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BRUNEL'S ROYAL ALBERT BRIDGE, THE TAMAR RAIL RIVER CROSSING

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Abstract: This article provides a critical and informative look at Brunel's Royal Albert Bridge. It analyses it's history, aesthetics, bridge loading, strength, maintenance, serviceability, construction, temperature effects, design for wind, durability, susceptibility for accidental or intentional damage, and for any future changes that may need to take place. It will enable the reader to gain a much deeper insight into this bridge, and appreciate its interesting features.

Keywords: *Brunel, Tamar, Saltash, Bowstring Suspension Bridge, Rail, Iron,*

1 Introduction to the Royal Albert Bridge

Designed by Brunel and finished in 1859, this is the fairly unique rail bridge that spans the River Tamar, between Plymouth and Saltash, which still to this day, is the only rail connection between Cornwall and England. It has two main spans both of 139m and the rail deck is 30m above then the mean spring high tide. It is best described as a Bowstring Suspension Bridge, which is actually 3 bridges in one. It is an arch bridge, it is a suspension bridge, and it is also a truss. It is predominately made out of wrought iron, including the two iconic tubular arches.

Figure 1: View of Royal Albert Bridge (foreground)

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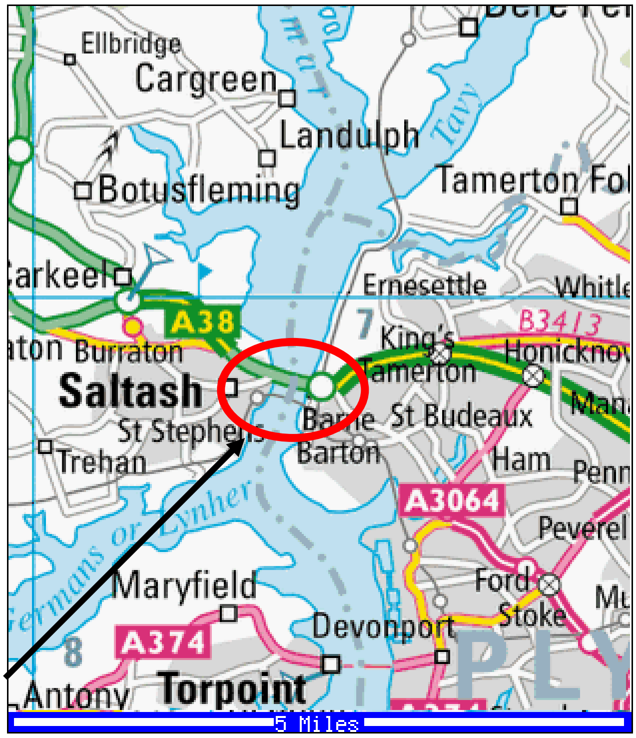

Figure 2: Location map of Royal Albert Bridge

2 History of the Bridge

The history of the bridge is an important part of how the bridge came to be in its design and construction.

The bridge was designed in 1855 for the Cornwall railway company, due to parliament rejecting Brunel's original idea for a train ferry across the estuary. Brunel then intended to build a single span bridge of 260m; however the Admiralty of the Royal navy rejected this proposal, as it was not suitable for their vessels to navigate from the river Tamar to the open sea. The Navy demanded that the bridge of the deck must be 30m above mean high tide, and the river must be fully accessible to the Navy at all times, including the construction phase.
A bridge with 2 91.5m spans and 2 61m spans was then proposed, but rejected after a site investigation found no suitable rock to build 3 piers.

He decided on the current format with 2 spans of 139m resting on a single pier in the middle of the river. It would also require 10 approach spans from the Cornish side, and 7 from the Devon side. Brunel's ideas were limited by the fact that there ground on either side was unsuitable for tension foundations using the technology of the day. (There is now an adjacent road suspension bridge with tension foundations). Brunel then designed a bridge that is very similar to the one you see today, other then it was wider and carried two lines of track. During this stage, the Cornish Railway company was experiencing some financial difficulties, so Brunel reduced the width and removed a line to save £100,000. The appointed contractor when bankrupt shortly before construction, so Brunel decided to take it on its self. This showed a determination to get the bridge built just as he wanted it.
The dates of construction milestones will be covered in Section 8.
The bridge was completed on the 11th April 1859, when the first train crossed it. The bridge was officially opened by His Royal Highness Price Albert on 2nd May 1859. Brunel did not attend any of these occasions due to ill health, and finally crossed his bridge on 4th May 1859 on a specially constructed open top wagon where he laid to view the bridge. He died on 5th September 1859, following a stroke. As a tribute, some friends raised some money and put up the big signs on the outer sides of the portals, simply stating "I.K BRUNEL ENGINEER 1859."

3 Bridge Aesthetics

The Royal Albert Bridge is a very unique bridge dating from the industrial era of the 1800's. This section will analyse how it measures up to Fritz Leonhardt's 10 rules of Bridge aesthetics. The rules are stated below and applied to the bridge. An overview of the bridge is shown in Fig 1.

3.1 Fulfilment of function

3.1.1 Fritz Leonhardt's Rule stated, and applied.

The Bridge should reveal its structure clear, pure form, and suggest an aura of stability.

