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ANALYSIS OF JAMES DREDGE'S VICTORIA BRIDGE, BATH

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Abstract: This paper examines the design of the hybrid suspension / cable stayed Victoria Bridge crossing the River Avon in Bath, England. This paper will study the suitability of the bridge to withstand the current day loadings imposed upon pedestrian bridges, and also seeks to appraise the bridge on an aesthetic level. It will discuss the history, present condition and future development of the bridge and its surroundings.

Keywords: *James Dredge, Victoria Bridge, Bath, Suspension Bridge, Western Riverside Development*

1 Introduction

Victoria Bridge (Fig. 1), located near to the Royal Victoria Park in Bath, England, on first appearance looks like it could be a typical 19th century wrought iron suspension bridge. However Victoria Bridge has some key features which optimized the structure and make it more efficient, reducing the quantity of iron required, and speeding up the construction time.

Figure 1: Victoria Bridge viewed from towpath

The key principal of the bridge is the 'Taper Principle'. Before the advent of steel in the late 19th century, suspension bridges were made from wrought iron chain, which were made up of individual eye bar rods pinned together. These cables were very heavy, and very expensive due to the quantity of iron required. It was known that the tension in the cable reduces slightly towards the middle, however it was written "*The differences of tension at the different points on the length of the chains, are, in fact, so trifling, that it is not worth while attempting to save weight and metal by nicety of proportion*" [1].

A brewer from Bath, James Dredge, noticed how structures in nature taper as the load decreases [2]. He came upon the idea that if you considered a bridge to be made up of two opposing cantilevers (Fig. 2), then the force in the chain supporting the cantilever could vary linearly from a minimal force at the middle to the maximum force at the support, and thus the area of the chain could be optimized to match the load upon it. The removal of weight from a traditional suspension bridge could be considered detrimental, as it means there is less damping of lateral forces. By using inclined hangers, Dredge introduced compression into the deck, this had the effect of stabilizing the structure against lateral loads.

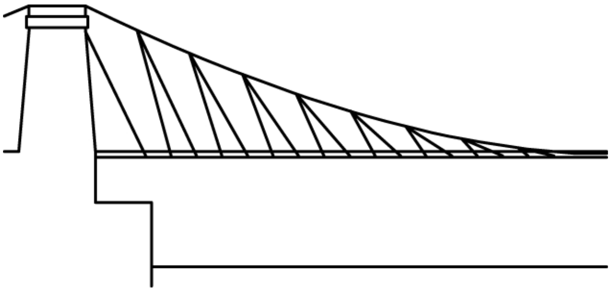

Figure 2: Sketch of half the main span of Victoria Bridge, each half is identical and acts as independent cantilever

1.1 Reason for the Bridge

Dredge was one of the shareholders in the Victoria Bridge Company, who had acquired the land to build a toll bridge over the River Avon to link Upper Bristol Road to Twerton [2].

The historical map of the area shows that Victoria Bridge was the only road crossing down river from Midlands Bridge. Twerton Suspension Bridge, was shown

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on the map, but was build after Victoria Bridge, by Thomas Motley, who had entered a cable stayed rival to Dredge's Victoria Bridge design [2]. (Twerton Suspension Bridge has since been replaced by Windsor Bridge).

On July 22 of 1836 Dredge patented his taper principle bridge [3], around this time he started construction of Victoria Bridge.

Victoria Bridge was opened by December of 1836 approximately 5 months after construction started. The strength of the bridge had already been tested once when, while partially constructed, a hurricane force storm hit Bath and the bridge remained undamaged. [2]

Victoria Bridge would have become an important link for traders wanting to get goods across the river without using the ferries at lower Weston, including Dredge, who no doubt used it to get his beer across the river from his brewery on Upper Bristol Road.

1.2 History of Taper Principle

Dredge went on to build around 50 other bridges all on the same patented taper principle. But he never received much recognition for his improvement on the traditional suspension principle [2].

When the Menai Bridge became damaged by winds in 1839, Dredge even offered to undertake the repairs to the bridge free of charge [4]. He was confident that the scrap value of the iron he could remove from the structure in converting it to his taper principle would pay for his fee. His proposal was ignored even after one Lord Western, who had visited Victoria Bridge and James Dredge, wrote a letter to Lord Melbourne asking again for Dredges proposal to be considered for the Menai Bridge [4]. Lord Western was astonished that Dredges principle had not been more widely accepted, stating in his letter that Victoria Bridge had left "so strong an impression upon my mind of the vast and immeasurable superiority of the principle on which it is built, over anything that has hitherto been attempted"[4]

Several reasons have been put forward for the demise of the taper principle suspension bridge. The main one being the invention of steel. Once suspension cables could be manufactured out of strands of steel, the use of iron chain stopped due to its cost and weight. Even Dredges optimized iron cable could not compete with the long spans possible with steel. No taper principle bridges were built after 1869 [2].

1.3 Description of the Bridge

Some key dimensions of the bridge are given in Table 1 below. They are only approximate values, which will be referred to in later calculations.

