A CRITICAL ANALYSIS OF SANTIAGO CALATRAVA’S BACH DE RODA BRIDGE, BARCELONA

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Abstract: This paper provides a detailed study of the aesthetics of Calatrava’s first bridge: el Bach de Roda. An appraisal of the loading and structure of the Bridge, which launched Calatrava onto the world stage as an articulate bridge designer as well as an accomplished Architect and Engineer, will be followed by an assessment of the Bridge’s foundations and construction. Finally the author will consider the future of the bridge, and how its use may change.

Keywords: Bach de Roda, Calatrava, Felipe II, Steel Arch Bridge, 1992 Olympics Barcelona

1 Introduction

In 1984, in preparation for its candidature as host city for the 1992 Olympic Games, Barcelona stepped up its program of urban regeneration. “Historically Barcelona has always taken advantage of the incentive provided by international events to improve its infrastructure.”[1] At this time Santiago Calatrava had recently come onto the world stage as a very capable Architect and Engineer, who was able to combine the two disciplines with skill and elegance in his design of the Stadelhofen Railway Station in Zurich in 1983. The Bach de Roda Bridge was to be his first bridge and he used his unique skills as both Architect and Engineer to start to revolutionise into the way the bridge designers approached aesthetics.

Until 1984, the city had undergone only small to medium sized projects in preparation as a potential host city. A major aim of the regeneration was to improve the transport infrastructure in the city, including roads and railways. The Bach de Roda Bridge (or the Felipe II Bridge as it is sometimes called) is often seen as the first of these major projects. It was designed to link two impoverished parts of Barcelona: San Marti to the East and Sant Andrea to the West. (Figure 1) The two areas are separated by railway lines which, as part of the regeneration project, were to be expanded and a new station built nearby. This only served to increase the separation of the two areas; thus the bridge was vitally important to ensure that this did not happen.

As part of the expansion of the railway lines and regeneration of the area, the Parc de la Clot was to be extended so that the embankments became useable parkland, creating “one of the most expansive green areas in Barcelona”[1]. Calatrava therefore had to take into account how he could integrate the Bridge’s use into the surrounding parkland and urban landscape and make it an iconic part of the regenerated Barcelona. A. C. Webster said that such a bridge is designed to “enhance civil spaces”[3], often a rarity for a bridge, but a trait that Calatrava has continued in his future works such as the Alamillo Bridge in Seville, a paper on which can be found in the 2008 proceedings of this conference by J. J. Orr.[4] K. Frampton also notes that Calatrava takes “the mere commission for a bridge into an occasion for creating a place”[5], giving Barcelona exactly what they wanted: something iconic. (Figure 2)
2 Aesthetics

Typically a very subjective and potentially emotive topic, this paper will look at aesthetics in an objective fashion using the guidelines first suggested by Fritz Leonhardt. The aesthetics of the bridge will therefore be judged on the following criteria [6]:
- Fulfilment of function
- Proportions
- Order
- Integration into the environment
- Surface texture
- Colour of components
- Character
- Complexity in variety
- Incorporation of Nature

Leonhardt also had refinement as another of his guidelines; this will be discussed under its own heading later in this paper (Section 4). A bridge does not necessarily need to fulfil each of these guidelines, however Leonhardt suggested that each should be considered during bridge design and only discounted should its inclusion be to the determent of another more significant guideline.

Calatrava, himself a trained and famous architect in his own right, held aesthetics in extremely high regard and wanted, with this his first bridge, to create something which was not only an impressive piece of engineering, but also an impressive piece of architecture. "In bridge design, there is a certain exercise in Engineering Aesthetics to be undertaken, and I feel that the integration of technology and aesthetics deserves special attention." - Santiago Calatrava [7].

2.1 Fulfilment of Function

Calatrava has been very clear in defining his structure with this bridge, unlike some of his later bridges, such as the Alamillo Bridge, which is certainly not what it seems.[4] Fulfilment of function is about being honest with structure you have selected and the material which you have chosen. The deck is unmistakably suspended from the steel arches with steel cables, clearly expressing the materials used, as shown in Figure 2. Calatrava said himself about his work “Whatever materials I've used were exposed. I could never imagine making a pillar in steel and cladding it in something else”[8]. It also apparent that the deck provides a tie for the arch, expressing the refinement required to minimise the arch section and required support structure.