Although the bridge actually a very complicated design comprising of 4 different bridge types, (arch, suspension, truss and beam) it comes across in a simple clear manner.

The approach spans are simple masonry piers with iron beams. This was all that was required as the spans are not required to be great, as there were no span restrictions, and there was easy access to make good foundations. Of the materials and techniques available at the time, this was an efficient use. Due to the tight horizontal curvature of the approach spans, train speed has to be low, due to the horizontal component of force acting when the train is travelling over. To improve this, diagonal restrains could be used, transferring the horizontal force more efficiently into the ground, or iron bracing between the legs. (Fig 3)

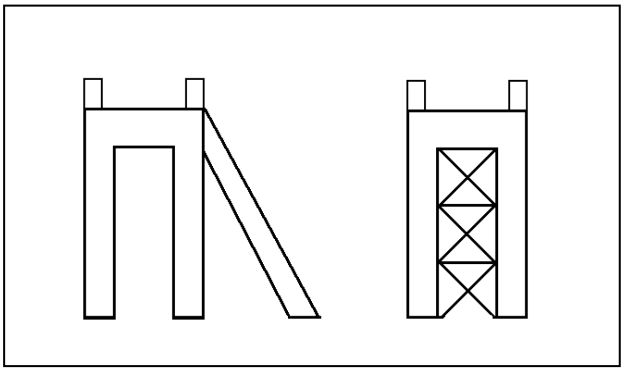

Figure 3: Drawing of possible improvements to approach spans

Moving on to the main spans, the structure is expressed well with big beefy tubular arches, a finer suspension chain part and the vertical truss elements. However it is a little unclear what part is doing what. The huge tubular arches imply that they are carrying a lot of downward load; however, they are mainly carrying longitudinal compression to keep the suspension bridge in tension. The basic structural forces of the main spans are shown in Fig 4.

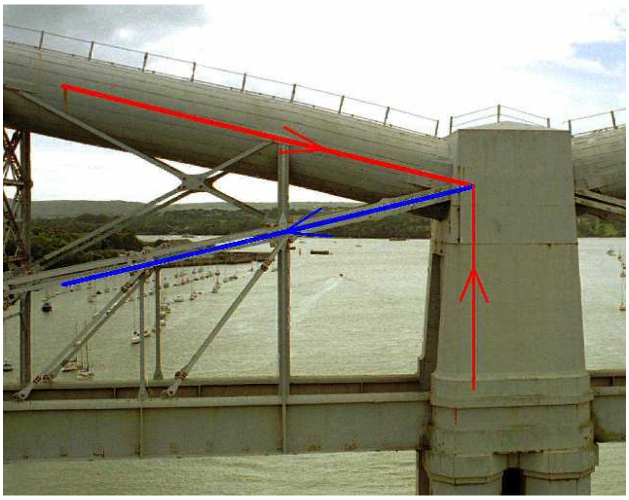

Figure 4: Photo showing forces acting on main span.

3.2 Proportions of the bridge

3.2.1 *Fritz Leonhardt's Rule stated, and applied.*

The bridge should convey an impression of balance between masses and voids, and between light and shadow.

There is something not quite right about the overall bridge proportions. Looking from afar with the approach spans, the main span sits with unease against the approach spans. The approach spans have a quite regimented pattern of beefy columns and a similar size deck. Then

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when the bridge reaches the main span, the columns are not significantly bigger to support all the extra weight of the main spans. Brunel chose to design it like this as it was the most efficient use of the construction techniques of the time. The approach spans are built from solid masonry, which was a well known building material and probably very cost effective at the time. As the main span columns are more important, and access to build them was more difficult, an iron construction was chosen.

Figure 5: Entire View of Royal Albert Bridge, including approach spans (foreground)

The iron piers are lot stronger then masonry, meaning it can be more slender. The size of the deck does not also change throughout the bridge. Although quite good for your eye to run left to right, it does not agree favourably to idea that if the span changes, the deck size should change. Also to keep proportions, the width of the spans should change with the depth of the span; however they don't as they are a consistent distance apart.

3.3 Order within the structure

3.3.1 *Fritz Leonhardt's Rule stated, and applied.*

There should be order in the lines and edges of a bridge.

Brunel has generally achieved a good order to his bridge with regimented approach spans, and regimented vertical truss members within the main spans see fig 5.

There is one part of the bridge which does not seem to have good order. When the approach span interfaces with the main span there is a horrible break of order, as the tubular arches terminate into the end columns. It just seems to end, where it may have looked better to carry it on, although not structurally correct. See fig 6.

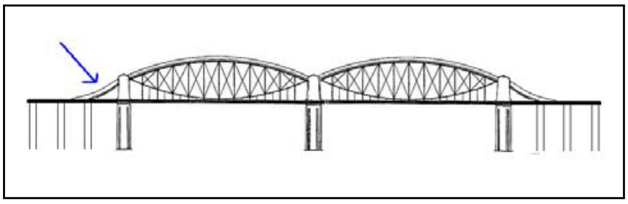

Figure 6: Possible visual improvement

3.4 Refinement of Design

3.4.1 *Fritz Leonhardt's Rule stated, and applied.*

There are many refinements which can be used to create an aesthetic bridge

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There is no structural significance for the use of the portals at either end of the span, but without them the bridge would not look as prominent, as the tubes would appear to terminate suddenly, but with no ending. The portals provide a big solid end to the arches. They also hide what would be ugly joints.

