A CRITICAL ANALYSIS OF THE PONT ALEXANDRE III BRIDGE, 8TH ARRONDISSEMENT, PARIS

V. J. Stephenson[1]

[1]*Undergraduate Student – University of Bath*

Abstract: This paper offers a detailed study of the aesthetics, design, construction and lifespan of the century old Parisian steel arch bridge known as the Pont Alexandre III. Assessment is initially undertaken of the aesthetics, followed by analysis of the structure, the loading and the serviceability of the bridge. Particular focus is given to the implications of the age of the bridge, the shallow nature of the arch and impact this has on the foundations, and the precedential construction methods used.

Keywords: *Paris Expo 1900, Pont Alexandre III, shallow arch, deep foundations, pre-fabrication*

1 Introduction

The 1900 World Exposition held in Paris was intended to celebrate the achievements of the last century in areas such as architecture, engineering, science and technology. Several of Paris' famous structures were built for the exposition, including the Musee d'Orsay, the Grand Palais, and the Pont Alexandre III bridge, required to enable the some 50 million visitors to cross the River Seine.

The design chosen was that of the architects Joseph Cassien-Bernard and Gaston Cousin, it being constructed in only two years by the engineers Jean Resal and Amedee d'Alby. The structure is a three-hinged single steel arch with a main span of 107.5m and total length of 160m. The 40m wide deck supports a road system and the abutments are formed of two masonry viaducts, through which run additional roadways.

A key requirement of the design was that it did not obstruct the view along the Invalides and Champs Elysees, the result of this being a very low bridge, only 6m in height, supported by a very shallow arch with a span to depth ratio of 1/17. The arch is constructed of 15 parallel ribs, each with 3 articulation points made up of cast steel voussoirs bolted together. The ribs are braced and connected using a series of steel struts.

The design encompasses a large amount of supplementary ornamentation along the deck and at the abutments.

2 Aesthetics

This paper utilises in its analysis the ten point framework offered by Fritz Leonhardt in his seminal work 'Bridges: Aesthetics and Design'. Whilst it must be noted that aesthetics and their success are a somewhat objective topic, the opportunity given by this framework to develop some level of subjectivity should not be overlooked.

The first of Leonhardt's criteria is that of fulfilment of function; addressing how the bridge communicates its structure. A structure that is honestly and simply demonstrated is generally considered to be the most aesthetically pleasing to the eye. Removal of unnecessary components and lack of superfluous ornamentation, that does not provide any addition to the structure, supports this.

The Pont Alexandre III is possibly one of the most ostentatiously decorated bridges in existence and on the surface would appear to greatly lack any clear fulfilment of function. However closer analysis serves to demonstrate a more complex design, composed of two key elements; a core structural arch that is both simple and fluid, and a "frosting" of other components.

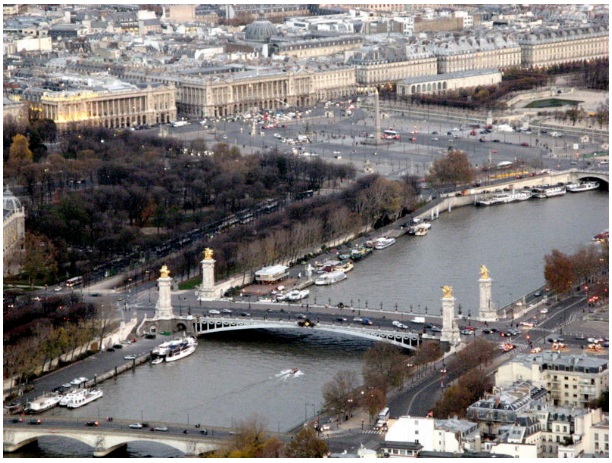
The bridge provides a highly symbolic representation of the political situation at the time; the first stone was laid in 1896 by Tsar Nicolas II of Russia and the bridge was dedicated to his father Alexandre III, moves that demonstrated the strength of the existing Franco-Russian alliance. The decoration of the keystones with beaten copper compositions of Nymphs of the Seine and Neva, bearing arms of Paris and Russia, also symbolise this relationship.

The time at which the bridge was designed is also important. At the turn of the last century the Art Nuvaue movement was influential in all forms of design, not least architecture, and this is clear to see here. The bridge is ornamented with extensive statues and facia pieces designed by influential French artists, so many so that this has often led to criticism in the past of its heterogeneous nature.

The bridge is flanked by four 17m high pillars at its entrance and exit, each topped with a bronze statue representing Pegasus held by Fame. The feet of these pillars hold four groups of water spirits with fish and seashells. The corners of the bridge also house four monumental candelabra surrounded by cupids and sea monsters.