Table 1: Key Dimensions

Element	Dimension (m)
Main span [2]	45.7
Deck width (Fig. 12)	5.8
Pier height from deck	6.4
Sag in chain [5]	6.6

1.3.1 Chains

Each of the two main span chains consists of 155 individual wrought iron links, arranged in 19 sections. Each link is approximately 2.5m long and has a rectangular cross section of 55mm*15mm. The end of each link is circular with a shear pin running through it to join it to the next link (Fig. 3). Two inclined hangers come off the main chain at each joint to support the deck The number of links used in each 2.5m stretch of chain varies from the pier to the central point. At the top of the pier the chain is made up from 12 links, which gradually decreases to 5 links at the central point., this is the taper principle.

Figure 3: Bolted connection on the chain, note that the number of links reduces from 8 to 7 at this node

The chains run over the top of the piers and down to the ground. The length of chain behind the piers is made up of 71 iron links, arranged in 8 sections. As in the main span the number of links in each section of chain decreases from 12 at the top of the pier to 7, where it is anchored into the ground. At each pin 2 inclined hangers come off the chain and are anchored into the ground, as a result the end anchor block is relatively small (Fig. 4).

Figure 4: Anchor blocks at the southern end of the chain

1.3.2 Piers

Each end of the bridge consists of two masonry columns 2.2m wide (perpendicular to span) and 3.4m deep. Each column tapers slightly towards the top, to complement the principle of the bridge. Each pair of columns is joined at the top by a masonry arch. The way the chain runs over the top of the piers suggests that the piers are not designed to take any considerable moment. However there is undoubtedly some moment introduced into the piers as the chain is not able to freely move over the top of the pier, also the first hanger is built into the side of the pier. (Fig. 5)

Figure 5: View of the northern pier

1.3.3 Hangers

At each node on the chain two inclined wrought iron hangers come off the chain to either support the deck or, beyond the piers, to dissipate the load into the ground. The cross section of each hanger is the same as that of each link in the chain 55mm*15mm. The angle of each hanger varies, where the angle of the hanger to the horizontal decreases towards the center so that "the obliquity, as well as the stress upon the chains achieves its minimum value."[6] Each hanger connects to the edge beam of the deck at approximately 1.1m centres (Fig. 6).

1.3.4 Deck

The deck consists of timber planks, which span in the direction of the bridge. The roadway was originally stoned [4], but at some later date, most possibly in the 1946 renovation it was replaced with asphalt. The timber planks span in the direction of the bridges span, and are supported by, and stapled down to, I beams at 0.5m centres. These I beams span the entire width of the bridge and connected inside the parallel flange channels (PFC's), to which the hangers attach (Fig. 6)

Figure 6: Hanger connection detail

To provide stability to the deck the PFC's are tied together under the deck by a truss system at approximately one every metre. Two fin plates run the length of the bridge and the tensioned rods run from the PFC under the fin plates and back up to the other PFC. This has the effect of compressing the deck in the transverse direction to prevent the I beams coming loose.

Table 2 below lists the elements of the deck as shown in Figure 7.

Table 2: Elements of the bridge deck

Number (Fig. 7)	Description
1	Inclined hanger bar (55x15mm)
2	Box section supporting balustrade
3	Approx. 260x75x28 PFC edge beam
4	30mm dia. truss rod
5	Truss connector block
6	2 No. 20mm dia. Truss rods
7	Fin plate (130x15mm)
8	Hanger connection block
9	Balustrade post
10	Deck surfacing
11	Timber planking
12	175h 75w 12thk I beam
13	160x75 timber packing between I beams

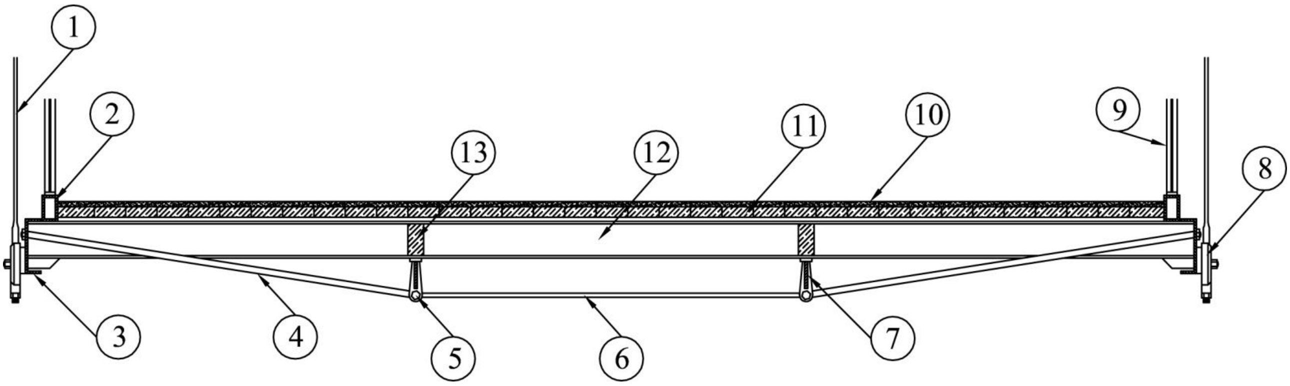


Figure 7: Cross section of the bridge deck

2 Aesthetic Appraisal

The famous bridge designer Fritz Leonhardt set out 10 areas of aesthetics. By analyzing how well Victoria Bridge performs in some of the key areas a conclusion can be drawn on its aesthetic.

