

A CRITICAL ANALYSIS OF THE LUSITANIA BRIDGE, MERIDA, SPAIN

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Abstract: This conference paper provides a critical analysis of the Lusitania Bridge in Merida, Spain. A number of different aspects concerning the bridge are taken into account in this conference paper, such as aesthetic qualities, construction, loading, wind effects and temperature. The Lusitania Bridge was built near a 2000 year old Roman footbridge, the La Akazaba, which crosses the Guadiana River at Merida, Spain. The construction of a new and modern bridge was necessary in order to relieve the old bridge, which has since been declared a footbridge. This paper was written for the Bridge Engineering 2 unit for the degree in Civil & Architectural Engineering and all analysis carried out is based on assumptions made by the author.

Keywords: Motor and Pedestrian Bridge, Steel Arch, Concrete Box Girder, Suspended Deck, Santiago Calatrava.

1 General Introduction

1.1 Background

The Lusitania Bridge, also known as the “Puente De Lusitania” Bridge is located in the Extremaduran capital city of Merida, in the Badajoz province of Spain. It crosses the Guadiana River, and connects the old town of Merida to the newly urbanized region of Poligono on the opposite bank. [1] The bridge was designed by the Spanish-born, world-renowned architect and engineer, Santiago Calatrava Valls.

1.2 Reasons for Construction

The bridge was constructed for, and commissioned by the Council of Extremadura, Junta de Extremadura, as a design-built project by the architect Santiago Calatrava and the construction firm Construcciones y Contratas SA. [2]

The bridge was built to alleviate the heavy usage of the Roman bridge, La Akazaba, which was the main entrance into the city from the west. The renovation and preservation of the old Roman bridge, which is now only used as a footbridge, coincided with the completion of the new and elegant Lusitania Bridge, which was planned and constructed between 1988 and 1991. **Figure 1** and **Figure 2** show the

new Lusitania and the old Roman bridge La Akazaba.



Figure 1: The old La Akazaba Bridge and the new Lusitania Bridge

1.3 Structure

The Lusitania Bridge is a foot and motor bridge with a total length of 465 metres and a maximum span of 189 metres. It can be classified as an arch bridge with a suspended deck. It consists of a 34 metre deep steel arch, a prestressed concrete deck, a central load-bearing box girder, and reinforced concrete piers, which are spaced 45 metres apart. [1]

The Lusitania Bridge was designed as an integral or monolithic structure. This means that there are no expansion joints present within the deck. This is a very important decision in the design, as it leads to lower construction and maintenance costs, due to the fact that expansion joints have to be serviced regularly to remove any dirt that accumulates there.



Figure 2: The old Roman La Akazaba Bridge and the new Lusitania Bridge in the background

The bridge structure is divided into 3 sections, as is common in cases where bridges span crossings. There are two 144 metre side spans that are supported by piers, which connect the central arch structure to the land on either side of it. [1] Bridges that are divided into three sections, usually have a break in their structure or syntax between the different sections, however Calatrava designed the bridge's cross section to flow uniformly and uninterrupted from one end to the other.

The cross section of the bridge comprises of a continuous concrete box girder and the road decks that cantilever from either side of it. This 4.5 metre deep box girder, or torque tube, constructed from "post-tensioned, pre-cast concrete elements" [1], acts as the "spine" of the entire bridge, as it is the main load bearing component. A 5.5 metre wide pedestrian walkway is located on the top surface of the box girder, and this walkway is elevated above the dual carriageways on either side of it therefore allowing the pedestrians clear views of the river and the old Roman bridge.

The cantilevered road decks are not in direct contact with the central box girder, and dead

and live loads are transferred to the box girder by means of "prestressed concrete wings". [1] These concrete wings, seen in **Figure 5**, cantilever from either side of the box girder, and opposing pairs are post-tensioned to each other by means of steel rods pairs that run through the box girder.

The central arch structure is the most striking feature of the Lusitania Bridge. It lies between the two road decks and supports them in the same fashion that a pair of scales would. This 131 metre long sickle shaped arch consists of three tubular steel arches, which are connected to each other by rigid components, therefore forming a triangulated 5 metre by 2.5 metre (axis to axis) section. The steel truss arch ends on both sides in two arched reinforced concrete abutments, which each contain approximately 29 metres of the length of the arch. [1] 23 steel rod pairs transfer the dead and live loads from the suspended deck to the truss-arch structure. These rod pairs are pinned to the lowest of the three steel arches at the top, and to either side of the 5.5 metre pedestrian walkway at the bottom. The first two rod pairs on either ends of the arch are connected to the truss arch within the reinforced concrete abutments.

