A CRITICAL ANALYSIS OF THE SACKLER CROSSING, KEW GARDENS, LONDON

B. Trenchard

1 Department of Architecture and Civil Engineering, University of Bath

Abstract: This article gives an analysis of The Sackler Crossing footbridge in Kew Gardens, London. Details of design and construction are considered, looking at factors such as the aesthetic qualities of the bridge, construction, loading, serviceability and foundations. The bridge is designed to fit in with the natural environment of the gardens, providing a new circulation route and feature, with the aim of attracting more visitors to the garden. The loading, structure, serviceability and foundations have been analysed and no evidence of any problems has been seen since construction. The paper was written for the Bridge Engineering 2 unit for the degree in Civil & Architectural Engineering and all analysis carried out is based on assumptions made by the author.

Keywords: Footbridge, Beam Bridge, Steel, Granite, Bronze

1 General Introduction

1.1 Background

The Sackler Crossing is located within the Royal Botanic Gardens at Kew, London. It is a pedestrian bridge spanning 70m across the two-hectare artificial lake, located to the west of the gardens, near the River Thames. The bridge follows a sinusoidal shape in plan and is constructed of granite and bronze just above the water level to give the impression of ‘walking on water’. The deck consists of 564 black granite sleepers laid horizontally on a structural steel frame. The balustrade is made up of 990 cast bronze uprights cantilevered vertically from the bridge deck [1]. There is a gap of 100mm between each bronze upright with no handrail along the top. This allows complete visibility through the balustrade when viewed from a right angle but it appears a solid element when viewed from an oblique angle.

The bridge was designed by London-based architect John Pawson along with consulting engineers Buro Happold and was opened on 16th May 2006. Construction work on the £1.4million bridge was carried out by Balfour Beatty Civil Engineering Ltd. The bridge was named “The Sackler Crossing” after the two philanthropists whose donation allowed the bridge to be built – Dr Mortimer and Theresa Sackler.

The bridge was inspired by the visions of two historical landscape designers at the Royal Botanic Gardens – William Kent (1658-1748) and ‘Capability’ Brown (1716-1783) [2]. Kent believed that all buildings and structures within the garden should blend into their surroundings and be ‘stumbled on as if by accident’. Brown expressed a preference for curves in his designs and believed in ‘the sinuous curve of grace’. Both these factors greatly inspired Pawson’s design for the Sackler Crossing.

Figure 1: The Sackler Crossing.

1.2 Motivation for Construction

The Royal Botanic Garden commissioned a new masterplan by architects Wilkinson Eyre in 2002. This
new masterplan aimed to increase visitor numbers and improve circulation around the gardens at Kew, especially areas that had previously been under used. Central to the plan was a new route around the gardens that consisted of an arc centred on the famous great palm house. Part of this arc included crossing the existing lake – therefore the new footbridge was commissioned.

There had previously been no bridge within the garden even though water features and the lakes were an important aspect of the landscaping. Therefore as well as improving circulation, the new bridge would also allow visitors a closer look at the lakeside planting and the wildlife around the lake. The bridge would also allow greater scope to display planting around the lake and on the islands.

![The Sackler Crossing](image)

**Figure 2:** Location of The Sackler Crossing within Kew Gardens and the new arc-shaped route created.

2 Aesthetics

The visual appearance of the bridge was considered important at a very early stage due to the garden's status as a World Heritage Site. The bridge is designed to “foster clear visual links between the man-made structure of the bridge and the natural contours of the setting” [2]. One of the widely accepted methods of assessing the aesthetic qualities of a bridge are the ten rules laid down by Fritz Leonhardt [3]. He states that if all ten rules are obeyed then there is a good chance that the bridge will be beautiful. If any of the rules are broken, then it is unlikely that the bridge will appear beautiful. The rules are not hard and fast due to the subjective nature of aesthetics and opinions will vary, however they do outline the widely accepted rules of designing a good-looking bridge.