2.1 Fulfillment of Function

With Victoria Bridge it is clear to see how the bridge functions as a structure. The 'chunky' nature of construction made out of iron and stone means that the function of each element is obvious. With modern materials it is possible to make structural elements ever more slender, and thus the relationship between strength and size can be distorted.

Most of the components and connections in the bridge are on show, which helps show off how the bridge is supported. This was crucial to Dredge as it was his first bridge, and hence was a showcase, from which he could adapt the design to future clients wishes.

The only detail on the bridge which looks out of place is where the last hanger in the main span disappears into the pier (Fig. 5). This is unlike all the other hangers which clearly connect to the chain, and hence it looks out of place.

2.2 Proportions

One element of the bridge which now looks out of proportion is the balustrade. At 1.6m high it is quite high for a pedestrian bridge. Also the fact that balustrade is the same colour as the other ironwork on the bridge means that in side profile it can clutter the view. It must be remembered that when the bridge was built it was used as a road for horse and cart. A higher balustrade would have be preferable, as the driver of the cart would be higher up off the deck.

When you approach the bridge on foot from the ends, the density of bars in the balustrade obscures the view of the bottom quarter of the chains. (Fig. 8) This disguises the functional element of the bridge as discussed in 2.1.

Figure 8: Southern approach

Another element which looks quite out of proportion are the anchor blocks (Fig. 4). In a traditional suspension bridge they would be taking the load from half of a cable. In Victoria Bridge, hangers into the ground reduce the load in the cable as it approaches the anchor block. This means a smaller anchor block is needed.

2.3 Order

The structure is highly ordered, connection are at regular intervals. Even under the bridge (Fig. 9) the regularity of the trusses and beams is aesthetically pleasing. The lines along the edge of the bridge are only broken by the protrusion of the connection detail (Fig. 6), but their order means they don't look out of place.

Figure 9: View of underside from towpath

2.4 Refinement of Design

Refinement is evident in aspects of the bridge, which is apt, as Dredge's set out to make what is effectively a refined suspension bridge.

The piers, for example, are refined in order to look more aesthetically pleasing. They taper upwards in both dimensions, so as to be less imposing. They are also narrower in one dimension, so they appear more slender as you approach the bridge.

2.5 Integration with the Environment

This is possibly the most unfortunate aspect of aesthetics which Victoria Bridge currently finds itself. At present the bridge is next to a disused brown field site at one end, and tightly wedged between an ugly industrial unit and a stone wall at the other.

The wall and industrial unit have been built after the bridge, and hence had to fit into its aesthetic. They achieve this quite well, partially due to the fact that most buildings in Bath all have to use the same Bath limestone. Even the metal cladding of the industrial unit is painted the same colour as the bridge.

From studying historical maps its evident that the bridge has never been surrounded by any particularly attractive features. A sawmill, a large railway siding and a few terraced houses. The bridge has however always fitted into the general Georgian aesthetic of Bath city.

In the future, should the Western Riverside Development get the go ahead the environment the bridge is in should be much more suitable. The plans as of summer 2007 highlight Victoria Bridge to the fullest.

After the removal of all the graffiti and overgrowth, the bridge should act one of the primary pedestrian routes into the city centre from the development, with trees planted at both ends. A landing station for boats will be built adjacent to the bridge, meaning that the bridge will be viewable from river level. Hopefully increased awareness of the unique features of the Victoria Bridge will result in it becoming more of a landmark in Bath.

The computer generated image below shows how the bridge would fit into the surroundings. The image is taken from the summer 2007 brochure. Unfortunately the drawing of the bridge makes it appear unattractively disproportionate, as the deck has been drawn much too thick.

Figure 10: Computer generated view of current redevelopment plans

2.6 Texture and Colour

The texture and colour of the piers is attractive, and fits into the textures found in Bath. All the ironwork on the bridge has been painted green. This appears to be the only colour that has been applied to the bridge, so may be original, although it was no doubt repainted in the 1946 restoration. The colour fits well with the surroundings, the river is a definite green colour as is visible in Figure 1. The colour of the bridge does tend to cause it to blend it into the background somewhat. Modern practice might say to highlight the structural elements, to clearly display the function by using colours such as red on the cables. However this would not have been seen as attractive in the 19th century, and hence the colour fits with the design of the bridge.

2.7 Aesthetics Conclusion

In its heyday Victoria Bridge was no doubt an attractive bridge, but due to vandalism, as described in the next section, it is not currently looking its best.

With Victoria Bridge the design certainly came before giving any consideration to aesthetics. This bridge was built to display Dredge's new cost saving features in suspension bridge construction and as a road link. It was not until Dredge started building bridges in gardens of stately homes and public parks that the aesthetic becomes important. As a result the design changes, to look more pleasing, but the overriding taper principle remains.

2.8 Vandalism

Victoria Bridge's location, in a relatively quiet and disused area of Bath, has led to a severe vandalism problem. Newspaper clippings held at the Museum of Bath at Work show that the bridge has had to undergo several repairs due to vandalism attacks, including an attack where a section of balustrade was ripped up, resulting in the bridge being closed for a while.

Also, as is clearly evident in figures 1,5,6 and 8 there is a lot of graffiti on the piers, and the edge of the deck. It is worst above the towpath, as the bridge is within easy reach. But even in less accessible areas graffiti is present, as the chains are of a width that it is possible to walk up and down them.

