A CRITICAL ANALYSIS OF THE GATESHEAD MILLENNIUM BRIDGE

T.O. Butler¹

¹Undergraduate Student – University of Bath

Abstract: This paper gives a critical analysis of the Gateshead Millennium Bridge, which sits between Gateshead and Newcastle upon Tyne, UK. The world’s only tilting bridge, basic structural analysis is undertaken to British Standard BS5400:2-2006 to establish loading and basic structural capacity, understand the how the structure works, its efficiency and how all this changes when tilted. The Leonhardt Method of aesthetic analysis is applied to explore the bridges appearance, and additional aspects attributed to the design including construction, geology, serviceability, dynamic stability and durability are also discussed.

Keywords: Gateshead, Millennium, Bridge, Arch, Steel, Tilting

1 Introduction

The Gateshead Millennium Bridge (Fig.1) is a tilting, arch bridge. It was the winning entry of a design competition set by Gateshead Council to create a bridge that spans the river Tyne from Newcastle’s Quayside to the Gateshead Quays and cost £22 million [1]. The entry was submitted by consulting engineers Gifford and Partners with Wilkinson Eyre architects. The brief was to create an iconic structure - a symbol of the regions, and immediate areas, prosperity and continued development. It primarily serves as a link between Newcastle’s trendy bar, restaurant & hotel scene and Gateshead’s ‘art quarter’, including the renovated flour mill - the Baltic Gallery. Recently the Sage (Fig.2), a music and conference venue, has taken residence in this ‘art quarter’. Both the Baltic and the Sage are significant structures in their own right, which has added pressure for the bridge to perform aesthetically as well as structurally.

Figure 1: The Gateshead Millennium Bridge [6]

The Quayside has historically been shrouded in industry. A lot of the old warehousing has been either demolished and built on or just converted into a range of upscale commercial & residential premises. On the Gateshead side this involved the conversion of the Baltic flour mill into a contemporary art gallery. On the Newcastle side a good example is the old Co-operative warehouse, which is now an upscale Mal Maison hotel, which sits just off the northern end of the bridge.

Figure 2: The Sage [6]

As well as fitting in with structures either side of the river, the bridge also had to compliment the rivers existing bridges. The six bridges all sit parallel along a straight stretch of the river and include some of the most iconic and notable bridges in the world - the Tyne bridge being the foremost. It is obvious from first impression that this bridge has influenced the design of the Gateshead Millennium Bridge, most notably in its sweeping arch. Fig.3 illustrates this. Other significant bridges include Robert Stephenson’s High Level Bridge, a recently refurbished double-decker bow-string girder bridge carrying both cars and the East Coast Mainline railway, and the Swing Bridge designed and paid for by Lord William Armstrong - the only other crossing at quayside-level. It was very important that these structures, steeped in history, weren’t undermined or indeed overshadowed by the new bridge.

A challenge of the bridge was to both to allow quayside-level crossing and yet also achieve enough clearance underneath for all manner of river traffic, including a large Royal Navel patrol vessel moored a hundred yards upstream at HMS Calliope, a Royal Naval Reserve Centre. In some respects these

¹ Mr. T.O.Butler – tb262@bath.ac.uk
Limitations have all contributed to the final solution of a tilting bridge.

2 Aesthetics

The concept of a bridge that moves in order to allow river traffic through is not a new one, the drawbridge probably being the earliest example. The Victorians developed swing bridges using mechanical machinery developed during the industrial revolution – there is an example of one on the river Tyne. Areas like Norfolk, heavily laden with waterways, also host a decent population of these bridges. Other popular moving bridge types include bascule, folding, retractable, lifting and transporter bridges. However the Gateshead Millennium Bridge is the first and still the only bridge in the world to tilt.

Aesthetics play a huge part in the bridge choice, of the selection of moving bridges listed above, not many offer any design potential for a striking, architectural structure likely to capture the hearts and minds of the local population. In some respects, the concept of a tilting bridge was the ultimate solution.

2.1 Fritz Leonhardt Analysis

Aesthetic evaluation of bridges is a contentious issue in engineering. Many academics have published work on the aesthetic analysis of bridges, however these generally tend to conflict with each other as the analysis is too subjective and down to personal taste. Fritz Leonhardt is widely regarded as one of the most important bridge engineers of the past century, and his rules on aesthetics break down into ten categories and are appreciated as a more objective approach to aesthetic analysis.

