STUDY OF EXTRADOSED BRIDGES

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September 2011

ABSTRACT

This paper presents a study of extradosed prestressed concrete bridges. Some issues need special attention, with the main goals purpose being:

- To define the concept of an extradosed structural system;
- To provide a summary of the trends of the extradosed bridges built to-date;
- To define a strategy for the design of an extradosed bridge;
- To assess the efficiency of a structure supported by cables to be provided with stiffness;
- To establish the competitiveness of an extradosed bridge over a cantilever constructed box-girder bridge and a cable-stayed bridge.

The influence of geometrical parameters, such as the height of the towers, girder depth and the size of piers in the structural behavior and in the design and construction of an extradosed bridge were also analysed. It is intended to get a critical sense of how each component of an extradosed bridge affects its structural behavior.

The paper also discusses the main factors that define the design of an extradosed bridge. From its setting in the vast world of bridges with different solutions to some critical details that must be considered in the final design. Many of these issues are generally relevant to any bridge with medium to large main span, as they represent important considerations for the design process of any prestressed concrete bridge.

To achieve these goals the design of an extradosed bridge is developed for a real case. This solution is compared with a cable-stayed deck and a cantilever box-girder deck. The design constraints are defined by the location of an already built cantilever box-girder bridge, which has a central span of 120 metres and side spans of 75 metres. This bridge was designed by GRID – Consultas, Estudos e Projectos de Engenharia SA, and it is located on the A13 Motorway over the Sorraia River, in the South of Portugal. A comparison is made in terms of material quantities for each solution, as well as its cost, to enable a general analysis of cost/efficiency of each structural solution.

Finally this paper intends to provide enough technical information about extradosed decks, so that a structural engineer can understand the key steps concerning the design and construction of a bridge of this type.

Keywords: **extradosed bridge, stay-cables, extradosed cables, cantilever construction, bridge design, prestressing.**

1. INTRODUCTION

With the improvement of construction methods, associated with a higher knowledge in the area of prestressed concrete, in recent decades new structural systems have emerged and have been used in the construction of bridges and viaducts. An example of this development is the case of a bridge known as extradosed. From 1980 to 2011 over 70 extradosed bridges were built worldwide, with different deck cross-sections and extradosed cables arrangements, while there are many more in the design phase. The word *"extrados"* defines the upper surface of an arch, thus the term "extradosed" was conceived. This designation was used by the French engineer Jacques Mathivat in 1988 to describe an innovative cables arrangement that he proposed for the Arrêt-Darré Viaduct (France, *Figure 1*), in which prestressing cables were placed outside the deck with large eccentricity over the piers, as opposed to tendons in the interior section of the girder as in a cantilever constructed box-girder bridge [*7*].

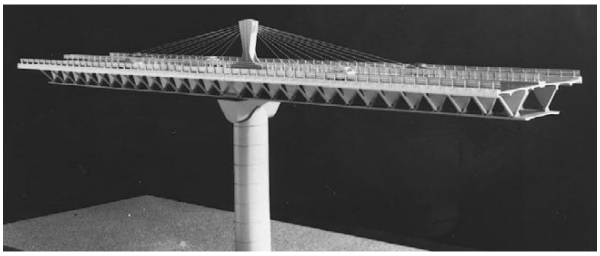


Figure 1 – Arrêt-Darré Viaduct, France [7].

Mathivat was inspired by the design used by Swiss engineer Christian Menn for the Ganter Bridge (Switzerland, *Figure 2*) which was completed in 1980. The entire design of this bridge was based on models of cable-stayed bridges, but it represents clearly the first example of an extradosed deck. Therefore it can be said that Mathivat finished Menn's initial concept, naming the tendons by "extradosed prestressing" as opposed to "stay-cables" and throughout this paper they are simply called "extradosed cables".

Figure 2 – Ganter Bridge, Switzerland [4].

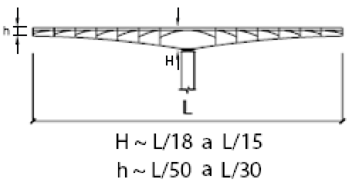
Extradosed bridges would be a mid way between a cantilever constructed box-girder bridge and a cable-stayed bridge, working part on the bending of the girder and part on the cable suspension of the deck, and combining some features of each one.

Sometimes there is some difficulty in defining the boundary between a cable-stayed bridge and an extradosed bridge. Visually, extradosed bridges differ from the cable-stayed ones by having shorter towers, as shown on *Figure 3*. The extradosed bridge's towers are typically a tenth of the main span, corresponding to a cable inclination of 15 degrees.

In this paper the term "extradosed bridge" is used to describe all bridges that have towers shorter than the conventionally used in cable-stayed bridges, usually with a height between a fifth and a fourth of the main span.

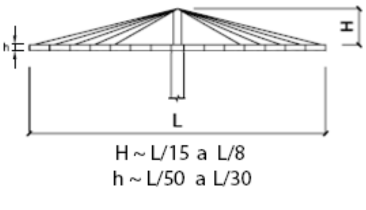
The reduced inclination of the extradosed cables lead to an increase on the stresses in the deck and a decrease in the vertical component of the force in the anchorages, contrary to what happens in a cable-stayed bridge. Therefore, the main purpose of the extradosed cables is to compress the deck, and not only to give vertical suspension to it, as in cable-stayed bridges.

