A CRITICAL ANALYSIS OF CASTLEFORD FOOTBRIDGE, ENGLAND

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Abstract: This paper is a detailed study of the aesthetics, design and construction of the Castleford Footbridge designed by McDowell+Bendetti and constructed by Costain in Castleford, Yorkshire. Analysis of the bridge structure, loading conditions and strength are carried out to British Standard (BS) 5400. The paper also analyses the construction process used, with particular attention paid to the innovative safety methods employed by Costain. This bridge is an iconic design that is being used to stimulate regeneration in Castleford.

Keywords: Castleford, Beam Bridge, Steel, Box Girder

1 Introduction

Castleford in Yorkshire is only 20 minutes from Leeds yet it has not shared the growth and regeneration that Leeds has since the closure of coal mines and mills in the area. Castleford was a mining town until the 1980s and 90s when all the local collieries closed down leaving the area with very high rates of unemployment.

In 2003 Channel 4 went to Castleford and started making a programme with the aim of kick starting the town’s regeneration by commissioning a number of “iconic” projects that the local residents of Castleford felt was needed.

The largest of these projects to take place in Castleford was the design and construction of a new pedestrian bridge across the River Aire in the town centre. The existing 200 year old bridge over the river is a major route for traffic in the town. The narrow footpaths either side of the traffic lanes meant this bridge was dangerous for pedestrians to use.

The original design of a floating bridge upstream of the weir in the town had to be changed as during flooding a barge was washed downstream coming to rest on the weir itself, proving the idea of a floating bridge to be at risk on a river that is prone to major flood events. This design was changed to a simple beam design and moved to a safer location downstream of the weir.

The relocation and change in design lead to a much longer bridge being needed and an increase in costs from £1.1million to £3.2million [1]. In 2007 work started on site and the bridge was completed and opened in 2008.

2 Aesthetics

The aesthetics of this bridge will be considered with regards to Fritz Leonhardt’s list of criteria for bridge design that he sets out in his work titled ‘Bridges’.

Figure 1: Castleford Footbridge from below

Fulfillment of function is the first area to consider in terms of a bridges’ aesthetics. Does the bridge reveal its structure in a clear way? Castleford Footbridge is a beam bridge and this is clear from its form. The bridge is made of two clear elements, the deck and the piers; it is obvious that the piers take the forces from the deck. The simplicity of this design hides the complexity of the
structure that could otherwise have made the bridge look and feel “wrong”.

The proportions of this bridge immediately look right and impart a feeling of confidence and stability. Each span between piers is equal and the 500mm deep steel box girders do not appear under or over sized. The handrail does appear slightly larger than it necessarily needs to be but I feel that it makes it look safer and acts as more than a simple fall restraint but becomes a place for people to rest against – something that a steel tube, for example, would not encourage. The handrail also adds to the aesthetics of the bridge as it has been designed as a continuous uniform structure with regularly spaced supports. The handrails and the girders below the deck lead the eye along the structure because as with the timber deck line they are not broken by anything. The deck is supported by cantilevers from the two box girders, these are recessed slightly from the edge of the deck but are still visible. They are regularly spaced and this order adds to the character of the bridge. A large concrete column in place of the piers is reduced. A large amount of uniformity, that works so well here, has certainly have detracted from the aesthetics as a large amount of uniformity, that works so well here, would have been lost. The steel piers are V-shaped and each side of the V is made up of two columns joined together by two webs, see Fig. (1). The use of 4 inclined columns means that the visual effect of the piers is reduced. A large concrete column in place of the V-shaped piers would have looked bulky and blocked views underneath the bridge. The curved shape of the bridge means that the piers are visible from the deck and this design makes them interesting to look at but it is also possible to look through them and beyond which adds to the aesthetics of the bridge.

A bridge must integrate into the environment that it is in. If it does not then it is unlikely to be used properly, particularly in the case of the Castleford Footbridge. The bridge design is very modern compared with the existing architecture around it, but being a beam bridge it remains low and unlike a cable stayed bridge, for example, it does not try to dominate the landscape. The low profile of the bridge is what allows it to work within the environment that it is in even though the modern design of it should, I think, prevent this.

The textures of this bridge have been kept very simple. Rather than confusing the structure with lots of different textures there is only two clear textures. The main structure of the bridge is all made of smooth steel and the deck and handrail are made of Brazilian Cumaru hardwood. The steel helps to show people which parts of the structure carry the loads but the slender piers and beams also lend themselves to a smooth finish. The deck and handrail looks smooth but next to the steel there is a clear difference.