2.1 Leonhardt’s Ten Rules of Bridge Aesthetics

1. Fulfilment of function
2. Proportion
3. Order
4. Refinement of Design
5. Integration into the Environment
6. Texture
7. Colour
8. Character
9. Complexity in Variety
10. Incorporation of Nature

2.2 Aesthetic Qualities of The Sackler Crossing

The structural steel frame of the bridge is hidden beneath the granite deck, through the use of granite downstands along each side of the bridge. This gives the appearance of a much thicker deck than is actually used. This enhances the concept that the bridge is floating just above the surface of the water and the overall look of the bridge is improved due to the columns and beams being hidden. The deck consists of black granite sleepers each 120x120x3000mm, but the thickness of the deck appears much greater than 120mm due to the granite downstand mentioned above. This extra thick deck makes the user confident that the bridge will not be vulnerable to vibration or dynamic effects. The heavyweight feel of the deck is contrasted by the lightweight, slender design of the bronze handrail. The dark colour of the bridge deck also means that from a distance, it blends into the background. This means that the observer’s attention is drawn away from the heavy deck, to the lighter bronze balustrade giving the bridge a more elegant, lightweight appearance.

The design of the balustrade to The Sackler Crossing is very simple and well-ordered, consisting of nearly 1000 bronze uprights. The simple minimalist design of the balustrade means that there are no conflicting elements. The symmetrical curve of the bridge further adds to its aesthetic appeal.

![The simple, well-ordered balustrade](image)

**Figure 3:** The simple, well-ordered balustrade.

The bronze uprights are sufficiently high to provide a safe barrier for users of the bridge whilst allowing visibility of the water and surrounding landscape, as specified in the brief.

Due to the bridge being fairly small-scale, and of simple design it was not necessary to use any complicated elements to make the bridge more appealing. The design of the Sackler Crossing is refined by the high-quality finishes and detailing on the bridge. For example, each of the 990 bronze uprights was cast and then hand-finished to a very high standard – smoothed sufficiently to be touched by the pedestrians using the bridge. The connections between the bronze uprights and structural steel have been completely hidden from view by using small granite downstand blocks. These are fitted to the edge of the granite deck between each of the bronze uprights; they also contain LED fittings to provide illumination to the balustrade at night.
The bridge’s design engineers, Buro Happold, built a full-scale model of a section of the bridge to check that the detailing would work correctly and to demonstrate to the contractors the quality of workmanship required. This is fairly uncommon in the design of footbridges and shows the attention to detail that went into the high-quality finishes on the bridge.

Integration into the environment was a key factor in the design of the Sackler Crossing due to the surrounding high-profile gardens. The result was a bridge that compliments and blends into the natural environment. It was the view of the early landscape designers at Kew Gardens that structures should become part of the natural environment and not stand out or contrast with it. This has certainly been achieved with the construction of the Sackler Crossing. The bridge blends into the environment due to the complete visibility through the bronze balustrade whilst viewing the bridge from a right angle. Then when viewed obliquely the transparency disappears and the natural bronze colour becomes visible. The bridge uses no bright colours and all structural elements such as the foundations and steel superstructure are almost entirely hidden from view. Whilst on the bridge, the pedestrian can see straight through the balustrade to the lake on the other side. Also the gaps between the granite sleepers on the deck allow the user to see through to the lake beneath enhancing the feeling of ‘walking on water’.

The materials used have been finished to a very high standard, which is very important on a footbridge because users of the bridge come into such close contact with the bridge every time they use it. The bronze balustrade has been given a very smooth texture and the granite deck has also been polished to a high standard, whilst still keeping the natural appearance for which it was chosen. The choice of smooth, hand-finished materials is perhaps not the obvious choice for a footbridge in a natural environment – the common choice would perhaps be to construct the bridge out of timber. Nevertheless, the bridge blends in well to the environment around the lake and creates a fantastic landmark for the garden.

The colours chosen have been designed to fit into the environment of the Royal Botanic Gardens. Natural colours have been used throughout – bronze/gold for the balustrade and black for the deck. The bridge has LEDs installed in the deck between each of the bronze uprights, so at dusk the bridge is illuminated to maintain the fantastic golden colour of the balustrade. The lighting scheme was also designed to reinforce the concept of ‘walking on water’; the transparency of the balustrade is maintained, with the illuminated balustrade reflecting on the surface of the lake [4]. There are 998 LEDs in total, but in these use less than 1kW in power [5].

Because the bridge is situated in a garden, it is obvious that the structure must make connections with the environment in which it sits. This is done in three aspects of the design of the bridge. The strong vertical lines of the bronze uprights represent the trees around the lake. The gentle S-Curve represents the curved shore-line of the lake and the gaps between the granite sleepers of the bridge deck brings the sense of walking on water.

2.3 Summary of Bridge Aesthetics

Probably the most inspiring aspect of the bridge is the way the visibility through the bridge varies with the angle from which you are observing.