Leonhardt said that for an arch “its shape expresses directly its ability to carry loads” [9]; this idealised shape is a parabola. Keeping true to this Calatrava has followed a parabolic shape for his arch, which works aesthetically, but also structurally minimises the section required. He has then specifically expressed this by continuing the outer canted arches down to the ground: highlighting the shape of the arch further.

The, at that time, unique feature of this arched bridge was the way in which it was restrained from lateral forces, this will be discussed in both structural design (Section 3) and refinements (Section 4) later. However, the way in which is does restrain the primary arch is again expressed very clearly. Figure 3 shows how the outer canted arch simply ‘props’ up the main arch, preventing it from racking. Even to a layperson this is intuitive and in being as such it shows how clear the structural form is. The only misguiding part of the design is that it appears as if both arches are supporting the whole deck, when in fact the primary arch is doing most of the work and the secondary canted arch is mostly only providing stability and support for the outer walkways. This illusion is not helped by the way in which the outer canted arches continue down to the ground with the angled concrete piers seen in Figure 2.

![Figure 3 – View of Canted Arch [10]](image)

2.2 Proportions

Leonhardt suggests that good proportions “must exist among the relative sizes of the various parts of a structure; among its height, width and breadth; among its masses and voids, closed surfaces and openings; and between the light and dark caused by sunlight and shadow.”[9] If we consider the superstructure only, the arches, despite that fact that they are supposed to be the major structural component look of comparable size to the deck, if not smaller. In the hierarchy of structure, these should be larger, as they are further down the hierarchy and in theory carry comparably more load.

If we then consider Figure 4 we can see more clearly the ratio of masses to voids and openings to closed surfaces. Traditionally a bridge will have much larger openings to closed surfaces, where as in this case, you can see the columns look very short and stocky and take up a much larger portion of the masses and voids than you would normally expect. This also then brings up another issue: the proportions between the super and substructure. Figure 4 shows this relationship very well: the substructure seems very heavy, while it is supporting this relatively slender and light appearing superstructure, which does not appear so logical.

![Figure 4 – Elevation[1]](image)
2.3 Order

Leonhardt proposes that there should be order in the lines and edges of the structure by limiting their directions. [9] Figure 4 and Figure 2 clearly show that Calatrava has made no visible effort to minimise the number of angles and lines used; resulting in a fairly complex looking structure, which may even seem confusing. He has used repetition in the shape and size of the main pier supports for the deck, which does provide some needed regularity to the structure.

Leonhardt also suggests that symmetry is an important function of order[9]; the structure is symmetrical in one plane, however this is then disrupted by the on plan skew seen in Figure 5. The result is the appearance of even more vertical cables as well as the lines of the different arches, which as Leonhardt put it “creates disquiet.”[9]

![Figure 5 – Plan](image)

2.4 Integration into the environment

The scale of the bridge in terms of the surrounding environment is very good: the peaks of its arches are not higher than the surrounding buildings, in fact they are actually substantially lower than some of the buildings. This is to be sympathetic to the intended low-lying park area that was to be created around the bridge and railway. It is important for this structure to link the communities. Calatrava has done this very carefully by not bracing the two primary arches with each other, which would have created a tunnel effect, but by leaving the space above the deck open as it were, creating a gateway between the two communities. Figure 6 almost gives the impression that you are crossing a traditional drawbridge, again enhancing this feeling of linking the two, once separated communities.

![Figure 6 – Crossing the Bach de Roda Bridge](image)

2.5 Surface Texture

The two materials used in the structure: steel and concrete are naturally opposite: steel is shiny and smooth and concrete is matt and rough. Calatrava has used smooth concrete, but with indented horizontal lines to give it a more uneven, if still ordered appearance, where as the steel remains smooth. He has only kept the concrete smooth where is forms part of the arch and in this way has defined these structures as special in a very subtle way. The steel has not been used in its typically shiny form, but has a matt paint on it, however due to its very nature it appears reflective to a degree and in doing so the difference to the concrete is again subtly highlighted.