As with the use of textures on this bridge the use of different colours has been kept to a minimum. The piers have been painted white, they are the only parts of the bridge that are this colour so they stand out and your eye is drawn to them. The steel box girders and cantilever supports for the deck are all left as a polished steel finish with no colour applied to them. The hardwood deck has also been left untreated and so shows its natural colour. The colours of this bridge work well and help to show the user the different structural elements of it helping them to understand how it works.

Although this bridge does not make the public wonder as to how it works I still think that this bridge has character. It certainly has character for the local residents that were involved in choosing the architects to design it and heavily involved in the design process itself. This feeling that the bridge has been created by the residents that use it most gives this bridge more character than one built without that level of involvement. The curving deck also gives the bridge its character. It could have been straight where its sole purpose would have been to cross the river, now it is a place for people to go to and becomes more than just a bridge but also a recreational area for the local community.

Although F. Leonhardt suggests that for the fulfiment of function the more simple a bridge is the more beautiful it is he also suggests that a certain amount of complexity can be visually stimulating. Beam bridges are inherently simple bridges and hence some of the earliest bridges were beam bridges, so there is often not much scope for adding complexity to them. Yet this has been done by creating V-shaped piers as opposed to columns. These piers are more complex than they might need to be but this makes them interesting and gives the bridge a lot of its character. The bridge also hints at being more complex than it first looks by having large flowing seats, see Fig. (2), rising.

Figure 2: Seating and handrails looking south [3]
out of the deck. These are structural to the bridge and allow it to carry more moment and resist torsion. But the integration of them into the bridge as seating makes them more useful serving a double purpose. They encourage the viewer to think more about the bridge and how and why these seats work.

Incorporating bridges into nature is very important in making them look in place in their environment. The bridge deck on plan is an ‘S-shape’ and although this was intended by the architect to be like “a magic carpet ride” [1]. The ‘S-shape’ seems to mirror the shape of the River Aire that it crosses, which is why I believe the shape of the deck works well in this location. Had it been spanning a road, for example, I feel the bending shape would have looked out of place. The seating adds an undulation to the bridge that mirrors the local landscape around Castleford that is quite hilly. The piers although not immediately taking inspiration from nature remind me of reeds reaching out from the river bed to support the deck.

2.1 Summary

Although rigidly following Leonhardt’s ten rules of bridge aesthetics will not guarantee a beautiful bridge it is safe to say that ignoring these rules will not produce a beautiful bridge at all.

The architects McDowell+Bendetti do seem to have covered in some way all ten of the rules. Some seem to me to have not necessarily been covered directly by the architects during the design process but have actually been indirectly achieved because of other design ideas. The incorporation of nature is a good example of this – the idea of a magic carpet ride has created an organic deck shape that mirrors the shape of a river.

This bridge works well in the environment that it is in and the architects have achieved an iconic and beautiful bridge.

3 Design, Construction and Safety

3.1 Design

The architects McDowell+Bendetti were chosen by the local residents and members of Wakefield Metropolitan District Council not for their experience in designing bridges – as this was their first – or for the design they had come up with in particular, but because they were willing to work with the local residents to achieve something that they wanted.

The original design was for a bridge that would float on the river, and it would cross upstream of Castleford’s weir where the span would be much less than crossing downstream. This design was changed to a bridge that floated on a single ‘barge’ in the centre of the river as the Environment Agency deemed the original design to be a flood risk.

During flooding in January 2005 a tug, weighing 30 tonnes, [4] broke free from its mooring upstream and washed down the river before getting stuck on top of the weir in Castleford. Had the bridge been in place the tug would have washed into it potentially causing serious damage to the structure. This meant the bridge had to be moved to a safer location downstream of the weir and the design would have to be changed to a fixed bridge. The ‘S-shape’ was then conceived and after testing on a scale model it was decided that this was the design that would be built.

3.2 Construction

Each bridge type has very different construction processes and the different designs alleviate some problems but this often creates problems elsewhere for construction. For example had a suspension bridge been built in Castleford the difficulties of constructing piers in a river would have been removed but these would be replaced with the difficulties of building tall towers or getting cables from one tower to the other.

The beam bridge design meant that 3 piers needed to be constructed in the river which is by no means an easy or safe operation.

The construction contract was won by Costain and work on site began in January 2007 [1]. All the steel elements of the bridge were prefabricated by the steel contractor, Rowecord, off site at their factory in Newport, South Wales.

