Abstract: This article provides an informative analysis of The Silver Jubilee Bridge as it stands today, and also through its construction. It will look into many aspects of bridge analysis, such as aesthetical and structural properties, as well as studying the detailing and refinements of the bridge design.

Keywords: Silver Jubilee Bridge, 
Suspended Cantilever Construction, 
Steel Truss, 
Arch

1 General Introduction
The Silver Jubilee Bridge is located near the city of Liverpool, and spans the river Mersey as shown in Figure 1. Construction began on the bridge in 1956 and it was completed in 1961. In 1975 work commenced to widen the bridge, and the finished bridge was opened in 1977. It joins the two towns of Runcorn and Widnes with two lanes for traffic running in both directions. It is currently the UK’s longest local authority owned bridge and is a grade II listed building [1].

Figure 1: Map showing the location of the bridge

2 Aesthetics of the bridge
According to Fritz Leonhardt, there are ten points for aesthetics of bridges that must be considered in the design stage. In the following section these shall be discussed with relevance to the Silver Jubilee Bridge.

2.1 Fulfillment of Function
The bridge clearly gives an impression of stability. This is provided by the large steel truss arch spanning over the top of the deck. This steel arch supports the slender deck by means of hanging cables stretching down on either side.

2.2 Proportions
The proportions of a bridge are an important factor. There should be a balance between aspects such as masses and voids and also spans and depths as well.

On the Silver Jubilee bridge there is a very large steel truss arch spanning over the river. This is complemented by a very thin deck supported by cables from the arch. Having such a large arch helps people to see that only a very slender deck is needed, as the arch is the main load bearing part of the structure. The truss arch continues through the deck at either end of the span, clearly showing how the forces are dissipated into the foundations within the ground.

This is one of the largest steel arch bridges in the world, and the height to length ratio of the arch looks right. Too tall and the arch would look ridiculously large, too shallow and the horizontal forces in the bridge would be huge, and it would not look comfortable as a bridge.

2.3 Order
There should be order in the edges and lines of the bridge. Often when too many columns are used, or they
are placed incorrectly, it can create too many edges, which reduces the order of the bridge. The silver jubilee bridge has good order when viewed on paper, however in reality, when viewing the bridge at an angle the truss members cross and it can become confusing to the eye. One area in which this bridge does have good order is in the vertical cable ties, these line up well together and the repetition helps to give an organised impression.

2.4 Refinements

The steel arch truss gets thinner towards the centre at its peak. This is an interesting detail, as it shows how loads build up throughout the structure towards the bases, where the truss tapers out. At the crown of the arch the truss appears to be constructed from members in an equilateral triangle formation, which stretch out towards the bases. At the base, the angle which the underside of the arch enters the pin joint is replicated on the other side of the joint with the truss leaving. This symmetry helps to show that the loads from the arch are carried through these piers and not by the truss on the other side. This is not the case at the top of the arch, where the truss seems to flow on to the land, giving the impression of large horizontal forces holding the arch up.

Another interesting detail is the very thin cables which support the deck from the arch. They are almost invisible under certain lighting, and give the impression of a floating deck. In addition to this the parapets that run along the edge of the deck run the entire distance of the bridge, and run past the truss sections of the bridge on the outside of the truss, making the slender deck a visible unbroken line along the entire bridge.

2.5 Integration into the Environment

The Silver Jubilee Bridge is located between two towns, crossing the river Mersey. It links two urban environments by bridging a relatively un-spoilt natural river environment. This is related in its design by having a large steel ‘industrial’ arch stretching over between the two towns, but also having a small slender deck that spans closer to the river.

2.6 Texture

A smooth finish has been used on the entire steel truss, this is very important in providing texture to the bridge. It enables the bridge to look sleek, modern and precise.

2.7 Colour

Colour is very relevant as the entire bridge is painted lime green. It is continuously being painted and takes about 5 years for a new coat to be applied [4].

The lime green colour makes this bridge really stand out, but also manages to hide certain aspects of the bridge. The cables that support the deck can almost disappear against strong sunlight, leaving just the large steel arch and slender deck to be seen. The colour choice for this bridge has helped it to be recognised easily from pictures and helps to emphasise certain structural elements.

The bridge can be lit up at night as shown in Figure 2, giving a colourful iconic structure that stands out for miles due to its height and the fact that there are clear lines of sight upstream and downstream of the bridge.