Cantilever-constructed box-girder bridge



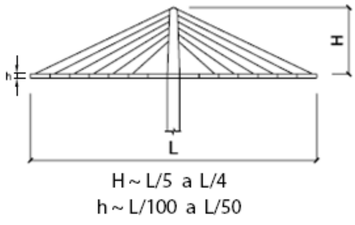
-Variable girder depth
-Internal and external tendons
-Max tendon stress at SLS of 0.70 f_{puk}

Extradosed bridge



-Constant or variable girder depth
-Extradosed cables
-Max cable stress at SLS of 0.60 f_{puk}

Cable-stayed bridge



-Constant girder depth
-Stay-cables
-Max cable stress at SLS of 0.45 f_{puk}

Figure 3 – Comparison between cantilever-constructed box-girder, extradosed and cable-stayed bridges.

Bridges with extradosed prestressing are characterized by having a low stress variation in the cables due to live loads, being the girder the component responsible for carrying these loads to the piers. For this reason, these bridges are sometimes called inefficient structures, for depending on this girder structural system. But the fact is that the details and technology found on an extradosed bridge come directly from box-girder bridges with external tendons as well as from cable-stayed bridges.

Comparing to a cable-stayed bridge, there are several advantages of an extradosed bridge for spans shorter than 200 m. As the live loads produce small stress variations on the extradosed cables [*7*], these can be deviated at the piers by means of saddles, allowing for more compact towers. Another advantage of this structural system is the fact that extradosed cables can be anchored near the webs of the box-girder, since the vertical component of the force in an extradosed cable is small compared to the one in a stay-cable, which is transferred directly into the deck without the need of diaphragms, thus saving material and reducing the deck's self-weight. Extradosed bridges are also able to use normal external prestressing anchorages, without having to use high fatigue resistance anchorages as needed in a cable-stayed bridge. Since the live loads and the superimposed dead loads are almost entirely accommodated by the deck, the extradosed cables do not need to be re-tensioned, being designed to carry only the self-weight of the structure [*2*].

The selection and characterization of a bridge structural system is a complex task and should be accomplished through a careful study, taking into account all critical factors such as spans ratio, number of supports, aesthetics, cost, the surrounding landscape integration and all the technical constraints which must be considered. Extradosed bridges have been widely used in urban areas, near airports where there are restrictions on the tower's height or in rural areas where it is desired an aesthetically pleasing solution but with reduced impact on the surrounding landscape.

2. EXISTING EXTRADOSED BRIDGES

It is estimated that over 70 extradosed bridges have been built to-date worldwide, with many more under construction and many others in the design phase. It is expected that more extradosed bridges have been built in countries where disclosure of information is blocked, as is China's case, where in recent years there has been a high increase in the number of public works, including many bridges.

Seventy two extradosed bridges were reported, providing a general outlook, which allows the understanding of when to adopt different solutions to solve singular situations.

2.1 EXTRADOSED BRIDGES BUILT TO-DATE

Extradosed bridges have been economically feasible solutions to span between 100 and 250 m, with a breakthrough design, they are becoming competitive solutions against traditional box-girder bridges and cable-stayed bridges. These bridges have been used instead of more conventional solutions because they have unique advantages, among which must be highlighted:

- A smaller girder depth than the one in a cantilever constructed box-girder bridge, allowing for a bigger clearance;
- A lower tower height than in a cable-stayed bridge (this feature is extremely important when there are height restrictions by a nearby airport);
- According to some authors, including Menn [*8*], in a deep valley where the piers are high, if the towers above the deck have a height close to half the height of the piers, this solution becomes aesthetically weak, being preferable to adopt an extradosed bridge, as it features shorter towers than a cable-stayed bridge;
- By adopting an extradosed bridge instead of a cable-stayed bridge or a cantilever constructed box-girder bridge, it is possible to use the same cross-section as the one utilized in the access viaducts. This way it is feasible to span a longer distance without increasing the girder depth, obtaining a better match between the access viaducts and the bridge;
- Finally, even in situations where none of the above conditions is crucial for the choice of an extradosed bridge, these will always be aesthetically attractive,

creating a greater positive impact on the population then a traditional girder bridge, which many consider to have small aesthetic merit.

The choice for an extradosed bridge becomes an increasingly practical option for average size spans, being possible to differ their appearance by changing the shape of the towers, changing the cables arrangement and even to be able to use a bigger range of deck cross-sections.

2.2 TRENDS IN EXTRADOSED BRIDGES

In an urban environment, the choosing of what bridge type to use is essentially conditioned by two main topics: the aesthetic reveals great importance and the construction methods have to be the least cumbersome as possible for those people who pass by the work site. In a city environment, the usual structural solution to span average distances is a cantilever constructed box-girder bridge. According to Menn, general population has never been captivated by modern construction of bridges, finding that girder bridges are usually boring to look at [*8*].