2.6 Colour of Components

The contrast between concrete and steel is not continued with their colour: they have been closely matched to be the same white colour. White has been used to allow the structure to integrate into the surrounding building stock and infrastructure, which is typically Spanish: mostly white. Despite this it still manages to stand out against the background buildings, but not in an landish and ostentatious way. The white colour also allows it to stand out against the blue sky and the simple colour scheme allows the structure to ‘do the talking’ rather than allow colours to cloud the form.

Shadows have been used, by angling out the edge of the deck, to darken the underside edge beam (Figure 7) and the facia beam has been made shinier to give the impression that the deck is thinner that it actually is, by drawing the eye to the thinner facia beam and away from the chunkier soffit.

![Figure 7 – Use of Colour](image)

2.7 Character

How to define if a bridge has character is a question people have been asking since Leonhardt first suggested these guidelines. He suggests that it should have a “certain deliberate effect on people.” [9] Personally I see this as whether I am impressed or intrigued by a structure because it is something special and different. I can not see how this bridge can not have character: it plays with sculpture, engineering and architecture in a way that has rarely, if ever, been done before with such success. At the time, before Calatrava has built any other bridges, it was a completely new approach and produced a unique structure. Since building his other bridges, it has become part of a family of special bridges around the world. The locals call it “Calatrava’s Bridge” to me this is an affectionate name, which shows the way in which people view the bridge as not simply as a piece of infrastructure, but a core part of and icon with their city.
2.8 Complexity in Variety

It is often suggested that complexity and character are linked and I think that this is particularly true in the case of the Bridge of the Arts de Roda. A concrete beam bridge could have probably done the same job as the Bridge, however a complexity in design was needed in order to create character and hence the required icon that Barcelona desired. The complexity not only derives itself from the revolutionary canted arches and sculpted piers accentuating the line of the arch, but also from the way in which this bridge is truly designed to be viewed from any angle. The skewed arches mean that as you view the structure from a variety of angles your impression of the structure changes and you are allowed to fully appreciate it.

2.9 Incorporation of Nature

Despite first appearances this bridge has a form influenced by nature. Figure 8 shows Calatrava’s initial sketches for the bridge. You can see that the arch form and cantilevering side arches are derived from a simple fish shape, following from Barcelona’s relationship with the sea. This can be taken even further in the plan, where the tails of the two fish are used to give the plan shape of each arch system.

3 Structural Design

You may have expected Calatrava to focus purely on the aesthetics of the Bridge with his architectural background, however this is certainly not the case. With his excellent grasp of engineering principles Calatrava did not simply take a prescriptive approach to the task, but lived up to his European title Ingénieur and was truly ingenious in his design.

If we consider the central span of the bridge shown in figure 9, its composite steel and concrete deck shown in figure 10, is hung with steel cables from a steel arch. The deck also acts as a tie across the arch in order to eliminate horizontal loading being exerted on the tops of the piers. The cables also help restrict sway in the arch when it is unevenly loaded, using the dead weight of the deck on the unloaded side to counter the upwards deflection of the arch. The edge deck girders are quite deep in comparison to the arch, this is partly to do with the construction load case for the bridge, described more fully in (Section 1.1), however it has the advantage of reducing the bending moments within the arch. Due to the depth of the beam, the arch is therefore mostly used to take the additional actions created by the superimposed dead and live loads.

The primary arch itself is a fairly common, if not ancient concept, however, where Calatrava really started playing around with the concepts of statics was in the way in which he afforded them lateral stability. Commonly in arched bridges this is done with the use of a truss connecting the two arches. Due to the on-plan skew of the arches this would have looked very messy and created the ‘tunnel’ feel described in (Section 2.4). In order to provide lateral stability against buckling for these arches Calatrava devised two outer cantered arches which resist any lateral loads, as shown in Figure 11. This is a very simple and ingenious solution, which allowed the top of the bridge to be clear of structure and open to the sky above. The arches also provide the boundaries for the pedestrian walkways required to link the two areas, their curvature also providing a large area to pause and appreciate the view of the city.