Not much can be done about this at present, other than regular cleaning.. In the future, with the potential Western Riverside Development the bridge will become a lot busier and probably under CCTV monitoring. This should result in the vandalism problem being almost totally eliminated.

3 Construction

The total cost of the bridge was £1760, today this would be equivalent to a £4.5m construction project. The majority of the cost was spent on the masonry piers and timber for the deck and falsework. The cost of the 21 tons of iron work was only 25% of the total cost [4]. Not much is known about the exact construction method employed during the construction of Victoria Bridge. There has only been one photograph discovered, of a Dredge bridge in Northern Ireland during construction [7]. This is discussed in Section 3.2.

3.1 Foundations and Ground Conditions

The ground conditions under the piers are likely to be fluvial deposits from the river. These are generally soft deposits, so it's possible that some substantial foundation system was required. If the loads were high and there was a risk of slippage, then one possible foundation system may have been timber piles. This would have involved the driving of tree trunks into the ground and capping off with timber planks or stone in order to provide a stable platform for the piers. (Fig. 11a)

The modern day profile of the river is set by the sheet pile edging, as visible in Figure 9. These would not have been there in 1836 as they are most likely made of steel, which hadn't been invented. The historical map of the area shows a more natural profile to the edge of the river.

If there was some kind of reinforcement to the edge of the river, on the southern side in particular, then it could be possible that shallow foundations were used (Fig. 11b). This would have relied on the river wall preventing slippage of the pier into the river. The wall could have been either a stone wall, gabions or iron sheet wall. In this case the foundations could be just crushed stone and or timber planks. Whichever method Dredge employed has worked, as no settlement cracks are visible on the bridge.

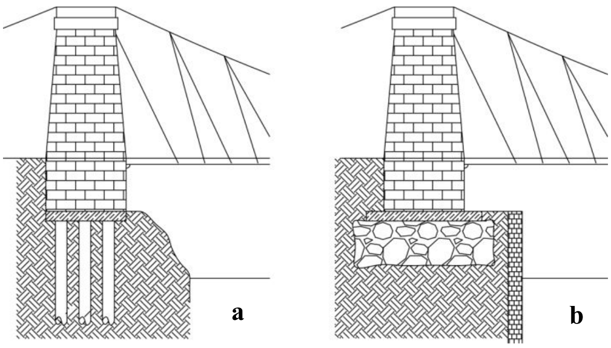


Figure 11: Two possible foundation systems under the southern pier.

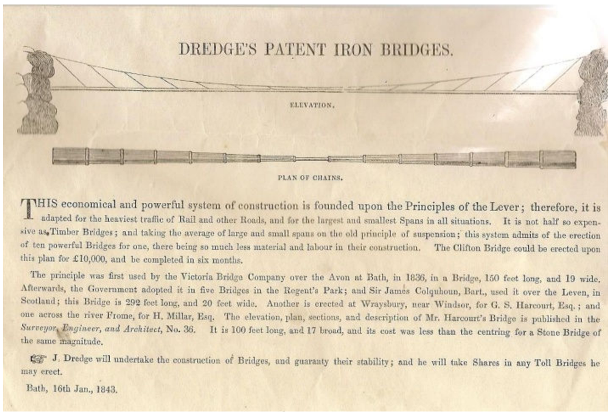
It is known that the construction of the chain began onsite in November of 1836, just a month before the opening of the bridge [4]. There have been suggestions that Dredge had constructed his decks with a progressive launching technique, common it modern day bridges. However the photograph found in Northern Ireland and the timeline of construction almost definitively points towards the use of a timber falsework erected in the river.

The falsework would have been wider than the deck, to allow access to down the sides. The ironwork frame of the deck would have been constructed off the falsework. The tensioning of the truss system would have stabilized the I beams, resistance from lateral movement would be provided by the timber. The timber is restrained by the box sections supporting the balustrade.

The last stage of construction would have been to construct and hang the chain, then attach the hangers to the deck and remove the falsework. As mentioned previously, this last stage took only 1 month to complete.

3.3 Durability and Repairs

The durability of Victoria Bridge is evident in that it has survived for so long. Even later Dredge bridges have not survived as well, with only a handful still standing. All of the operational bridges have undergone some restoration at some stage, varying from re-timbering of the deck to total dismantling and reconstruction [7]. As this was Dredges first bridge, he wanted to make sure it definitely survived well, as he used it as his flagship bridge which was mentioned in advertisements that he sent out (Fig. 12).



DREDGE'S PATENT IRON BRIDGES.

ELEVATION.

PLAN OF CHAINS.

THIS economical and powerful system of construction is founded upon the Principles of the Lever; therefore, it is adapted for the heaviest traffic of Rail and other Roads, and for the largest and smallest Spans in all situations. It is not half so expensive as Timber Bridges; and taking the average of large and small spans on the old principle of suspension; this system admits of the erection of ten powerful Bridges for one, there being so much less material and labour in their construction. The Clifton Bridge could be erected upon this plan for £10,000, and be completed in six months.