Whilst on the bridge, the S-Curved shape means that users get a changing perspective of the surrounding landscape as they travel across the bridge. The Sackler Crossing provides both a landmark structure for Kew Gardens, whilst also blending well into and complementing the natural environment. These are two qualities which are often very difficult to achieve simultaneously.
3 Construction of The Sackler Crossing

The construction of The Sackler Crossing was carried out by completely draining the lake over which it is designed to cross. This was made possible due to the construction of the bridge occurring at the same time as required maintenance to the islands and lake itself. This gave the construction team a very unusual opportunity to have access to the bed of the lake and carry out construction using a causeway (see Fig 7). This represented significant cost savings compared to building the bridge from the banks of the lake, using either cranes or some form of cantilever or pre-fabrication construction sequence. Once construction was complete, the lake was then re-filled using its connection to the River Thames that runs along the perimeter of Kew Gardens.

![Figure 7: Aerial photograph showing construction of the bridge using a causeway across the drained lake.](image)

It is very much the norm for bridges to be constructed with access to the river/road/railway beneath restricted to only one or two night closures, therefore having complete access to the bed of the lake made construction easier than most other footbridges.

However, the construction was made tricky due to work being carried out within the gardens whilst they were open to the public. This caused obvious logistical problems as well as environmental considerations. The exact location of the bridge had to be determined by the location of tree roots within the lake – ensuring that the foundations did not cause any damage to the trees. The foundations consist of nine 457mm diameter driven steel piles, which extend above the surface of the lake also forming the supporting columns of the bridge. A steel superstructure was then attached to the columns, and the granite planks making up the deck were bolted to this frame. The design of this steel frame included a tolerance of 100mm to allow for the interface between the piles and the frame [6]. This was required due to the possibility of inaccurate placement of the piles – because the lake of the bed consisted of clay soil it would not be possible to move the piles once installed.

The bronze fins making up the balustrade on each side of the bridge were attached to a backplate in groups of four or five. This backplate was then attached to the structural steel frame. Small downstand blocks of black granite were then installed between each fin, dowelled into the main granite sleepers. Each of these granite blocks also contains the LEDs used to light the bridge after dark.

The construction of the bridge was also being followed by television cameras for the BBC programme “A Year at Kew”, adding additional pressure on the construction team!

4 Loading

The loads to be considered for the analysis of the bridge are:

- Dead
- Superimposed Dead
- Live Traffic
- Wind
- Temperature

These will be considered in accordance to the load combinations stated in Part 2 of BS5400 [7] for both ultimate limit state (ULS), to prevent collapse and serviceability limit state (SLS) to ensure the bridge is serviceable.

The first load case considers dead load, superimposed dead load and live traffic load. The following load factors are taken from BS5400 [7]:

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<th>Table 1: Partial Load Factors, γf, for load combination 1</th>
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<tr>
<td>Dead Load</td>
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<td>– Steel</td>
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<td>Superimposed Dead Load</td>
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<td>Footbridge, Live Load &amp; Parapet Load</td>
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The partial load factor for possible inaccuracy due to analysis, γf3, is taken to be 1.10 for ULS and 1.00 for SLS in all cases.

These load factors are much lower than for buildings because the accuracy for construction of bridges is far greater than for buildings. Also, construction tolerances are much less for bridges and these are more closely monitored during construction.

4.1 Dead Load

The dead load of the bridge consists of the granite deck and the steel frame supporting it. Each of the 564 granite sleepers has a mass of 130kg [6]. Therefore the total weight of the granite deck is:

\[ 564(130 \times 9.81) = 719kN \]  \hspace{1cm} (1)

Assuming that this is applied over a straight span of 70m, for simplicity:

\[ 719 \div 70 = 10.3kN/m \]  \hspace{1cm} (2)
It has been assumed that the structural steel frame supporting this granite deck consists of primary beams mounted on the bridge piers at 7m centres. Longitudinal secondary beams connected to these primary beams then support the granite deck, with tertiary beams in-between the primary beams to prevent twisting. UB356x171x57 steel beams have been assumed throughout. The width of the bridge is 3m. For simplicity, the frame is considered to be linear throughout the following analysis. See Fig. 8 for details.