This decoration is without doubt intended to impress the masses with its splendour, but this bridge manages, rather unwittingly perhaps, to impress through its structural form also. The line of the arch is naturally accentuated by the river beneath it and the viaducts that sit above the abutments serve to clarify the nature of the supports, whilst also integrating the surrounding infrastructure and the bridge.

The fascia to the bridge makes careful use of Colour, another of Leonhardt's framework components. The main structural arch and struts are white which when situated in front of the dark underside of the bridge serves to highlight the workings of the structure. Elsewhere colour and texture are formed from the use of natural materials such as stone, iron and bronze, and generally suit the environment very well. This is partly due to the location of the bridge and its proximity to other buildings designed for the 1900 Expo with the same architectural influences. The age of the bridge also brings into consideration the effects of weathering and decay. Here this has had little impact with the masonry being in good order throughout, although a little discoloured from pollution.



Proportion is another fundamental factor that Leonhardt considered. The proportions of this arch are of great importance historically, with the lowering of an arch to that level very rarely having been seen before. The slender nature of the bridge does almost pull it out of proportion, to the point where it could be questioned how the bridge remains standing. The deck is also unnaturally slim, and appears to disappear altogether in the centre. This delicate framework to some level leads to the abutments and associated pillars appearing too large and unrefined in comparison.

As a whole though the bridge is a success when considering proportion and this is reflected in the issues of Character and Complexity, also included in Leonhardt's considerations. The ability of a structure to intrigue and excite can add to its charm, and this is certainly achieved here through this bridge's slender, almost tape-like proportions, and wide, flat profile. Too much complexity however will prove detrimental; this can be avoided by ensuring that there is no excess of redundant members used in the design, or elaborate detailing to the structure without good cause. This particular bridge requires delicate analysis of this point because although there is extensive detailing to the bridge, which may at some level over-complicate the aesthetics, the core structural form remains ascetic.

The creation of Order in the design is also instrumental in a bridge's success, and this is a factor that takes into account the multiple angles at which a bridge can be viewed. A multitude of lines that tangles up the profile of a bridge will work against it aesthetically by breaking the fluidity that a bridge structure naturally promotes. Such fluidity is demonstrated to great success with the underside of the Pont Alexandre III and the line of the arch is a strong and powerful statement.

The deck is less successful in that the numerous lampposts and candelabra along the parapet serve to clutter up the strong horizontal profile of the bridge, weakening it slightly. The relative smallness of the posts when compared with the span of the bridge does work to limit this impact however.

Integration into the Environment is considered by Leonhardt to be instrumental in successful aesthetics and here there are both positive and negative points to consider. The almost whimsical nature of the design of the bridge structure and decoration undoubtedly fits with the Art Neuvaeu inspired Exposition monuments. The largely horizontal profile of the bridge does also compliment the low-rise nature of the immediate built environment, and the wide sweep of the river beneath.

In this respect the bridge is a great success, however the very choice of an arch structure has to be considered as poor. Arches are best suited to valleys or gorges where the substantial horizontal forces can be supported without the need for large abutments. This bridge, with its particularly shallow arch and subsequently particularly large horizontal forces demonstrates this perfectly as the abutments and foundations here are enormous. This undoubtedly caused significant difficulty during construction, with corresponding cost, safety and time implications.

Refinement of design and the Incorporation of nature are the final components of Leonhardt's framework. The incorporation of the viaducts into the bridge abutments signifies a considerable level of refinement and works to accentuate the bridge's integration with its surroundings. Incorporation of nature is less apparent in this structure, although it is also less relevant.

In summary the Pont Alexandre III is a bridge of two halves, on the one hand a very fluid arch form is used successfully, although above this extensive and ostentatious decoration has been liberally applied in a manner that does not serve to compliment the inherent simplicity of the structural components.

Structure and Materials

The Pont Alexandre III bridge is fundamentally a steel arch, supporting a series of bracing members and above this a deck. Until around 1860 steel was expensive to produce and as such was only made in small quantities, with all large metal structures being constructed of wrought or cast iron. The introduction of the Bessemer and open-hearth processes allowed for the production of cheap steel to become commonplace. After 1890 the Bessemer process was gradually supplanted by open-hearth steelmaking, which originated in Germany and culminated in the development of the Seimens-Martin process in France, which allowed for closer control over the composition of the steel being produced.

Parallel development to that in Britain took place across Europe, although continental steel makers did not in general match up to the qualities achieved by the UK and lower strength values should be applied. Continental codes of practice and design specifications closely related to the manufacturing developments, and this should be kept in mind.