The issues of installing piers in the middle of the river with depths varying from 0.5m to 7m [2] were carefully considered by the construction and design team. The use of a pile cluster at each pier was considered and in the end the design was refined to each pier being an 1800mm diameter reinforced concrete pile. The construction team considered all the possible options of how to install these piles safely. A ‘floating platform’ or modular jack-up barge [2], Fig. (3), more used to marine work, was chosen over the use of a temporary jetty or a rock causeway. Both of the discounted options would have included a lot of work to be carried out in the river before installation of the piles could begin. The decision was made to not use cofferdam around each pile, which would have required a lot of pumping to remove the water from the large areas created by the cofferdams. Steel casings were driven down into the river bed at the locations of the piers. From the jack-up barge the material inside the casings was removed by an auger. Once drilled to the required depth the pile could be filled with concrete and reinforcement, at this stage 4 high tensile Macalloy bars were also installed [2]. The top of the steel casing above the water level would be cut down in line with the concrete once it had cured. Precast pile caps were installed to each pile, each with a ‘limpet’ attached, Fig. (4). The limpet was a fabricated steel unit attached to the pile cap that extended above the water level creating a workable area [2]. When the pile cap was in place (with limpet) the Macalloy bars were stressed to 90 tonnes each and then grout was applied to seal the cap.
This part of the construction process was completed in October 2007 [1].

The steel legs that would be fixed to the pile caps and complete the piers, manufactured by Rowecord to an accuracy of ±12mm, were brought to site. A steel plate was attached to the top of the pile caps, the limpet creating a safe working platform, and then the legs were attached to this plate and temporarily tied together to keep them in the correct position.

Once the legs were in position the bridge deck sections could be brought to site and installed. An 800 and a 500 tonne mobile crane had to be used to place the deck sections, these are some of the largest cranes in the country and required access roads to be dug up and reinforced before their arrival. The bridge sections were installed in 5 days and nights [1] to minimize disruption to Castleford.

The Cumaru hardwood deck was installed in panels that were prefabricated on site before being lifted by crane into place on the bridge. It took 8 months, through the winter, to install 35 tonnes of wood to complete the bridge and Costain achieved less than 10% wastage.

The bridge was opened in July 2008, along with a fish ladder up the weir that had been constructed at the same time as the bridge at the request of the Environment Agency.

3.3 Safety

Bridge construction is a dangerous process, particularly as inevitably some working at height will be required, which is very dangerous; the number of fatal injuries to workers caused by ‘falls from height’ in 2007/08 was 58 [5]. Constructing a bridge over a river which is prone to flooding therefore is even more difficult and dangerous. The main contractor, Costain, achieved the construction of this bridge safely by an increased use of prefabrication and innovative temporary works solutions.

![Figure 3: Jack-up barge - steel casing being driven](image)

When looking at the construction of the piers and their foundations in the middle of the river the construction team considered the various ways that are often used to reach these positions. The use of a stone causeway was considered but this would have meant considerable damage to the river ecosystem and diversion of the flow around the causeway. A temporary jetty was also considered which would have reduced the damage to the river bed and ecosystem but there would have been a lot of work to be done to construct the structure in the river itself. The working platform would have been high above the normal river level so there would have been increased risks of working at height when using the jetty. The decision was made to use a working platform called a ‘jack-up barge’, which is more commonly seen on marine works, see Fig. (3). This meant there would be minimal damage caused to the river bed and ecosystem and allowed the working area to be moved from pier to pier as well as getting very close to allow easier access for plant. This also proved to be very safe and useful, when in June 2007 severe flooding stopped construction as river levels rose 3.5m. The ‘barge’ was jacked up as the river levels rose and importantly when they receded there was very little clean up or remedial works required before work could continue again. This would not have been true of a fixed jetty system or a stone causeway which would have been damaged by the rise in water level.

![Figure 4: The Limpet](image)

The ‘jack-up barge’ had solved the issue of getting access to the piers and foundations for construction. The use of a cofferdam to create a large area around the pier and foundation free of water to allow construction was ruled out. This was because a large area of water would have had to have been pumped out from inside them, which is very costly. Instead the construction method described in Section 3.2 of installing steel casings for the foundations meant there would be no need to pump out water or for operatives to enter a confined space. Then on completion of the piles the use
of the ‘limpet’ attached to the pile caps, see Section 3.2 and Fig. (4), was another innovation that made the construction much safer. The limpets removed the need for cofferdams to be installed around the piles in order to gain access for pre-stressing the Macalloy bars. The limpets reduced the amount of pumping required to remove water from the work area but also created a working platform at the required level to safely access the pile cap.