The principle was first used by the Victoria Bridge Company over the Avon at Bath, in 1836, in a Bridge, 150 feet long, and 19 wide. Afterwards, the Government adopted it in five Bridges in the Regent's Park; and Sir James Colquhoun, Bart., used it over the Leven, in Scotland; this Bridge is 292 feet long, and 20 feet wide. Another is erected at Wraysbury, near Windsor, for G. S. Harcourt, Esq.; and one across the river Frome, for H. Millar, Esq. The elevation, plan, sections, and description of Mr. Harcourt's Bridge is published in the *Surveyor, Engineer, and Architect*, No. 36. It is 100 feet long, and 17 broad, and its cost was less than the centring for a Stone Bridge of the same magnitude.

☞ J. Dredge will undertake the construction of Bridges, and guaranty their stability; and he will take Shares in any Toll Bridges he may erect.

Bath, 16th Jan., 1843.

Figure 12: Dredge advertisement poster, discovered by J. Popplewell of Paglesham, Essex, in a 19th century writing box, a family heirloom.

Repairs to Victoria Bridge include the re-surfacing of the deck, repainting of the ironwork and patch repairs to damages ironwork caused either by corrosion, stress or vandalism.

The ironwork in the underside of the deck has suffered some considerable corrosion, and the surface of the iron is rough and in some places flakey. The repainting of the ironwork has helped in preventing further corrosion, as evident in Figure 13, only the underside of the box section supporting the balustrade (Fig. 7, Item 2) is currently suffering severe corrosion from water ingress down the side of the bridge surfacing. This is a considerable design flaw in the bridge, in that it does not feature a drainage channel anywhere on the deck. The impermeability of the surfacing means all water runs to the edge, but the upstanding box section at the edge means water must flow down between the timber and the box section. This allows a considerable flow of water to trickle down the ends of the I beams, as visible in Figure 13.

Figure 13: Corrosion to the underside of the deck above towpath.

The condition of the chain is generally good, some paint has started to peel off, which has lead to the start of light corrosion to some links. Mould growth and algae growth on the underside of the chain is also evident on most of the chain. The structural condition of the links has also been checked at some stage, as there is a repair to one of the links, as shown in Figure 14. The damaged link has had two equally sized iron bars welded to either side of the link. The fact that only one link has needed repair, out of hundreds on the bridge is testament to its ongoing durability.

Figure 14: Algae, rust and repair to damaged link

4 Structural Analysis

This section will evaluate the structural capacity of Victoria Bridge, and comment on its suitability to meet modern day British Standards.

In some cases the bridge will have assumed to be made of steel, as the British Standards do not refer to wrought iron. The material properties of wrought iron are slightly different to steel, values that have been assumed are given in Table 3.

Table 3: Properties of Wrought (Pure) Iron

Property	Value
Coefficient of thermal expansion [8]	12*10-6/^{o}C
Young's modulus [8]	190kN/mm^2
Ultimate tensile strength [8] (see note 1)	340N/mm^2
Yield stress [8]	210N/mm^2

NOTE 1: Dredge assumed an ultimate tensile strength of 403N/mm^2 and individually load tested the chain rods to 140N/mm^2, implying a factor of safety of about 3. [2]

4.1 Loadings

The loading will be calculated in accordance with BS 5400:2-2006. The design loads used by Dredge are also known, they will be compared to modern specifications.

4.1.1 Dead Load

A dead load takedown of all the structural elements of the bridge was carried out using the dimensions given in Table 1&2. The load takedown was then calibrated by ensuring that the total amount of iron employed in the structure was approximately equal to the 21 Tons quoted by Dredge. The average dead load in the main span was averaged over the area of the bridge to give a final un-factored value of 0.8kN/m^2.

4.1.2 Superimposed Dead Load

The architectural ironwork (Balustrade), timber deck and asphalt surfacing make up the superimposed dead load. By assuming a 50mm timber deck, 25mm asphalt surface and a balustrade of 0.5kN/m run. The superimposed dead load averaged over the area of the bridge was found to be 1kN/m^2, un-factored.

4.1.3 Live/Primary Live Loads

When it was designed Victoria Bridge was to be a road bridge. Loadings of the day, suggest that a value between 6kN/m^2 and 7kN/m^2 would have been used for vehicular traffic and potential military use [2].

Now that the bridge is only a pedestrian bridge a lower value is specified in BS 5400 Clause 6.5.1. The loading is given as k x 5kN/m^2, where k is given Eq. 1 below.

$$k = \frac{Nom. HA\ UDL\ for\ length\ of\ bridge * 10}{L + 270} \quad \textbf{(1)}$$

The nominal HA load for a bridge of 45.7m length is 26kN/m^2, given from BS 5400 Clause 6.2.1. Therefore k is equal to 0.824. Clause 6.5.1.1 allows for further reduction in UDL for pedestrian bridges over 2m wide. Resulting in a final UDL of 3.7kN/m^2. This is just over 50% of the original design load.

4.1.4 Secondary Live and Accidental Loads

Secondary live loads caused by the dynamic movement of vehicles, or accidental vehicular loading need not be considered, as the bridge is adequately protected by bollards. Proposals for nearby development include the removal of the road leading to the bridge and the use of the bridge for construction traffic would likely not be permitted. From the river, the piers are protected by the sheet walling. The height of the bridge above water level is quite low compared to other bridges along the river, but there would be other bridges on the river that would prevent a tall boat reaching and hitting the deck of Victoria Bridge.