Loads are transferred from these arches to reinforced concrete piers, which are themselves slightly angled to match the profile of the arch. The approach spans of the bridge, a typical section of which is shown in Figure 12, are constructed with prefabricated, post-
tensioned concrete box sections supporting the same composite steel beam and concrete deck. These have been chosen due to the small spans between piers and also they provide a low profile bridge, allowing the arches to be highlighted in the design.

![Figure 12](image)

**Figure 12** – Typical section through approach span [1]

Calatrava has been careful not to hide any connections. Figure 12 shows how he has fully exposed the pins of the arch and cable hanger connections, refining them to their simplest form. You can even see in Figure 13 where the web-stiffeners on the deck edge girder have been left exposed to completely show off the how the structure works. This also relates to the fulfilment of function described in section 2.1, in the honesty Calatrava has used in his design.

![Figure 13](image)

**Figure 13** – Connection Photograph

4 Refinements

The refinements in this bridge are partly what make it unique, consequently the most obvious refinement to the design is the inclusion of the cantered arches to provide lateral stability to the primary arches. This was a new concept in terms a bridge design, which has worked, I think, very successfully. There are also a number of other more subtle refinements to the design, such as hiding the deck edge beam behind the parapet. Figure 14 shows this more clearly, you can see how the deck is supported from the bottom flange, this helps ‘lose’ the depth of the beam, but also has advantages for restraint of the girder from buckling. By accommodating a larger edge girder, Calatrava was then able to increase the slenderness of the arch as described in Section 3. Figure 5 highlights another clever detail, one which will not be appreciated by most people: the secondary beams supporting the deck slab beams have been designed to be parallel to the railway lines. This is a refinement which would have saved both time and money during construction, as it meant that all of the beams were the same length.

The final refinement for this Bridge is probably the most important: the use of a single designer, who was both architect and engineer, allowed this project reach its full potential and be so successful. The approach of Calatrava from an architect’s and sculptor’s perspective, meant that the form was not restricted in anyway and his innovative engineering approach only helped to compliment the design further.

![Figure 14](image)

**Figure 14** – Simplified Edge Girder and Parapet Detail

5 Loading

The Bridge will have been designed to Spanish loading criteria (reference [12]), however this assessment will be to BS 5400-2:2006 [13], which will follow similar principles. A wide variety of loads will have been considered in the design: dead, superimposed dead, live traffic, wind and temperature loading; combined with a variety of load cases. Loads will be factored according to, not only the load case, but also depending on whether it is serviceability limit state (SLS) or ultimate limit state (ULS). This is done using equation 1.

$$F_d = F_k \cdot \gamma_{fl} \cdot \gamma_{f3}$$

Where $F_d$ is the factored design load; $F_k$ is the characteristic load, $\gamma_{fl}$ is the partial load factor & $\gamma_{f3}$ is safety factor to allow for inaccuracies in analysis. Values of $\gamma_{fl}$ are obtained from Table 1 in BS 5400-2[13], and these vary depending on the load case. Values of $\gamma_{f3}$ are obtained from either BS 5400-3,-4 or -5, depending on the material used. In this case: for steel reference [14] defines $\gamma_{f3} = 1.10$ for ULS and $\gamma_{f3} = $ for SLS. In this paper design loads will be calculated for the ULS, to give an estimation of the maximum permissible load on the structure.

Under BS 5400-2, bridges are then checked for a variety of load combinations, very often designs for large bridges will also have a number of other combinations which designers will check, but the five required ones are listed in Table 1.

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<tr>
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<th>Permanent loads plus primary live loads</th>
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<tr>
<td>2</td>
<td>Comb 1, plus wind and temporary erection loading</td>
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<tr>
<td>3</td>
<td>Comb 1, plus temperature and temporary erection loading</td>
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<td>4</td>
<td>Permanent loads, plus secondary live loads and associated primary love loads</td>
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<tr>
<td>5</td>
<td>Permanent loads plus loads sue to friction at supports</td>
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Table 1 – Load Combinations [15]
5.1 Dead and Superimposed Dead Loads

Dead load is the self weight of the bridge and its structure, where as superimposed dead load is all that has been added on, such as parapets and asphalt. With the limited detail provided on Figure 10, the bridge dead load is assumed equivalent to 4.3kN/m² or 112.3kN/m. The equivalent superimposed dead load is assumed to be 0.86kN/m² or 30.3kN/m.