![Figure 8: Plan of the assumed structural steelwork of bridge. Bold lines show primary beams connected to the bridge piers, lighter lines show the longitudinal secondary beams and dotted lines show tertiary beams.](image)

Diagonal members will also be incorporated to provide cross bracing of the frame. These have not been shown in Fig. 8, but their weight has been included in the loading. The weight of structural steel sections has been taken from the Corus publication Structural Sections [8]. The dead load of the structural steel frame is assumed to be 115kN. Applied over the length, this is:

\[ 115 \div 70 = 1.65kN/m \]  

4.2 Superimposed Dead Load

The superimposed dead load will consist of the bronze balustrade and the LED lighting system – however the loading due to the LEDs will be negligible, so will be neglected. The mass of each bronze upright is approximately 15kg, so the total loading of the balustrade is:

\[ 990(15 \times 9.81) = 146kN \]  

Spread over the 70m length, this will be:

\[ 146 \div 70 = 2.08kN/m \]  

4.3 Live Pedestrian Loading

The live loading for a footbridge over 30m in length is calculated from an initial value of 5kN/m², reduced according to a reduction factor, k, which is found in Eq. (6). The nominal HA universally distributed load (UDL) is found from Table 13 in BS 5400-2.

\[ k = \frac{\text{nominal HA UDL for bridge length}}{30} = \frac{20.1}{30} = 0.67 \]  

Therefore, the live loading is:

\[ 0.67 \times 5 = 3.35kN/m^2 \]
\[ 3.35 \times 3 = 10.1kN/m \]  

4.4 Total Loading

The total loading can now be calculated for the ultimate limit state by adding the above loads and including load factors.

\[ w = \gamma_{f,t} \left[ \gamma_{p} W_{d1} + \gamma_{p} W_{ad} + \gamma_{p} W_{low} \right] \]
\[ w = 1.10 \left[ (1.15 \times 10.3 + 1.05 \times 1.65) + 1.75 \times 2.08 + 1.50 \times 10.1 \right] \]
\[ w = 35.6kN/m \]  

The loading for serviceability is therefore:

\[ w = \gamma_{f,t} \left[ \gamma_{p} W_{d1} + \gamma_{p} W_{ad} + \gamma_{p} W_{low} \right] \]
\[ w = (10.3 + 1.65 + (1.20 \times 2.08) + 10.1) = 24.5kN/m \]  

Additional loading due to temperature will be considered later in this paper. Loading due to wind is not necessary for a pedestrian bridge at ground level, especially as the location of this bridge means that it is sheltered by the surrounding trees within Kew Gardens.

Impact loads on the piers of the bridge are not applicable because the deck of the bridge is so close to the surface of the lake. The balustrade of a footbridge must be able to take a load of 1.4kN per metre run. Impacts on the bridge deck/parapet are not considered above this 1.4kN/m because the lake does not have any water traffic.

It is not obvious from pictures of the bridge whether barriers are present to prevent accidental loading of the deck by vehicles. If barriers are not present, 25 units of nominal HB loading should be applied to represent accidental vehicle loads. However, because the bridge is within a closed site – i.e. members of the public cannot drive within the garden, the risk of vehicles crossing the bridge is vastly reduced. If there is a chance of maintenance vehicles straying onto the bridge though, it is important to check this loading, to prevent collapse.

5 Strength

The strength of the structural steel frame of the bridge will now be considered under the ultimate limit state.

5.1 Bending Strength

Each span has been assumed to be 7m. The critical loading condition is shown in Fig 9. The greater loading, \( w_{1s} \), is equal to the fully factored total load. The lower load, \( w_{2s} \), is equal to just the unfactored dead load. Loading has been divided by two, considering just one of the two longitudinal beams (As in Fig. 8).

The modelled bridge is statically indeterminate, so computer analysis has been carried out to determine the bending moments. The maximum bending moment is found to occur in hogging above the second to last support from the ends, and is equal to 100kNm.
The moment capacity of the assumed UB356x171x57 beam will now be calculated. The grade of steel is assumed to be S275 and the plastic modulus of the beam is $1.01 \times 10^6 \text{mm}^3$ [8]. The moment capacity of the assumed steel beam is therefore:

$$m_c = p_x s = 275 \times 1.01 \times 10^6 = 278kNm$$  \hspace{1cm} (10)

It can be seen that the beam selected is therefore over-designed and one of a smaller capacity could still be used safely.