The Lusitania Bridge possesses a four-tier load path. The loads from the deck are transferred to the steel rod pairs. These rod pairs transfer the loads to the truss-arch structure, which in turn transfers the load to the reinforced concrete abutments. The loads from the concrete abutments and the side spans are then transferred to the ground through the bridge piers.

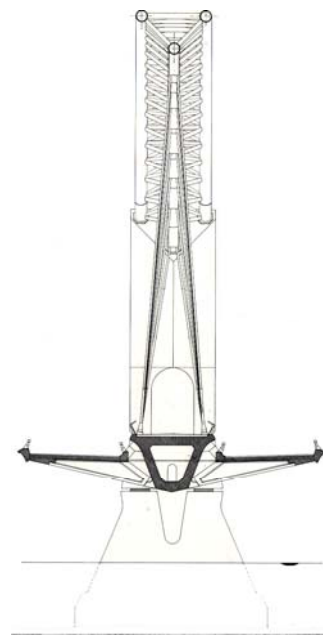


Figure 3: Cross Section of Lusitania Bridge through arch and deck

2 Aesthetics

In order to assess the aesthetic qualities of a bridge, one can consider Fritz Leonhardt's ten rules of bridge aesthetics [3], from his epic book *Brücken*, as listed in 2.1. Fritz Leonhardt believed that if one abides by these ten rules, then the bridge can be deemed as being aesthetically pleasing. Leonhardt's rules of aesthetics however vary with Calatrava's ideologies on how the quality of a bridge can be assessed. Calatrava believes that the keys to good design were put forward by the ancient Roman architect, engineer and writer, Marcus Vitruvius, and are still applicable in today's world. [4]

*"There are three concepts, three keys to be found in the books. One concept is **utilitas**, which means utility, the second is **firmitas**, which means stability, and the third is **venustas**, which means beauty. These are the three key aspects with which any work built by man can be analysed."* Santiago Calatrava

Daniel Barbaro, the Renaissance bishop who translated Marcus Vitruvius' work, also suggested three other factors that Calatrava also considers in his designs, which are namely fortitude (strength), bonitas (goodness) and intellectus (intelligence). [4]

Therefore summing all of the above, Calatrava's set of rules for bridge design would be utility, stability, beauty, strength, goodness, and intelligence.

In this paper I have analysed the Lusitania Bridge according to Leonhardt's ten rules, however also taking into account Calatrava's ideas on the aesthetics of the bridge.

2.1 Leonhardt's Ten Rules of Bridge Aesthetics

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

2.2 The Aesthetics of the Lusitania Bridge

The Lusitania Bridge shows very clearly how it works, and immediately imposes upon the viewer a sense of security, with its steel truss-arch structure, and thick reinforced concrete arch bases and piers.

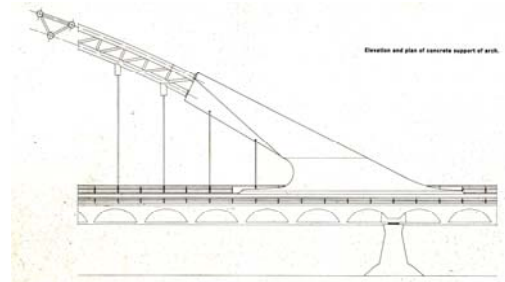


Figure 4: Detail Showing Concrete Base of Arch and Decking Detail

There is no sense of instability about it, as the arch is centred above the roadway and is not tipping to one side, as is characteristic of Calatrava's arches. The strength of the slender arch also seems to be fortified by the two twin imposing buttresses found at either end, as seen in **Figure 4**. The elevated pedestrian walkway allows the pedestrians unobstructed views of the river and the old Roman bridge, whilst also allowing them to see where they are heading. We can see clearly how the bridge fulfils its function, yet at the same time Calatrava has managed to incorporate strength into his design.