Should floodwater ever reach the deck of the bridge it would almost certainly cause the destruction of the bridge, as happened with several other of Dredges bridges. In later examples, Dredge adapted his designs with elaborate cross bracing designs to protect from flood water. The likelihood of the river flooding to such a height is hopefully minute, as the river level is controlled by the weir further downriver and it would probably also result in considerable flooding of the city.

Figure 15 below shows what happened when a overweight vehicle is driven onto a Dredge bridge. This unfortunate accidental loading happened to the Balliévy Bridge in Northern Ireland. It was functioning as a public road bridge up to the 12th of September 1988 when a 27t lorry got lost and attempted to cross the bridge, despite weight limit signs.

The damage was so extensive that the bridge could not be repaired. The remains of the bridge are held in storage. [7]

Figure 15: Death of Balliévy Bridge (from Ref. 7)

4.1.5 Wind Load

The maximum wind gust speed can be calculated from BS 5400 Clause 5.3. The modification factors that have to be considered for the bridges location include, altitude factor, distance from the sea, the urbanization factor and that Bath is in a valley, which could cause wind tunneling. Taking all these into account gives a maximum wind gust speed (V_d), of 38.8 m/s. From this the dynamic pressure head (q) can be calculated to be 0.923 kN/m^2.

The shape of the bridge means it fits well in the categories given in BS 5400, which means that wind tunnel testing would likely not be required. There are no aerofoil effects, re-entrant angles or super elevation effects to consider on the bridge.

The horizontal wind load (P_t) acting on the bridge is calculated by multiplying q by the projected area of the bridge, and a drag coefficient. The projected area of the bridge is 29m, this takes into account the thickness of the deck, and also the area of the hangers and chain, as they are flat bars. When there is live load on the bridge the projected area increases to 85.3m. The drag coefficient for both cases is 2, the minimum that can be used for pedestrian bridges. This gives a horizontal force of 54kN or 157kN (with live), which is assumed to act at the centre of the bridge.

The longitudinal wind force (P_L) is a nominal force acting on the bridge and puts the deck into compression and tension, as there are no bearings at the ends of the deck. The force on the live load, and the force on the superstructure must be considered. They were calculated to be 34kN and 14kN respectively. This gives a total force of 48kN, acting at the centroid of the bridge.

The wind can also act vertically on the bridge, causing uplift, or down force. As there are no aerofoil effects it can be calculated easily by multiplying q by the plan area and a lift coefficient. Assuming a lift coefficient of 0.4, gives a vertical force (P_v) of ±96kN.

These different wind load cases should then be considered in one of the 4 combinations given in Table 4. Combination 2 is usually found to be dominant.

Table 4: Wind load combinations

	Combination	P_t (kN)	$\pm P_v$ (kN)	P_L (kN)
1	P_t	157	0	0
2	P_t with $\pm P_v$	157	96	0
3	P_L	0	0	48
4	$0.5P_t$ with P_L and $\pm 0.5P_v$	78.5	48	48

4.1.6 Temperature Load

Variation in the effective temperature will cause the iron elements to expand and contract. Two locations where this may cause a problem are in the PFC's running the length of the bridge and in the transverse I beams.

Differential temperatures in the bridge deck are not likely to cause much of a problem, as the timber deck and iron structure are not structurally jointed together. Hence there will be practically no stress at the interface.

The ends of the PFC are butted up close to the piers, although not attached, there is little room to expand, and hence stress could build up in the PFC. The maximum stress in the member can be calculated using Equation 2.

$$\sigma = \Delta T \alpha E \qquad \textbf{(2)}$$

Where:

ΔT = Change in temperature from datum (^oC)
α = Coefficient of thermal expansion ($*10^{-6}/^oC$)
E = Young's modulus (N/mm^2)

Assuming a potential temperature change of 25^oC, this gives a stress of $57N/mm^2$. Which, assuming the PFC size from Table 2, gives an sectional area of $3510mm^2$, hence a force of 200kN, assuming no expansion room at the ends. This force could only be a compressive force due to temperature increases in the PFC's as they are free to contract. This force could potentially cause the PFC's to buckle. The compressive strength of the PFC can be calculated from BS 5950-1:2000 Clause 4.7, as it is not steel it is required to reduce the capacity slightly for the lower yield stress of wrought iron. The PFC is restrained at approximately 0.5m centers by I beams or tension rods, which will restrain buckling. The maximum permissible compressive force in the PFC is calculated to be 737kN. This is well above the potential maximum force in the member due to temperature of 200kN. It is unlikely that a full 200kN would be put into the PFC, as long as there is some room at the ends.

$$\delta = \Delta T \alpha L \qquad \textbf{(3)}$$

Where:

L = Length of member (mm)

Equation 3 gives the lengthening of the beam that would be observed if it was free to expand. Assuming the same values as in Equation 2 and the bridge length of 45700mm, gives an expansion of 13.7mm (6.85mm at each end). As long as there is at least this amount of space at the ends no stress would be put into the PFC's.

If the I beams expand then they will apply a lateral force to the PFC's, this would increases the stresses in the truss rods that ties the 2 PFC's together. The level of stress in the truss rods is hard to ascertain, as the level of pre-stress is unknown. Also, the rods would be expanding due to temperature as well, which means the stresses could be lower, if the whole bridge expanded laterally.