From the 72 extradosed bridges studied, one can draw some important lessons in order to understand the typical cases of use of an extradosed solution. Of the 72 extradosed bridges considered:

- 36 have a main span between 100 and 150 m;
- Only 11 have one tower, corresponding to two extradosed spans;
- 43 have 2 towers;
- 12 comprise more than 3 extradosed spans;
- 50 are roadway bridges and many of them are part of motorways;
- Only 3 are railway bridges;
- 11 are of mixed use, including roadway, railway and/or pedestrian circulation;
- 58 have a concrete deck;
- 8 have a composite or a hybrid deck, mixing the use of concrete and steel;
- 37 have lateral suspension only;
- 30 are strictly centrally suspended.

From the results obtained, 20 of the 72 bridges studied have a span to depth ratio at mid-span of 50 or more and 19 of these 72 bridges have a span to depth ratio at the pier section between 30 and 35. These results are in accordance to those suggested by Mathivat, who stated that the span to depth ratio should be around 50 at mid-span and 30 to 35 at the pier section [*7*].

3. DESIGN OF EXTRADOSED BRIDGES

Chapter 3 discusses the most important aspects that have to be considered for the design of an extradosed bridge, by presenting a review of the design loads to be considered in accordance to the Eurocodes; discussion of various design methodologies; mentioning of the proportions of the elements that compose an extradosed bridge, including cross-sections and the cables arrangement. This chapter aims to explore the structural behavior of an extradosed bridge and to determine what considerations should be made to its design.

3.1 GENERAL DESIGN CRITERIA

3.1.1 Stiffness in the extradosed cables or in the deck

Extradosed bridges have two different structural systems, the cable suspension system and the stiff deck bending system. One can choose which of the two systems will have a greater influence on the bridge structural behavior, by varying the ratio between the stiffness of each system. By reducing the deck stiffness, the bridge has a behavior similar to a cable-stayed bridge; on the other hand, by increasing the stiffness, it will behave more like a traditional box-girder bridge. This stiffness ratio (β) is then defined by the following ratio:

$$\beta = \frac{Load\ carried\ by\ the\ extradosed\ cables}{Total\ vertical\ load} \text{ x } 100 \qquad (1)$$

It is estimated that an extradosed bridge has a stiffness ratio of around 30%. [*9*]

3.1.2 Type of connection between deck and piers

There are two main types of connection between the deck and the piers, either fixed or on simple supports. In an extradosed bridge, the manner in which the deck is fixed to the piers is the most appropriate, providing a better structural behavior when considering the live loads action. This solution should always be adopted, except when the piers are too short to accommodate the displacements caused by creep, shrinkage and uniform temperature gradients of the deck [*1*].

3.1.3 Influence of side span length

The span distribution in a bridge is usually conditioned by topographical, geological and water issues. Kasuga suggests that the side spans should be 0.6 to 0.8 of the main span, to balance the negative bending moment in the deck on each pier side [*5*].

3.1.4 Tower height

Mathivat was the first to define a recommended height for the towers of an extradosed bridge, by suggesting a span to tower height ratio of 15 [*7*]. After carrying parametric studies, Komiya suggested a span to tower height ratio between 8 and 12 and Chio Cho suggests that the tower's height should not exceed 10 % of the main span [*6,1*].

3.1.5 Cross-section depth

Mathivat suggests that the deck should have a span to cross-section depth ratio between 30 and 35, for a constant depth section. For a variable cross-section's depth, Komiya suggests a span to cross-section depth ratio of 35 at the pier section and of 55 at mid-span, on the other hand, Chio Cho, suggests ratios of 30 and 45, respectively [*7,6,1*].

3.1.6 Type of suspension

There are two main types of suspension: central suspension and lateral suspension, then there are some hybrid configurations, with central and lateral suspension combined. According to the SETRA recommendations, central suspension is a good choice for bridges with four lanes and a central reservation. Laterally suspended decks have a typical width of less than 20 m [*11*].

3.1.7 Extradosed cables arrangement

As for cable-stayed bridges, there are three types of extradosed cables arrangements: the fan configuration, the harp configuration and a mix between the two creating a semi-fan configuration, more often used.

3.2 DESIGN LOADS

According to the Eurocodes, to design an extradosed bridge, one should consider several loads, including the structure's self-weight, the superimposed dead loads, the live loads, a temperature gradient in the deck, a temperature differential between the cables and the deck, a uniform temperature variation in the deck and creep and shrinkage time dependent effects.

3.3 DESIGN OF EXTRADOSED CABLES

3.3.1 Preliminary design of the extradosed cables at Serviceability Limit States

In a cable-stayed bridge the preliminary design of the stay-cables is made taking into account a maximum stress variation due to live loads. This stress value limits the maximum force on the stays at Serviceability Limit State (SLS) to 45% of the ultimate tensile strength (f_{puk}) of the strands that compose them. This value is associated with the need to prevent potential negative consequences of stress fatigue of the steel cables. However, with the evolution of the stay-cables technology, several authors propose to increase the allowable stresses at SLS from 0.45 f_{puk} to 0.50 f_{puk} during service or even to 0.55 f_{puk} during construction, if devices are adopted to limit the bending stresses in the anchorages [*10*]. This is an indirect way of accounting for the effects of fatigue of steel in the design of the stay-cables.

