14 then the load is

2\times19.4\times503+11\times0.6\times19.4\times503

= 83,920.52 \text{ kN.}

Adding the safety factors

83,920.52\times1.1\times1.5=138,468.858 \text{ kN}

and the total is 669,768.86 kN (which is still lower than the load that can be supported by the bridge).

The size of the bridge (any extra load at a specific place is insignificant to the total load) and the difference between the total load under combination 1 at the USL with HA and the total strength of the bridge shows that the bridge is capable to stand every combination of loads.

As the bridge can stand the traffic in the whole width then it can be used also for trains and pedestrians instead of traffic.

8. Temperature and Wind effects

8.1. Temperature effects

The arch of the bridge is allowed to move vertically by the temperature effects. It may rise or fall by 18 centimeters due to heating or cooling. Also the deck can be expanded by 420 millimeters.

Typically the coefficient of thermal expansion for steel is $\alpha=12\times10^{-6} / \degree \text{C}$. If there is a difference of 25\degree\text{C} then

$\Delta L = \alpha\times L \times \Delta T$

$=12\times10^{-6}\times503\times25$

$=0.1509 \text{ m}$

$=150.9 \text{ mm}$

The result is less than 420 millimeters. For the deck to expand 420 millimeters, it is needed a temperature difference of 70\degree\text{C}.

In case the deck was not allowed to move horizontally then there would be a stress equal to

$\sigma=\alpha\times E \times \Delta T$

$=12\times10^{-6}\times200\times10^{9}\times25$

$=60\times10^6 \text{ N/m}^2$

$=60 \text{ N/mm}^2$

The result is multiplied by the safety factors $\gamma_D=1.10$ and $\gamma_h=1.30$

Then

$60\times1.1\times1.3 = 85.8 \text{ N/mm}^2$

which is extremely high. Especially in Australia, the temperature difference between summer and winter is much more than 25\degree\text{C} resulting an even higher stress.

8.2. Wind effects

According to BS 5400-2:2006 the maximum wind gust speed is calculated by

$V_d = S_p \times V_s$

Where $V_s = V_b \times S_p \times S_a \times S_d$

And

$S_g = S_b' \times K_F \times T_g \times S_h'$

The $V_b$ is the basic hourly wind speed taken from the highest winds occurring once every 50 years. The highest for the Britain is 30 m/s (a similar map is in every code around the worlds as it is in the Australian one). For the needs of this paper $V_b=30$

According to BS 5400-2:2004 for the Sydney Harbour Bridge

$S_p = 1.05$

$S_a = 1$

$S_d = 1$ (taking the highest as the direction factor is different in Australia)

$S_b' = 1.75$

$K_F = 1$

$T_g = 1$

$S_h' = 1$

Then

$S_g = 1.75\times1\times1\times1 = 1.75$

$V_s = 30\times1.05\times1\times1 = 31.5$
and

\[ V_d = 55.125 \text{ kN/m}^2 \]

The great openings between the steel members are reducing significantly the surface area. Also the depth of the deck is not that deep regarding to the width of the bridge. So the wind is not causing problems to the structure.

9. Serviceability

The bridge can handle much more weight than nowadays standards. At the time, it was constructed, the standards were even lower. At that period, the bridge was crossed, except with cars, but with also few people on their horse or their stage-coach.

The reason that the construction was so strong is probably that it was the era that the cars started being widespread. Also the bridge engineers were reinforcing their structure as they were not sure that it was stable.

10. Durability

The steel bridges are vulnerable to the corrosion. The bridge should be keep painted in short periods as the paint protects the steel parts. The inspections for any damaged parts should continue.

If it is checked in regular bases and all the damaged parts are replaced, the bridge will not have any problem of collapsing.

Last year, the bridge celebrated the 75 years from the opening date (fig. 12). The structure can easily be stable for at least another 75 years.

11. Further Improvement

The bridge is already a landmark for the city of Sydney so any changes in aesthetical are possible not to be accepted by the citizens.

The structure is stable even with the nowadays standards so there is not any need for further reinforcement.

The only negative of the bridge is because of its shape can not expanded. The nearby Harbour tunnel helped in reducing the traffic jam on the bridge (fig. 13). In future, maybe, there will be need for another underwater tunnel in the area.

Figure 13: The Sydney Harbour Bridge on the left and the Harbour tunnel on the right

![Figure 12: The celebrations of the 75th years from the opening](image)
Table 1: The bridge in numbers

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of arch span</td>
<td>503 metres</td>
</tr>
<tr>
<td>Height of top of arch</td>
<td>134 metres about mean sea level</td>
</tr>
<tr>
<td>Height to top of aircraft beacon</td>
<td>141 metres above mean sea level</td>
</tr>
<tr>
<td>Width of deck</td>
<td>49 metres</td>
</tr>
<tr>
<td>Clearance for Shipping</td>
<td>49 metres</td>
</tr>
<tr>
<td>Height of Pylons</td>
<td>89 metre above mean sea level</td>
</tr>
<tr>
<td>Base of each abutment tower</td>
<td>68 metres across and 48 metres long (two pylons rest on each abutment tower)</td>
</tr>
<tr>
<td>Total length of bridge</td>
<td>1149 metres including approach spans</td>
</tr>
<tr>
<td>Bearing Pins</td>
<td>Each of the four pins measures 4.2 metres long and 368 millimetres in diameter</td>
</tr>
<tr>
<td>Thrust on bearings</td>
<td>Under maximum load approximately 20,000 tonnes on each bearing</td>
</tr>
<tr>
<td>Number of rivets</td>
<td>Approximately 6,000,000</td>
</tr>
<tr>
<td>Largest rivet</td>
<td>Weighed 3.5 kilograms and was 395 millimetres long</td>
</tr>
<tr>
<td>Longest Hanger</td>
<td>58.8 metres</td>
</tr>
<tr>
<td>Shortest Hanger</td>
<td>7.3 metres</td>
</tr>
<tr>
<td>Total weight of steelwork</td>
<td>52,800 tonnes including arch and mild steel approach spans</td>
</tr>
<tr>
<td>Weight of arch</td>
<td>39,000 tonnes</td>
</tr>
<tr>
<td>Concrete used for bridge</td>
<td>95,000 cubic metres</td>
</tr>
<tr>
<td>Granite facing used on pylons &amp; piers</td>
<td>17,000 cubic metres</td>
</tr>
<tr>
<td>Rock excavated for foundations</td>
<td>122,000 cubic metres</td>
</tr>
<tr>
<td>Allowance for deck expansion</td>
<td>420 millimetres</td>
</tr>
<tr>
<td>Allowance for arch expansion</td>
<td>The arch may rise or fall 18 centimetres due to heating or cooling</td>
</tr>
<tr>
<td>Number of panels in arch</td>
<td>28, each 18.28 metres wide</td>
</tr>
<tr>
<td>Record tonnage erected</td>
<td>589 tonnes of steelwork was erected on the arch in one day on 26 November 1929</td>
</tr>
<tr>
<td>Paint required</td>
<td>272,000 litres of paint were required to give the Bridge its initial three coats. (last accessed 8th April 2008)</td>
</tr>
</tbody>
</table>

12. References

[8] Figure 1 available from http://www.photoeverywhere.co.uk/east/sydney/slides/45-sydneycbd.mp3 (last accessed 8th April 2008)
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[11] Figure 7 is available from
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[12] Figure 8 is taken from Technology in Australia.
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[16] Figure 13 is taken from the google maps.
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