The Lusitania Bridge is beautifully proportioned. The bridge can be seen to have a regional scale, with its 465 metre long, 189 metre span dimensions, which were dictated by the wide Guadiana River. [1] The eye is drawn to the 34 metre deep, 189 metre spanning arch structure, which has a span: depth ratio of 5.6. This slender arch presides over the two 139 metre side spans, and a sense of balance and stability is achieved by Calatrava as its light appearance connects to the two massive, concrete bases found at either ends. The transition from the slender arch to the thicker concrete bases occurs gradually, as the concrete abutments seem to flow into the steel arch and visa versa. The depth of the deck is also in proportion to the arch and the overall dimensions of the bridge, as is the spacing and size of the bridge piers.



Figure 5: Structural Wings of Deck

The structural wings mentioned before in part 1.2 leave semicircular gaps between them, which creates shadows on the box girder to which they are attached. The depth of the deck and the box girder appears much shallower than if these gaps were filled in, as can be seen in **Figure 5**. These gaps are all positioned beautifully at regular intervals and are in the right proportion with the deck, so as not to distract from the viewer's attention. Calatrava manages to lighten the span of the bridge further, by not placing the road decks in direct contact with the box girder. This leaves a gap between the two allowing a line of light to penetrate through the structure on both sides of the bridge, as can be seen in **Figure 5**.

The balustrades of the pedestrian walkway and of the highways are also relatively inconspicuous, and blend in with the deck when the bridge is viewed from a distance. However, once on the bridge, they can be seen to give the user a feeling of safety, as they are broken outwards at mid-height, with the lower portion of the balustrades covered by a grill.

One can argue that the concrete piers of the bridge, seen in **Figure 6**, have a rather strange shape and might seem stocky for this bridge. However, this shape was very well thought of by Calatrava. As the bridge has two bearing points, Calatrava could have had two circular columns leading down to the ground. However this would have led to the formation of vortices between the columns within the river. Also, if two columns were used instead of one, then when the bridge was viewed from an oblique angle, there would be a forest of columns creating an opaque barrier.

Calatrava therefore decided to fuse these two columns together, giving them an aerodynamic shape at the bottom, allowing water to pass by the bridge more freely. Calatrava also refined his design further by removing part of the concrete between the two columns, as the load only spreads out at a 45° angle from the bearing point. In this way he also managed to conserve building materials.



Figure 6: Concrete Abutments of Lusitania Bridge

When Santiago Calatrava began designing the Lusitania Bridge, he had to evoke a sense of harmony with the old Roman bridge located 600m upstream. He managed to do this by mirroring the rhythmic structure of the old Roman bridge in the way he spaced the piers at 45 metre intervals. Calatrava also pays homage to the old Roman bridge, in the design of the arch abutments. The amount of concrete used for these bases relates to the mass used to construct the old Roman bridge nearby. [5]

Calatrava also tried to add a certain amount of energy to the landscape by creating an elegant slender steel arch. This arch connects to the deck of the bridge by steel rod pairs. The steel rod pairs are arranged in such a way so that when the bridge is viewed from an oblique angle, they do not cross over and create an opaque barrier. They also offer unhindered views of the river and of the old Roman bridge.

The steel rod pairs on either side of the road, rise up and gradually converge as they reach the arch, and this gives the people walking along the central pedestrian pathway and above the traffic lanes, the feeling that they are walking down the isle of a cathedral, with its tall narrowing ceilings.



Figure 7: Steel Rods and Arch Structure

Spotlights positioned at the base of each steel rod, and luminaries placed within the arch and at the sides of the balustrades, recreate this cathedral-like walk during the night as well, as can be seen in **Figure 8**.

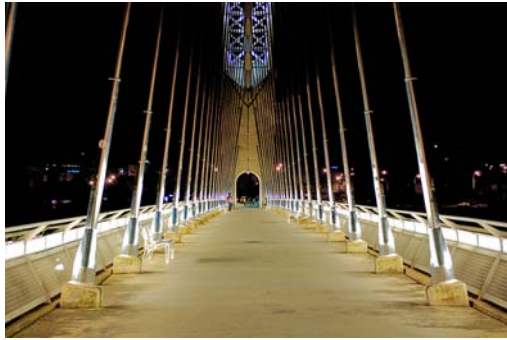


Figure 8: Night View of Pedestrian Walkway

The deck, arch bases and piers of the bridge all have a smooth, grey, matt, concrete finish. The arch and balustrades of the bridge were painted white. These colours were chosen so as not to be too bright against the old Roman bridge, which is made up of reddish brown granite. The steel rod pairs that connect the deck of the arch were not painted, in order to blend in with the background when the bridge is viewed from a distance.