Perhaps the tubular arches should have been tapered at the ends, as the bending movements would be less near the ends, and it would have saved weight and material. However at the time, iron was plentiful and relatively cheap, and it would have required many more calculations and made the construction much more complicated, and probably added expense to a bridge that had a very limited budget

There are many details on this bridge which you do not notice from a distance, but when you look closer, there re many interesting refinements.

3.5 Integration into environment

3.5.1 *Fritz Leonhardt's Rule stated, and applied.*

Depending on what effect a bridge designer is trying to achieve, certain bridges simply would not be appropriate

When Brunel built this bridge, Plymouth was a major ship building city and a major naval port. It was also the time of the industrial revolution. The bridge is a perfect statement of power over nature. It is big, brutal and imposing. Located in a built up estuary it echoes the feel of the area.

Figure 7: Close up of approach spans

3.6 Surface Texture

3.6.1 *Fritz Leonhardt's Rule stated, and applied.*

Texture is very important in bridges, but often ignored.

Brunel certainly has not ignored texture. He has obeyed all the rules of thumb.

For piers and abutments rough finishes should be used; the approach span piers are finished with masonry block work (see fig 7) Even the main span piers which are finished in smooth iron, have been made from four octagonal columns to split them up and appear rough.

For fascia beams and slender columns smooth finishes should be used; the deck and main tubular arches have a smooth iron finish.

Matt finishes should be used; only matt finishes on this bridge have been used.

3.7 Colour of components

3.7.1 *Fritz Leonhardt's Rule stated, and applied.*
Colour can add to the effect of a bridge, or spoilt it.

Currently the main span is painted in a battleship grey, which is very apt, as it reflects the areas proud navy traditions. It also tends to dull down the main span, which is a good thing, as a bright bridge in the estuary would look completely out of place. It also makes the structure the main feature, not the colour.

The approach spans are made from the granite, which looks very natural and fits in perfectly with the surrounding area.

As the bridge is runs East West, long shadows are not cast outside the bridge area.

3.8 Character

3.8.2 *Fritz Leonhardt's Rule stated, and applied*
Very difficult to define, but all bridges should have character.

This bridge certainly has character; this is partly down to the fact that it is very unique, especially within the West Country, it is very prominent structure.

It is quite a brutal structure with spindly piers and beefy tubular arches; however it still comes across as quite elegant, particularly if you remember this bridge was built around 148 years ago. Also the fact that modern locomotives travel over this old structure gives a bizarre contrast between old and new.

It many interesting characteristics too, such as when the bridge was being tested by locomotives at 30mph,the bridge vibrated so much it couldn't be recorded, so the maximum speed is limited to 15mph, now 10mph and it still vibrates and wobbles at that speed. Viewing the Royal Albert Bridge from the Tamar road crossing, the slow speed of trains crossing creates an elegant effect, giving the impression that the trains are slowing down to admire Brunel's work.

There is also a significant amount of deflection within the bridge deck, as when unloaded, the rails deck is in 2 visible humps over the two spans. When loaded, the bridge deck flattens out to the horizontal.

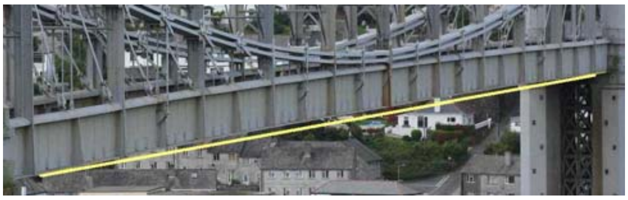

Figure 8: View emphasizing humped deck when unloaded.

The character of the bridge has been enhanced since 1961 with the construction of the Tamar (road) Bridge. It is suspension bridge that is a very modern design, made of steel trusses and reinforced concrete; it contrasts brilliantly with the old iron and stone Royal Albert Bridge. It has allowed many more people to appreciate the details of Brunel's bridge up close.

3.9 Complexity in variety

3.9.1 *Fritz Leonhardt's Rule stated, and applied*
It is possible to be visually stimulated by a certain amount of complexity in a bridge, which is contradictory to the keep it simple rule.

Brunel has got this rule spot on. This is an amazingly complex bridge, a suspension bridge put into tension by a compression arch which is held down by the weight of the deck, and held together by trusses. But it comes across as a simple bridge being a self supporting truss on vertical piers, but managing to seem much more then that. Everything that should be there is there and it has few fussy details. It is a self supporting truss that everything is contained within the arch and deck.

3.10 Incorporation in nature

3.10.2 *Fritz Leonhardt's Rule stated, and applied*
Incorporating nature into the design of a bridge is advantageous.

Brunel shows very little use of nature in the Royal Albert Bridge. It has to be remembered that this bridge was constructed during the industrial revolution when man was trying to better itself, and looking back at nature was considered backwards.

The only possible incorporation of nature Brunel has used was the tubular arches. Their construction is not too dissimilar to human bones, which have an outer layer of compact bone, with an inside structure of spongy material, which could be likened to small struts, as found inside the bridges tubes.