5.2 Vehicular Loading

The bridge is likely to have been designed to Spanish Norma IPA-98 [12], which simply applied 4kN/m² across the whole bridge as well as six 100kN point loads in three axles of two wheels measuring 0.2m x 0.6m [12]. BS 5400 takes a different approach and vehicular load is split into ‘normal’ loading: HA loading and ‘exceptional’ loading: HB loading. The bridge is then split into notional lanes, as defined by clause 3.2.9.3, the number or size of which do not necessarily correspond with the actual number of lanes. In our case, the bridge has five notional lanes, despite only having four in real life. There are a number of load cases with combinations of the two types of loading, these are defined in Figure 13 of BS 5400-2. Two notional lanes are loaded with full HA loading, whilst the remaining lanes are loading with one third of the full HA loading. HA loading is then dependant on the length of the bridge, and this is defined in Table 13 of BS 5400. Knife edge loads (KELs) of 120kN across the lane are then applied at the position on the bridge as to create the most onerous case. HB loading is typically 30 units, where each unit is equivalent to 10kN per axle, where there are four axles in contact with the bridge at varying separations: 10, 15, 20, 25 & 30m, in our case the 10m separation would give you the most onerous sagging case if placed at the centre of the span.

5.3 Pedestrian Loading

By BS 5400-2 Clause 7.1.1, due to the length of the bridge the pedestrian loading can be reduced as defined by the following equation:

\[ F_{dped} = k \times 0.5kN/m^2 \]

where \( k = \frac{\text{nominal HA UDL} \times 10}{L + 270} \)

\( F_{dped} = 3.90kN/m^2 \) (3)

I suspect, however, that this is lower than the bridge was actually designed for. Under BS 6399-1 an area where people may congregate, such as a public balcony is defined as a C5 area and has a loading of 5.0kN/m². As Calatrava designed these parts of the bridge for people to stop and appreciate the views from the bridge, I believe this is a more accurate loading considering the conditions. In fact, is it also the loading applied to bridges of less then 36m in length under BS 5400-2.

5.4 Accidental, Breaking and Acceleration Forces

Again under BS 5400-2 these forces can be simplified. Under accidental vertical loading should be given by Figure 14 in BS 5400-2 or an equivalent force to apply a 1.1N/mm² load on the bridge deck. The bridge supports must be designed to withstand a lateral force from breaking and acceleration forces, the worst case is taken of either 8kN/m plus 250kN or 25% of the total applied HB loading. In the case of this bridge, the 8kN/m with the additional 250kN gives a much higher load: 618kN than the 25% HB loading, which is only 300kN.

5.5 Vehicle Collisions & Parapet Loading

The parapets of the Bach de Roda bridge are not conventional in design, by any means. Typically a bridge will have specifically designed parapets designed to resist vehicle impact. The Bach de Roda bridge uses the remaining part of the deck edge girders, which protrude out of the deck, as shown in Figure 13, as parapets to resist vehicle impact. In order to assess their suitability, I applied the typical impact loading [13]: 25 units of HB loading (250kN) over the span suggested in BS 5400-2: 4.5m. Simply analysing as a point load applied to a fully fixed beam, equation 4 yields a deflection of 193mm. In general this sort of deflection is quite acceptable considering the loading applied to the parapet and typical deflections of other parapets under collision loading, which can be as high as 380mm.

\[ \delta = \frac{PL^3}{192EI} = 0.193mm \] (4)

This deflection, however, would leave a substantial plastic deformation in the girder. In my opinion, this is unacceptable, as it is a key structural member and the deformation will affect its capacity. There is also then the issue of repair, as it is a continuous member, repair to this girder will be very difficult, expensive and would require substantial works and disruption to the rail lines below.