2.8 Character

This bridge has gained character by the striking colour scheme, and also by the ability to hide the supporting cables in certain lights. This makes the bridge interesting and invites the public to question how the bridge may work.

2.9 Complexity

Overall the bridge is quite simple in design, with one large arch suspending a slender deck via some support cables. However if the bridge is closely examined, it can appear much more complex due to the large curved truss system in place, within the arch.

2.10 Integration into Nature

Many of the most advanced structural forms appear in nature; however this has not been taken into account in the Silver Jubilee Bridge, as it was not necessary to mimic natural forms on such a large scale.

2.11 Surrounding Structures

One major problem with this bridge is that it is situated right alongside another bridge, which happens to be a very cheap and nasty looking box section railway bridge. The designs for the Silver Jubilee Bridge look very impressive; however this view can never be achieved in real life due to the close proximity of this second bridge.

The height of the second bridge also gives the impression that the Silver Jubilee Bridge has an unnecessarily thick deck when viewed in bad light or from a distance (when it is hard to distinguish between the two bridges).

It can also appear that the two bridges are actually one bridge, which then looks very strange, due to the positioning of the pears for the railway bridge, being unsymmetrical to the arch of the Silver Jubilee Bridge.
It is very disappointing that this second bridge even exists, as it tends to negate many of the aesthetically pleasing features that the Silver Jubilee bridge would have if situated on its own in this environment.

3 Construction

Construction of the Silver Jubilee Bridge began in 1956. The process of suspended cantilever construction was used, which is commonly used in the construction of large steel truss arch bridges.

3.1 Construction Process

The approaches to the bridge were cleared of existing buildings and structures, in order for work to begin. The foundations were set for both piers at either side of the river.

After the initial parts of the steel truss (the sections between the banks of the river and the piers) had been completed, the suspended cantilever construction was started from both sides. Once these had met in the centre, the ties could be hung ready to lift the sections of the deck into place.

The sections of the deck could then be lifted into place, starting from the centre and working outwards.

Finally all the surfacing and parapets would be added to the structure, along with detailing and super-imposed loads such as lampposts.

3.2 Suspended Cantilever Construction

Cantilever construction is commonly used throughout the world, especially in the construction of steel arch bridges. The main disadvantage is that it can cause large moments to occur at the base of the construction. The Silver Jubilee Bridge spans too far for this type of construction, and would simply collapse from the huge moments incurred from its own self weight. However these can be reduced by using suspended cantilever construction. This method involves using temporary towers and ties, to support the structure and reduce the hogging moments at the bases. This also has the effect of redistributing stress throughout the members in a truss, which will be discussed later. Suspended cantilever construction is shown on the Silver Jubilee Bridge in Figure 3.

With the cranes in place on the truss, the next section of the steel arch would be manoeuvred into place using a barge on the river below. Having the river below the bridge is very useful for transportation of the materials, and meant that the sections could be prefabricated off-site and then brought up the river from where they were produced. This also meant that materials could be stored away from the main site, where it may have been difficult or expensive to use land nearby, and then brought to site by barge when needed.

The ties would then be stressed ready to take the load of another part of bridge to be lifted, and the cranes would begin to raise the next steel truss section. Once it was in the right place it would be attached to the previous section, so that the crane could move up onto it and the whole process could be repeated.

3.3 Temporary Supports and Ties

In the construction of the bridge, large temporary towers and tiebacks were used, to support the arch during construction. These can be large structures themselves, and on many bridges are built into the design of the bridge, such as cable-stayed bridges. In the Silver Jubilee Bridge, the bottom half of these temporary supports have been left in place, and look perfectly in place within the truss system at either side of the arch.

The temporary tower can clearly be seen in Figure 3, and the cables would travel from anchors in the ground, up over the towers, and then to a section of the truss. These ties would take the forces induced by the construction crane and self weight of the bridge itself (shown in Figure 4), until both sides connected, and the cables could slowly be released. Having these supports on either side, also allows a small amount of flexibility when trying to connect the two sides together, as they can be pulled apart or relaxed, so that both sides connect neatly in the centre.

3.4 Construction of the deck

As the deck is constructed the load on the arch will increase. It would be best to construct the deck from the centre and work outwards in both directions simultaneously, as this would load the arch symmetrically from the centre where it is best adapted to carry loads.