3.11 Summation of the Bridge Aesthetics

Even though Brunel built this bridge well before Leonhardt's rules were set down, overall Brunel has actually obeyed most them. However there are features that make the bridge look ugly, but these features come across as character.

4 Loading of Structure

The structure has been designed to take the dead load of its self weight, the heavy loads of trains passing and wind loading. It has also been designed to take the loads imposed on it during the construction procedure. These loads would be torsional effects of floating it down the river and lifting it.

Within the main two spans the loading pattern is quite complex. However how it loads the piers is relatively simple

4.2 Loading of the main spans

This bridge is a loading circle; it is difficult to know where to begin, as there are three main systems acting on this bridge. Take one of them away and the bridge would fail. Firstly imagine the bridge as a simple suspension bridge (fig 9)

The suspension cables are put into tension, with the bridge deck slung below. The piers are put into a big compression and the tension is held by the ground. In this case the tension can not be held by the ground, as the re was no suitable rock for the foundation technology of the time.

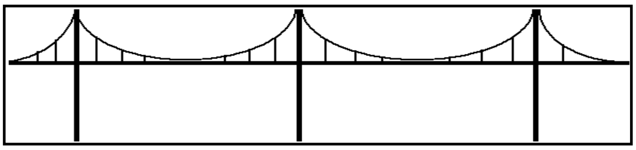

Figure 9: simple suspension bridge

As Brunel could not tie back the cables to the ground, or generate enough tension in the cables by holding them only by the end piers, as they would simply fall inwards. He had to provide them with tension in another manner. His solution was to add 2 tubular compression arches. These would hold the piers apart from each other, and provide tension in the cables. See Fig 10,

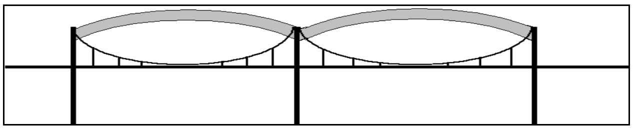

Figure 10: Suspension bridge with compression arch and trusses.

This is still not a good design, as when a train travels onto one of the span, the suspension chains go into tension and pull the piers together. This is resisted by the tubes, but they will have a tendency to buckle upwards. To stop this happening, and to provide essential stiffening for the whole structure, as it would be too flexible for a train to pass over, vertical trusses are added between the tubular arch and the deck. See Fig 11. This also is very clever as when a train is on the span, it tries to pull the deck down, which also pulls the tubular compression arch down, which is beneficial in stopping it buckle upwards.

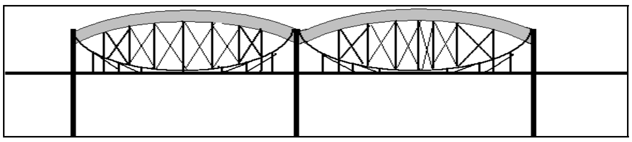

Figure 11: Suspension bridge with compression arch and trusses.

4.2.2 Simplified loading calculations. (No factors)
Firstly look at a single span of 139m long, assuming that it a simple suspended chain in figure 12

Drop of chain approximately 12metres
Freight train weight approximately 8000 tonnes [2]
Single span weight approximately 1060 tonnes [3]

Firstly assume that the train is at least the length of the span, so it is a continuous UDL and convert it into KN

8000×10^3kg x 9.81 = 78.4 MN

Assume that all the span weight is acting on the suspended chain.

1060×10^3kg x 9.82 = 10.4 MN

Total weight acting down = 88.8MN
Per metre = 88.8 /139 = 0.639 MN/m^3

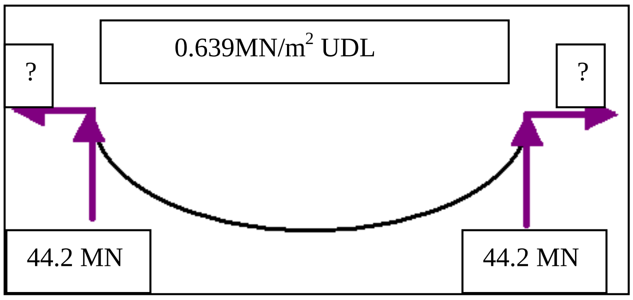

Figure 12: Simplified loading diagram

We wish to find out the horizontal load, as this is the tension within the chain, and also equal to the compression within the tubular arch. Take a free body diagram around the mid point of the chain (see Fig 13)

Moments around point A to find H

Anti-Clockwise
44.2MN x 139/2 = 3071.9 MNm

Clockwise
0.639 x 139/2 = 44.4 MN x 139/4 = 1543 MNm
H x 12m = 12H MNm

Resolving
12H = 3071.9 – 1543 = 12H = 1528.9
H = 127.4 MN

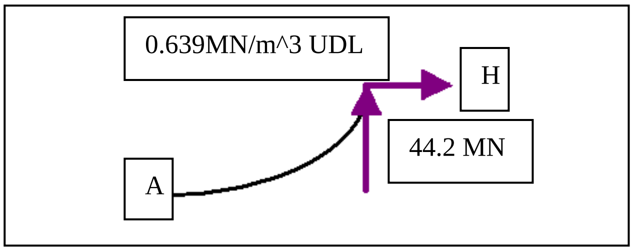

Figure 13: Simplified free body diagram

Therefore the horizontal force in the span is 127.4MN

The maximum member force can now be calculated by using the resultant force from the horizontal and vertical forces.