I believe that Leonhardt's rules that a bridge must portray character and complexity, translate to Calatrava's rules of *venustas* and *intellectus*, as the definition of character [12] is "the qualities that make something interesting or attractive." Calatrava mentions that people tend to link beauty with intelligence, and in order for something to be interesting it must stimulate the mind.

"This is very interesting, because when we discuss the aesthetics of something that primarily has to be stable, we can only link beauty and stability with intelligence." – Santiago Calatrava

The Lusitania Bridge is not only a very attractive bridge to look at both night and day, but it also possesses a very interesting and intelligent structure.

In **Figure 9** we can see that the cross section of the central box-girder was designed according to the shape of a bull's head, as Santiago Calatrava always tries to incorporate vegetal and animal forms in his designs. [2]

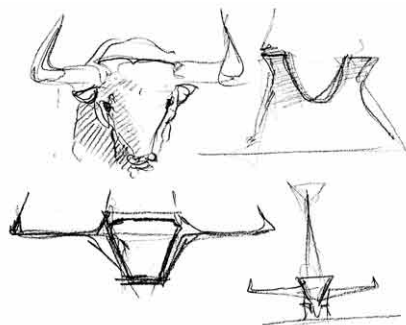


Figure 9: Design of Cross Section and Piers Based on Head of Bull

Calatrava also believes that a bridge must possess *bonitas* (goodness) and in the case of the Lusitania Bridge, even though this design is nowhere near traditional, there is a sense of austerity about it, or even respect, for the old Roman bridge nearby.

2.3 Summary of Aesthetics

It can be seen that the bridge complies with all of Leonhardt's rules of aesthetics, however upon closer analysis it can be seen that Calatrava's ideologies on bridge design do not vary that much from what Leonhardt suggested.

3 Bridge Loading

Bridges are designed according to limit state philosophy. This implies that a bridge must be checked at the Ultimate Limit State (ULS), in order to prevent collapse, and it must also be checked at the Serviceability Limit State (SLS), in order to make sure that the bridge is serviceable. [3]

The loads that will be considered are:

- Dead
- Super-imposed dead
- Live traffic
- Wind
- Temperature

As the Lusitania Bridge is located in Spain, this paper will take into account the Eurocode [7], as well as the British Standard BS 5400 design codes [6].

BS 5400 considers 5 load combinations which have to be checked at the SLS and the ULS, however the Eurocode also takes these load combinations into account in four different Load Models.

Partial load factors, which include the partial load factor, γ_{fi} , and the further factor γ_{FB} , obtained from BS5400, have to be applied to the nominal loads calculated for each of the above load conditions.

3.1 Dead And Superimposed Dead Loads

The dead loads of the bridge were calculated according to various assumptions. These characteristic dead loads seen in **Table 2** were then factored using the values obtained from **Table 1** to give the final design dead loads seen in **Table 3**.

3.1.1 Steel Arch-truss (SAT)

It was assumed that the three steel tubes each had a diameter of 1metre and a wall thickness of 50 mm.

Characteristic Dead Load of Arch: (1)
 $0.15 \text{ m}^2 \times 131 \text{ m} \times 78500 \text{ kN/m}^3 \times 3 = 4.6 \text{ MN}$.

3.1.2 Concrete Cross Section of Bridge (CCS):

The cross sectional areas of the box girder, road decks and structural wings were combined and modelled as a rectangular cross section of reinforced concrete, 6m deep by 5m wide.

Characteristic Dead Load of Cross Section:
 $30 \text{ m}^2 \times 465 \text{ m} \times 24000 \text{ kN/m}^3 = 335 \text{ MN}$ (2)

3.1.3 Concrete Arch Abutments (CAA):

The abutments were modelled as rectangular blocks of dimensions 5.5 x 6m x 29m.

Characteristic Dead Load of Abutments: (3)
 $5.5 \text{ m} \times 6 \text{ m} \times 29 \text{ m} \times 24000 \text{ kN/m}^3 \times 2 = 46 \text{ MN}$

Table 1: Values of γ_{fi} and γ_{f3} for Concrete and steel

	γ_{fi}		γ_{f3}	
	ULS	SLS	ULS	SLS
Concrete	1.15	1.00	1.10	1.00
Steel	1.05	1.00	1.10	1.00

Table 2: Characteristic Dead Loads (MN)

SAT	CCS	CAA	Total
4.6	335	46	385.6

Table 3: Design Dead Loads (MN)

	SAT	CCS	CAA	Total
ULS	5.31	423.78	58.19	487.28
SLS	4.6	335	46	385.6

The superimposed dead loads which are insignificant are factored by $\gamma_{fi} = 1.75$ at the ULS, and 1.2 at the SLS. The super-imposed dead loads are assumed to be insignificant compared to this large dead load.