4.2 Loading Combinations

BS 5400 states 5 loading combinations that must be checked at service limit state (SLS) and ultimate limit state (ULS). The load case for secondary live loads need not be considered on Victoria Bridge as it is not subjected to vehicular traffic. Also the load case which includes friction at supports need not be considered here. The load combinations must be multiplied by the relevant design load factors (γ_{fl}) given in Table 5, and additional factor γ_{f3} (1 at SLS and 1.1 at ULS.)

Table 5: Dead load factors, γ_{fl}

Load		Combination		
		1	2	3
Dead	ULS	1.05	1.05	1.05
	SLS	1.00	1.00	1.00
Super-imposed Dead	ULS	1.75	1.75	1.75
	SLS	1.20	1.20	1.20
Primary Live	ULS	1.50	1.25	1.25
	SLS	1.00	1.00	1.00
Wind	ULS	0.00	1.10	0.00
	SLS	0.00	1.00	0.00
Temperature	ULS	0.00	0.00	1.30
	SLS	0.00	0.00	1.00

4.3 Element capacities

To perform a basic structural analysis the capacity of a few key elements of the bridge can be checked against the load combination in Table 5 that gives the worst effect on that element. Some element that may prove critical are the deck, hanger and chain. For a more complete structural analysis a computer model of the bridge could be produced using software such as STAAD Pro. This would allow the more complex load combinations to be considered more accurately, as well as being able to model dynamic loadings.

4.3.1 Chain capacity

As the connections in the chain are all pinned, the chain will not take lateral loads. The worst case load combination is therefore when there is the highest vertical force. The occurs in load combination 2, including vertical wind loading.

The forces in the hangers, and hence the forces in the chain can be determined by resolution at the joints.

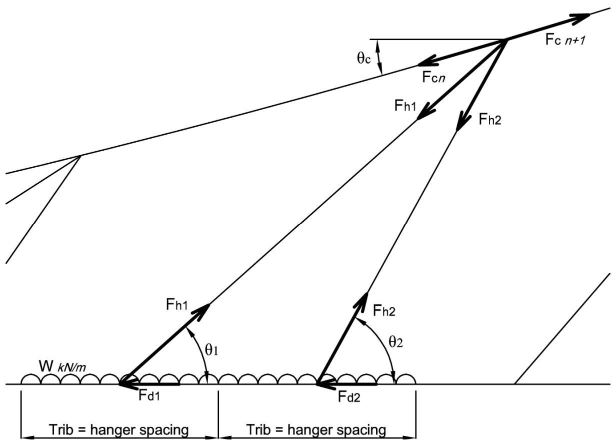


Figure 16: Forces in the bridge deck, hangers and chain

With reference to Figure 16, it can be assumed that the loading on the deck is transferred to the edges, and can be assumed to act as a line load (W). For the worst case loading condition described above, W is 22.2kN/m at ULS. The force transferred into the hangers (F_h) varies depending on the obliquity of the hanger (θ), the resulting compression force in the deck (F_d) is also dependant on the obliquity of the hanger.

The forces at the node of the chain consist of the two hanger loads and the load of the preceding section of chain, which are all taken by the succeeding section of chain. The angle of the chain (θ_c) is assumed to be a constant 17^o, although in reality the angle of the chain varies due to sag. Using a constant value of θ_c gives a constant step up of the force in each section of chain (F_c).

By tabulating the calculation, the forces in each section of the chain was found to vary from 234kN at the central section, to 1570kN at the top of the pier, with an increase of 167kN at each node in between. At the centre there are 5 links in the chain, each link takes 1/5th of the load, which is 47kN. At the pier there are 12 links in the chain, each link takes 1/12th of the load, which is 131kN, these links have the highest load. Given that the link cross section is 55mm by 15mm, it can be deduced that the max stress in the links is 131,000/(55*15)=159N/mm^2. Taking the modern value for ultimate yield stress of 340N/mm^2 gives a factor of safety of 2.14 at ULS. Given that the ironwork is old, has deteriorated slightly and will not have been manufactured to modern standards, a factor of safety of nearer 4 may be preferable.

4.3.2 Hanger capacity

As the hangers become more inclined towards the middle the force will increase, as they all support the same tributary area of the bridge deck. The hanger closest to the centre is inclined at 6^o from the horizontal. The worst case loading is the same as for the chain. Therefore a simple calculation for the tension in the hanger could be $T=(22.2*1.1)/\sin 6=234$kN. This relates to a stress of 234,000/(55*15)= 284N/mm^2, which gives a factor of safety of only 1.2. The stress may not be this high, as some of this load is likely to be taken by the first chain section, the first chain section consists of 5 links, whereas the hanger is just 1.