2.1.1 Fulfillment of function

In terms of revealing the structure, the Gateshead millennium bridge is structurally honest. Its inclined parabolic arch clearly supports the deck, whilst its chunky abutments, which house the hydraulic rams, top the arch from splaying. In the tilted position the bridge looks well balanced and sturdy (Fig.8).

2.1.2 Proportions of the bridge

The proportions of the bridge have been given much thought. The arch is of the same depth/span ratio as the Tyne Bridge it sits up stream of (Fig.3); this compliments the existing structure and helps the two coexist together. The main arch itself is tapered, getting broader towards the base (Fig.4), proportional to the forces through it. The deck is substantially bigger than the arch supporting it, however the arches inclination against the deck compensates for this.

2.1.3 Order within the structure

As an arch, the bridge has no significant edges or lines, the hangers are well positioned evenly apart and hang perpendicular to the plate of the kite-shaped arch, the cables don’t cross each other. This gives the bridge excellent order.

2.1.4 Refinement of design

This bridge detailing is very contemporary, both in the finishing of the deck and its components. The kite-shaped section of the arch (Fig.4) with its flat, aerodynamic surface and shape, combined with its discreet tapering and broadening towards the base give the bridge create a sense of quality engineering and performance. This improves the image of the bridge both from it looking stronger and more beautiful.

2.1.5 Integration into the environment
It was always important for the bridge to fit in with the new, modern and trendy surrounding of the Quayside. It does this seamlessly with its bold and contemporary architecture and particularly with its location. It arrives directly in front of the Baltic, almost as if it were a piece of exhibited art itself for the gallery.

2.1.6 Surface texture
The bridge is made from steel, and is shot blasted and paint finished. It is smooth and clean, giving the arch and deck a very sharp, crisp and modern look. The deck subtly uses different paving surfaces for both the pedestrian and lower cycling sections – dark, gritty asphalt for the pedestrians and the light, smooth timber decking for the cyclist.

2.1.7 Colour of components
In all the images featured, the white finish gives a light and visually pleasing feel to the bridge. Fig.4 particularly demonstrates how the light colour contrasts with shadows created to accentuate the slenderness and beauty of the arch. The hangers, although not painted, are very thin and blend into the skyline, helping draw attention to the arch.

2.1.8 Character
Perhaps the most subjective of Leonhardt’s categories, character is hard to define. The author would certainly say that this bridge is steeped in character. It is a sleek, contemporary alternative to the existing Tyne Bridge, contrasting its complex parabolic truss arch and towering masonry abutments. The people of Tyneside love their new bridge so much they’ve put it on their beer – testament to the character this bridge bestows.

2.1.9 Complexity
The arch is no new concept, and despite the arch being inclined and the forces from the stays not acting in plane with the parabola, it is still reasonably simple to deduce how the structure works.

2.1.10 Incorporation of nature
Nature is a difficult thing to incorporate into a structure in such a built up and urbanised area. Certain features of the bridge, such as its stainless steel ‘hedge’ partition for the pedestrians and cyclists draw on ideas from nature – using a broader, more solid looking barrier than just a fence, to separate the two. Most importantly, the movement of the bridge has been likened to a ‘blinking eye’ – the local nick-name for the structure. This almost poetically links in with it being a symbol of the eye-opening development of the area.

3 Structural Design
The bridge is an inclined 2-pin arch. It is difficult to judge whether or not the arch is tied. The deck is

**Figure 5:** The Bridge set against the Baltic Gallery [6]

**Figure 6:** Bridge Deck [6]

**Figure 7:** Newcastle Brown Ale label featuring the bridge

**Figure 8:** Bridge when tilted [6]
curved, so carrying the lateral forces through it is naturally going to want to straighten and buckle the deck. Also, during construction, a temporary tie is used to prevent splaying of the arch [2].

Therefore, although a proportion of the horizontal load probably is taken axially through the deck, for simplicity of analysis I will assume it is untied and all lateral loading is taken by the abutments. When the bridge is tilted, it becomes a butterfly arch, with the cables sitting horizontally, taking some of the self-weight of the deck arch back into the main arch.

3.1 Structural Components

The structure is almost completely constructed from steel. The main arch is kite-shaped in section, which doubles in size between the base and the apex of the arch. The steel plates used for fabrication are 35mm thick, with an array of lateral and longitudinal internal stiffeners running through the length of the arch [1]. The arch is 45m above river level and spans 105m. It is inclined at ~15˚ to the vertical, supports the deck from 18 galvanized steel stay cables, anchored into the arch.