The strength of the primary cross-beams above the bridge piers will now be considered. Each primary beam (except for the end beams) carries the load from two longitudinal beams, over a total distance of 7m. The point load on each primary beam is therefore:

$$P = 17.8 \times 7 = 124.6kN$$  \hspace{1cm} (11)

Therefore, the maximum moment is:

$$M_{\text{max}} = 124.6 \times 1.5 = 187kNm$$  \hspace{1cm} (12)

The maximum bending moment in the primary beams is therefore also lower than the moment capacity calculated in Eqn. 10. Therefore the assumed UB356x171x57 is safe in bending for the primary beam.

5.2 Shear Strength

The maximum shear force experienced by the longitudinal beams of the bridge deck is for the critical load condition shown in Fig. 9 above. A shear force of 76.6kN is experienced at the second support from the right. The maximum shear force on the primary beams is 124.6kN.

The shear capacity of the assumed section is:

$$P_s = 0.6 p_x A_e = 0.6 \times 275 \times (8.1 \times 358.0) = 478kN$$  \hspace{1cm} (13)

Therefore there is no risk of failure due to shear if using the assumed steel beams.

5.3 HB Loading

If there are no barriers to prevent vehicles straying onto the bridge, then the deck must be able to withstand 4 wheels of 25 units nominal HB loading, to represent accidental vehicle loads. It is not possible to determine from pictures of the bridge whether these barriers exist or not, so analysis must be carried out. Figure 12 shows the assumed vehicle that may stray onto the bridge. The distance between the axles has been taken to be 6m because it is unlikely that any vehicles larger than this size would be operating around the garden. Also, larger vehicles would have difficulty negotiating the curve of the bridge.

Each wheel of the vehicle in Fig.12 transfers 25 units of HB loading, which is equal to 62.5kN per wheel. The worst case of loading, considering just one longitudinal beam is shown in Fig 10.

Again, by computer analysis the maximum moment is found to be in hogging, above the second to last support. This moment increases from 100kNm without HB loading, to 179kNm with HB loading.

The increased loading on the primary beams due to HB loading is therefore:

$$P = 124.6 + 2(62.5) = 250kN$$  \hspace{1cm} (14)
The maximum moment in the primary beams is:

\[ M_{\text{max}} = 250 \times 1.5 = 375 \text{kNm} \quad (15) \]

This bending moment obviously exceeds the moment capacity of the assumed beam, calculated in Eqn. 10. A suitable beam to use under this loading would be UB406x178x74 of grade S275 steel. Alternatively, a higher grade steel could be used with a smaller section size. For example, a UB356x171x51 beam of grade S460 steel could be used.

The maximum shear force for HB loading on the primary beams would be 250kN. This is well within the capacity of either beam considered.

It can be seen that a much higher bending moment is introduced if HB loading must be included in the calculations. A better solution would be to introduce a barrier to prevent accidental vehicle loading of the bridge. This would have to be in-keeping with the surrounding environment of the bridge and not obstruct pedestrian movements around the garden.

5.4 Parapet Loading

The bridge parapet must take a load of 1.4kN per metre run. The spacing between the bronze fins making up the parapet is 100mm, therefore the load can be approximated to a 0.14kN point load applied to the top of each bronze fin. Assuming the balustrade is 0.9m high, the maximum moment in each fin is:

\[ M_{\text{max}} = 0.14 \times 0.9 = 0.126 \text{kNm} \quad (16) \]

Assuming each fin is 150x20x900mm, the section modulus is:

\[ s = \frac{bd^2}{6} = \frac{20 \times 150^2}{6} = 75 \times 10^3 \text{ mm}^3 \quad (17) \]

Assuming the bronze has a strength of 200N/mm², the moment capacity of each fin is therefore:

\[ m_c = p_s = 200 \times 75 \times 10^3 = 15 \text{kNm} \quad (18) \]

We can see that the parapet is therefore adequate for the 1.4kN/m loading.

6 Serviceability

The serviceability of the bridge deals with the deflection, vibration and wind-induced oscillation. Wind loading is not considered for The Sackler Crossing because it is low to the ground and sheltered by trees. Wind loading only needs to be considered for long-span, exposed footbridges.

6.1 Deflection

Deflection will be calculated for both the longitudinal beams and the primary cross beams.

6.1.1 Longitudinal Secondary Beams

The beam used to model these beams on the bridge is statically indeterminate, therefore computer analysis has been used to calculate the deflection. The calculation assumes that it is a UB356x171x57 of steel grade S275, and loaded with both the total factored loading calculated in Eqn. 9 (split between the two longitudinal beams) and the HB loading calculated in Sec. 5.3.