In extradosed bridges, the indirect method has been the most widely used for preliminary design of the cables, as it involves a simpler method of calculation. This way, the extradosed cables are first designed by limiting the stresses at SLS and then they are checked for the fatigue limit state and ultimate limit sates (ULS).

Globally it is necessary to highlight both the SETRA recommendations and Japan Prestressed Concrete Engineering Association's specifications which were based on the studies of several authors, including Mathivat and Kasuga. These recommendations suggest maximum allowable stresses at SLS depending on the stress range due to live loads, as shown in *Figure 4*.

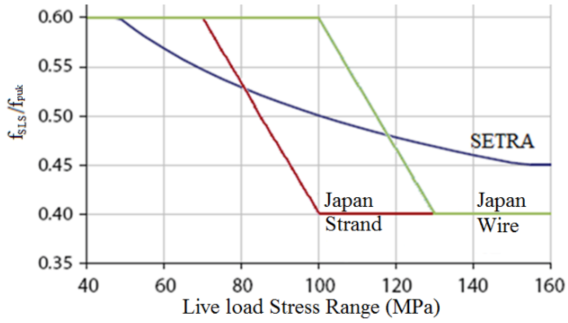


Figure 4 – Maximum allowable stress in cables at SLS.

Figure 4 shows that the SETRA recommendations limit the stresses in extradosed cables at SLS to values between 0.45 f_{puk} and 0.60 f_{puk} for a maximum stress due to live loads between 140 and 50 MPa, respectively.

These recommendations suggest that one adopts the same maximum allowable stress for all extradosed cables, given the highest stress range due to live loads among all cables [*5*].

The Japan Prestressed Concrete Engineering Association's specifications propose that the allowable stresses in the extradosed cables at SLS vary from 0.40 f_{puk} to 0.60 f_{puk} for a maximum stress range due to live loads in a strand between 100 and 70 MPa, respectively, and 130 to 100 MPa for a range of stresses in the steel wires that make up the strands. These Japanese recommendations allow the choice of different maximum allowable stresses at SLS for each cable that composes the suspension system of an extradosed bridge, in opposition to the SETRA recommendations [*5*].

3.3.2 Verification of the extradosed cables at Ultimate Limit States

The ULS check of the extradosed cables has to be done after the preliminary design at SLS and after having been checked for fatigue limit state.

According to the SETRA recommendations, the stress in the extradosed cables at ULS should be 0.75 f_{puk} for cables that have been mechanically tested to verify the maximum resistance to fatigue and 0.67 f_{puk} for cables that have not been tested mechanically [*11*].

4. THREE BRIDGES: A BOX-GIRDER, AN EXTRADOSED AND A CABLE-STAYED

In order to study the competitiveness of the structural system discussed throughout this paper, an extradosed bridge is designed as well as a cable-stayed bridge, which are compared to a cantilever constructed box-girder bridge, that has already been built over the Sorraia River on the A13 - Motorway in Portugal, which was designed by GRID - Consultas, Estudos e Projectos de Engenharia SA. The design of the cable-stayed and extradosed solutions is carried out respecting the design constraints of the existing structure.

4.1 DESCRIPTION OF THE BOX-GIRDER BRIDGE

The cantilever constructed box-girder bridge already built is actually made of two parallel concrete box-girders with a total length of 270 m, having a main span of 120 m and side spans of 75 m. Each deck consists of a single cell box-girder of prestressed concrete casted in place, with variable depth. The side elevation of the structure is illustrated in *Figure 5* [*3*].

The deck is bending free at the central piers (P1 and P2) and it is on simple supports on the edge piers.

Each deck illustrated in *Figure 6*, consists of a single-cell box-girder with 14.45 m width and a height ranging from 6.0 m at the piers to 2.55 m in the mid-span, and it is prestressed in the longitudinal and transverse directions. The webs of the box-girder have a constant inclination, varying its thickness of 0.60 m, on the central piers, to 0.40 m in mid-span. The upper inner girder slab has a thickness of 0.25 m at the transverse mid-span and 0.55 m over the webs. The side cantilevers vary their depth from 0.175 to 0.45 m, respectively in the free and fixed sections.

4.2 DESIGN OF AN EXTRADOSED BRIDGE

The extradosed bridge is the first of two to be designed in order to carry out an economical competitiveness analysis between the cantilever constructed box-girder bridge presented above, and two bridges with cables, a cable-stayed bridge and an extradosed one.

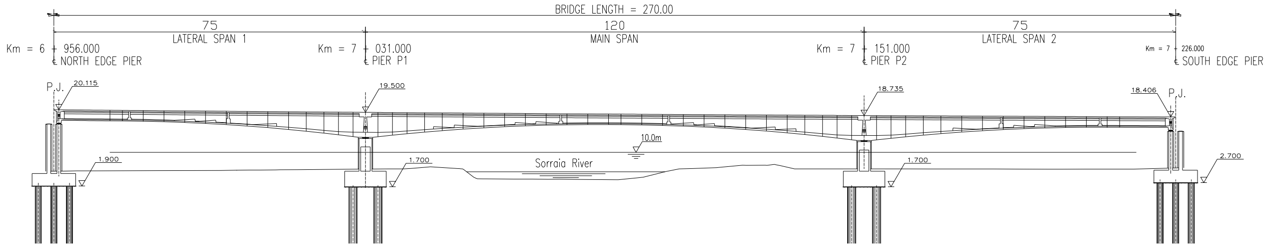


Figure 5 – Side elevation of the cantilever constructed box-girder bridge over the Sorraia River [3].