$\sqrt{}(127.4^2 + 44.2^2)$ = 135MN maximum tension force within chains, and maximum compression force in the tubular arches. The chain force will be approximately 4 times smaller, as there are two sets of chains on each side.

4.3 Loading of the piers and approach spans

These are much simpler, as these spans are just a deck (beam) over piers. It is a continuous beam over the top of the piers. It would be designed to take max loading on every other span, to generate maximum bending moments in the decks. For simple calculations, it could be assumed as simply supported beams as this would be conservative as far as beam design is concerned.

4.3.1 Horizontal loading on the approach spans.
As the approach spans are highly curved it the horizontal plane, they undergo big sideways moments when a train passes over the top.

4.3.1.2 Rough calculations for horizontal moments on approach spans.
Weight of train: 8000 tonnes
Train speed: 16 kph (4.4 m/s)
Approach radius: 500m (approximated from OS map)

Centripetal force = mass x velocity^2 / radius

CF= (8000x10^3 kg x 4.4^2) / 500 = 316049 Newtons outwards thrust.

To simplify calculations I have assumed that the structure is a 3 pin portal frame; in fact it is a non-pined portal frame. I could use virtual work to make the calculations more accurate.
Approx weight of one approach span, acting from the mid point: 150 tonnes
Assume 1/10th of weight of train acting on one approach pier.

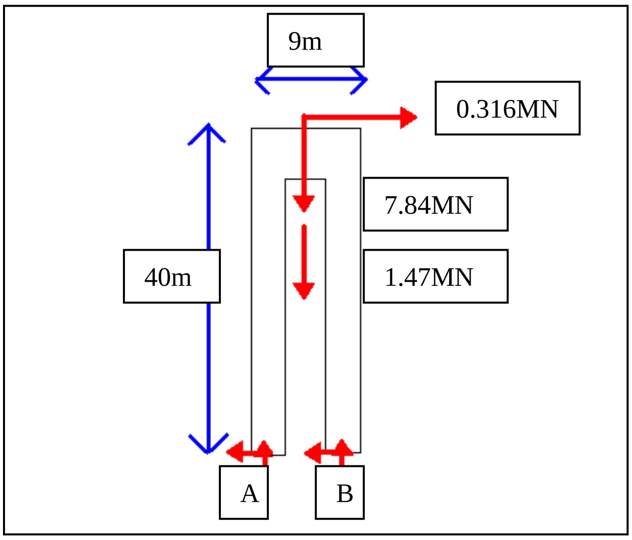

Figure 14: Forces acting upon approach spans

Take moments around point A to find vertical reaction at B.
(40 x 0.316) + (4.5 x 7.84) + (4.5 x 1.47) = 9 x Vb
54.54 MN = 9Vb
Vb = 6MN
Va = Total downward force – Vb = 3.3MN

To find the horizontal reactions, the point of zero moment is assumed to be 1.5m in from the right. Taking moments from only at the right hand side of the frame.

1.5 x 6 = 40 x Hb   Hb = 0.225MN
Therefore Ha = 0.09MN

This is quite a significant force, and any increase in either train weight, or more importantly train speed, would make the horizontal component even bigger.

5 Strength

Brunel chose to use wrought and cast iron for the main spans of the bridge. He could have used steel, but chose not to as its properties were not fully understood yet, and it was seen to be very risky. It was also quite expensive today it would be like having the option of plastic and GFRP bridges over the common steel and concrete bridges.

Wrought irons ultimate compressive strength is 200 MPa
Wrought irons ultimate tensile strength is 400 MPa [4]

6 Serviceability

This is probably the governing factor for this bridge, as being a railway bridge, it cannot deflect too much as the trains will not be able to travel over the humps and dips. If this were a recently built bridge, it would probably fail, as the deflections are very big. However Brunel knew this when he designed it, so the deck is purposely bent upwards so that when it deflects, it deflects to the horizontal. See fig 8. This was a good use of the materials and technologies at the time, and enabled money to be saved, instead of stiffening it up. Vibrations are also quite big within this structure, as it's a bow string structure and has a tendency to vibrate. Again, it would probably fail modern tests standards for vibrations.

7 Maintenance

The bridge is a single line rail bridge, which has major implications for the servicing of the bridge. If a component needs replacing, be it track, or the bridge, the whole bridge must close. Due to this being the only rail link to Cornwall this is quite a drastic course of action. This means most of the maintenance happens over night. This is particularly hazardous for the work force as they have to contend with the darkness as well as great height.

To gain easier access to inside the tubular Arches and to the bearing areas, in 1921 ugly walkways were erected at both ends of the main spans, obscuring Brunel's name. These are essential for the safety of the workforce, and to make maintenance easier. In 2006 the access walkways were moved on the inner face of the tubular supports. This has enabled the metre high words "I.K BRUNEL ENGINEER 1859" to be fully viewable.

Full access for inspection and internal maintenance is available internally in the tubular arches; however it is still a hazardous operation, as the tubes are full of bracing, which require some agility to clamber over.