The maximization of off-site prefabrication particularly in the case of the steel structure for the bridge meant the amount of work to be carried out in the river was greatly reduced. The hardwood deck was not prefabricated off site but the construction team took the decision that it was safer and that greater quality could be achieved if as much of the deck as possible was fabricated on site and then lifted onto the bridge. This greatly reduced the amount of time spent working at height and above the river.

4 Foundations and Geotechnics

The foundations used for the Castleford Footbridge were carefully considered and designed by the construction team from Costain with particular attention paid to safety and the environment. There are three different types of foundation on this bridge each with a different way of combating the geology of the site, Fig. (5) shows the different foundations used on the bridge, the southern foundation is on the left.

4.1 South Abutment Foundation

Where the bridge lands on the southern bank of the river the restrictions to the site and slightly improved ground conditions mean that a pad foundation system was adequate to support the bridge. The deck transfers loads through the bearings into a large reinforced concrete beam running perpendicular to the deck. The beam is supported by three circular columns that transfer the loads down into the pad foundation. This abutment and foundation design is a simple yet effective system that I think has some elegance to it, as normally abutments are large structures but this is a small structure that does not detract from the bridge, see Fig. (6).

4.2 Pier Foundations

Pile groups were considered for use at the three piers but in the end the construction team went for a single large diameter pile to support each pier. As this bridge crosses a river and is therefore on the floodplain the top layer of earth is a mix of sand and gravel (alluvium) which is poor at taking loads, therefore the piles are not going to be friction piles but will be end bearing piles. Each pile was cored down through the alluvium and into the layer of Weathered Mudstone below which is much better at taking loads. The area around each pile cap was made up with stone to protect the area around the piles from scour.

4.3 North Abutment Foundation

At the northern abutment the ground conditions meant that a pad foundation similar to the one at the southern abutment would not be possible. It was decided that using reinforced soil would be a possible way to overcome this or to use piles. A reinforced soil abutment was chosen as it was better for the environment and meant that some of the temporary gabion jetty could be incorporated into the final abutment.
The foundation consists of an initial rock mat foundation with steel cages laid on top. Each layer is made up of frictional stone fill with stone making up the face behind the steel cage. This foundation type works very well on the northern side of the river as here the banks are natural, unlike the south bank that has a brick wall and buildings running along it, and so this rock face blends well with the existing land. The small more standard concrete abutment containing the bearings is well concealed by the ground and does not detract from the bridge or the environment, see Fig. (7).

5 Loading

This bridge will have been designed to the British Standard codes of practice BS5400 which covers the design and construction of bridges, including steel footbridges. This code was used in the following sections 5 Loading and 6 Strength to analyse the Castleford Footbridge design.

5.1 Assumptions

In order to carry out the analysis of the Castleford Footbridge I have had to make some assumptions using the information that is available. Where I have made an assumption it will be clearly stated but there are some that I have had to make at the start of the analysis that will continue throughout. These are mainly to do with the dimensions of the bridge, particularly of the cross section of the deck, Fig. (8).

![Castleford Footbridge cross section](image)

Figure 8: Castleford Footbridge cross section

Figure (8) shows the separate elements of the bridge cross section; A= the two longitudinal box girders, B= the top box girder or “seat” and Table 1 gives the maximum values for it, C= the transverse box girder, and D= the cantilevered webs. All structural steel in the bridge is assumed to be 18mm thick (t=18mm).

| Table 1: Assumed values for Castleford Footbridge |
|-----------------|------------|
| Section Element | Height x Width |
| A               | 500 x 300 mm |
| B               | 700 x 300 mm |
| C               | 500 x 700 mm @ 1m c/c |
| D               | 142.5 x 1400 mm @ 0.5m c/c |

5.2 Dead and Superimposed Dead Loads

The dead load (DL) of a bridge is the weight of the materials that are structurally integral to the bridge itself. The superimposed dead load (SDL) of a bridge is the weight of materials that are part of the bridge construction but do not act structurally, such as parapets and decking. Both these loads are constant throughout the lifetime of the bridge; unlike live loads, see Section 5.3. Table 2 shows the dead and super imposed dead loads of the bridge, to calculate these I assumed g= 9.81m/s² and the mass of steel, m.= 7850kg/m³. For design purposes the factors of safety (γfl) are applied to the DL and SDL, the factors used below are γfl= 1.05 for DLs and γfl= 1.20 for SDLs.

| Table 2: Dead and Superimposed Dead Loads |
|-----------------|------------|
| Element         | Load kN/m  |
| Timber (SDL)    | 2.36       |
| Steel           | 11.25      |
| Total SDL + DL  | 13.61      |
| Factored Total Load | 14.64     |

5.3 Live Loads

The bridge at Castleford is a pedestrian bridge so does not experience any loading from vehicles. The seats that rise up from the deck level start at each end of the bridge. This means that vehicles cannot access the bridge, purposely or accidentally.