3.2 Live Loading

3.2.1 Notional Lanes

Bridge Traffic loading is applied to notional lanes, which are independent of the actual lanes delineated on the road. [8]

The Lusitana Bridge consists of two, 7 metre wide dual carriageway road decks, separated by a 5.5m pedestrian walkway. The Eurocode states that for carriageways that are physically divided into two parts by a permanent road restraint system, then each part has to be separately divided into notional lanes. From **Table 4.1** in the Eurocode 1, the number of

notional lanes of each separate carriageway was calculated to be 2. The width of the notional lanes is 3m, and the width of the remaining area is 1m.

3.2.2 HA and HB Loading

BD37/88, which is specifically used for Highway Bridges, and the Eurocode both refer to two types of loading, 'normal' and 'abnormal'. Eurocode 'normal' traffic loading is the equivalent of HA loading in the British Standards, and consists of uniform loading and a tandem of four wheels in each notional lane. Eurocode 'abnormal' loading is the equivalent of HB loading in the British Standards. Load Model 1 described below, deals with HA loading.

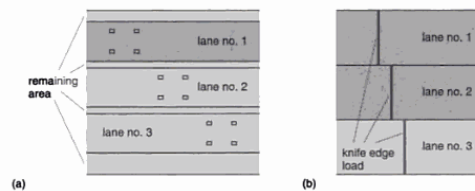


Figure 10: (a) Eurocode 'normal' loading; (b) British Standard HA loading [8]

3.2.3 Load Model 1 (LM1)

Load Model 1 deals with concentrated and uniformly distributed loads, and it is used for general and local verifications. It consists of:

a) double-axle concentrated loads (tandem system: TS), where each axle has a weight of:

$$\alpha_Q Q_k \text{ kN} \quad (4)$$

b) Uniformly distributed loads,

$$\alpha_{qk} q_k \text{ kN/m}^2 \quad (5)$$

The values of α_q and α_Q are given in table NA.1 of the UK National Annex [9] and are shown in Table 4 below. The values of Q_k and q_k are taken from table 4.2 in the Eurocode, and are different for each notional lane. These values are factored by a_Q and a_q to give the characteristic live loads shown in the tables 4 below.

4: Concentrated Live Loads

Notional Lane	Tandem Axle Load Q_{ik} kN	Adjustment Factor α_Q	TS (kN)
1	300	1	300
2	200	1	200
Remaining Area (q_{ik})	0	0	0

Table 5: UDL Live Loads

Notional Lane	UDL q_{ik} (kN/m ²)	Adjustment Factor α_q	UDL (kN/m ²)
1	9	0.61	5.49
2	2.5	2.2	5.5
Remaining Area (q_{ik})	2.5	2.2	5.5

In order to get the design live loads, we have to further factor the characteristic live loads with γ_{fl} . The γ_{fl} of HA loading alone at ULS is 1.5, and at SLS is 1.2.

Table 6: Design Live loads

Notional Lane	Tandem System Q_{dk} (kN)		UDL (kN/m^2) q_{dk}	
	ULS	SLS	ULS	SLS
1	450	360	8.24	6.59
2	300	240	8.25	6.6
Remaining Area	0	0	8.25	6.6
Total Loads	750	600	24.75	19.75

3.2.4 Load Model 2

LM2 consists of a single axle load, $\beta_Q Q_{ak}$, which is applied at any point on the carriageway. $Q_{ak} = 400$ kN. The National Annex states that the value of $\beta_Q = \alpha_{q1} = 1$, and that the contact surface of each wheel is taken to be a square of sides 0.4 m.