A single walkway rail is installed over the top of both arches, allowing slightly safer maintenance, as the work force can easily clip their harnesses on, and have something solid to hold.

8 Construction

The following section will explain how the bridge was constructed. It is presented in approximate chronological order

The bridge used 2,650 tonnes of wrought iron, 1200 tonnes of cast iron, 12997 m³ of masonry and 396 m³ of timber in its construction [1]

8.1 Foundations

4/07/1853 The first foundation stone for the Cornish side's land pier was laid with a big ceremony. The foundation was dug down to bed rock, and levelled off. This was the most effective and easy way for the foundation to be constructed, as pile foundations were not suitable and labour was cheap.

By September of that year, the peaceful Tamar Estuary had been transformed with many workshops, for the processing of the huge amount of iron required for the bridge. In 1853 this was the best option, as using prefabricated components from a factory was not really an option. Also the tubes were too big to carry by rail. Iron could be brought in sheets and bars quite easily on the railway, and labour was cheap and plentiful locally. Not prefabricating components and relying on local labour has the effect of reducing the quality of the components. This however was the way things were done in those days, so Brunel accounted for this in his safety factors.

8.1.2 Caissons

June 1854 The 1st caisson Cylinder was floated out and sunk, sealed, and pumped of water. The
Air was pumped in at 35psi (241000 N/m^2), and water was pumped out. This badly affected the workmen at first. Cramps, faintness and insensibility were reported, and 1 man died. Up to 40 men worked inside the 37 foot (11.2m) diameter and 85 feet (26m) deep cylindrical caisson. To get to bedrock, 12ft (3.6m) of mud and loose stones were excavated, then another 3ft (0.91m) of rock.
February 1855 Using the caisson as protection, the masons started to dress the bedrock and build up the granite masonry to make the pier.
December 1856 The pier was capped, ready for cast iron columns, and the bridge lifting.

Caisson construction was chosen as it was a relatively new technology that seemed to offer many benefits, with little known disadvantages at the time. It provided a method of ensuring that the foundations were built on solid rock, and enables a well constructed underwater pier. At the time the side effects of working in compressed air were known, but not understood. Unfortunately for the workforce, they were cheap, easily replaceable, and had few rights, so they had to put up with the horrific conditions. At the time this was not seen as an issue, as many people died on many other projects. There was no such thing as health and safety then. Building up a pier by dumping lots of material in the estuary, could have been used, however, this would have provided an unknown base to build the piers off. It would probably experience great settlement which would have to be accounted for in the design of the bridge.

8.2 The 2 main truss spans

The tubular arches are not actually circular; they are actually in the form of a huge polygonal torus made from straight sections. This is because a smooth circular section of the required size was impossible to produce at the time, so they were made from small components on site. The edges of the straight sections can attract stress concentrations, which are not good; a circular section would avoid this. The tubes are not completely hollow, they have many circumferential and longitudinal stiffeners inside to resist against buckling and provide some torsional resistance.

Whilst building the foundations, the main truss spans were being constructed in temporary quays at Saltash passage. Each one was constructed in its entirety on land, one at a time. These trusses are amazingly huge, amazingly heavy pieces of iron

This was the best method of construction available at the time. Building the trusses on land was a lot easier and safer then building them at height. The quality of the work could also be inspected easily. It also meant that the navigation channel could remain un-blocked for a lot longer time. Today, the bridge would probably be lifted up in much smaller prefabricated sections.

Figure 15: Close up of the bridge deck, and truss

The main truss spans are constructed in this manner:
Slung beneath each tubular arch is a plate girder roadway which carries the railway track. It has quite deep plate girders on either side which help stiffen the bridge to resist any localized forces caused by passing trains. The deck and tubes are connected to each other by eleven pairs of vertical trusses, as well as connecting to the suspension chains. The suspension system set up so far would be far too flexible for a train to pass across, so it is further restrained through a system of diagonal bracing made from wrought iron. These are pinned at either end and connect the tubular arches to the chain links. Also transverse struts and diagonal stays hold each pair of vertical struts. For a close up of details see Fig 16.

An important detail is how the chains were attached to the tubular arches. Potentially it is asking for trouble, as the forces within the tube are spread around the circumference, where as the forces in the chains and hangers are very local. This could cause unsustainable stress concentrations. Brunel solved this by specifying a complex arrangement of plates which spread out the chain forces into the tubes. Hidden from public view, the tubular arches are finished at either end with flanged plates which are shrouded by the portals at either end.

Figure 16: Photo of truss details

Figure 17: Photo of the 2 span being lifted into position

8.3 Lifting of the main spans

1st September 1857 Pontoons were sunk beneath either end of the Cornish truss, then using the high tide, the truss floated off the quay. Using 5 Royal Navy Boats and 500 men, the truss was manoeuvred into position, floating above the centre and west pier. As the tide went out, the truss rested upon the piers. The pontoons were removed and the important task of raising the truss 100ft (31m) upwards began. 3 Hydraulic jacks were placed under each end to lift the truss 3ft (0.9m) at a time. On the western pier, masonry was then built up underneath. On the centre pier, packing had to be used, as the cast iron columns were made in 14ft (4.3m) sections. These are braced internally and externally, to resist against buckling and other torsional effects. The span rose 6ft (1.8m) per week until completion on July 1st 1858. As shown in fig 17, the Eastern span, was lifted using the same method, once the west span was fully complete. The bridge was structurally completed in February 1859.