At the time of construction it was common for sizes to be decided upon by the manufacturer, usually to meet customer requirements. Manufacturers produced catalogues giving dimensions, and often design properties of the various sections they produced. Those members manufactured in France at the turn of the century were standard continental sections in production from a very early date.

Determining the quality of the steel is difficult, but the high profile nature of this structure with its political implications means it is likely high quality steel sections were used. The age of the structure means that obtaining an exact technical specification is not easy, but research combined with well-informed assumptions allows for a relatively accurate detailed analysis to be carried out. Unfortunately technical data for French steel members was not available, but a suitable correction factor applied to British values of the time can be applied. The following data is obtained from Ref. [2]. British values of 1879 give the Ultimate Strength of Mild Steel as 494N/mm^2 in tension, 463 N/mm^2 in compression and 371 N/mm^2 in shear. Applying the recommended factor of safety of 4 gives allowable stresses as 108 N/mm^2 in tension, 116 N/mm^2 in compression and 93 N/mm^2.

Some other general considerations must also be taken into account when analysing an old structure with modern design principles. Old steel cannot be used with the high stresses permitted today without a detailed analysis of the material being undertaken. Current conclusions from research would suggest that early structures were under-designed for the effect of wind loading, however it should be appreciated that such structures were far more robust than modern ones. Modern practices for imposed loading can be applied. An increase in knowledge means that most requirements have been reduced from those used in the past.

Fabrication and Construction

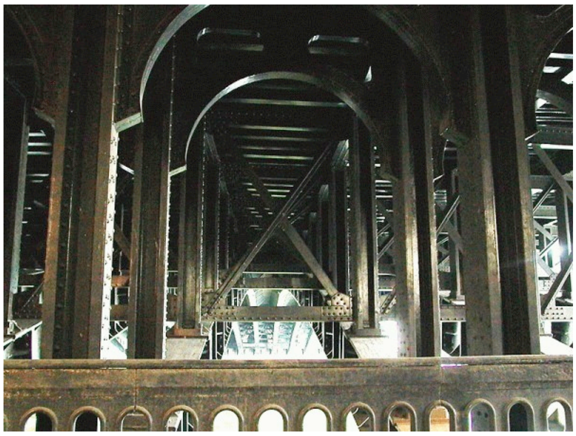
The steel components were founded and forged at a factory in Le Creusot, a traditional stronghold of the French steelmaking industry, currently dominated by ArcelorMittal, the largest steel manufacturer in the world. It is feasible to suggest that this steel was produced using the open-hearth process, due to the steel being of French origin. This is also supported by the British Standard guidelines of the time, which suggested that steel used in bridge construction must be produced by the open-hearth process.

The fabrication of the bridge is a good example of the advancements taking place in the construction industry at the time. Up until the end of the 19th century steel members had been used only when supported on brickwork, with intermittent columns used to split spans. There was no interconnecting other than simple bolting to hold members in position.

The development of wholly steel framed structures that made use of extensive bolting and/or riveting to hold a detailed array of members in place was current at the time of this bridges construction, and the Pont Alexandre III is a particularly exquisite example of this.

These pre-cast members were then transported to the bridge location on barges and bolted together in-situ. The construction made use of a large crane covering the width of the Seine, with the erection centres being suspended from overhead trusses so as not to obstruct the river.

The underside of the bridge and the complex nature of the steel work are shown in the following images:



The structure encompasses 15 arch ribs, connected to each other and the deck through a series of bracing struts. There are three hinges along the length of the arch, one at each abutment, and one at the apex. The arches are mounted on steel cushions at the abutments, so as to compensate for expansion and contraction of the structure. The shallow nature of the arch induces very large horizontal forces at the supports and this has led to the requirement of very large foundations, and subsequently the use of pneumatic caissons in their construction.

Foundations

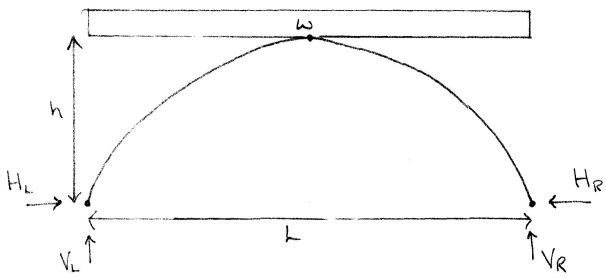
Paris sits in the central portion of the geological region of France known as the Paris Basin, constructed of beds of sedimentary rock, which in the central section is composed of mainly Tertiary rocks, mostly limestone's. The standard suggested safe bearing capacity for this type of rock is approximately 2500kN/m^2.