3.2.5 Load Model 3

LM3 in the Eurocode deals with ‘abnormal’ loading and is the equivalent of HB loading in the British Standards. The British NA of the Eurocode 1 [9] takes into account the maximum induced effect of a vehicle in accordance with Special Types General Order (STGO) and Special Order (S0) Regulations. The choice of vehicle model depends on the project in question, and the country in which the project is taking place. I have decided to choose the SV196 vehicle, which represents a single locomotive with a STGO Category 3 attached. It was chosen as the gross weight of the vehicle train does not exceed 196 tonnes, and this is similar to the HB vehicle defined in the BS5400 which has a gross weight of 180 tonnes, when full HB loading of 45 units is considered. The SV196 vehicle axle arrangement is shown below in **Figure 11**. [9]

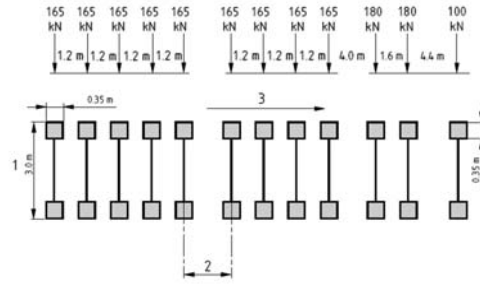


Figure 11: SV196 Axle Configuration

The distance 2 on the diagram is taken to be 1.2 metres, as this would provide the most critical condition. The different axle loads are also multiplied by the various dynamic amplification factors taken from table NA.2 in [9]. This vehicle is then combined with the concentrates tandem loads and UDL loads obtained from LM1, and the SV196 vehicle is placed in notional lane 1, or can straddle two notional lanes, to produce the most severe load case.

3.2.6 Load Model 4

LM4 deals with crowd loading on bridges, and consists of applying a UDL of 5 kN/m² over the full width of all the road decks. As the Lusitania Bridge has two 7 metre wide road decks, this would amount to a load of 70 kN/m.

3.2.7 Breaking And Acceleration Forces

The breaking force, Q_{1k} , denotes the longitudinal force acting on the surface of the carriageway. The National Annex states that the upper limit of the breaking force should be taken as 900 kN. The value of Q_{1k} is calculated by taking into account the total maximum vertical loads that correspond to LM1.

$$Q_{1k} = 0.6\alpha_{Q1}(2Q_{1k}) + 0.10\alpha_{q1}q_{1k}w_1L \quad (6)$$

$$Q_{1k} = (0.6)(1)(2)(300) + (0.10)(0.61)(9)(3)(189)$$

$$Q_{1k} = 671.28 \text{ kN}$$

In order to get the design breaking force, this value is then factored by the γ_{fl} , which is 1.25 at ULS for longitudinal loads, and $\gamma_{f3} = 1.10$. [6]

$$Q_d = 671.28 \text{ kN} \times 1.25 \times 1.10 = 923.01 \text{ kN} \quad (7)$$

4 Strength

The strength of the bridge is assessed by analysing the bending moment forces in the deck, and symmetric and asymmetric loading along the length of the deck.

4.1 Symmetric and Asymmetric Loading

Figure 12 shows the bridge under symmetric loading. The live and dead loads from both road decks are transferred to the structural wings, found immediately beneath them, which undergo compression. As the loads on both road decks are similar, they counter-balance each other with the use of the steel rod pairs that run through the box girder.

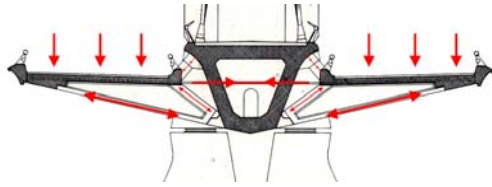


Figure 12: Symmetric Loading

In the case of asymmetric loading, when there are vehicles present on only one bridge deck, we can see how the torsion box comes into effect with the use of diagonal tension members that connect the road decks to the top of the box girder.

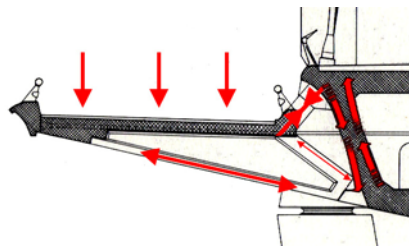


Figure 13: Asymmetric Loading

4.1 Bending

Before we can begin calculating the maximum moment in the deck, we have to make the assumption that the bridge is a 189 metre continuous beam, which is supported at three ground piers along each of its two 144 m side spans, and by the steel rod pairs in the central span. We also assume that the weight of the steel rod pairs is negligible with the loads supported by the cables, and that it is flexible and resistance is small and can be neglected. The bridge connects to the riverbanks in concrete abutments, therefore the ends are assumed to be fixed. The bridge piers possess flexible bearings, which prevent the box girder from moving in a lateral direction. [1] The 23 rod pairs running from the arch to the deck were post-tensioned to take the 172.14 MN design dead load of the 189 metre span only. $172.14 \text{ MN} / 23 = 7.48 \text{ MN}$ per rod pair.