Constructing the deck from one side, would lead to the arch being loaded unsymmetrical, and without the weight of the deck on the other side of the arch, could cause the arch to collapse in on itself. The construction could begin from both sides simultaneously; however,
this could also cause unnecessary stresses at the quarter spans of the arch. It could also lead to complications when trying to fit the central section of deck.

The first section of the bridge would be lifted into place from a barge on the river below, and attached to the cables hanging from the centre of the arch. This could then act as a platform from which to begin lifting the next sections of the bridge deck, working outwards in both directions. This would ensure that the loading on the arch remained symmetrical.

This can easily be shown by calculating the forces and moments within the arch, once half the deck has been constructed. For the purpose of this example it can be assumed that the arch is weightless and the weight of the half deck is 2,000 tonnes (20,000kN), and the length of the constructed deck is 165m (half of the total 330m).

\[
W = \frac{20000}{165} = 121kN/m
\]

The moment at point ‘D’ can be used to give a comparison of how constructing the deck in different ways will affect the stresses within the arch.

3.4.1 Beginning from one side

This is shown in Figure 5.

![Figure 5: Deck construction beginning from one side](image)

Using simple static equilibrium equations and then taking moments about ‘A’ and ‘C’, the reactions can be calculated;

\[
\begin{align*}
H_A &= 9.6MN \\
H_B &= 9.6MN \\
V_A &= 5.0MN \\
V_B &= 15.0MN \\
\end{align*}
\]

The moment at \(D\) = 298MNm

3.4.2 Beginning from the centre

This is shown in Figure 6.

![Figure 6: Deck construction beginning from the centre](image)

In this situation the following reactions are obtained;

\[
\begin{align*}
H_A &= 14.4MN \\
H_B &= 14.4MN \\
V_A &= 10MN \\
V_B &= 10MN \\
\end{align*}
\]

The moment at \(D\) = 33MNm

The second type of deck construction (from the centre outwards) produces a significantly lower moment at the quarter span, and so induces much smaller stresses within the arch.

3.5 Problems faced in Construction

3.5.1 Wind effects during construction

One of the main disadvantages to cantilever construction is its susceptibility to torsion effects and moments caused by wind loading. Just before completion the bridge has two large cantilevers, jutting out from either side of the riverbank, which is why this construction technique is often avoided in parts of the world which frequently have strong gusts.

The temporary towers and tiebacks could resist the moments caused by the vertical self weight of the bridge and construction equipment, however there were no lateral ties to help resist the moments caused by wind loading. The main arch is constructed from a large steel truss system, made up from individual steel members. If this arch were to be enclosed then the area on which the wind would act would be far greater, and there would be a high risk of collapse during strong winds.

Once the two cantilevers are connected in the middle the moments in the base caused from wind loads are drastically reduced. Instead of twisting each cantilever, the wind loads now attempt to push the arch over, which the structure and connections can resist more easily.

The design of the completed Silver Jubilee Bridge has overcome these risks by having relatively thin members for both the arch and the deck. Therefore having a small area on to which the wind can act.

3.5.2 Meeting in the middle

Construction began from both sides of the river simultaneously, therefore it was imperative that survey coordinates and measurements were accurate and precise right from the start, in order for the two sides to meet in the middle. Although steel is a very ductile material, and truss systems are more flexible than closed sections, it was important that the two sides meet, so that when they were connected, there wouldn’t be any residual stresses or strains in the members. These could lead to fatigue failure later on, and therefore reduce the lifespan of the bridge.

4 Loading

The Silver Jubilee Bridge is subject to many different types of loads, and its design reflects this. In the majority of bridges the dead load makes up 30% of the total weight, with the live loading contributing to the other 70%. However, the large steel arch provides a large amount of self weight, and so for this bridge dead load
makes up around 70%, with the live (traffic) load providing about 3,000 tonnes, or 30% of the total weight. These loads are transferred through the structure and into the foundations. Simple analysis techniques can be used to give rough sizing of the components of the bridge.

4.1 Dead and Super-Imposed Dead Loads

The total dead weight of the steel within the bridge is approximately 6,000 tonnes. However, with the addition of the concrete deck and surfacing, the total weight is over 10,000 tonnes.

For the analysis of the bridge, during design, these loads must then be multiplied by the safety factors shown in Table 1.