The method of lifting the bridge was a very good solution, using the technologies of the time. The use of the tide saved many jacks and cranes, though required precision planning. Today we would lift sections using barge mounted cranes, as this would require a lot less labour and use of machinery so would be more economically efficient.

8.4 The Land Piers

8.4.2 The land supports for the main span
The land piers were constructed from granite, 9 metres wide and 5 metres thick. They were built by local stone masons who used scaffolding to work off as the piers rose with the rising of the main truss spans. Once the piers had reached the height of the track, portals were constructed of bricks and stone, all encased in cast iron. These formed the outer support for the expansion bearings of each span.
Today, these piers would likely be built of pre-cast concrete sections, as it reduces the amount of people working at height, material costs would be lower, construction time would be quicker, and the build quality would be more consistent. At the time, iron columns like in the centre could have been specified, as this would speed up construction, but would have increased costs.

8.4.3 The Approach span piers
These were constructed from granite, using local labour, in much the same way as the main span piers, apart from they were not so massive and that each pier, is actually 2 piers, rising from the ground. The reasons for doing this is that big piers are not required as the loads are less, but as the approach span is a curve in the horizontal plane, there are sideways loads acting on the piers, so spreading them out helps resist this.

9 Temperature effects

The temperature affects this bridge in two ways.

9.2 Overall temperature increase/decrease

Iron, being a metal is quite prone to expansion and contraction due to temperature change as it takes the heat from around it. Although free from the extreme cold (relative to UK, due to its south-westerly, location near the sea) it can experience quite high temperatures during the summer .The bridge deals the expansion and contractions in two ways. Firstly the deck is on roller bearings hidden within the piers. These allow the deck to move small amounts without the deck experiencing a build up of stress and strain. Above the deck is timber that supports the sleepers and track. This coupled with small gaps between the steel running rails allow the bridge deck to expand and contract a small amount
The tubular arches and suspension chains are affected by the change of temperature too. These rest on roller joints housed within the portals this works well as the main part of the span is a tied arch, so it simply rests on the bearings in the portals and does not put any horizontal load, or moments into them as they are directly connected to the tension chains. Allowance for thermal expansion is accounted for by making the whole bridge quite flexible, the tubular arches are allowed to flex vertically, as the tubular arches not required to stay a set shape. This does cause issues with the vertical trusses, as they are now put under big stresses and strains. Fortunately the bottom deck can move vertically (small amount) so when the bridge heats up, the bridge moves up, and when it cools, the bridge moves down.

9.3 Variation in temperature between top and bottom surfaces.

As this bridge has quite a big surface area, it is quite an important factor, as surfaces exposed the sun will expand more so then areas of shade.

The main bridge deck to a certain extent is shaded by the main tubular arch, as it runs east to West, it is also decked out with timber, which is less susceptible to expansion and contraction, and is not directly connected to the structure.

Differential temperature variation has been taken into account on the main tubular arch, and other parts of the bridge, by allowing it to be flexible. Like much of Brunel's work, it is over engineered, so the members are able to take the increased forces imposed on them.

10 Wind effects

The bridge design was not governed by the design for wind, as it is not a lightweight bridge design, or a long span suspension bridge. It is most likely governed by the design for dead load and the heavy live loads.

There is some thought about wind in the design. The main block to the wind, the large tubular arches, are made in a shape, that enables wind to pass around easier then a box section. The bridge is fairly slender, which Brunel may have had to take allowance for in his designs, as a strong wind would could cause a huge moment, (as the piers are quite tall) The bridge was not designed to be like an aerofoil (see 1st Severn Crossing) so the passing of trains over the bridge would not cause a severe effect to the wind flow.

The approach spans are a very un-aerodynamic design, as they are quite beefy box shapes. Fortunately, both are in a plan curve, which helps resist against the wind pushing the bridge over. They built using a well known technology of the time, so Brunel was confident they would not fall over. The piers could have been improved it by making them out of iron circular sections, like the centre pier of the main span. This would allow the approach spans to be further apart and less in the wind. The wind could also blow around the circular sections better. This though would have caused more expense to the project through material and specialist labour costs.

11 Durability

The bridge has stood for over 150 years with no major redesigns or upgrades, or extreme maintenance other then weekend closures, so quite clearly durability has been excellent. That's not to say the bridge has required little maintenance.

11.2 Iron components

Being near the coast, on an estuary in a saline environment, iron is particularly at risk from corrosion. Rusting is a big worry, as iron will oxidize when exposed to air, and/or water, which on this bridge it frequently is.

The equation for rusting of iron is:

$$4Fe + 3O_2 = 2Fe_2O_3$$

Due to this the bridge needs painting at regular intervals. It is next due to be painted during 2008/09 as part of an £8 million refurbishment [1] The bridge will be stripped down to the metal and painted with 4 coats, a total of 3750 litres of paint. This is quite a costly expense, but for the majority of the refurbishment the bridge can remain open, essential for the local economies.