Both the arch and deck come together at the end supports to form a fixed connection at the bearing, housed in the concrete abutments, where a hydraulic ram comes into contact with a paddle which drives the tilting mechanism.

The end supports were a feat of engineering in their own right. The bridge couldn’t use the quayside for foundations for the bridge, so entirely independent abutments had to be created within the channel of the river itself. This involved a comprehensive geological survey being carried out. Construction of the abutments, which were cast in-situ, involved the building of coffer dams and extensive piling for a substantial substructure [1] which certainly indicates that taking the arch as untied is a reasonable assumption.

3.2 Structural Efficiency

The structure doesn’t behave very efficiently, foremost because it is not a tied arch. This is why it required such a heavy and carbon intensive ground work solution. This is purely down to the brief of the bridge though, and in order for the minimum clearances to be achieved, having a tie isn’t possible.

Additionally, the forces that the arch is being subjected to are out of plane with its parabola, which causes large lateral moments the base of the arch – this is one of the reasons why it the arch gradually doubles in section at the base, in proportion with the moments it carries. Again, although this is inefficient use of the arch, the bridge wouldn’t function properly otherwise.

4 Construction

The construction of the Gateshead millennium bridge was particularly challenging. The first challenge was that the structure couldn’t rely on the quayside for any structural support [1]; therefore the abutments had to be cast in-situ in the river channel behind coffer dams (Fig.12). These abutments are steam-lined in plan so as not to inhibit river flow, or cause any unnecessary stress to the structure itself.

The bridge construction was a serious challenge, as the site wasn’t large enough to facilitate in-situ construction of the arch. Watson Steel won the sub-contract to manufacture and assemble the bridge, as
they had previous experience on complex steel work projects. In the end, construction of the bridge sections took place at the sub contractor’s yard in Bolton, where they were then transported by road to AMEC’s Hadrian’s Yard [2], 1.5 km downstream, where full assembly took place, in preparation for a lift-in-one scheme.

Manufacturing and assembling the structure off-site had several advantages to it, the most obvious being quality control. Trials had been carried out on a mock section to see which methods of fabrication worked [2], critically the welding. Sections were butt-welded together, a particularly strong method of fusion, and were then ground down to an architectural finish. The steel plates were cut using special steel manufacturing software to ensure accuracy, and the structure was constantly surveyed throughout assembly to ensure correct positioning [2].

Another advantage of assembly off site was the ease of construction. With no site constraints, work could be carried out in a very suitable, industrial environment (being a disused ship building yard). An example of this would be the specially made “paint pens” – enclosed platforms which moved along and encased the structure. Here, the temperature and humidity could be controlled during the application of the full paint system.

Additionally, the programme, always a critical element of any construction project, was greatly enhanced by the life-in-one scheme. It meant that site occupation and closure of the rivers navigational channel was reduced considerably [2].

From a health and safety perspective, to prevent unsafe access at height, the arch was fully assembled, welded and painted whilst at ground level (Fig.14). The 200 t arch was then lifted into position and propped in place, with substantial temporary works at the base preventing the arch from splaying, yet still allowing rotation [2]. The prop used was the central section of the lifting beam that would be used for final lifting.

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From this position the deck sections could be welded together and subcontractors could get access to complete works on the parapets, decking and lighting.

Final assembly took place in a riverside area of the yard, including the cable tensioning and main deck welds. Although initially rejected, the proposal of a life-in-one scheme became feasible when the yard became available. The Asian Hercules II, a 3200 t inshore floating crane, at the time the largest in the world, was leased to float the bridge the 1.5km upstream to the site.

The lifting beam system was attached to either end support, 9m above the base trunnions [2], allowing sufficient clearance of the structure. It was slung from either end and lifted by the floating crane. During transit the bridge was positioned sideways to give more control over its movement, and was orientated into its final position once at the site (Fig.15).
5 Loading

Being a British structure, opened in 2002, it would have been designed to BS5400-2:2006 Ref. [3], therefore this is what will be used to assess the bridge in this report. The code states in 4.4 that there are five loading combinations that need to be satisfied. They are as follows.