There is also the issue of the parapet’s height, as it is only approximately 500m above the road level, this may just stop a car, but any HB type vehicle may jump the parapet. This then requires the parapet on the pedestrian walkway to provide some resistance to an impact loading, although, this would be reduced from the full 25 units of HB loading, as some energy will have been dissipated by the girder. For the vehicle to do this though, the deck suspension cables will have to have been broken. The cables will also provide some resistance to collision, before they break. More concerningly, they pose a real risk of very serious injury to the occupants of the vehicle if the velocity of the vehicle is such that they act like cheese wires and also do not yield, they may slice through or part of the way through the vehicle. Finally, if they do yield and fail, this would compromise the composite action of the
deck girder and the arch, causing the girder to be stressed even further. This may cause plastic deformation or even failure, if not fully considered in design.

5.6 Wind Loading

The bridge has been analysed for wind loading using a basic calculation method from BS 5400-2 and reference 15. Assuming the wind speed to be approximately \( v = 30 \text{m/s} \), due to its coastal location, effects due to tunnelling may occur due to the alignment with the grid of Barcelona’s city plan mean \( S_z = 1.1 \). Assuming \( S_y = 1.07 \) & \( K_z = 1.59 \) then \( v_c \) is given by equation 5 and the corresponding horizontal force \( P_h \) is given by equation 6, where the area of elevation, \( A_e = 3.7 \text{m}^2 \), \( q = 0.613v^2 \) & \( C_D = 1.3 \).

\[
v_c = vK_1S_1S_2 = 56.1 \text{m/s} \quad (5)
\]

\[
P_h = qA_eC_D = 9.23 \text{kN/m} \quad (6)
\]

The vertical wind loading \( P_v \) can then be calculated using equation 7 where the plan area per m length, \( A_p = 35 \text{m}^2 \) and the coefficient of lift, \( C_L = 0.35 \).

\[
P_v = qA_pC_L \quad (7)
\]

The result seems very high initially when compared to the horizontal force, this however is due to the width of the bridge compared to its span: its span is 46m and its width is about 35m, which increases its lift force quite dramatically. This would therefore need to be considered in design of the bearings and connections to the abutments, and in its relation to the natural frequency of the bridge, which as Section 12 shows is quite low.

5.7 Seismic Loading

Although seismic loading is considered in some parts of Spain, due to it proximity to the African and Eurasian plate boundaries, I have assumed that no special seismic loading case has been considered for the Bridge. For the frequency and magnitude of the earthquakes in the area, realistically the existing load cases and safety factors applied to the structure would provide adequate resistance to minor tremors.

6 Temperature Effects

Due to the potential for large temperature variations in Spain, I have considered the effect that temperature variation has on the main edge beam. I have assumed a typical summer variation in temperature, after a very hot day, with the soffit cooling much more rapidly at dusk. Assuming \( \alpha = 12 \times 10^{-6} \) and \( E_{\text{steel}} = 205 \text{GPa} \), equations 8 & 9 yield the results shown in Figure 15.

\[
e_v = \alpha \Delta T \quad (8)
\]

\[
\sigma = E\varepsilon_v \quad (9)
\]

Using simple bending theory and the average stress, \( \sigma_{av} = 43.05 \text{N/mm}^2 \), we can equate this stress to an applied additional bending moment due to temperature:

\[
M_{\text{bT}} = 349 \text{kNm}.
\]

This is certainly a noticeable portion of the moment capacity of the component and highlights how important it will have been to consider these effects in the design of the bridge and loading conditions shown in Table 1.

7 Creep

The main part of the bridge is of a steel construction: so creep effects can be considered negligible. The concrete box section edge beams will have an element of creep, which will create larger deflections than predicted through strength analysis; however, due to the small spans between piers, these will be small.

8 Strength

The Bridge will have been designed to the Spanish design codes, including “EA-95-Steel”[16], which is a permissible stress code. My assessment, however, will be to BS 5400, where similar principles are used. For these basic strength assessment calculations, this paper assumes only UDL HA loading is applied to the road and 5.0 kN/m over the walkways, as defined in section 5.3, shown in Figure 16 below.

\[
F_{d} = 181.7 \text{ kN/m}
\]

Figure 16 – Typical Bridge Loading

This paper will assess the member stresses of the central arched span.