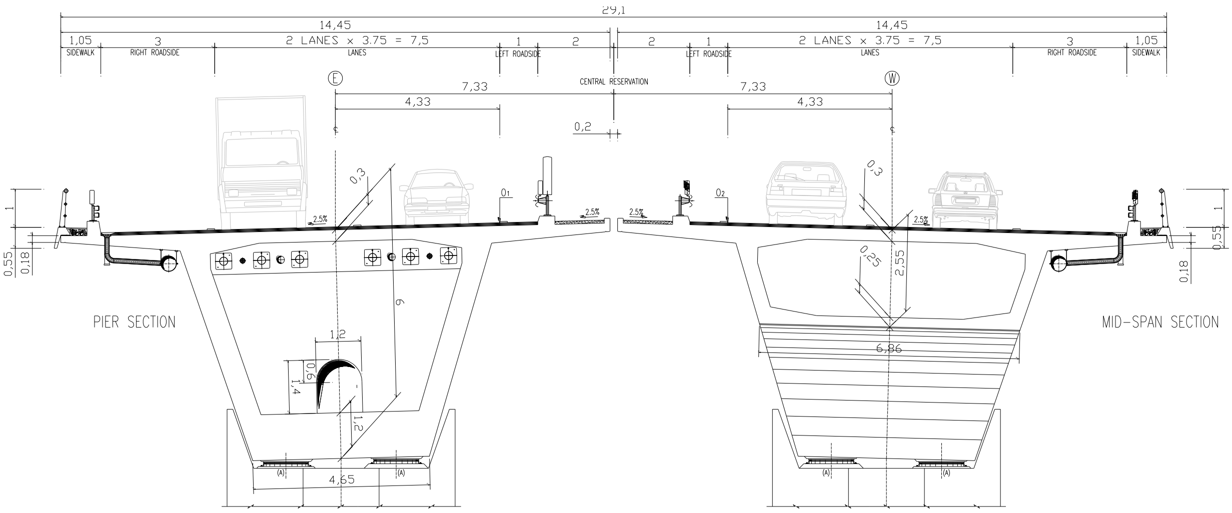


Figure 6 – Deck cross-section of the cantilever constructed box-girder bridge over the Sorraia River [3].

The extradosed bridge is designed to provide a deck as slender as possible, but stiff enough so that the live loads do not create stress variations in the extradosed cables greater than 50 MPa. Limiting the stress variation, one can adopt the maximum allowable stress in the cables of 0.60 f_{puk} at SLS, according to the SETRA recommendations, being able to use ordinary external prestressing anchorages.

The deck is designed so that every section remains uncracked at SLS and the re-tensioning of the extradosed cables is avoided, taking advantage of the girder stiffness and the internal tendons to compensate the superimposed dead loads. The cables are deviated across the towers by saddles, with appropriate radius of curvature and preventing them from slipping.

4.2.1 Extradosed cables arrangement and girder cross-section

A harp arrangement of the extradosed cables is adopted in order to decrease stability problems in the tower, associated with the merging of all cables at the top of the tower. This way, all cables have the same slope, producing a better looking side elevation of the bridge, and avoiding the apparent crossover of the cables. Moreover, this configuration prestresses the deck more than a semi-fan arrangement, evidencing the true behavior of an extradosed bridge and less the one from a cable-stayed bridge.

The deck has a span to depth ratio of 34.3, with a main span of 120 m, equal to the one observed in the box-girder bridge presented above and with a constant depth of 3.5 m.

The superstructure is built progressively by balanced cantilever, first building the central piers' segments 15 m long. Then, through the use of formwork travelers, ten 5 metres long segments are built from each side of the tower. With the cantilever phase completed, the closure segment is poured as well as the lateral 17.5 metres long segments.

The box-girder cross-section has a constant height of 3.5 m, because it is considered inappropriate to adopt a variable deck height, as the main span is not too long. However, there are differences in the pier and span sections, in which the first one has a deeper lower slab than the second one, with the purpose of resisting greater negative bending moments. The first three deck segments have the pier section's features and the other 7 segments have the mid-span deck section's.

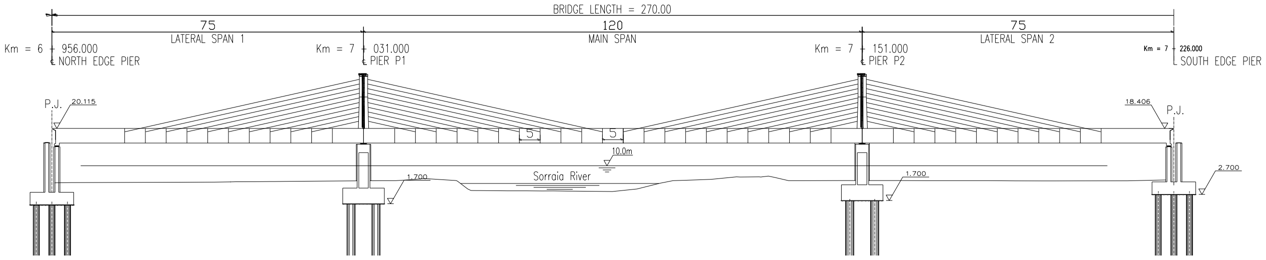


Figure 7 – Side elevation of the extradosed bridge.