<table>
<thead>
<tr>
<th>Load</th>
<th>Limit State</th>
<th>( \gamma_{f1} ) to be used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead: Steel</td>
<td>ULS</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00</td>
</tr>
<tr>
<td>Dead: Concrete</td>
<td>SLS</td>
<td>1.15</td>
</tr>
<tr>
<td>Super-Imposed Dead</td>
<td>SLS</td>
<td>1.00</td>
</tr>
</tbody>
</table>

4.2 Live Loading (Traffic)

Live loading on the Silver Jubilee Bridge is completely made up of vehicles, as there are no pavements and therefore there is no access to pedestrians. For this scenario both HA and HB loading must be taken into account.

There are two lanes of traffic flow in each direction on the bridge, making four lanes altogether. However in order to calculate the traffic loading on the bridge the entire carriageway width will have been divided up into notional lanes, of which the standard width is 3.65 meters (m). Once this has been determined, both HA and HB loading could be applied to the bridge. The bridge was originally built with just two lanes of traffic, but was widened in 1977 to four lanes. For this to happen, traffic loading would have had to be recalculated, especially as the bridge was beginning to get congested during peak times.

4.2.1 HA Loading

This loading is uniformly distributed along two of the lanes and then a third of its value is distributed along the other lanes. In the case of the Silver Jubilee Bridge, the worst two lanes that could be heavily loaded would be the central two. This is because the deck is supported at either side by cables, and so large loads should be positioned for analysis of the largest bending moment across the deck. The value of this load varies depending on the length of the bridges longest span, and is calculated using the formula;

\[
W = 151 \left( \frac{1}{L} \right)^{0.475} \text{kN/m} \]

The Silver Jubilee Bridge, being a single arch bridge, has only one main span 330m long, however this span is broken up into smaller sections due to the hanging cables supporting the deck at regular intervals of approximately 12m. The value of ‘W’ for spans shorter than 30m is always taken as 30kN/m, and so the Formula (1) would not have been used in the case of this bridge.

As well as the HA loading, a knife-edge load (KEL) is also applied at the point which it will have the biggest effect. This is usually the centre between two supports, when checking for bending, or close to a support when checking for shear. The value used for KEL is 120kN per notional lane.

4.2.2 HB Loading

HB loading would also be applied when analysing the bridge, to account for abnormally large trucks travelling across the bridge. Due to the short spans on the bridge, the worst case of HB loading would involve short trucks 9.6m in length, as this would produce the highest bending between two supports. HB loading also means that there are areas of no loading spreading 25m in front and behind the main truck load. This could have an adverse effect on the bridge as it would mean that the two adjacent spans are not loaded, and so offer no resistance to bending, causing a higher bending moment in the loaded span. 

4.2.3 Combined Loading

Both these loads are then multiplied by safety factors \( \gamma_{f1} \) and \( \gamma_{f3} \) and then applied on every other span along the full length of the carriageway, in order to produce the largest hogging and sagging moments alternating throughout the deck, for analysis, as shown in Figure 7.

![Figure 7: Loading case, deflections and moments](image)

This would be different for the analysis of other parts of the bridge. For example, when designing the steel cables that support the deck, it would be necessary to load the deck along its entire length, so as to produce the largest tension in each cable. Or when designing the arch truss system, it would be necessary to load one half of the deck, in order to load the arch asymmetrically, which is when an arch is weakest and so susceptible to collapse.

In a gridlock situation, with all four lanes fully loaded with traffic, the bridge would be subject to an addition weight of about 3,000 tonnes distributed along its deck [1]. This would vary depending on the types of vehicle.

4.2.4 Design Responses

For the bridge to be safe and usable it must pass both Ultimate Limit State (ULS) and Serviceability Limit State
(SLS) checks. The ULS is to ensure against collapse, and the SLS, which is mainly determined by deflection, is to check that the bridge can be used. Due to the large span of the deck, there would be large deflections, at the centre, when fully loaded with traffic. For this reason, on the Silver Jubilee Bridge, the deck was designed to be constructed so that it bowed upwards towards the centre, as shown in Figure 9. After all of the surfacing and finishing details had been constructed on top, it would then lie relatively flat. This would reduce the overall deflection, as it would only sag due to live loading, as opposed to both live and dead, if it had been constructed flat.

**Figure 9: The bowed deck under construction**

The bridge was originally expected to carry 11,000 vehicles per day, but since it was widened, this capacity has increased from the expected 60,000, and now regularly exceeds 80,000 vehicles per day. This is one of the main arguments behind the construction of a new bridge further down the river.