Using BS5400 the standard pedestrian loading on footbridges with a loaded length <36m is 5kN/m², Castleford footbridge is 131m, >36m, therefore the pedestrian load can be reduced by k, calculated using Eqs. (1, 2, 3).

\[ w_{ped} = 5.0k. \]  
\[ k = \frac{10H_{Audt}}{1 + 270}, \]  
\[ H_{Audt} = 36\left(\frac{1}{7}\right)^{0.1}. \]

\[ w_{ped} = 5.0 \times 0.551 = 2.76 \text{ kN/m}^2. \]

There is no need to consider the effects of crowd loading on this bridge as it is not in a location that is likely to see any large crowds of people using it. The pedestrian load on the bridge therefore is 11.3kN/m.

5.4 Wind Loads

Wind loads on bridges are complicated as they act on the bridge in numerous planes and can have an exaggerating or relieving affect on the dead and other live loads acting on the bridge. Using BS5400 I have analysed the wind loads upon the Castleford Footbridge.

5.4.1 Wind Speed

The local site conditions have a great affect on the wind that the bridge will experience, in particular the
maximum wind gust speed \(V_d\) and the site hourly mean wind speed \(V_s\), BS5400 takes account of this and calculates these, using BS5400-Figure 2 to get the basic hourly mean wind speed \(V_b\) for the site.

\[ V_d = S_d V_s \]  
\[ V_s = V_b S_p S_a S_d \]  

(4)  
(5)

| Table 3: Values for Wind Calculations [6] |
|-----------------|-----------------|
| \(V_d\)         | 23.8 m/s        |
| \(V_s\)         | 23.46 m/s       |
| \(V_b\)         | 23 m/s          |
| \(S_d\)         | 1.00            |
| \(S_p\)         | 1.00            |
| \(S_a\)         | 1.02            |
| \(S_d\)         | 1.00            |
| \(C_D\)         | 2.0             |
| \(C_L\)         | ±0.5            |

5.4.2 Nominal Transverse Wind Load
The transverse wind load acts horizontally at the centre of the area of the bridge being considered.

\[ P_t = q A_1 C_d \]  
(6)

\[ q = 0.613 V_d^2 = 347.2 \text{ N/m}^2. \]  
(7)

\[ P_t = 347.2 \times 85.15 \times 2 = 59.1 \text{ kN}. \]  

5.4.3 Nominal Longitudinal Wind Load
The longitudinal wind load acts at the centre of the area of the bridge being considered and is the greatest of either:

a) the nominal longitudinal wind load \(P_{LS}\) alone,
b) \(P_{LS} + P_{LL}\) and the nominal longitudinal wind load acting on the live load \(P_{LL}\).

\[ P_{LS} = 0.25q A_1 C_D \]  
(8)

\[ = 0.25 \times 347.2 \times 7.79 \times 2 = 1.35 \text{ kN}. \]  

\[ P_{LL} = 0.5 q A_1 C_D \]  
(9)

\[ = 0.5 \times 347.2 \times 7.79 \times 2 = 2.7 \text{ kN}. \]

\[ P_{LS} < P_{LS} + P_{LL} \therefore P_{L} = 1.35 + 2.7 = 4.05 \text{ kN}. \]

5.4.4 Nominal Vertical Wind Load
The vertical wind load acts at the centre of the area of the bridge being considered and is an upward or downward force.

\[ P_v = q A_1 C_L \]  
(10)

\[ = 347.2 \times 537.1 \times \pm 0.5 = \pm 93.2 \text{ kN}. \]

5.4.5 Load Combination
The wind load \(w_{\text{wind}}\) is a combination of the wind loads calculated above, and is the greatest of:

a) \(P_t\) alone,
b) \(P_t \pm P_r\),
c) \(P_{LS}\),
d) \(0.5P_t + (P_L \pm 0.5P_r)\).