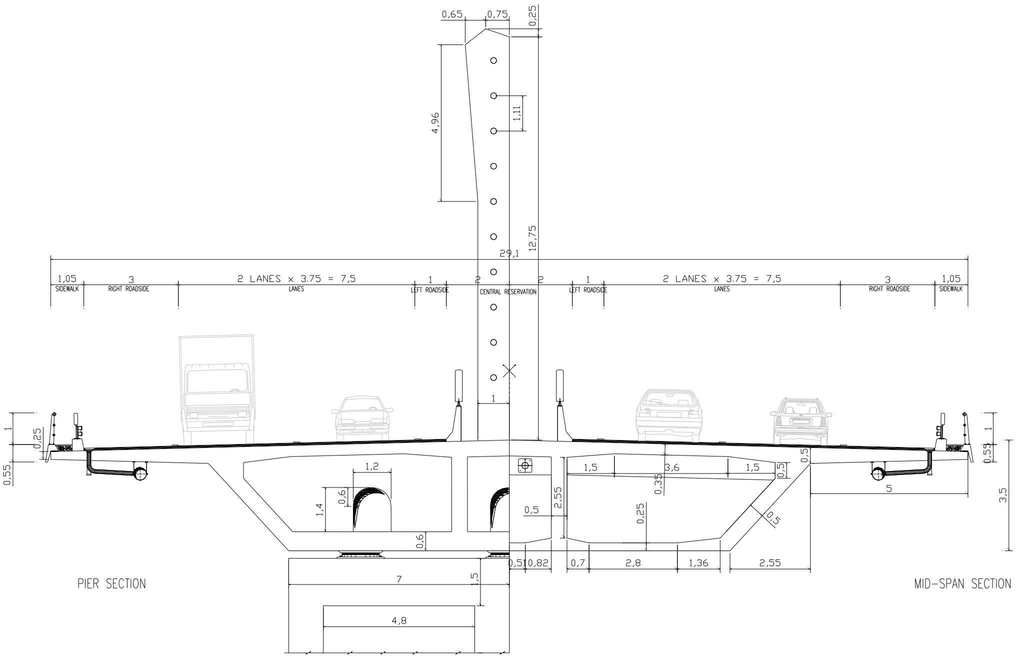


Figure 8 – Deck cross-section of the extradosed bridge.

The bridge has two central plans of extradosed cables, which all have the same cross-section, being composed by 55 strands of 15.2 mm of diameter, totalizing 80 extradosed cables. These are anchored at transverse ribs 1 m high and 0.5 m wide. In the design of the extradosed cables, after several iterations, the stress variations due to live loads in the most stressed cable was of 71 MPa, according to *Figure 4*, corresponding to a maximum allowable stress range at SLS of 0.55 f_{puk}.

4.3 DESIGN OF A CABLE STAYED BRIDGE

A cable-stayed bridge is also designed, adopting a very slender concrete deck, and thereby reducing the material usage to optimize the solution. This way, the loads are carried to the piers through the stay-cables directly to the towers, and creating low bending moments over the deck. Thus, the bridge is designed with only one load carrying system, being the stay-cables the elements responsible for this duty, and being designed for a maximum allowable stress of 0.45 f_{puk} at SLS.

The deck is designed in order to remain entirely uncracked at SLS and stay-cables re-tensioning is considered to compensate the displacements due to the superimposed dead loads.

The stay cables are deviated over the towers using anchorages, since they have a high inclination, which do not allow them to be deviated by means of saddles.

4.3.1 Stay cables arrangement and deck cross-section.

The stay-cables are placed in a semi-fan arrangement, to decrease stability problems in the tower, associated with the merging of all cables at the top of the tower, but trying to set them as vertical as possible. This configuration makes the anchorages detailing a more difficult task during construction, since each stay-cable has a different slope. The structural behavior of a cable-stayed bridge should be similar to a simply supported beam with spans equal to the spacing between the stay's anchorages on the deck.

The deck has a span to depth ratio of 88.3, with a main span of 132.5 m, slightly longer than the one in the other structural solutions and has a constant depth of 1.5 m. This span to depth ratio is between 50 and 100, as normally adopted for a cable-stayed bridge with this span range. This three span cable-stayed bridge has two side spans of 68.75 m, with the deck being symmetrical to each tower [*10*].

The deck is also built by the balanced cantilever construction system, starting from the first 7.35 m long segments for each side of the towers, which are built using a formwork supported from the ground. Then through the use of formwork travelers, eight more 5 metres long segments are built to each side of the tower. The stay-cables are installed as the concrete segments are constructed.