4.3 Wind Loading

Wind loading can play a major part in the design of large structures, such as this bridge. The deck stands at 24.25m above sea level, with the peak of the arch at approximately 86m [1]. At these heights the wind is often stronger because there are smaller frictional effects caused from the ground. Wind loading effects can be calculated from BS 5400.

4.3.1 Loading on the Deck

Loading could be calculated for different parts of the bridge analysis. Firstly the maximum gust is calculated using:

\[ v_c = v \times K_1 \times S_1 \times S_2 \]  

(2)

The value for \( v \) could be taken as 30ms\(^{-1}\) for the area around Liverpool.

\( K_1 \) is the wind coefficient and is obtained from a table in the British Standards. The deck is approximately 330m long and 24m above sea level, giving a value of 1.48 for \( K_1 \).

\( S_1 \) is a funnelling factor. This would be taken as 1, as funnelling effects on the deck, caused by surrounding buildings, would be minimal.

Finally \( S_2 \) is the gust factor, obtained from the same value as \( K_1 \). For the deck on the Silver Jubilee Bridge, this value would be 1.17.

Therefore the maximum wind gust that could act upon the Silver Jubilee Bridge deck would be:

\[ v_c = 30 \times 1.48 \times 1 \times 1.17 \]

\[ v_c = 51.9 \text{ms}^{-1} \]

From this value, the wind load in N, which acts at the centroid of the deck, would be calculated using the two formulas;

\[ P_t = q \times A_t \times C_D \]  

(3)

\[ q = 0.613 v_c^2 \]  

(4)

\( A_t \) is the area on which the wind acts. The deck spans 330m, and could be estimated at 2.5m deep. However the bridge could be fully loaded with vehicles, therefore the height of the vehicles must be added to the depth of the deck, as any load applied to this traffic will be transferred to the structure. The British Standards suggests an additional 2.5m to be added to the depth for a road bridge. This gives a total value of 5m deep, and 330m long, giving \( A_t \) to be;

\[ A_t = 5 \times 330 \]

\[ A_t = 1650 \text{m}^2 \]

\( C_D \) is drag coefficient, and is a function of the breadth/depth ratio. Assuming the bridge deck is approximately 18m wide and 2.5m deep. This leads to a \( C_D \) value of 1.3 (obtained from a table in the British Standards).

These values give a total load acting on the centroid of the deck as;

\[ P_t = (0.613 \times 51.9^2) \times 1650 \times 1.3 \]

\[ P_t = 3.54 \text{MN} \]

The wind loads applied to the deck are an important part of the design for the Silver Jubilee Bridge, due to the lack of lateral support along the length of the longest span. One way in which the deck could be stiffened, to help cope with these loads, is to have lateral bracing on the underside of the deck. Here it would be hidden from view and so would not impede on the aesthetical properties of the bridge. Without some sort of bracing or other stiffening approach, the deck would be come subject to bending in plan, causing large tensions and compressions to build up along either side of the deck.
4.3.2 Loading on the Arch

The wind load on the arch would also be a substantial load, and must be taken into account during design. In bridge design aerodynamic effects are ignored, and so the main way of reducing the total wind load, is to reduce the total area on which the wind acts. This is one of the main advantages to having open parapets lining the deck. On the Silver Jubilee Bridge the arch is constructed from large steel members forming a truss. If this were to be a complete concrete arch, not only would it have to be bigger, in order to cope with the extra self-weight, but the horizontal loading caused by the wind, would be huge, due to the increased area. The truss allows for the arch to have a relatively small area on to which the wind loads can act, and so is a more economical design.

4.4 Temperature Effects

Changes in temperature can produce large stresses to build up in structures, especially large bridges such as the Silver Jubilee Bridge. Temperatures around this bridge can vary from -14°C up to 34°C, which is a total effective temperature of 48°C.

4.4.1 Expansion Effects on the Deck

The thermal expansion of both concrete and steel is 12\times10^{-6}m/m/^\circ C. This means that if the 330m long steel/concrete deck of the Silver Jubilee Bridge increases in temperature by 10°C, then the length will increase by;

\[
\Delta L = L \times \Delta T \times \alpha 
\]

330 \times 10^3 \times 12 \times 10^{-6} \times 10 = 39.6\text{mm}

If there is no room for the deck to expand, this expansion is converted into a compression force within the deck, which in the case of a slender deck, such as on the Silver Jubilee Bridge, could lead to failure in buckling. If the Silver Jubilee Bridge deck were to increase in temperature by 48°C, it would need to expand by 190mm. This is a significant expansion, and would need to be catered for by expansion joints at certain points along the deck, either at the ends, or staggered along the deck.