Table 1: Loading Combination [3]

| Combination 1 | Permanent loads with appropriate lives loads. |
| Combination 2 | Combination 1 with wind and erection loads |
| Combination 3 | Combination 2 with temperature effect and erection loads. |
| Combination 4 | Secondary live loads from vehicle collisions with superstructure |
| Combination 5 | Permanent loads with friction at bearings |

5.1 Dead Load

The structure is almost entirely steel, apart from fixtures, surfacing, and the concrete abutments. The weight of the arch alone is 200t [2], with the total bridge weight being 850t [1]. This means that for steel, a dead loading UDL of 79.4 kN/m longitudinally is obtained.

5.2 Superimposed Dead Load

Superimposed load is permanent, non-structural load that acts on the structure. It is treated differently because over the structures life this loading is subject to greater change, and so requires a higher factor of safety. This includes all bridge surfacing, balustrades, lighting and furniture.

Assuming 10mm of resin bound aggregate system (22kN/m³ density); 1.32 kN/m is obtained for the surfacing. Assessment of the rest of the SDL is difficult without having construction detailing to hand, however conservative estimation puts the furnishing and balustrades at 2 kN/m, giving a total of 3.32kN/m.

5.3 Live Load

As a pedestrian and cycle bridge with bollards at either end, any vehicular loading can be neglected. 7.1.1 [3] gives nominal pedestrian loading as \( k \times 5.0 \text{kN/m}^2 \) for bridges >36m in length.

\[
k = \frac{\text{Nominal HA UDL for loaded length} \times 10}{L + 270}
\]  

(1)

The nominal HA UDL can be taken from table 13 [3] as being 22.7 kN/m for a 100m span. Using eqn. (1) along the bridges 105m length live loading is

\[
w_{live} = k \times 5.0 = 0.61 \times 5.0 = 3 \text{kN/m}^2
\]

Therefore over the 6m loaded deck width, live loading is calculated as being 18 kN/m.

5.4 Wind Load

Wind loading methods for highway and rail bridges <200m and footbridges <30m are identified in [3]. For bridges that exceed these levels, such as the bridge in question, special consideration should be given to the dynamic effect of said bridge. However, as a general indication of wind induced stress on the structure, the methods outlined should suffice.

Firstly, maximum gusting wind needs to be established, this is done so in eqn. 2, below.

\[
V_d = S_g V_a
\]  

(2)

\[
S_g = S_{br} K_f T_g S_{hr}
\]  

(3)

where:

\[
V_a = V_{br} S_p S_a S_d
\]  

(4)

Table 2: Values

<table>
<thead>
<tr>
<th>Notation</th>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_{br} )</td>
<td>Bridge and Terrain</td>
<td>1.44</td>
</tr>
<tr>
<td>( K_f )</td>
<td>Fetch Correction</td>
<td>0.91</td>
</tr>
<tr>
<td>( T_g )</td>
<td>Town Reduction</td>
<td>0.81</td>
</tr>
<tr>
<td>( S_{hr} )</td>
<td>Topography</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\[
V_a = V_{br} S_p S_a S_d
\]

\[
V_a = 25 \text{ ms}^{-1}
\]

\[
S_p = 1.05
\]

\[
S_a = 1.005
\]

\[
S_d = 0.74
\]

\[
V_d = 1.06 \times 19.52 = 20.37 \text{ms}^{-1}
\]

5.4.1 Horizontal Wind Load

Nominal transverse wind loading is derived from

\[
P_t = q A_1 C_p
\]  

(5)

\[
q = 0.613 V_a^2
\]  

(6)

\[
q = 0.613 \times 20.27^2 = 252 \text{Nm}^{-2}
\]

Table 4: Total area in elevation, \( A_1 \)

<table>
<thead>
<tr>
<th>Component</th>
<th>Length</th>
<th>Depth</th>
<th>Total Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch</td>
<td>133m</td>
<td>1.664m</td>
<td>442m²</td>
</tr>
<tr>
<td>Deck</td>
<td>105m</td>
<td>2.1m</td>
<td></td>
</tr>
</tbody>
</table>
As a complex structure with a kite-shaped arch and curved deck, the structure is going to have some streamlined characteristics, and wind tunnel testing would be required to find $C_p$, the drag coefficient. This is not available however, and so a rough value will be attained from [3]. The b/d ratio of the deck is ~ 3.87, based on average width and average depth. This gives a value of 1.4 for $C_{p_d}$; however figure 5 specifies that the minimum value taken for foot/cycle Bridge is 2.0.