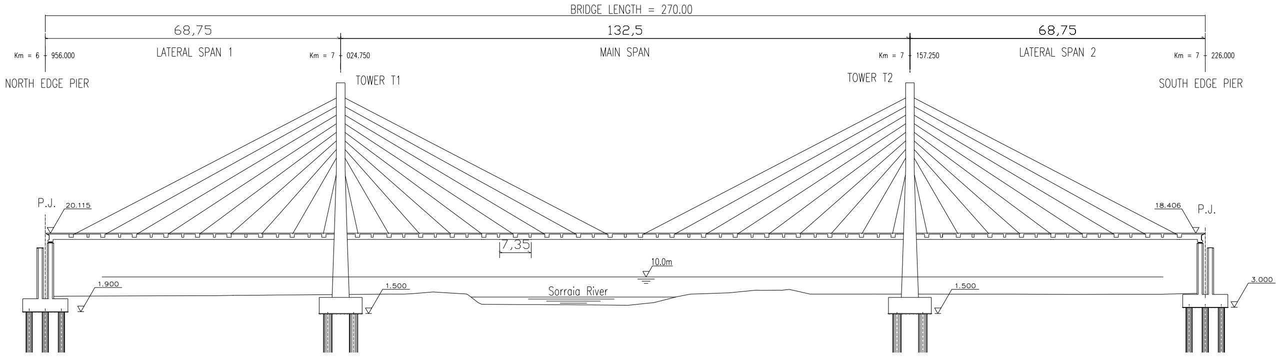


Figure 9 – Side elevation of the cable-stayed bridge.

The cross-section of the deck, illustrated in *Figure* 10, presents a constant 1.5 m depth of the main longitudinal girders. Transverse ribs are adopted every 3.675 m, at the stay's anchorages sections and midway between them. Thus, the upper slab has a cylindrical bending behavior with a span of 3.675 m, being adopted a slab thickness of 0.25 m.

The bridge has two lateral stay-cables planes that are anchored at the edge of the transverse ribs, which introduce rigidity to the deck, connecting the two longitudinal side beams. The stay-cables have a number of strands ranging from 22 on the 1st pair of stays, 31 on the 2nd, 3rd and 4th pairs, and 43 strands on the remaining 5 pairs, adding up 72 stay-cables.

The deck section provides convenient size for the prestressing tendons to be placed inside the longitudinal main lateral girders, without influencing the transverse tendons which are placed in the transverse ribs and the stay-cables anchorages which are positioned at the end of them.

4.4 COMPARISON BETWEEN THE THREE BRIDGES

In order to do an analysis on the feasibility of an extradosed solution in relation to a cantilever constructed box-girder bridge and a cable-stayed bridge solution, a comparative analysis is done between the amount of material used in each solution, an estimate of the material's costs for each bridge is done and an aesthetic analysis is carried out to highlight the advantages of an extradosed structural solution.

4.4.1 Material's quantities

Comparing the quantities of materials used for each solution, it is concluded that the cantilever constructed box-girder bridge uses 9% less concrete than the extradosed solution and the cable-stayed bridge uses 28% less. The extradosed bridge is the one with least amount of prestressing steel, with the traditional box-girder solution having 13% more and the cable-stayed one with 15% more prestressing steel.

As for the use of rebar, this comparison is very relative, since the transverse rebar in the extradosed and cable-stayed structures is not designed, being suggested to adopt the same ratios as used in the traditional box-girder bridge already built.

4.4.2 Cost comparision

A cost estimate of each bridge is done in terms of the unit costs of each material and the quantities that each solution shows.

Extradosed cables should have a lower price than cable-stays, taking into account that the first ones use current anchorages, but this is not verified because stay-cables' technology is more available on the market than extradosed equipment.

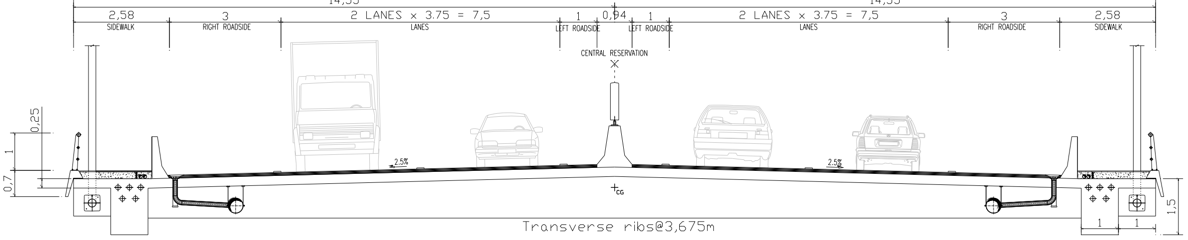


Figure 10 –Deck cross-section of the cable-stayed bridge.

Table 1 – Cost estimate of each bridge.

	Concrete [m^3]	Long internal tendons [ton]	Long external tendons [ton]	Stay-cables [ton]	Extradosed cables [ton]	Trans tendons [ton]	A500 Rebar [ton]	Cost in million Euros	Cost Ratio
Box-Girder Bridge	1310000	1328	387	0	0	268	1056	4.3	0.86
Extradosed Bridge	1499062	465	0	0	2180	356	607	5.1	1.00
Cable-stayed Bridge	1036296	386	0	1725	0	1087	500	4.7	0.94

Table 1 presents the total cost of materials used for each of the presented solutions, based on the same unit cost.