In the design of the bridge, it must be assumed that any expansion joints could become clogged and so stop any expansion of the bridge. The additional compression force that builds up, due to the bridge not being able to expand, can be calculated using the following formulas;

\[
\sigma_{\text{max}} = \varepsilon \times E
\]

\[
N = \sigma_{\text{axia}} \times A
\]

At the top of the deck, is where the largest temperature difference is felt. Due to variation in temperature change through the depth of the deck, the axial force is calculated from stresses at the neutral axes (N/A).

Assuming the N/A is at the centre, this maximum stress can be halved to find the stress at this point. The cross-sectional area of the deck is approximately 27m^2 (27 \times 10^6\text{mm}^2).

4.4.3 Effects on the Arch

As the arch heats up and cools down, it will deform, and the curvature will change slightly. By having a truss system forming the arch, it has reduced the effects of thermal expansion, by allowing the structure to deform more easily. At the two bases of the arch, there are pin joints, which allow each side of the arch to rotate by small amounts, allowing the curvature to change. These are shown in Figure 10.

4.5 Other Load Effects

There are many other types of loading that would also be considered when designing the Silver Jubilee Bridge, due to its location and usage.

4.5.1 Shrinkage and Creep

The deck on the bridge is constructed from concrete, which can shrink and creep over time, producing additional stresses and strains within the structure.

4.5.2 Stress Relaxation of Steel Cables

Over time steel cables under tension will lengthen and reduce the stress upon them. This would seriously effect the deflections in the deck under loading, and could become a serviceability issue over time.

4.5.3 Residual Stresses in the Steel

Residual stresses could easily occur in the truss members themselves, formed in production. They could form when the bridge is being constructed, at connection points. In the long run, they can lead to localised failure, and may require repair or replacement of certain parts of the bridge.

4.5.4 Settlement of Supports

The main steel arch on this bridge reaches the ground at either side of the river, with the foundations going deep into the ground to cope with the forces transferred to them. The total weight of the bridge without live loading is over 10,000 tonnes [1], which nearly all travels down through two foundations. This load is very large and consolidation of the soil after construction is almost guaranteed. Problems only really arise when there is a
difference in settlement between the two sides, which leads to a change in how loads are transferred, and can also induce additional stresses.

Before construction began, there would have been extensive geological surveys carried out, in order to calculate soil settlements, and account for them in the design.

4.5.5 Earth and Water Pressures

The Silver Jubilee Bridge spans across the river Mersey, and so is subject to changing water pressures, during high and low water table levels. Earth pressures would also affect the foundations of the bridge, causing stresses to build up over time. Britain has a very low chance of experiencing a large earthquake, and so this type of loading does not need to be accounted for.

4.5.6 Construction Loads

Suspended cantilever construction, means that many parts of the arch can experience tension when under construction, and then, once released by the tie backs, experience compression, and vice versa. This means that that many of the members will have been designed to cope with much larger forces then they have to deal with now, which can seem uneconomical.

Another problem faced with this type of construction is its susceptibility to wind loading during construction. Acting as a large cantilever protruding from the ground with a uniformly distributed wind load spread along it, it creates huge moments at the base of the half arch.

4.5.7 Snow Loads

Snow loading for this bridge would have been taken at approximately 0.5kN/m², spread over the entire deck.

4.5.8 Stream-flow and Scour from the River Mersey

The arch goes down into large piers situated near the banks of the river, which then go down into large foundations. These foundations and concrete piers will be subject to loads from the river. The stream-flow will induce a horizontal load on the piers. This has been reduced by making the design of the piers a more streamline shape.

Scour is also a problem, as it can lead to additional settlement of the foundations. The foundations under these piers will be very deep, so that scour of the sediments around the top of the foundation has little effect.

4.5.9 Skidding and Impact Loading

The design will include previsions for skidding of vehicles, which can produce lateral loads on the bridge deck, and also impact loads on parapets and structural members. These loads will often govern parapet design, and on the Silver Jubilee Bridge additional members jut out from the sides of the bridge to offer lateral support to the parapets.

5 Costing

The Silver Jubilee Bridge cost £3m to construct at the time it was built in 1961 [4]. Up to 50% of this cost may well have been taken up by foundation construction, due to the size of the excavations needed.