$$P_t = 252 \times 442 \times 2.0 = 22.28kN = 0.2kNm^{-1}$$

5.4.2 Vertical Wind Load
Vertical wind loading can act as uplift or an additional downward force. This is given by

$$qP_v = qA_3C_L$$

(7)

<table>
<thead>
<tr>
<th>Component</th>
<th>Length</th>
<th>Width</th>
<th>Total Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch</td>
<td>105m</td>
<td>3m</td>
<td></td>
</tr>
<tr>
<td>Deck</td>
<td>133m</td>
<td>8.13m</td>
<td>1396m²</td>
</tr>
</tbody>
</table>

Table 5: Total area in plan, $A_3$

The lift coefficient, $C_L$, is ±0.75, as the degree of super-elevation is ~5°. $q$ is defined in eqn.6.

$$P_v = 252 \times 1396 \times \pm 0.75 = \pm 254kN = \pm 2.42kNm^{-1}$$

5.4.3 Longitudinal Wind Load
Longitudinal wind loading is given by the summation of the following of the expressions

$$P_{LS} = 0.25qA_1C_D$$

(8)

$$P_{LL} = 0.5qA_1C_D$$

(9)

The bridges solid area, in the transverse section is 180m² and the live loading area is 10m².

$$P_L = P_{LS} + P_{LL}$$

(10)

$$P_L = 22680 + 1827 = 24.5kN$$

5.4.4 Wind Load Combination
There are four separate wind loading combinations to establish worst case. They are as follows

Table 6: Wind loading combination

<table>
<thead>
<tr>
<th>Combination</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_t$ alone</td>
<td>22 kN</td>
</tr>
<tr>
<td>$P_t$ with ± $P_v$</td>
<td>276 kN</td>
</tr>
<tr>
<td>$P_v$ alone</td>
<td>24.5 kN</td>
</tr>
<tr>
<td>0.5 $P_v$ with $P_t$ ±0.5$P_v$</td>
<td>163 kN</td>
</tr>
</tbody>
</table>

5.5 Temperature Loading
Temperate change can have a big influence on the bridge design. As a 2-pin arch with zero capacity for lateral movement at the end supports, any expansion of the steel due to temperature change will generate additional stresses within the structure. Similarly, cold-induced contraction will have the same effect. The structure is entirely made from steel, with only minor components on the extremities of aluminum; therefore the structure will expand at the same rate. This means expansion of the arch and deck should be proportional to an expansion of the stay cables, therefore stress should only be felt longitudinally through the structure, and not transversely.

5.5.1 Effective temperature
BS5400:2 gives guidance and isotherm maps for the derivation of minimum and maximum shade air temperature in Figures 7 & 8. These return -14°C for the minimum and 33°C for the maximum. As at footbridge, these temperatures can be adjusted for a 50-year return period, by alleviating the temperatures by 2°C respectively, meaning the effective bridge temperatures are -12°C to 31°C. On its day on installation 20th November 2002, the temperature was in the region of 8°C. This gives temperature changes of 23°C and -20°C. The maximum possible strain of the structure can be sought using

$$\varepsilon = \alpha \times \Delta T$$

(11)

Where $\alpha$ is the coefficient of thermal expansion, which is 12x10⁻⁶/°C. This gives strains of 0.000276 and −0.00024.

$$\varepsilon = \frac{(L_{final} - L_{initial})}{L_{initial}}$$

(12)

Using eqn. 12, expansion and contraction of the arch respectively is 37mm and -32mm. The force induced into the arch can be determined from

$$F = E\varepsilon A$$

(13)

The steel grade, $E$, is 355N/mm². The steel area section averages at 244500mm² over its length, not including the longitudinal stiffeners. This gives axial forces of 24kN in compression and 21kN in tension for expansion and contraction. The contraction acts as a relieving force, therefore can be neglected. The deck will feel a similarly force with expansion, doubling the additional lateral force taken in the end supports. This will be taken as 0.5kN/m over the structure.