With the tension in the hangers increasing with the inclination it is perhaps an oversight that Dredge did not apply the taper principle to the hangers also. The tensions in the hangers appear to vary from 234kN to only 23kN. This effect was explained by W. Turnbull in his paper ‘Dredge’s suspension bridge explained upon the principle of a lever*’* [6]. He explained “*Another condition in the system of calculation might be, to have the effects of all the suspending* [hanger] *forces equal; we do not mean the absolute magnitude of the forces, but the effects as referred to their particular direction, when compared with the state of equilibrium; this would manifestly give a series of equal differences for the tensions on the chain*”

4.3.3 Deck capacity

Dredge’s design was criticized for inducing compression into the deck and not suitably allowing for this force. Compression is induced by the inclination of the hangers, which generates the reaction forces (F_d), as shown in Figure 16. If you are considering the bridge to be made of two entirely independent cantilevers, as suggested by Dredge, these reactions add up resulting in a large compression force at the pier, most of which is carried by the PFC, as not much will be transferred by shear into the rest of the deck. However the two cantilevers are connected across the middle, this has the effect of making the two compression forces act against each other, creating a tension force in the PFC. The tension capacity of the PFC’s are a lot higher than the compression capacity. The maximum compression force will be produced when there is a maximum load (dead, super-dead, live and wind all at ULS) on one half of the bridge, and a minimum force on the other half (dead, and super-dead at SLS). The maximum compression load in the PFC’s due to out of balance forces on the bridge is calculated to be 560kN, in each PFC, for combination 1 loads (Table 5). This is below the ultimate compressive capacity calculated in Section 4.1.6 of 737kN. However the compression will be higher due to wind or temperature forces in combination 2 and 3 loading.

In combination 2 lateral wind loads will also induce compression and tension forces in the PFC’s. As there is no diagonal bracing under the deck, lateral loads will taken purely by the deck as if it were a beam on its side, putting one PFC in tension and the other in compression. The magnitude of these forces works out at approximately ±290kN tension or compression. This is added to the compression due to out of balance loading, which due to the reduced factors of safety in combination 2 and 3 works out as 480kN, so that the total compression in combination 2 becomes 480kN+(290*1.1)kN = 799kN. In combination 3 the temperature effect from Section 4.1.6 is added instead of wind to give 480kN+(200*1.3)kN = 740kN. Both of these are near too, but over, the ultimate compression capacity of the PFC of 737kN.

In the British Standard the wind and temperature loads are calculated using measured data of maximum wind speeds and temperatures based on a 120 year return period. As of now, Victoria Bridge is 173 years old, meaning statistically it should have seen at some time wind speeds and temperatures worse than used in the British Standard. In conclusion, could it therefore be said that the bridge had been 'load tested' against these environmental loads, as it has stood the test of time, and hence is adequate?

4.4 Natural Frequency Effects

BS 5400:2-2006 Annex B stipulates that the fundamental natural frequency of pedestrian brides must be greater than 5Hz vertically.

$$f_0 = \frac{C^2}{2\pi l^2}\sqrt{\frac{EIg}{M}} \qquad \textbf{(4)}$$

In order to evaluate the vertical natural frequency, the serviceability loading is assumed to include the superimposed dead load, but not the pedestrian live load. This relates to a load per metre (M) of 11.2kN/m. The I value for the bridge's width at midspan is roughly equal to $6x10^{10}$ mm^4 = 0.06m^4. This is put into Equation 4 gives a natural frequency of 7.8Hz.

Vibration should therefore not be a problem for the bridge deck, although the frequency is relatively low. This has been noticed on the bridge, as the deck is quite flexible, one person jumping on the deck can cause a slight resonation. Also, when there is a group of people walking across the bridge, some resonation begins in the chains. It could therefore be suggested that the natural frequency should be checked in other parts of the bridge, this could be best done in computer modeling.

4.5 Serviceability

Serviceability checks for cracking or creep are not required in this case as the bridge is not made of concrete. For an iron structure such as this, suitable serviceability checks would be deflection checks. Deflection of the I beams would want to be minimized to prevent the deck from bowing, which would be noticed as water would pond in the middle of the deck. Assuming a uniform load at serviceability of 6kN/m, the deflection can be found simply, with Equation 5, which is based on the assumption of a simply supported uniformly loaded beam.

$$\delta = \frac{5wL^4}{384EI} \qquad \textbf{(5)}$$

The I value for the beams is 15,420,601mm^4. The effective length of the beams is reduced, as they are partially supported by the truss system at third points. The effective length could be assumed to be 0.85 of the actual length (5.8*0.85 = 4.93m). This in Equation 5 gives a central deflection of 16mm. Modern day BS:5950 for steel, would suggest a limiting deflection to be span/250, which would be 23mm, hence the bridge passes this serviceability check.

5 Conclusions

Dredge principle received much scrutiny by mathematicians of the day, which resulted in heated debate, and even ridicule [2]. From the structural analysis carried out in this paper, it seems apparent that although the forces in the chain have been reduced, to allow tapering the cross section of the chain, this has come at the cost of inducing potentially troublesome forces in the hangers and deck. These forces would not be present in traditional suspension bridges, although in Dredge's bridge they do help reduce the effect of the 4 pin mechanism of a traditional suspension bridge, which normally leads to lateral stability issues.

One area where the design could be improved is in the angle of the hangers. The original document explaining the principle of the bridge [6], states that there is no conditional equation to set the position and angle of the hangers, and that *"successful application of the principle to practice, must in a great measure depend upon the sagacity and skill of the engineer by whom the fabric is raised"*. If the angle of the hangers is required to vary then a further refinement would be to taper the size of the hangers. Alternatively, the angle of the hangers could be fixed, using the analysis method in Section 4.3.1, using a fixed angle for the hangers does not affect the force in the chain.

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