5.1 Maintenance and Running Costs

Since its completion in 1977, the local council has spent millions of pounds maintaining and running the Silver Jubilee Bridge. These range from the small costs such as the lighting bills for the street lamps and lighting of the arch, up to major repair of structural members. One of the largest maintenance jobs carried out on the bridge was the replacement of the parapets in 2003 costing approximately £4.5m.

There is also the job of painting the bridge to protect it from the elements. This is done continuously from end to end using up to 50,000 litres of paint in up to five coats [4].

Other contracts carried out have been removing and repairing defect concrete, road resurfacing and joint replacement. The total cost in maintenance and repair since widening the bridge totals over £9m [1].

6 Design

All of the loadings would have to be taken into account in the design of the bridge. There are many different combinations of loads, and variations of how they are applied, and to which sections of the bridge.

6.1 Design of Hanging Cables

When designing the cables to take the load of the bridge deck dead load and the live loading caused from traffic, each section would be loaded in accordance with the traffic loading. Each pair of cables (one on either side of the deck) supports a 12m span of deck. The entire deck weighs roughly 4,000 tonnes;

6.1.1 Loads

Dead loads within the deck can be assumed to be made up of 60% concrete and 40% steel. Using the values from Table 1, the total dead loads can be calculated.

Steel (γf1 = 1.05):
40,000 x 0.40 x 1.05 = 16,800kN

Concrete (γf1 = 1.15):
40,000 x 0.60 x 1.15 = 27,600kN

Total:
16,800 + 27,600 = 44,400kN

Length of deck = 330m

Dead Load:
44,400 / 330 = 135kN/m

HA Loading per lane (4 lanes) = 30kN/m

HA Loading consists of two of the lanes being fully loaded, with the other lanes having a third of the load.

2(30 x 1) + 2(30 x 1/3) = 80kN/m

HB Loading would take up two lanes, which includes 112.5kN per wheel on a sixteen wheel truck.

112.5 x 16 = 1800kN
6.1.2 Combination 1 Loading with HA

Total Loading (Dead + HA Live);

\[ 80 + 135 = 215kN/m \]

Each pair of cables supports a 12m long section of deck, and so each cable supports;

\[ 215 \times 12 = 2580kN \]
\[ 2580 / 2 = 1290kN \]

The cross sectional area of each cable can now be calculated using;

\[ \sigma = \frac{F}{A} \]
\[ \sigma_y = 275N/mm^2 \] for steel
\[ A = 1290 / 0.275 \]
\[ A = 4691 \text{ mm}^2 \]
Radius of cable = 38.6mm 
Diameter = 78mm

6.1.3 Combination 1 Loading with HA and HB

HB combination, with full HA loading on one other lane and a third HA loading on the remaining lane.

Dead: \[ = 135kN/m \]
HB: \[ 112.5 \times 16 = 1800kN \]
HA: \[ 1(30 \times 1) + 1(30 \times \frac{1}{3}) = 40kN/m \]

\[ 12(135 + 40) + 1800 = 3900kN \]
\[ 3900 / 2 = 1950kN \]

The cross sectional area of each cable can now be calculated using;

\[ \sigma = \frac{F}{A} \]
\[ \sigma_y = 275N/mm^2 \] for steel
\[ A = 1950 / 0.275 \]
\[ A = 7091 \text{ mm}^2 \]
Radius of cable = 47.5mm 
Diameter = 95mm

6.2 Parapet Design

The parapets are made from steel box sections, and would have to be designed to stop vehicles from exiting the bridge off the side, in the case of an accident. Collisions with parapets are based on 25 units of HB loading colliding with the parapet [3]. Simple impulse and momentum formulas can be used to calculate the forces occurring in such collisions.

Assuming a 40 tonne truck is driving at 100mph (45ms\(^{-1}\)), and collides with the parapet at an angle of 5°.

\[ v = 45 / (1 / 0.05) \]
\[ v = 2.25\text{ms}^{-1} \]

\[ F \times \Delta t = M \times \Delta v \]

Assuming a Force of 250kN;

\[ 250,000 \times t = 40,000 \times 2.25 \]
\[ t = 0.36s \]

Using basic equations of motion;

\[ v = u + at \]
\[ 0 = 2.25 + 0.36a \]
\[ a = -6.25\text{ms}^{-2} \]

\[ s = ut + \frac{1}{2}at^2 \]
\[ s = (2.25 \times 0.36) - (\frac{1}{2} \times 6.25 \times 0.36^2) \]
\[ s = 0.405m \]

This data would be used in a lab, to test a section of the parapet, to make sure it deformed this much under these conditions.