Deflection for the secondary beam is 9.2mm at the centre of the far right span shown in Fig. 10. Although this seems a lot, this is only experienced when exceptionally large HB loads are applied. Under normal pedestrian conditions, the deflections are much lower at around 1-2mm.

Even the large deflections calculated would not cause any damage or usability issues for the bridge. This is because there are spaces of around 10mm between the granite planks making up the deck and 100m spacing between the bronze fins making up the parapet. This means there will be no induced load within the deck or parapets due to deflection.

6.1.2 Primary Cross Beams

Steel beams UB406x178x74 of grade S275 have been assumed for the primary beams. The loading to calculate deflection has been simplified, assuming half the beam acts as a fixed cantilever (see Fig. 14). The total load on the beam is made up of the serviceability total loading found in Eqn. 9 and the HB loading calculated in Section 5.3:

\[ P = (12.3 \times 7) + (2 \times 62.5) = 211 \text{kN} \quad (19) \]

![Figure 14: Simplified loading to calculate the deflections of primary beams.](image)

The beam has a second moment of area, \( I = 27,310 \text{cm}^4 \). Therefore, the deflection is:

\[ \delta = \frac{Wl^3}{3EI} = \frac{211 \times 1.5^3}{3 \times 200 \times 10^6 \times 273 \times 10^{-6}} = 4.35 \text{mm} \quad (20) \]

This deflection is deemed acceptable for a footbridge.

6.2 Vibration

The vibration of footbridges is critical to ensure the bridge is suitable for use. Vibrations can be set up by people’s footsteps and if these vibrations have a frequency higher than 75Hz, they can make people feel uncomfortable using the bridge. If they have a frequency lower than 5Hz, then they can cause excessive movement of the bridge and potentially collapse. Low-frequency vibration was seen on the Millennium Footbridge in London on its day of opening in 2000.
These calculations assume that the longitudinal beams of the bridge are steel UB356x171x57 and are of grade S275. The natural frequency can be calculated approximately using the following formula:

$$\omega_n = (\beta_n l)^2 \sqrt{\frac{E}{ml^3}}$$  \hspace{1cm} (21)

Where:

$$\beta_n l^2 = 15.42 \text{ for a clamped-pinned deck}$$

$$E = 200 \text{GPa for Steel}$$

$$l = 16040 \text{cm}^4 = 160 \times 10^{-6} \text{m}^4 \text{ for UB356x171x57}$$

$$m = \text{mass per metre of bridge deck}$$

$$l = \text{span}$$

$$\omega_n = 15.42 \sqrt{\frac{200 \times 10^3 \times 2(160 \times 10^{-6})}{1161 \times 7^4}} = 73.9 \text{Hz}$$  \hspace{1cm} (22)

This frequency is just within the limits of 5-75Hz. Although on the upper boundary, the actual natural frequency is likely to be lower than this because the equation assumes a clamped-pinned beam. In reality the bridge deck will behave more like a pinned-pinned beam. Unfortunately the equation does not allow for easy modelling using a pinned-pinned beam and is therefore not completely accurate. However it does give us some idea that the natural frequency is within the acceptable range.

7 Temperature

The effects of expansion and contraction due to temperature variation are very important when designing a bridge to prevent induced stresses. The expansion due to temperature effects is given by:

$$\varepsilon_T = \alpha \Delta T$$  \hspace{1cm} (23)

Where \(\alpha = \text{coefficient of thermal expansion} = 1.25 \times 10^{-5} \text{ per } ^\circ\text{C for steel. Therefore the expansion due to a 25\text{C temperature increase is given by:}$$

$$\varepsilon_T = 1.25 \times 10^{-5} \times 25 = 313 \mu\varepsilon$$  \hspace{1cm} (24)

The extension of the 70m span bridge, due to this temperature increase is therefore:

$$\Delta l = 313 \times 10^{-6} \times 70m = 21.9 mm$$  \hspace{1cm} (25)

The sinusoidal shape of the bridge means that this will not be completely accurate for the extension. Firstly, the total length of the bridge will be greater than 70m due to the curve. Secondly, the extension due to the temperature increase will result in some lateral extension and twisting of the steel frame. This means that longitudinal extension cannot be accurately calculated without the mathematical equation for the curve of the bridge.

8 Foundations & Geotechnics

The bridge piers of The Sackler Crossing also form the steel driven piles. They are 457mm diameter piles driven straight into the clay lakebed [6].