In the case of the Castleford Footbridge combination b) is the greatest load so \(w_{\text{wind}} = 152.3 \text{ kN} / 131 = 1.16 \text{ kN/m}.\)

5.5 Temperature
Changes in the local ambient temperature can create large forces within structures, particularly bridges. To relieve these forces within the structure it is necessary to design expansion joints to allow the bridge to move. Designing to BS5400 a 1:120 year return period is necessary except for pedestrian bridges where a only 1:50 year return period is required, which means the temperatures used for a 1:120 return can be relieved by 2°C. The Castleford Footbridge has expansion joints at both ends of the bridge deck to allow the movement from changes in temperature. Assuming the expansion joints are free to move and an increase above the datum temperature of 20°C, using Eqs. (11, 12) and the coefficient of thermal expansion for steel \(\alpha = 12 \times 10^{-6}/\text{°C}\), the expected change in length of the bridge can be calculated.

\[ \epsilon = \alpha \Delta T \]  
(11)

\[ = 12 \times 10^{-6} \times 20 = 400 \mu\epsilon. \]

\[ \delta = \epsilon l \]  
(12)

\[ = 400 \times 10^{-6} \times 131000 = 52.4 \text{ mm}. \]

It is necessary to consider the effect temperature changes like the one considered above would have on the bridge if the expansion joints became blocked. The expansion joints stop the build up of stresses in the bridge structure but if they were unable to move it is important to understand the size of the stresses that would be created. Figure (9) shows the calculated profiles of strain and stress. Stress is calculated using Eq. (13) and assuming \(E_{\text{steel}} = 205 \text{ kN/mm}^2\).

\[ \sigma = E \epsilon. \]  
(13)

**Figure 9**: Temperature/Strain/Stress Profiles

The stresses in Fig. (9) only exist if the bridge is restrained from moving. Using the calculated stresses it
is possible to calculate a compressive force that is created within the bridge and the associated moment.

\[
F = \frac{8A}{2} \times 84960 = 2.96 \text{MN (c)}.
\]

\[
M = \frac{\bar{d}l}{y} = \frac{82 - 12.3 \times 3.451 \times 10^9}{462} = 260 \text{kNm}.
\]

This shows that if the movement joints are not properly maintained a considerable compressive force can be created within the bridge.

5.6 Natural Frequency

Vibrations can cause problems for bridges particularly footbridges which are usually light weight bridges. The Millennium Bridge in London famously experienced excessive vibrations from pedestrians crossing it, the phenomenon this bridge experienced is known as Synchronous Lateral Excitation. The lateral excitation was caused by a sideways force exerted by pedestrians as they walk but they also exert a vertical force which can cause problems in terms of vibrations for a footbridge. The fundamental natural frequency \(f_0\) of a bridge can be calculated, Eq. (16), and it has been found that providing \(f_0\) is between 5 and 75 Hz the bridge will not show excessive vibrations. The fundamental natural frequency is found for the worst case position on the bridge, this is either of the two end spans which are two of the three longest spans of the bridge and they are essentially fixed-pinned beams. The first value \((\beta_n)^2\) depends on the type of beam being considered and is lowest for a fixed-pinned beam when \((\beta_n)^2=15.42\).

\[
f_0 = (\beta_n)^2 \cdot \frac{EI}{\text{m}^4} \quad \text{(16)}
\]

\[
f_0 = 15.42 \times \sqrt{\frac{205 \times 10^6 \times 3.451 \times 10^{-3}}{13.6 \times 26^4}} = 5.20 \text{ Hz}.
\]

This shows the Castleford Footbridge satisfies the vibration serviceability requirement as \(f_0\) exceeds 5 Hz, according to Annex B of BS5400-2.

5.7 Loading Combinations

The various loads calculated in Section 5 are combined together and the greatest of these loads is used as the design uniformly distributed load. The loads are applied in a way that will cause the most adverse total effect. In the following combinations all \(\gamma_0\) values are from BS5400-2 Table 1.

5.7.1 Combination 1

Considered here are the permanent loads and the primary live loads. In the case of a footbridge, and the Castleford Footbridge, the primary live loads are that of the pedestrians, calculated in Section 5.3. The live loads are applied with a factor of safety \(\gamma_0=1.5\).

\[
w_{\text{design}} = 14.64 \times (1.5 \times 11.3) = 31.59 \text{kN/m}.
\]

5.7.2 Combination 2

Considered here are the loads calculated in combination 1 and the loads from wind \(w_{\text{wind}}\), see Section 5.4.5. The wind load is applied with a \(\gamma_0=1.4\).

\[
w_{\text{design}} = 31.59 \times (1.4 \times 1.16) = 33.21 \text{kN/m}.
\]