The use of pneumatic caissons was common at the time of this bridges construction as the dangers of caisson disease were not yet influential enough to have warranted their demise. Caissons are large structures used in the construction of underwater foundations, being preformed above ground and then sunk during the construction process before becoming an integral part of the foundations themselves. Pneumatic caissons are often used in difficult subsoil conditions where the pressurised lower working chamber provides a safe dry working area for the excavation of material. The Pont Alexandre III caisson was of steel construction with dimensions 33.5m by 44m, with the 44m parallel to the width of the bridge. The base of the right bank caisson is at a depth of 18.75m and the left bank at 19.4m.

It is likely that the walls of the caisson were of corrugated steel plate, hollow to allow for the addition of concrete to provide weight during sinking. The caisson is open at the top and bottom (beneath the working chamber), with a cutting edge at its base to aid in it's sinking. Once at the required depth the caisson is filled with concrete and becomes the abutment foundations to the bridge. It is this mass that is required to withstand the horizontal forces in the structure.

Structural Analysis

The structure is to be analysed as a three-pin arch. It is favourable for arch structures to withstand only axial compression loading, but this is rarely the case, and the shallow nature of this arch requires the analysis of the structure in bending also. Basic analysis shows the reactions at the supports to be as follows:



$$V_L = V_R = \frac{wL}{2}$$

TAKING MOMENTS ABOUT THE APEX:

$$\left(\frac{wL}{2}\right)\frac{L}{4} + \left(H_R \cdot h\right) = V_R\left(\frac{L}{2}\right)$$

$$\frac{wL^2}{8} + H_R \cdot h = \frac{wL^2}{4}$$

$$H_R = \frac{wL^2}{8h}$$

For the given values of w, h and L, when the moment in the arch is equal to zero at all points along the span, the line of thrust is shown to be located within the structure. This is the ideal scenario as it is then that no bending will be induced.

Ref. [3] states that if a three-pinned arch takes up the shape of the bending moment produced for a horizontal beam of the same span, with the same loading applied, then no moment will result and the force line and the member will be coincident.

It can be seen that for the above statement to be upheld the structure will need to be parabolic in shape. However the loading cases which will be dealt with here will prevent the coincidence of force line and member shape from being possible as they include the application of partial UDL's and concentrated non-central loads, for which the bending moment distributions will not be parabolic.

Loading

The Pont Alexandre III predates any British Standard design manuals, and as such this is likely also to be the case with regards the French equivalent. Here analysis will be carried out using application of BS 5400 and the current Eurocode manuals, more specifically BS EN 1993-2 Design of Steel Bridges, and BS EN 1991-2 Traffic Loads on Bridges.

The loads that are required for consideration include dead, super-imposed dead, live and wind, along with temperature effects and impact loading. Eurocode guidelines consider four separate live traffic load models, which are combined in various ways so as to provide a series of load cases against which the structure is checked.

Every characteristic load applied to the structure is factored by the partial load factors γ_{fl} and γ_{f3} to obtain the design loads, where $\gamma_{f3} = 1.1$ for all ULS cases, and 1.0 for the SLS design. The values of γ_{fl} vary depending on the load case being examined.

Dead and Superimposed Dead Loads

Study of the layout of the underside bracing combined with an estimation of the deck construction allows for the total dead load of the deck and bracing to be conservatively estimated as $10kN/m^2$. The self-weight of each rib of the arch is approximately 2.5kN/m. Additional loading from the stone parapet and iron ornamentation can be conservatively estimated as 10kN/m for each side of the bridge. For dead loads γ_{fl} = 1.05 at the ULS, and 1.00 at the SLS. Superimposed dead load, which are comparatively negligible, apply the factors of γ_{fl} = 1.75 at the ULS and 1.20 at the SLS.

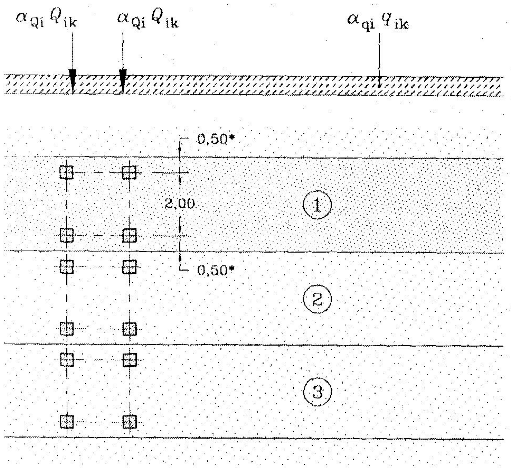
Vehicular Live Loading

Eurocode design applies the theory of notional lanes whereby the carriageway is split into a series of lanes of width 3m, with any additional width being considered separately. The deck on this bridge is unusual in that its 40m width is split into four relatively even sections, the inner two being the carriageway and the outer two making up the pedestrian promenade. Such a large pedestrian area makes crowd-loading considerations particularly important.