The maximum loading on each pile will be equal to the total loading found in Eqn. 8, the HB loading found in Section 5.3 and the self-weight of the primary steel beams. Assuming these steel beams are UB406x178x74 of steel grade S275, they have a mass of 74.2kg/m. Therefore the loading due to the primary beams is:

$$w = 74.2 \times 9.81 = 0.728 kN/m$$  \hspace{1cm} (27)

The total loading on each pile is therefore:

$$P = (35.6 \times 7) + (4 \times 62.5) + (3 \times 0.728) = 501 kN$$  \hspace{1cm} (28)

The lakebed is clay soil and therefore the piles are likely to be fairly long to be able to take the loading. The length of piles will now be calculated. This will only be a rough estimation because in-situ tests of the soil’s shear strength would be needed to carry out accurate calculations.

It is assumed that the average undrained shear strength, \(S_u = 100 kN/m^2\) and the coefficient of friction, \(\alpha = 0.45\) for London clay. The piles are circular hollow section, 457mm in diameter and assumed to be 16mm thick [9] and unplugged. The allowable loading on a pile is the lowest found from the following two equations:

$$\sigma_T = E \varepsilon_T = 200 \times 10^3 \times 313 \times 10^{-6} = 62.6 N/mm^2$$

$$F_T = \sigma_T A = 62.6 \times 7260 = 454 kN$$  \hspace{1cm} (26)
\[ Q_a = \frac{Q + Q_b}{2.5} \quad \text{or} \quad Q_a = \frac{Q}{1.5} \quad (29) \]

\[ Q = q_s A_p = q_s \left( \pi d_1 + \pi d_2 \right) d_z = \left( \alpha S_n \right) \left( \pi d_1 + \pi d_2 \right) d_z \]

\[ Q_s = 0.45 \times 100 \times \left( \pi \times 0.457 + \pi \times 0.441 \right) d_z \]

\[ Q_s = 123d_z \text{kN} \quad (30) \]

\[ Q_b = q_b A_p = (S_n N_c) A_b \]

\[ Q_b = 100 \times 9 \times 0.0222 = 20.0 \text{kN} \quad (31) \]

We know the loading on the pile, \( Q_a = 501 \text{kN} \), therefore the length of pile required will be the maximum found from the two equations above, in Eqn. 29.

\[ 501 = \frac{123d_z + 20.0}{2.5} \]

\[ d_z = \frac{2.5 \times 501 - 20.0}{123} = 10.0 \text{m} \quad (32) \]

\[ 501 = \frac{123d_z}{1.5} \]

\[ d_z = \frac{501 \times 1.5}{123} = 6.11 \text{m} \quad (33) \]

Therefore the steel piles will be approximately 10m long, depending on site tests for the shear strength of the soil.

The loading on the abutments will be less than the piles because they are only supporting a span of 3.5m instead of 7m. Therefore the total loading on each abutment will be equal to the total loading found in Eqn. 8, the HB loading and the self-weight of the primary beam:

\[ P = (35.6 \times 3.5) + (4 \times 62.5) + (3 \times 0.728) = 377 \text{kN} \quad (34) \]

Applying this load over the 3m width of the abutment gives a uniformly distributed load of:

\[ w = 377 \div 3 = 126 \text{kN/m} \quad (35) \]

9 Durability

The materials used in the construction of The Sackler Crossing mean that it will last for many years without the need for much maintenance.

Steel has been used for the main superstructure and piles for the bridge. Steel is very durable and research suggests that the corrosion of steel piles in regular soil is negligible except if the soil is very acidic (pH less than 4) [10]. It is also worth noting that the majority of a pile’s strength is achieved at the base of the pile, where corrosion is at its lowest due to a lack of oxygen.

Corrosion rates of steel in fresh water are lower than those in salt water and are equal to approximately 0.02-0.05mm/face/year in a pH between 4 and 9. Some form of organic coating or cathodic protection should be applied to the piles to provide some extra protection and reduce corrosion rates. Cathodic protection in the form of galvanizing will result in making welding the sections much more difficult. Better protection might be in the form of an epoxy or polyester coating. This will not be necessary for the pile beneath the ground, but would be beneficial for the pile submerged in water and in the splash zone above the water level. Providing protection should mean than the first maintenance of the steel on the bridge will not be necessary for 20-25 years after construction.

The design life of the steel piles and structural steel frame can be increased by providing thicker sections and using steel with a higher yield stress. Also, slightly longer piles should be used to reduce the stress within them and introduce some redundancy.