The maximum moment was calculated to be 19.76 GN, for the HB load case when two

SV196 vehicles are placed on each separate road carriageway in the centre of the 189m span, and when a the UDL live loads from LM1 are spread across the central 189 metre span. The span is supported by steel rods that are vertical along its length, and the bending moment diagram can be seen to take the form of a “jelly” as it were, underneath the central span.

$$M = \omega l^2 / 10 + PL / 4 \quad (8)$$

$$M = (24.75)(7)(2)(189^2) / 10 + (196000)(2)(189) / 4$$

$$M = 19.75 \text{ GN}$$

This value seems extremely large, but it might be justified judging from the shear size of the piers and of the truss-arch bases.

5 Foundations

There is no information regarding the foundations of the bridge, however they were assumed to be pile foundations, due to the weak ground conditions of the Guadiana River, and for economic reasons. The piers were cast on top of the piles, and the bottoms of the piers were designed to resist the effects of scour around the pile head.

6 Wind Loading

The wind loads acting on the bridge were calculated according to BS EN 1991-1-4:2005.

6.1 Wind Loading Parallel To Deck

In order to calculate the wind force in the x-direction, which is the force that is parallel to the deck width, the following expression is used.

$$F_w = 0.5 \rho V_b^2 C A_{\text{ref},x} \quad (9)$$

The basic wind velocity, V_b , which is recorded at a height of 10 m above ground level, can be calculated using the following expression.

$$V_b = C_{\text{dir}} \cdot C_{\text{season}} \cdot V_{b,0} \quad (10)$$

$V_{b,0}$ is the fundamental value of the basic wind velocity and due to the fact that there was no information regarding this value for the specific location of the bridge, this value was assumed to be 15 m/s due to the fact that Merida is located inland and is not close to the sea. The value of V_b was taken to be 15 m/s, as the Eurocode recommends that the values of C_{dir} and C_{season} should be taken to be 1.0.

C is the wind load factor and this value is obtained from the following expression.

$$C = c_e \cdot c_{f,x} \quad (11)$$

c_e is the exposure factor, and was found to be 2.0 at a height (z) of 10 m located in terrain category II, according to figure 4.2 in [11].

$c_{f,x}$ is the force coefficient for wind action on bridges, and is taken to be 1.30, as is recommended by the Eurocodes [10]. Even though the windward face is inclined due to the presence of the box girder, the N.A to the Eurocode [11] states that the value of F_w should not be reduced.

$$C = (2.0)(1.3) = 2.6 \quad (12)$$

$A_{ref,x}$ is the reference area of the face along which the wind force acts. The depth of the area on which the wind force acts is equal to $d + 0.6$ m, for open parapets on both sides of the deck, obtained from Table 8.1 in [10]. The depth of the box girder is 4.5 m therefore $d = 4.5 + 0.6 = 5.1$ m. The recommended value of ρ is 1.25 kg/m^3 [10]

$$F_w = (0.5)(1.25)(15^2)(2.6)(5.1) \quad (13)$$

$$F_w = 1.86 \text{ kN/m}$$

This value might be slightly inaccurate due to the fact that the wind velocity was assumed.

6.2 Wind Forces Perpendicular To The Deck

The Eurocode 1 [9] states that the recommended value for the longitudinal wind forces in the y -direction should be taken as 25 % of the wind forces in the x -direction for plate bridges. This produces a longitudinal wind force of 0.47 kN/m.

The BS5400 [6] approach is not so simple and involves longitudinal wind loading on traffic as well. The British Standards state that for a superstructure with a solid elevation, the longitudinal wind load on the superstructure is equal to:

$$P_{LS} = 0.25qA_1C_D \quad (14)$$

The wind loading on the live traffic load is equal to :

$$P_{LL} = 0.5qA_1C_D \quad (15)$$

C_D is interpolated from figure 5 of BS5400. The ratio of b/d is required, where $d_1 = 4.5$, and $d_3 = 2.5\text{m} + 4.5\text{m} = 7\text{m}$. b in this case is equal to 19.5 m. C_{D1} was found to be approximately 1.4, and $C_{D3} = 1.45$

$$q = 0.613V_d^2 \quad (16)$$

V_d is the maximum wind gust speed and is calculated according to the site hourly mean wind speed and the gust factor. It is assumed to be 100 m/s for the worst case scenario.