5.5.2 Temperature variation through structure
Different materials transfer heat at different rates, this is particularly important to consider for the bridge deck locally, where the top surface can often hold more heat that the bottom section of the deck. This creates a change in the rate of expansion through the cross section, and can subsequently cause bending moments within the structure. As a steel box deck [3] outlines
how temperature may vary with distance from the surface:

![Temperature various through deck](image)

**Figure 16**: Temperature various through deck [3]

5.6 Snow Loading

Clause 5.7.1 of [3] states that snow loading can generally be neglected for loading combinations 1 – 4, however as an opening bridge, consideration should be given. BS6399: Part 3: 1988 Ref.[4], Figure 1 gives basic snow loading for Newcastle upon Tyne as 0.8kN/m², this gives total loading of 6.4kN/m along the deck. Loading over the arch can be neglected due to its inclination.

5.7 Design Loading

Each loading has its own factors of safety for ultimate limit state (ULS) and service limit state (SLS), these have been tabulated below.

**Table 5**: Loading factors [3]

<table>
<thead>
<tr>
<th>Load</th>
<th>ULS</th>
<th>SLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead</td>
<td>1.05</td>
<td>1.0</td>
</tr>
<tr>
<td>Super Imposed Dead</td>
<td>1.75</td>
<td>1.2</td>
</tr>
<tr>
<td>Live Combination 1</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Live Combination 2 &amp; 3</td>
<td>1.25</td>
<td>1.0</td>
</tr>
<tr>
<td>Wind</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Temperature</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Snow</td>
<td>1.0</td>
<td>0</td>
</tr>
</tbody>
</table>

These values for γFL give the following loadings, which have been separated between the arch and deck.

**Table 6**: Final loading over the bridge

<table>
<thead>
<tr>
<th>Load</th>
<th>Location</th>
<th>ULS (kN/m)</th>
<th>SLS (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead</td>
<td>Arch</td>
<td>19.6</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td>Deck</td>
<td>63.7</td>
<td>60.7</td>
</tr>
<tr>
<td>Super Imposed Dead</td>
<td></td>
<td>5.81</td>
<td>4.0</td>
</tr>
<tr>
<td>Live Combination 1</td>
<td></td>
<td>27</td>
<td>19.8</td>
</tr>
<tr>
<td>Live Combination 2 &amp; 3</td>
<td></td>
<td>22.5</td>
<td>18</td>
</tr>
<tr>
<td>Wind</td>
<td>Arch</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Deck</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Temperature</td>
<td>Arch</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Deck</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Snow</td>
<td>Deck</td>
<td>6.4</td>
<td>0</td>
</tr>
</tbody>
</table>

These values are very conservative, and due to the unique nature of the structure a lot of assumption and estimation was necessary to acquire the values. It should be noted that computer aided analysis would be used to simulate these scenarios to gain an accurate image of the loading on the bridge.

5.7.1 Combination 1

All permanent loads with appropriate live loads give a total unit loading of 103kN/m of the deck and 19.6kN/m over the arch.

5.7.2 Combination 2

Combination 1, with the addition of wind loading (there were no erection loads) give a total of 100.4kN/m of the deck and 20.5kN/m over the arch.

5.7.3 Combination 3

Combination 1, with the addition of temperature loading gives 98.8kN/m over the deck and 20kN/m over the arch. This puts combination 1 as the worst case factored loading for ULS, therefore what shall be used in the structural analysis.

6 Structural Analysis

6.1 Arch analysis

As the bridge tilts, it is important to analyse the structure in both its positions.

6.1.1 Normal position

Analysis of the arch has the added complication of the stay cables acting out of plane with the parabola, generating moments in the arch which get bigger towards the base. For ULS loading:

![Bridge Section](image)

**Figure 17**: Bridge Section
It should be noted that for the arch and deck, the centroid is approximate 3/5ths of the parabola height. This was verified by drafting the deck in AutoCAD to get the mass properties. The hydraulic rams, used to push against the paddle at the bearing, which in turn tilts the structure, feels a great deal of compression. Resolving around the bearing gives \( R = 70 \text{ mN} \). Breaking this down into reactions at A & B we get

\[ C_{\text{max}} = H \sqrt{1 + 16 \left( \frac{h}{L} \right)^2} \]  

\( (16) \)

\[ \text{Figure 18: Reactions at A & B} \]

The force component normal to the parabolas plane, identified in figure x, generates a moment in the arches normal plane, down to its fixed base.

\[ \text{Figure 19: Moment in arch} \]

Over the length of the structure 18 cables are used. Each cable has a diameter of 45mm, with a tensile strength of 1350N/mm\(^2\). Assuming 5mm strands were used, each cable consists of 49 strands, giving a total cross sectional area of 962mm\(^2\). This gives a tensile capacity of 222kN/m over the length of the structure, which adequately takes the 129kN/m calculates in Fig.18.