To reduce corrosion and rusting within the structural steel frame, drainage holes should be provided in areas where standing water could collect. This will reduce the chances and rates of corrosion occurring.

The aluminium bronze used on the balustrade of the bridge is corrosion resistant and will therefore require no protection. Likewise, the granite making up the deck is very durable and resistant to erosion. The deck will be more than adequate for heavy pedestrian traffic for many decades of use.

Fatigue should not be an issue with a pedestrian footbridge because there will not be any large cyclic loads which would be experienced on railway bridges, for example.

The Sackler Crossing should not be subject to much vandalism because it is contained within Kew Gardens so all users must have paid to enter the site. The materials used are also very resistant to vandalism. Granite, bronze and steel will be strong enough to resist anyone trying to inscribe anything into the surface. The only form of vandalism it could be subjected to is spray painting, however there is not an effective solution to this problem – no materials are resistant to spray paint. The likelihood of anyone smuggling spray paints into Kew Gardens however is very unlikely, this sort of graffiti is usually carried out on an opportunistic basis anyway.

The bridge is unlikely to be of a high enough profile to be under threat from terrorist attack. These attacks are usually aimed at well-know structures or those with very high usage.

10 Future Improvements

The Sackler Crossing is a well-designed bridge suitable for its location and use. For this reason it is difficult to suggest improvements that could have been made with the original design or that could be made in the future.

It is unlikely that changes will be required to the bridge in the future because pedestrian loads should remain the same. It can often be a different case for road bridges where HGVs are constantly getting bigger and new design loads are being introduced, causing many
bridges to be strengthened. The only change that would mean strengthening the bridge would be change of use. For example, if Kew Gardens decided they wanted the bridge to take maintenance vehicles or some form of visitor transit vehicle then the bridge would require alteration. Depending on the circumstances this could potentially be easily accommodated. The granite bridge deck and bronze balustrade could be un-bolted from the steel frame and strengthening could be carried out to the steel superstructure before replacing the granite deck.

One improvement on the original design would have been to introduce some form of barrier to prevent vehicles straying onto the bridge. (If this has not already been done beyond the extent of pictures of the bridge). This would have significantly reduced the load required on the bridge and smaller sections could have been used saving materials and money. However, the introduction of this barrier would need to be very near the bridge to prevent vehicles driving around them. The introduction of this barrier may significantly reduce the visual appearance of the bridge.

The foundations of the bridge are made up of just one row of piers. Some may argue that sets of three piers should be used in place of each single pier (See Figs 16 & 17). This would introduce redundancy into the design so if one pier failed, the bridge, as a whole would remain standing. This would allow impacts from boats if they were ever used on the lake. However, the increase in cost associated with using three times as many piles would always outweigh the advantages. This is especially the case when boats do not currently use the lake. Piling is exceptionally expensive – it would usually be cheaper to design a single row of piles to resist impact than introduce additional piles. Using more piers would also reduce the architect’s vision of creating a bridge that allows users to ‘walk on water’.

<table>
<thead>
<tr>
<th>Figure 16: Plan of the current bridge piers on The Sackler Crossing.</th>
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<td><img src="image16.jpg" alt="Figure 16" /></td>
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<th>Figure 17: Plan of a potentially more robust set of piers, but much more expensive.</th>
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<td><img src="image17.jpg" alt="Figure 17" /></td>
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11 Conclusion

The Sackler Crossing is a very elegant, well-considered design that creates the intended focal point within Kew Gardens. The construction is to a high detail, which is important for a pedestrian bridge because users are in much closer contact with the bridge than a highway or railway bridge. The bridge is built of high-quality materials that do not completely blend into the surroundings like timber, creating the iconic structure that was required. The bridge also does not stand out like a concrete or steel bridge would, creating an eyesore in the garden.

The design of the bridge, using combined piles and bridge piers meant that construction costs and labour on site were reduced. The materials used to build the bridge mean it will require very little maintenance and will be fairly resistant to damage and wear and tear.

The bridge was found to meet all loading requirements and its natural frequency is within tolerance to prevent vibration effects when people cross.

Overall, the bridge fulfils its function very well and provides much improvement to Kew Gardens. There are very few improvements that can be suggested for the bridge, which is testament to its design and construction. The brief required an iconic footbridge that blended into the natural environment of Kew Gardens and this has certainly been fulfilled.

References