5.7.3 Combination 3

Considered here are the loads calculated in combination 1 and the loads from temperature effects \(w_{\text{temp}}\), see Section 5.5. The temperature load is applied with a \(\gamma_0=1.3\).

\[
w_{\text{design}} = 31.59 \times (1.3 \times 22.60) = 60.96 \text{kN/m}.
\]

5.7.4 Combination 4

Considered here are the loads calculated in combination 1 and the appropriate secondary live loads. In the case of a footbridge the secondary live loads are loads from collisions with the structure. These can often be very large forces if the bridge is accessible by vehicular traffic, or water vessels are able to come into contact with the bridge structure. It is assumed that the Castleford Footbridge does not have any secondary live loading on it. This can be assumed as there is adequate protection at the abutments so that vehicles cannot access the deck or parapets. The bridge has three piers in the river bed but this section of the River Aire is not navigable and a weir immediately upstream of the bridge has been shown, in flooding and testing [1], to stop vessels accidentally floating downstream over the weir and into the piers.

6 Strength

Having considered the loads acting on the Castleford Footbridge it is possible to use these results to look at the strength of the bridge.

6.1 Bending

To simplify the calculations here the bridge has been simplified to a number of fixed-fixed and fixed-pinned beams. The moments are then calculated at the points where there is a local maximum in the bending moment diagram.

From Section 5.7 it is clear that the greatest uniformly distributed load to be applied to the bridge is
combination 3. It is this value of w that is used to calculate the maximum bending moment on the bridge, shown below using Eq. (17).

\[ M = \frac{wl^2}{8}. \quad (17) \]

\[ M_{\text{max}} = \frac{60.96 \times 26^2}{8} = 5151 \text{ kNm}. \]

This maximum moment should be checked against the moment capacity of the section, values for common steel sections can be found in the Corus “Structural Sections” book but it does not give values for hollow box sections. The hollow rectangular box girders used for the Castleford Footbridge were custom built for the project so values from tables will not be accurate but using similar dimensions adequate values for this check can be found. The moment capacity of the section is calculated using Eq. (18), the plastic modulus is the value required from steel tables and with the closest properties to the girders in the bridge S = 4885 cm³ [7]. It is assumed that the steel used in the bridge is grade S355 which gives a yield strength \( p_y = 355 \text{ N/mm}^2 \).

\[ M_c = p_y S \]
\[ = 355 \times 4.885 \times 10^6 = 1734 \text{ kNm per box}. \]
\[ M_c = 3 \times 1734 = 5203 \text{ kNm} > 5151 \text{ kNm}. \]

The moment capacity calculated using Eq. (18) is for a single hollow rectangular steel box, the Castleford Footbridge cross section can be assumed, although this will be a slight underestimate, to have 3 similar box girders and so multiplying the original \( M_c \) by 3 gives the total section capacity which is more than the maximum moment calculated above.

### 6.2 Deflection

To check that the bridge can adequately withstand the dead loads upon it the deflection at the centre of the largest span should be checked against the span/deflection ratio for that type of bridge. As this is a steel footbridge the maximum deflection is given by \( \delta_{\text{max}} = \text{span}/200 \), using Eq. (19) the deflection at the mid span point can be calculated.

\[ \delta_c = \frac{5wl^4}{384EI}. \quad (19) \]

\[ = \frac{5 \times 14.64 \times 26^4}{384 \times 205 \times 10^6 \times 3.451 \times 10^{-3}} = 0.123m. \]

\[ \delta_{\text{max}} = \frac{26}{200} = 0.130m. \]

This shows that the deflections of the major spans of the bridge are adequate. They are quite close to the maximum deflection but this is allowable as for simplification of analysis here the bridge is taken to act as separate beams where actually it is a continuous beam over the main supports and so the deflections will be less in reality.

### 6.3 Buckling

It is important to check bridge decks for buckling. Buckling of decks will be caused by compression forces within the bridge. The Castleford Footbridge has pinned/roller supports at either end and so this means no compression forces can build up within the deck. It is possible though to check for buckling of the deck by assuming the expansion joints and bearings are blocked and damaged and therefore not free to move. Section 5.5 calculated a compressive force within the deck due to temperature changes and blocked expansion joints of \( F_c = 2.96 \text{ MN} \), I can now check that the Euler Load (lowest critical load) is greater than \( F_c \) over the longer 26m spans, using Eq. (20).

\[ p_e = \frac{p^2 EI}{I^2} \]
\[ = \frac{\pi^2 \times 205 \times 10^6 \times 3.451 \times 10^{-3}}{26^2} = 10.33 \text{ MN}. \]

This shows that that the Euler load is greater than the potential compressive force that would occur within the bridge if the expansion joints were not maintained properly and therefore the bridge is unlikely to buckle.