Here the 20m wide carriageway can be split into six notional lanes with an additional area of width 2m. The lanes are numbered in order of the favourability of the effects of the loads, with Lane 1 being the most unfavourable.

Live Load Model 1is the general load case used in the initial design and is a combination of both concentrated and uniformly distributed loads. It consists of two partial systems, a double-axle concentrated load system (TS) in which each axle holds weight of α_Q x Q_K, where α_Q are the adjustment factors, and a UDL system where the weight per square metre of notional lane is equal to α_q x q_k, where α_q are adjustment factors also. The TS should assume that the load on each axle is split between two wheels, each with square contact surface of side 0.4m.

Diagrammatically this is represented as follows:



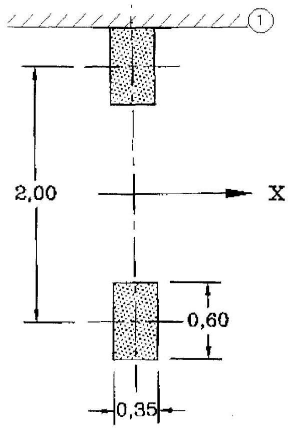
This load model should be applied to all of the notional lanes and the additional area. In the absence of specification of the factors α they should be given a value of 1.00. Values of Q_K/q_k are given in Table 4.2 of Ref. [7] are as follows:

Lane No.	TS	UDL
1	300 kN	9 kN/m^2
2	200 kN	2.5 kN/m^2
3	100 kN	2.5 kN/m^2
Others	0 kN	2.5 kN/m^2
Remaining Area	0 kN	2.5 kN/m^2

This all combines to give a general characteristic loading for the Pont Alexandre III of a 600kN point load and 79.5kN/m UDL. The worst-case scenario is when the point load is in the centre of the span.

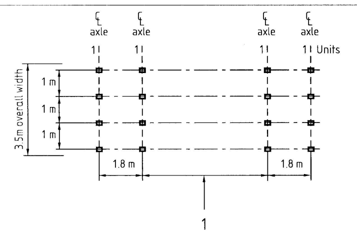
A factor of γ_{fl} = 1.50 is applied to these loads at the ULS when they are considered independently, and 1.25 when considered in conjunction with wind or temperature effects. The values are 1.20 and 1.00 respectively at the SLS.

Live Load Model 2 covers the placing at any point on the carriageway of a single axle load of value $\beta_Q Q_{ak}$ where β_Q = 1.00 and Q_{ak} = 400kN. The load acts over the axle as shown below where the contact surface of each wheel has dimensions 0.35m by 0.60m.



Key
X Bridge longitudinal axis direction
1 Kerb

Live Load Model 3 covers special vehicle loading and is best explained through the corresponding details on HB Loading in BS 5400. Guidance is given for the minimum number of HB loading units to be 30. Each unit equates to 10kN per axle, and with four wheels per axle this equates to 2.5kN per wheel. A choice of inner axle spacing's is given, of 6, 11, 16, 21 or 26m, with corresponding overall vehicle lengths of 10, 15, 20, 25 and 30m. The overall vehicle width is given as 3.5m. Diagrammatic representation of the loading model is shown below:



Key
1 Inner axle spacing — 6, 11, 16, 21 or 26 m, whichever dimension produces the most severe effect on the member under consideration.

Figure 12 — Dimensions of HB vehicle

The assumed effective pressure of the wheel load is 1.1 N/mm^2. Factors of γ_{fl} are given as 1.30 and 1.10 for ULS and SLS respectively when the load is being considered independently, and 1.10 and 1.00 with the addition of either wind or temperature effects.

Live Load Model 4 relates to crowd loading on the bridge. It is represented by a UDL equal to 5kN/m^2, applied to the whole length and width of the deck.

The concentrated loads relevant to load models 1 and 2 should be taken as uniformly distributed across the whole contact area. The spread angle of the loads through the deck to the substructure is 45 degrees.

Braking and Acceleration Forces

These forces are calculated as a fraction of the total maximum vertical loads from load model 1 likely to be applied to lane number 1, and are applied as a longitudinal force at the surface level of the carriageway. The characteristic value, Q_{lk} is given as:

$$Q_{lk} = 0.6\alpha_{Q1}(2Q_{1k}) + 0.10\alpha_{q1}q_{1k}w_iL$$

With α values taken as unity and a deck length of 107.5m, Q_{lk} is calculated as:

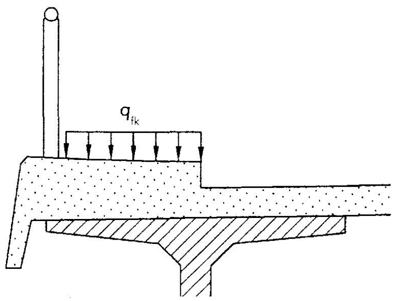
$Q_{lk} = 650.25kN$

A positive and negative notation of this value relates to the braking and accelerating force respectively. The partial factor $\gamma_{fl} = 1.25$ is applied, along with γ_{f3} to give a final ULS design load of 894kN, and SLS design load of 813kN.