The axial force through the arch and the reaction forces at the end supports can be found using

\[ H = \frac{wL^2}{8h} \]  

\( (14) \)

\[ V = \frac{wL}{2} \]  

\( (15) \)

\[ \text{Figure 20: Forces in arch} \]

For the ultimate limit state design loads, these return \( H=4251\text{kN}, V=7287\text{kN} & C_{\text{max}}=8437\text{kN} \). For the axial force \( C_{\text{max}} \), the grade 355 steel arch can tolerate 87MN of compression over its average cross sectional area of 244965mm\(^2\), which is comfortably within the ULS.

6.1.2 Tilted position

When the structure is tilted, the forces in the structure change. There isn’t space in this report to analysis this in depth, however figure x demonstrates that because the structure is working more efficiently, forming a butterfly arch, and live loading is removed, the stresses through the bridge are less critical than it’s its upright position.

\[ \text{Figure 21: Tilted section} \]

The compression reaction force required in the rams is significantly diminished (\( R=1069\text{kN} \)) as live loading is removed and the dead loads are more balanced. Similarly, there is less tension per unit length in the cables.

7 Serviceability

Certain components of the structure are designed to limit necessary maintenance, this includes rubbish traps that accumulate litter when the bridge tilts, which falls to the ramp ends under gravity. Maintenance hatches have also built into the arch and deck so that internal inspections can be made safely, with no intrusion to the structure.
8 Foundations and Geotechnics

The substructure required for the end supports was substantial; this is due to both the massive lateral forces and the fact that the bridge couldn’t use the quayside for any support. This led to the end support structures being cast in-situ within the river channel.

The ground conditions are complex and consist of non-uniform layers of riverbed gravels on glacial till which sits on top of coal measures - relatively weak mudstone and siltstone [1]. This meant the pile caps had to go down to different depths at each support due to the slope of these layers. These conditions, combined with the large horizontal and lateral loading culminated in a substantial foundation scheme - 14No. 20m deep 1.5m Ø piles were bored for each support. This is on a comparable scale to the London Millennium Bridge which uses 16No. 2.1m Ø at each end to support tensile forces of 30mN in weak London Clay.

9 Natural Frequency

The structures natural frequency is particularly important for pedestrian bridges. The frequency should be above 5Hz [3], if it is lower than this then there is a large risk of user-induced excitation and vibration, which could subsequently cause the bridge to be uncomfortable to users.

Due to the structures complexity, finding the accurate dynamic behavior of the bridge would only be possible through wind tunnel testing and computer modeling. Even finding an approximate value from the many methods available, including that indicated in [3], wouldn’t give an appropriate value even as an estimate.

The structure was wind tested by the University of Western Ontario. This involved the simulation of 49m/s and 33m/s wind speeds over a 1:50 scale model in the closed and open conditions respectively. It was also tested at nine angles of tilt and five of wind azimuth. The testing concluded that the structure didn’t suffer from any “aeroelastic instabilities” [5].

10 Durability and Vandalism

The steel bridge is coated in a highly resistant paint system, with a long-life design, as re-painting the structure will be a particularly difficult task. The camber of the deck will encourage run-off of de-icing salts over the epoxy bound aggregate and prevent chloride ingress and corrosion.

In terms of structural decay, the stay cables will lose capacity faster than the deck and arch due to dynamic relaxation of the strands; however the cable anchorages are accessible from within the sections through hatches so can be replaced and re-tensioned throughout the bridges lifespan, with enough capacity in the cables for them to be taken out of action one at a time.

The bridge is conveniently located only 100 yards away from Newcastle’s Crown Court, in a rather affluent and well presented area. As a result of this, zero tolerance is taken on any graffiti within half a mile of the quayside, let alone the bridge.

11 Future Changes & Improvements

There are no planned future changes to the structure; the only thing that may realistically change is superficial aesthetic detailing (e.g. lighting)

In terms of improvements to the structure, the author believes a lot less steel could have been used in the design, with the overdesigning clearly shown in the analysis. The shape could have been kept using thinner steel sheets making the bridge lighter and more efficient and consuming less power when it tilts, yet still retaining its aesthetic appeal.

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References

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