8.1 Arch

Worst case loading is over half the arch, equation 10 shows that this yields an extremely high moment of 6007kNm. The section, shown in Figure 17, is approximated from drawings provided in reference [1]. Its I value is approximately 8.40x10^8 m^4, resulting in a
stress of about 295N/mm² (Equation 11) in the extreme fibres of the member, which is within acceptable limits if a grade S355 steel was used.

\[
M_{\text{max}} = \frac{wL^2}{64} = 6007kNm \tag{10}
\]

\[
\sigma = \frac{M_y}{I} = 295N/mm^2 \tag{11}
\]

![Figure 17 – Arch member section](image)

8.2 Edge Beams

The resulting horizontal tie force from the arch acting on the edge beam, as shown in Figure 9, can be calculated using equation 12, the resulting stress in the member can be shown (equation 13) to be 148N/mm².

\[
H = \frac{wL^2}{8k} = 5340kN \tag{12}
\]

\[
\sigma = \frac{H}{A} = 148.3N/mm^2 \tag{13}
\]

The resultant stresses from the loading of the deck, must then be added onto the axial stress. These can be calculated from assuming that the beam is simply a continuous beam over supports. Due to the short spans, we find that the resulting maximum moment is only about 85.6kNm in hogging, resulting in an additional stress of 10.6N/mm². The final stress therefore is about 159N/mm², which is again well below the threshold, but account will also have to be taken for the aforementioned temperature effects as well as localised reductions in strength due to welding. This continuous design also allows the provision for the RC deck to remain continuous over the support cables and then develop concrete plastic hinges at these points, increasing capacity of the deck further.

8.3 Cables

The tension in the cables can then be derived from the support reaction of the analysis of the deck as a continuous beam. Assuming that the steel cables are 20mm diameter and that they are designed to be just a single cable, and are only doubled for redundancy, then the expected stress in each cable will be 890N/mm². Although this seems very high, it is well within the permissible limits of a high-tensile steel cable.

9 Serviceability

Due to the large width of the bridge, the vertical wind uplift exerted on it is quite large. In order to minimise this, the edge of the deck has been profiled, to make the bridge more aerodynamic. The result of this is that for the wind to pass under the bridge it has to travel further than across the top, working in the same way as an aircraft wing, but in reverse, this creates a down force, which reduces the effects of the uplift.

10 Foundation Design & Geotechnics

Barcelona is built at the mouth of two rivers and on a flood plane. This has created large quantities of sands, gravels topped with alluvium. Figure 18 below shows a geological map of the area, the location of the bridge is shown with the orange dot. The ground conditions are described, in Catalan, as “Plana alluvial, graves, sorres i lutites Holocé Superior”, translated as a quaternary layer of mudstone overlaid with sand, gravels and a layer of alluvium. Much as you would expect from an area with two rivers in close proximity.

![Figure 18 - Geological Map of Area [17]](image)

The tied arch means that any horizontal forces in the plane of the arch have been accommodated. The piers therefore only have to sustain the vertical load of approximately 2100kN each as well as any lateral forces exerted on the bridge, such as wind effects, as the sliding bearing will resist movement of this bridge in this plane and therefore exert a horizontal force on the piers and in turn the foundations. The ground conditions call for piles, most of their capacity will be achieved in end bearing on the mudstone, with the limited capacity of the sands and gravels. In order to carry the expected loads, pile groups of about four 800mm diameter piles would be typical under each pier. Piles will be a bored pile, to provide the ability to drill through any larger boulders in the old flood plane, because driven piles may kick out. Bored piles, such as CFA also induce much less vibrations and create less noise than driven piles for the surrounding residential area. The canted arches exert some horizontal forces, therefore ground beams linking the two outer pile groups have been provided to ensure that these horizontal forces are not taken by the piles.