### 7 Serviceability

When considering serviceability the deflections of the bridge and bending conditions will be analysed, these have been looked at in Section 5. The creep of the bridge is also something that should be taken into account but steel creep is negligible and so it is not necessary to consider the creep of the Castleford Footbridge here.

The serviceability of the completed structure is something that should be considered at the design stage so that on completion there is easy access to all the main elements of the bridge, for example a pre-stressed concrete box-section bridge must have easy access to all the pre-stress tendons for inspection. The simplicity of the design of this bridge means that all the major elements of the bridge can be inspected relatively easily. Any moving parts of a structure like this must be checked regularly to make sure that they are still functioning as they were designed to. The bearings and expansion joints are both at either end of the bridge and so can be inspected from the bank with relative ease; due to the S-shape of the bridge deck it is also possible to view the bearings from the deck itself.

### 8 Durability and Vandalism

The Castleford Footbridge is constructed from two main materials, steel and Cumaru hardwood. These materials are both strong and hardwearing materials that are ideal for a bridge like this. The steel is painted to protect it from rusting. The timber has been treated to protect it but it is still more likely to need replacing before the steel elements of the bridge. On visiting the Castleford Footbridge in 2009 the timber has faded from
being exposed to sunlight and rain etc. but it is not showing any signs of warping or cracking that other types of wood show when left outside. The high quality of finishes to the bridge has meant that it is still in good condition with only the fading of the timber making a noticeable difference to the bridge after completion. Due to the timber creating grooves in the deck and having strips of fiberglass, with anti-slip grit applied to it, built into each decking board, during periods of light frost and ice in the winter de-icing salts may not need to be applied to the bridge deck. Only when there is a heavy ice layer over the deck may these salts need to be applied. De-icing salts are a problem for many structures but particularly bridges as they are corrosive and cause staining to materials as they run off the deck. The reduction of needing to apply these salts will help to reduce corrosion of the steel and damage to the timber as well as staining of the steel elements. Any staining should be quite easy to clean off of the steel surfaces although I feel the expense and dangers of cleaning the steel above a fast moving river may mean that this will not take place as often as it may be required.

Vandalism can be a problem to structures of all types; bridges in built-up areas are often targets for vandals as unused areas between piers can be places for vandalism to take place without being noticed. The Castleford Footbridge is in the town centre and this could have lead to high levels of vandalism taking place on it but on visiting the bridge in 2009 it was clear that there was very little vandalism to the bridge. I believe this is because of the way in which the project was run. The involvement of the local community in the design of the structure has meant they feel a much stronger bond to it than if they had not been involved in the design process. The simplicity of the design and the minimal amount of materials used has meant that compared to other types of bridge constructions there is little area that can be reached for vandalism to take place on.

9 Future Changes and Improvements

Highway bridges often need to have changes made to them sometime after completion of construction. Often new lanes need adding to the deck or below the bridge, this takes place so much now that many new bridges are constructed with an in-built redundancy, such as having piers placed at much wider centres to allow extra lanes to be constructed beneath the bridge. Castleford Footbridge however does not seem to have any in-built redundancy to the structure. This is because there is no reason to have any as there will be no need to make changes to the bridge in the future.

There is a bridge close to the footbridge carrying vehicles so there is no need to try to add traffic lanes to the bridge. Also in adding vehicle lanes to the bridge it would need to be changed beyond recognition; the seats that are so important to the structure and the aesthetics of the bridge would need to be removed, the timber deck would need replacing and the piers would need changing as well. The bridge is very wide and so even if the use of the bridge was to increase dramatically there would be no need to increase the width of the deck to accommodate higher pedestrian numbers.

This bridge is well designed and constructed and I do not see any need to or indeed opportunity to improve on what is already an iconic bridge and a symbol of Castleford’s regeneration.

10 Conclusion

The Castleford Footbridge is an interesting and exciting structure that is more than a bridge over a river to the local community of Castleford. The bridge is a symbol of regeneration and a place to meet people and relax; it is this that helps to make this bridge such a success. This paper has looked at the aesthetics that make this bridge so striking and has considered the loading conditions on it, with reference to BS5400, which it would have originally been designed to. This bridge will fulfill its function well for sometime yet and will remain an icon for Castleford.

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