Pedestrian Loading

The pedestrian section of this bridge is not separated from the carriageway by any substantial structure and as such no additional footbridge loading criteria need to be considered. Hence, the load models for the pedestrian loading of the bridge consist of a UDL, q_{fk} and a concentrated load, Q_{fwk}.

The UDL has a recommended characteristic value of 5 kN/m^2 and is considered to act as shown below.



The characteristic concentrated load value is 10kN and is designed to act on a square surface of sides 0.1m. Application of the relevant partial factors, where $\gamma_{fl} = 1.30$, gives a design UDL of 7.15 kN/m^2 at ULS and 6.5 kN/m^2 at SLS, and design concentrated load of 14.3kN at ULS and 13kN at SLS.

Impact Loading

The nature and location of this bridge, in the centre of Paris, brings about the need for careful consideration of the type of impact loading it may sustain. The carriageway it supports is not a highway as such and so the traffic flow over it is not likely to be travelling at great speed, although it is possible that it may be very heavy at certain times of the day. In addition to this the bridge spans a busy river channel carrying multiple types of vessels in great numbers, and does so at a relatively low height above the water level.

The design of the parapet as a stone balustrade set back from the edge of the deck and as such supported by it as a dead weight supplementary component, rather than working with it in some structural capacity, means that the impact of vehicle collision with the parapet can be supposed to be negligible. The brittle nature of the stone means that on impact the parapet would fail dramatically and as such no load would be transferred to the supporting structure.

Impact loading due to collision from water traffic beneath the bridge is however important. Even though there are no piers or supports in the water along the span, the low nature of the arch means that impact with the underside along the profile should be considered. Impact from river traffic leads to the requirement for specification of the corresponding frontal and lateral dynamic design forces [8]. Standard values for the dynamic forces due to certain vessels are shown in the table below:

Table C.3 – Indicative values for the dynamic forces due to ship impact on inland waterways.

CEMT[a] Class	Reference type of ship	Length ℓ (m)	Mass m (ton)[b]	Force F_{dx} [c] (kN)	Force F_{dy} [c] (kN)
I		30-50	200-400	2 000	1 000
II		50-60	400-650	3 000	1 500
III	"Gustav König"	60-80	650-1 000	4 000	2 000
IV	Class „Europe“	80-90	1 000-1 500	5 000	2 500
Va	Big ship	90-110	1 500-3 000	8 000	3 500
Vb	Tow + 2 barges	110-180	3 000-6 000	10 000	4 000
VIa	Tow + 2 barges	110-180	3 000-6 000	10 000	4 000
VIb	Tow + 4 barges	110-190	6 000-12 000	14 000	5 000
VIc	Tow + 6 barges	190-280	10 000-18 000	17 000	8 000
VII	Tow + 9 barges	300	14 000-27 000	20 000	10 000

[a] CEMT: European Conference of Ministers of Transport, classification proposed 19 June 1992, approved by the Council of European Union 29 October 1993.

[b] The mass m in tons (1 ton = 1 000 kg) includes the total mass of the vessel, including the ship structure, the cargo and the fuel. It is often referred to as the displacement tonnage.

[c] The forces F_{dx} and F_{dy} include the effect of hydrodynamic mass and are based on background calculations, using expected conditions for every waterway class.

The impact force due to friction, F_R, which acts simultaneously with the lateral force F_{dy} is determined from the expression:

$F_R = \mu F_{dy}$

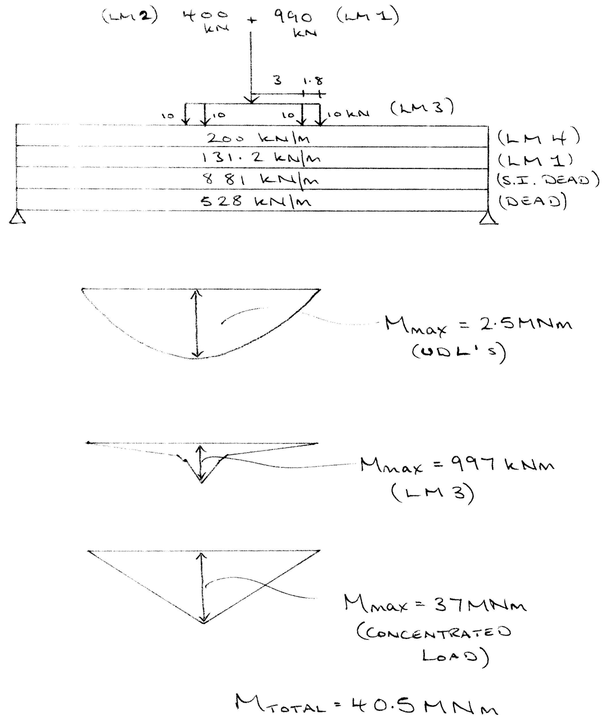
where μ is the friction coefficient with a recommended value of 0.4.