11 Construction

An arched bridge was not only selected for its aesthetic qualities, but also for its ability to span large distances without internal supports. This quality was also important during construction. The railway the bridge spans had to remain in use during most of the construction. In order to do this Calatrava designed the
edge deck beam to support the dead weight of itself during the construction stage. This will have been
designed to ULS, ignoring SLS conditions; it is this
which has caused the large depth of the edge beam.
The construction therefore can be classified as a pre-
fabricated beam and in-situ slab construction.
Following the construction of the deck, which will
have been completed by welding together pre-
fabricated edge beam sections supported on temporary
trestles, the railway was able to be re-opened. The
arches were then constructed in three sections, as
shown in Figure 19 and supported with temporary
props on the deck and edge beam (Stage 4), shown in
Figure 20. This forcework was all kept at deck level
and above, to ensure that the railway was kept open.

\[
f_0 = \left(\frac{\beta_n l}{\sqrt{m_l}} \right)^2 = 4.81 \text{ Hz} \quad (14)
\]

This value is unacceptable, however this is most
likely due to the assumptions made in the calculations,
as it is very close to 5Hz. If a more complete analysis
was carried out, where the full deck and bridge
construction, member sizes and fixities were fully
known then this value would, no doubt, increase.
However, due to its lightweight steel construction, the
natural frequency will be quite low, which is therefore
a point of consideration during design.

13 Durability

Large bridges in the UK are designed for a 120
year lifespan. This bridge will have probably had a
similar requirement. Its reinforced concrete is very
durable and with extremely rare use of de-icing salts in
Barcelona, this should improve the durability
considerably. The steel has been painted for aesthetic
reasons, but this will conveniently provide a corrosive
resistant barrier, ensuring that its durability is good
also, providing it is maintained. However it should be
considered that Barcelona is in a salty atmosphere, due
to its proximity to the sea, and this salty air will
accelerate corrosion of the steel compared to an inland
bridge. The steel structure has also been left exposed,
apart from where it is in contact with concrete, this
allows easy inspection and maintenance. Maintenance
has also been considered in providing two steel cables
at each hanger giving redundancy, should one need
replacing.

14 Vandalism

Due to the nature of the area and the location: over
a railway and in parkland; the bridge was and is a
prime target for vandalism. Guards have been put in
place to stop people being able to get onto the arches.
However the major problem is graffiti, Calatrava made
no special provisions to prevent this happening.
Subsequently the piers, abutments and stairs have been
covered in graffiti, as the cover makes it a prime area
for people to congregate.

13 Future Changes

The Sagrera Park, of which the bridge defines the
start, is due to undergo another huge urban
regeneration part of a project costing some €1.8 billion
[18] to provide a high speed rail link between La
Sagrera and Nus de la Trinitat. This involves putting
large portions of the track underground. The plans
would in fact render the structure obsolete, however the
park’s masterplan includes the bridge, which is kept
intact and modified to include a glass done below it to
cover the new high-speed track. [19] This ensures that
the bridge’s iconic status is not lost, but in reality may
be enhanced as the area is regenerated. Calatrava originally designed the structure to be part sculpture and so in the future it may in fact take on this role more fully.

15 Suggested Improvements

The bridge has been extremely well refined, however there are a few improvements which strike me as possibilities. Firstly is the application of anti-graffiti paint on the concrete surfaces which have been covered in graffiti, this is a very simple, but unfortunately expensive solution to the problem. The second improvement is also aesthetic: I would like to express the outer canted arch from the inner arches by changing their colour to show that they have a different function. Provided the correct colour is chosen, this would also really express the bridge against the background landscape, as well as highlighting the shape of the arch.

The final improvement is to consider the use of the edge girder as the parapet and collision barrier for vehicles. Without looking at the original design calculations for the bridge, cannot say confidently that the girder would remain serviceable after such impacts. I believe that it would not and that, although a neat solution to the problem and aesthetics of an Armco barrier, it is not suitable and the potential risks are too high. Therefore I would look to integrating an Armco barrier or specifically designed component to be retrofitted to the bridge to resist or reduce this impact loading, rather than simply relying on the edge girder.

16 Conclusion

Calatrava’s first bridge was a great success on architectural, engineering and sculptural levels, launching him to worldwide recognition for his talents as a designer. Even with the possibility of the bridge no longer being required, it is testament to Calatrava that the city planners want to keep this bridge as a sculpture in its own right. Maybe bridge aesthetics has found its holy grail in Calatrava?

References

[7] Calatrava, S., Quoted by Alan Sibbald, School of Engineering and the Built Environment Napier University (Edinburgh), Chairman’s Address: Edinburgh and East of Scotland Association Institution of Civil Engineers, Why build bridges?