6.3 Simple Design Calculations for the Arch

Once the deck loading has been calculated, and the maximum tensions in the cables are known. The loads exerted on the arch can be considered. The worst case loading for bending of the arch is when one side of the arch is fully loaded with live loading, and the other side is unloaded, as shown in Figure 11.

![Figure 11: Worst case loading for the arch](image)

6.3.1 Dead Load

The total dead load is 10,000 tonnes, of which 60% can be assumed to be steel and the remaining 40% as concrete. Using the safety factors in Table 1, the total dead load is;

Steel (\(\gamma_f = 1.05\));

\[ 100 \times 10^6 \times 0.60 \times 1.05 = 63\text{MN} \]

Concrete (\(\gamma_f = 1.15\));

\[ 100 \times 10^6 \times 0.40 \times 1.15 = 46\text{MN} \]

Total Dead Load:

\[ 63 + 46 = 109\text{MN} \]
\[ 109 / 330 = 330\text{kN/m} \]

The live load (W) is exerted onto the arch from the hanging cables. HB loading takes up about 60m, including the 25m in front and behind the truck, of no loading. Therefore only three HB loads can set on half of
the deck (165m), as well as the HA loading that is included in this load combination.

**HB:**
\[1800 \times 3 = 5400\text{kN}\]

**HA:**
\[40 \times 165 = 6600\text{kN}\]

Total Live Load:
\[5400 + 6600 = 12,000\text{kN}\]
\[12,000 / 165 = 73\text{kN/m}\]

Moments can be taken about points ‘A’ and ‘C’, to determine the horizontal and vertical reactions;

\[H_A = 57.1\text{MN}\]
\[H_B = 57.1\text{MN}\]
\[V_A = 58\text{MN}\]
\[V_B = 63\text{MN}\]

The point with the largest moment will be the quarter span, half way between point ‘C’ and point ‘B’;

\[M_{\text{MAX}} = 695.5\text{ MNm}\]

This value would be used to calculate the sizing of members within the truss arch system. It is a very big moment, and axial forces would also need to be taken into account. These high values would require members in the region of 1000mm deep.

This type of loading would also have to be checked, for dead loading on one half of the bridge and no loading on the other half, if the deck were to be constructed from one side of the bridge across to the other.

7 Past Alterations

The two lane bridge was originally designed to carry 11,000 vehicles per day. This quickly became exceeded on a daily basis as the areas around Liverpool began to develop, and the population increased. In 1975 work began to widen the bridge deck and approach spans from two lanes to four lanes, and this was completed in 1977, when the bridge was renamed the Silver Jubilee Bridge.

Another major alteration was the parapet replacement, completed in 2003.

8 Future Changes

Future changes of the bridge include many different possibilities, and strategies that have been put forward.

8.1 The Mersey Gateway

There has clearly been a need for a larger bridge, in order to cope with the escalating amounts of traffic. The Silver Jubilee Bridge now regularly exceeds 80,000 vehicles per day, and any small disruption to the traffic flow can cause major congestion that spreads back to the surrounding access roads.

The Silver Jubilee Bridge has already been widened once, and although the arch was clearly designed to carry the extra loading that the bridge incurred, it is unlikely to be economically sound to widen this 46 year old structure again. Which is why plans have been proposed for a new bridge to be constructed upstream of the Silver Jubilee Bridge, to reduce the congestion in the area. This bridge would be a large cable-stayed bridge, carrying a three lane dual carriage and providing relief for the Silver Jubilee Bridge. It could be completed as early as 2014 [1].

![Figure 12: View of the proposed new bridge](image)

8.2 Future Possibilities

With the completion of the new bridge, the congestion on the Silver Jubilee Bridge should reduce, and there has been talk of converting it to carry just public transport, and have a pedestrianised section. This would dramatically reduce the loading on the bridge, and so maintenance and repair costs may reduce, as well as the lifespan of the bridge increasing.

Acknowledgements

A guideline conference paper was produced and distributed by Professor Tim Ibell of Bath University, which has been followed in order to produce this Bridge Engineering 2 conference paper on the Silver Jubilee Bridge.

References