The forces should be applied at a height of 1.5m above the water level and over an area of height 0.5m, with a corresponding form relating to the shape of the arch profile.

Bending

Calculation of the maximum moment in the span of the bridge requires analysis as a simply supported beam to be undertaken. This will provide the shape of the bending moment distribution and this can be compared against the shape of the arch to analyse the moments for which the structure should be designed.

Consideration of the dead, super-imposed dead and principal live loads (LM1 to 4) yields the following results:



It is clear that as there is a pin at the apex of the arch, no moment can exist here and as such the moment distributions shown here require some adjustment. The numerical values however can be largely relied upon to provide the basis for a fair design.

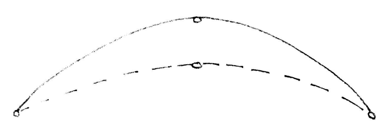
Buckling

The buckling mode analysis of three pin arches can suitably be compared with that of struts. The application of the Euler critical buckling load relates to the applied axial load that will cause the member to buckle. This axial load refers to the horizontal reaction through the arch structure. The Euler critical buckling load, P_E is given as:

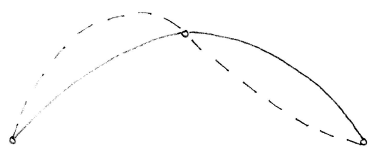
$$P_E = \pi^2 EI/L_e^2$$

The two main buckling modes are shown below:

Snap-Through Buckling (symmetric)



Sinusoidal Buckling (asymmetric)



Ref. [2] quotes the E value for steel as 13,400 ton/square inch, which equates to 206 kN/mm^2. The value of I, second moment of area, is given as Ar^2 where r is the radius of gyration. Choosing a suitable cross section from the tables presented in [2] gives a value of r equal to 228mm and Area of 28390mm^2. As such a value of I of 1476×10^6mm^4 is obtained.

The Euler buckling length, L_e for a pin-ended strut is equal to the actual length. In the case of this shallow arch that can suitably be assumed equal to half the bridge span and as such is given as 54m.

The buckling load can then be calculated as:

$$P_E = \pi^2 \times 206 \times 10^3 \times 1476 \times 10^6 / 54000^2$$

Hence $P_E = 1029$kN

Temperature

Temperature effects are key to the consideration of any structure, not least bridges due to their considerable span dimensions. The two main temperature effects in bridges are the overall increases and decreases, known as effective temperature, and variations in temperature that exist between top and bottom surfaces, known as temperature differences.

Design is usually undertaken to a 120-year return period where the co-efficient of thermal expansion for steel is 12×10^{-6} per degree. Consideration of contraction and expansion of the structure is vitally important as it induces considerable stresses that can lead to failure of members.

Wind

Wind loading to bridges is a vital criterion of their analysis due to the large spans they incorporate and the impact this has on the size of the forces. Wind effects also play a key role in the production of vibrations in the structure, which can cause issues with fatigue of components and general durability of the structure.

Wind analysis as specified in BS5400 makes use of 120-year return values and applies for heights up to 10m above ground level and 300m above sea level. Paris is located at 35m above sea level and the bridge is very low, as such this analysis can be applied to the Pont Alexandre III, although some adaptation is required when considering the wind speeds as such.

The design of the bridge itself also means that wind considerations are not highly significant. The low profile of the deck eliminates considerations such as loading on piers above deck height, such as those required when considering suspension bridges. The arch itself is also very rigid and sturdy, with extensive bracing and deep member dimensions. Its location sandwiched between two large, solid masonry viaducts again works to provide additional resistance to wind induced deflections.

The maximum wind gust speed is obtained from:

$$V_c = v \cdot k_1 \cdot S_1 \cdot S_2$$

where v is assumed to be 28m/s, k_1 is the wind coefficient, obtained as 1.66, S_1, the funnelling factor, does not apply here and so is given as 1.0, and S_2, the gust factor, is obtained as 1.24.