The extradosed solution appears to be a viable alternative to both the cantilever constructed box-girder bridge and the cable-stayed bridge.

The already built bridge is only 14% cheaper than the extradosed solution, and the cable-stayed bridge is 6% cheaper. This estimate does not include the cost of construction methods, which may change the ratio between the costs presented by the three discussed solutions.

However, the cantilever constructed box-girder bridge already built was developed by a team of engineers whose main goal, was to optimize the solution to present the lowest possible cost. Taking into consideration that the extradosed and the cable-stayed bridges are still in a preliminary design stage, it is thought that these solutions can still be optimized to become even more competitive with the built solution. The optimization of the extradosed bridge can start by adopting a deck cross-section with variable depth, reducing the volume of concrete and consequently lowering the final cost of the solution.

4.4.3 Aesthetics comparison

As a final comparison point, a critical analysis of the aesthetics of each solution is carried out, with help of 3-dimensional models of each bridge.

As discussed throughout this paper, an extradosed bridge strives for integration with the surrounding landscape without discarding the beauty recognized by the general population. Through the use of extradosed cables, the designer can set his trademark, by being able to adopt many different configurations to dodge the constraints imposed on the design.

The following figures illustrate 3D models of the three bridges presented along this paper, highlighting their integration with the surrounding landscape.

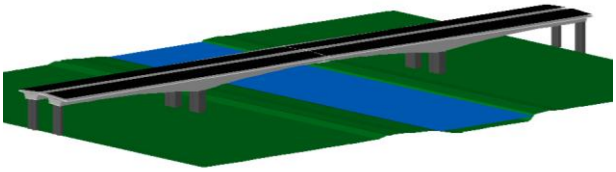


Figure 11 – 3D model of the cantilever constructed box-girder bridge.

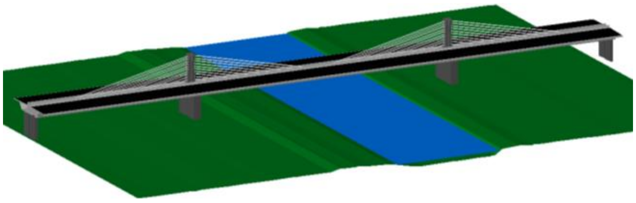


Figure 12 – 3D model of the extradosed bridge.

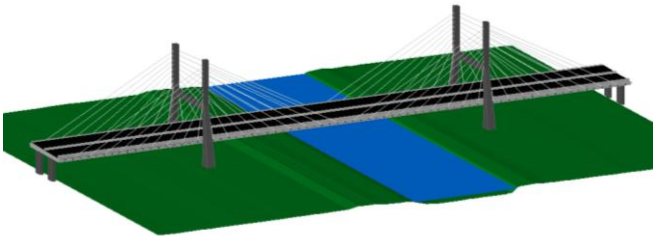


Figure 13 – 3D model of the cable-stayed bridge.

Thus, it is the opinion of the author that the extradosed solution is often aesthetically more favorable, as it has a stronger character than a traditional box- girder solution, and does not have towers as high as the cable-stayed solution, which overloads the surrounding landscape.

5. CONCLUSIONS

This paper presents the main conclusions taken from the analysis of 72 extradosed bridges built to-date, with main spans between 66 and 312 m and combining a variety of cables arrangements, types of suspension and distinct deck cross-section. The extradosed bridges studied have a typical span to depth ratio of 50 in the mid-span and between 30 and 35 in the pier section, with these ratios being adopted for bridges with main spans between 100 and 200 m. For bridges with longer spans, some authors have adopted higher slenderness, reaching typical dimensions of cable-stayed bridges, with a ratio near 100.

This paper provides an insight of the design criteria for an extradosed bridge that should be followed. The design should consider several loads, including the structure self-weight, the superimposed dead loads, the live loads, a temperature gradient in the deck and a temperature differential between the extradosed cables and the deck.

Regarding the type of suspension, it is concluded that a deck cross-section with lateral suspension is more appropriate for a deck up to 20 m wide and central suspension for wider decks

Extradosed cables should be light colored to avoid a large temperature differential between them and the deck. The design of the cables should be done by limiting the stresses at SLS to 0.60 f_{puk}, when the stress variation due to live loads is lower than 50 MPa in every cable and then they must be checked at ULS and Fatigue Limit State. This stress variation in the cables due to live loads is influenced by the type of fixation between the deck and piers, with a fixed connection better suited to lower these values than a released one. The type of connection between the deck and piers is conditioned by the effects of shrinkage, creep and uniform temperature gradients, which in short piers, does not allow them to accommodate the displacements created by these effects.

Finally, the two designed bridges, an extradosed solution and a cable-stayed one are compared with a traditional box-girder solution already built. This comparative study shows that extradosed bridges are economically competitive solutions for main spans around 125 m.

An extradosed bridge presents itself as an aesthetically attractive alternative, allowing the deck to adopt a slender shape than a traditional cantilever constructed box-girder bridge and with towers shorter than a cable-stayed solution. This type of bridge is certainly a step forward on bridge design, and has been gaining more importance worldwide in recent years for its positive contribution in the field of structural engineering.

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