A_1 is equal to the width of the deck, 19.5 m multiplied by d_3 , as it is greater than d_1 .

$$P_{LS} = (0.25)(6130)(136.5)(1.4) \quad (17)$$

$$P_{LS} = 292.8 \text{ kN}$$

$$P_{LL} = (0.5)(6130)(136.5)(1.45) \quad (18)$$

$$P_{LL} = 606.6 \text{ kN}$$

These values might be slightly overestimated due to the large value of V_d that was assumed.

7 Temperature Effects

Changes in temperature have an important effect on the overall design of a bridge, and have to be considered at an early stage, as they may lead to severe structural problems later on in the design due to large stress forces that may build up.

Two temperature effects are taken into account in this paper. The first is effective temperature, which deals with overall temperature increases or decreases, and the second is temperature difference, which takes into account variations in temperature between the top and bottom surfaces. [3]

The Lusitania Bridge piers are covered by flexible bearings, [1] allowing small movements to occur between the deck and the piers. This results in smaller moments and shear forces being produced. The Lusitania Bridge was also designed as an integral structure [1], and this means that there are no expansion joints present. The coefficient of thermal expansion, α , for steel and concrete is taken to be $12 \times 10^{-6}/^\circ\text{C}$.

7.1 Effective Temperature

The strain along the deck is calculated using the following expression:

$$\varepsilon_T = \alpha\Delta T \quad (19)$$

A temperature fluctuation of 40°C was assumed as Spain's Mediterranean climate can fluctuate greatly between different seasons.

$$\varepsilon_T = (40)(12 \times 10^{-6}/^\circ\text{C}) \quad (20)$$

$$\varepsilon_T = 480 \mu\text{e}$$

The change in length of the bridge was calculated according to the following expression:

$$\Delta l = (480 \mu\epsilon)(465\ 000) \quad (21)$$

$$\Delta l = 223.2\ \text{mm}$$

The stresses that will form in the bridge deck were calculated using to the following expression:

$$\sigma = E\epsilon = (210000)(480 \times 10^{-6}) \quad (22)$$

$$\sigma = 100.8\ \text{N/mm}^2$$

7.2 Temperature Difference

As the Lusitania Bridge has a concrete box girder with a height of 450mm, and an assumed 100 mm concrete surfacing on the top, according to the British Standards [6], the following temperature profile seen in Figure 15 was deduced.

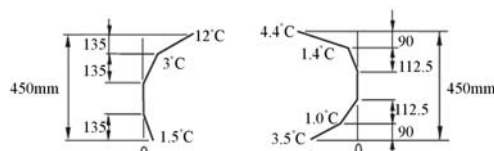


Figure 15: Temperature Profile of Cross Section with morning on the right and night on the left

8 Construction

The Lusitania Bridge was constructed during Spain's long and dry summer season, during which the flow of the Guadiana River ceases, and isolated pools can be seen in some parts of the river. A provisional gravel fill was laid down upon the dry riverbed, and scaffolding was set up in order to support the central box girder, and the two highway road decks on either side of it. In order to cast the central span of the bridge, where no piers are present, provisional piers were erected atop of a provisional gravel fill. Once the box girder was in position, it was post-tensioned causing it to rise slightly, and therefore allowing the supporting scaffolding to be removed from below.

9 Vandalism

It can be seen from a number of pictures that vandals have spray-painted certain areas of the concrete pedestrian walkway, and certain areas of the bridge piers. This has no effect on the bridge's structure whatsoever, however it has a major effect on the aesthetics of the bridge. In my opinion, spray-painting on a "Calatrava" is no different to drawing a moustache on the Mona Lisa. Possible solutions to this problem would be to employ security watchmen, or to

install security cameras on the arch bases, however this would have to be decided by the local authorities, and would increase the cost of maintenance considerably.

10 Suggested Improvements

The massive dead loads and abutments of the bridge, speak for themselves on this matter. They should be reduced in size. This could have been avoided if the bridge cross section was not made completely out of concrete, but was made out of steel instead. This would not only have reduced the cross section depth, but would have also reduced the size of the piers providing a more attractive end view of the bridge

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