This gives V_c as 57.6 m/s.

The horizontal load, P_t is given as:

$$P_t = q \cdot A_1 \cdot C_D$$

where $q = 0.613V_c^2 = 2034$ N/m^2, $A_1 = 214$ m^2, C_D, the drag coefficient, is obtained as 0.6.

This gives P_t as 261 kN.

The longitudinal load, P_L is given as:

$$P_L = 0.25 \cdot q \cdot A_1 \cdot C_D$$

where $A_1 = 80$m^2 and hence $P_L = 24$kN.

Wind loading to the parapet should also be considered, the value of which is dependant on whether the parapet is open or closed, and the type of loading being considered on the deck, be it dead or live.

The thickness to length ratio of the parapet is less than 0.5; hence a drag coefficient of 1.3 is used. Applying the same factors for funnelling and gusting gives a value of $P_t = 283$kN.

Actions on piers are not applicable to this bridge.

Uplift is a key consideration in bridge wind analysis. The uplift force, P_v is given as:

$$P_v = q \cdot A_3 \cdot C_L$$

where A_3, the plan area of the deck is 4280m^2 and C_L, the coefficient of lift, is 0.15.

Subsequently, $P_v = 1306$kN.

Analysis considers the different combinations of these loads so as to obtain the worst-case scenario. The combinations are as follows:

P_t alone
P_t in combination with P_v
P_L alone
0.5 P_t in combination with P_L and P_V

Natural Frequency

For long span structures vibrations can often become an issue, whereby excessive movement can detract from the use of a structure, or compromise its structural strength and stability. Human sensitivity to vibration is directly related to frequency, amplitude and damping.

The causes of vibrations are wide ranging and include wind, plant, people, traffic, and in certain environments earthquakes and wave action. The mass and stiffness of a structure relates to how it responds to the vibrations. The ability of a structure to dissipate energy is classified as damping and is usually created through friction in structural and non-structural components.

The calculation of the natural frequency of a structure is not an easy task, and as such a very simple assumption would be to ensure the natural frequency of a structure is greater than 4.5Hz to prevent it becoming excitable. Some other estimation methods are shown in the table below and relate to the type of member in question and load incident on it.

Refurbishment and Maintenance

The age of this bridge instantly heightens the importance of the maintenance and durability considerations, as the materials used will be close to their design age. The standard design life for any bridge is recommended by the guides as 100 years, a milestone the Pont Alexandre III has passed and so it is not surprising that the whole bridge underwent a refurbishment programme in the 1990's.

The construction techniques of the time at which it was built may have been somewhat more simplistic technologically speaking, but they were used to produce structures of the highest quality and robustness, the Pont Alexandre III is no exception to this. Most of the original structure remains in tact and any replacements have not hindered the general use of the bridge, certainly not to the extent by which the safety of its users was ever in question.

The ornamentation and non-structural components of the bridge have not lasted so well. There is extensive discolouring to the stonework on the viaduct abutments to the bridge and this can also be seen on the balustrades along the deck side. The bronze decorations are inherently high maintenance and require regular cleaning. The high profile nature of the bridge means that funding is available for this, although it is not necessarily a good thing. The valuable nature of the ornamentation also incurs its own costs in that the bridge requires close surveillance to ensure these important historical and cultural works of art are not lost.

Future Life

The Pont Alexandre III has lasted incredibly well for its 100 years of life and remains a very important landmark in the Parisian urban environment. It is likely that some time in the near future further restoration work will be necessary, and the frequency of the need for these works will increase over time. In this respect it may eventually become sensible, for economic reasons more than anything, to replace the bridge rather than continue to provide partial improvement.

Conclusions

This paper has provided an introductory analysis of the Pont Alexandre III in Paris. Analysis of existing bridges is a fundamental component of the continuing monitoring of existing structures, particularly so when they are as old as this bridge is.

I hope to have presented a detailed consideration of the aesthetic merits of the bridge, whilst providing appraisal of its weak points, kept in the context of the great importance this structure has in French political and social history.

The age of the bridge has ensured that explicit structural analysis has been somewhat difficult, however with the aid of resources, and some informed judgement, I hope to have provided a clear insight to the structure of this quietly complex bridge.

Modern day design manuals provide a good basis for the assessment of the impact of traffic loading and have been used here to model the traffic on the bridge. It can be shown however that the resulting structural implications of this loading do not translate back to the arch so directly.

The consideration of steel arches is an ongoing theory, which as yet has meant that very few and limited design rules for steel arches are available in international steel construction codes. Research by institutions such as the TUE (Technische Universiteit Eindhoven) provide some of the most comprehensive work to date and should be considered one of the first places to investigate when considering this topic.

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