11.3 Track timbers

Originally built with longitudinal track timbers, these were found to be in an unacceptable state, so in 1919 they were replaced with cross sleeper timber. These were again replaced in 2002, this time reinstating the longitudinal track timbers, a modern imitation of Brunel's original design [1]. As you can see the choice of track timbers, was a wise choice, as they have only wholly needed to be replaced twice in the bridges 150 years.

11.4 Approach spans

The piers have required very little maintenance over the years, due to them being constructed with granite blocks. This is an extremely hardwearing material, and was built to a high standard. It is still inspected for signs of wear and tear. The mortar used to hold it all together has required touch ups over the years. It has to be checked for vegetation growth. The iron deck and track timbers have required much more inspection and maintenance.

12 Susceptibility to accidental damage

As this is a rail bridge, it free from the dangers of motor vehicles crashing into parapets, and other motor vehicle issues. As the trains travel so slowly on the tracks other the bridge, a derailment is highly unlikely, so any damage is equally unlikely.

There is quite a high risk of accidental damage to the centre pier as it's very exposed to strikes by boats and ships. Fortunately, large ships, other then naval vessels, do not navigate the channel. The bridge is not on any flight path or near any airfields, so little risk there. Fire could be quite an issue if it were allowed to spread onto the bridge. It could be started by electric cables shorting, or a locomotive catching fire whilst crossing the bridge. If this were to occur, the only combustible material is the timber deck; however this is quite thick and would char. The main effect of a sustained fire would be its effect on the iron of the bridge. Localised heating would initially cause the iron to expand. This would put huge stresses and strains on the surrounding structure. If this did not fail the structure, the iron may start to melt and loose its strength. This could cause either local failure or catastrophic bridge failure.

13 Susceptibility to intentional damage

The bridge is mainly free from visual vandalism, (apart from bottom of land piers) as the railway is sealed to the public at both ends, so the public have no access to the bridge.

The main issue for intentional damage is the exposed centre pier in the main span, and the land piers either end of the main spans. If any of these were removed, at least one main span would fall, in its entirety into the river Tamar. The centre pier is at high risk of being struck by a boat or ship, and even if the pier is not removed, it could be sufficiently damaged to fail under the weight of a passing train. Due to being surrounded by water, the centre pier is fairly isolated against other forms of intentional damage. The land piers could be damage quite easily by ramming lorries or even explosives. The bridge is not really a terrorist target but in the event of a war, it may be a target, as demolishing it would block water access to the royal navy submarine pontoon.

14 Possible future changes which the bridge may have to undergo

As a rail bridge, since its construction, it has experienced an increase in rail traffic, both in weight and frequency, and then a decrease, coinciding with the increase in popularity of the motor vehicle. Now rail traffic is increasing again.

14.2 Widening

Now although trains are getting shorter, they are becoming more frequent as people switch to trains. This is particularly true for people visiting Cornwall on holiday, as firstly it has become a big magnet for tourism again in recent times, and the road network is poor, so it is quicker to get to Cornwall by train. The bridge is limited to traffic as it is only as a single rail line across. If the level of rail traffic increased enough that the single line was significantly impeding traffic, a dual line may be required. If this was the case, it would be uneconomical to widen and strengthen the Bridge, as it would require so much engineering to make this possible. Currently the track runs directly beneath the tubular arches, so adding another line, would require it to be cantilevered off, outside of the piers. It would be far more economical to build a new dual line bridge probably further downstream, to avoid the tight curvature of the approach track, see Fig 2. The building of a new bridge would make the Royal Albert Bridge obsolete, and questions would remain as to what would happen to it.

14.3 Strengthening

The future is difficult to predict, but we are likely to expect a switch of more freight to the railways. This could mean longer heavier trains, possibly above the bridges design weight. This would result in the need for bridge strengthening, probably involving additional trusses being installed along the length of the bridge, to stiffen it up, and provide more strength. Or a more drastic approach would be to replace each iron component with steel, which is much stronger then the wrought iron. A slower speed restriction may be required for heavier trains.

14.4 Railway electrification

Although talked about for many years, the south west line (London to Penzance) is planned to be electrified (overhead catenary) this would involve installing overhead wires above the track. The bridge was not designed for this, but sufficient clearance does exist for the installation of catenary wires and their supports. Special attention would be needed however, as putting live exposed electric cables on a bridge made from iron, may cause arcing and other problems. It would also make maintenance more difficult.

14.5 Climate Change

It is predicted that with climate change, the UK will experience more extreme weather such as high winds and more concentrated bursts of rain. More regular extreme winds may cause damage to the bridge, so the design may have to be altered to stop this happening. Increased concentration of rainfall could cause localized flooding on the bridge, if the drainage is not up to the task. Alterations may be required. With climate change, extreme temperatures are also predicted. This may put lots of stress and strain on the bridge, as it contracts and expands more then it was designed for. Also the bigger variations may cause fatigue within the metal.

The sea level is also predicted to rise, which would affect the bridge, as the piers would be more underwater for more of the time, which may weaken and erode them, particularly if the iron piers are submerged.

15 References and Acknowledgements

This conference paper is made up of factual information from various sources as well as the engineering judgement of it's author which may or may not be correct.

15.2 Research sources

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15.3 Photo Acknowledgements.

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