DESIGN CHALLENGES IN CABLE-STAYED CONCRETE BRIDGES

Jose Romo CEO FHECOR

Javier Andueza Bridge Department Director FHECOR

Lino Rivero Regional Manager Middle East FHECOR

Abstract

Cable stayed bridges, are nowadays the most popular solution for spans ranging from 300 to 800m. In the case of concrete decks, the standard spans are in the ranges between 250 and 400m.

Nevertheless, the use of high strength concrete helps break that limit. Cable Stayed Bridges with concrete decks could span up to 500m at the mid span by using lighter cross sections, thanks to the reduction of the thickness of the different elements of a deck's cross section.

1 Introduction

Concrete is nowadays the most popular material to build short-span bridges in the world. The possibility of using local skilled resources, easily available and with a low workforce demand for the concrete deck construction, places the concrete in an unbeatable as structural material. Furthermore, the short training required for constructing those types of structures, gives also the change to local resources which placed concrete bridge in a predominant position all over the world.

Figure 1: Monotower cable stayed bridge: Usk River FHECOR

Cable Stayed Bridges with prestressed concrete decks are therefore a common solution form the early years of introduction of this typology [1]

In this paper a review of the design approach, taking into consideration the current possibilities of the structural concrete is presented, as well as its implications in the cable-stayed bridge design.

2 General design principles of concrete decks

Serviceability Limit State (SLS) is normally the governing condition in cable-stayed concrete deck's design. In modern codes, different SLS's design situations are stated: quasi-permanent, frequent, rare and characteristic. Those situations are associated to different probability of occurrence, and therefore to different cracking limitations criteria.

Codes established different conditions related to the estimated crack opening or even the condition of no tensile stress for the different scenarios depending also of the environment situation; see for instance Eurocode 2 [2].

When the deck is constructed in stages, not only longitudinally but also transversally, the SLS conditions becomes more complex, as the concrete is subject to time-dependant effects, while the cables are being prestressed in several stages, resulting in the prestress forces not being applied to the full concrete cross section, at one stage.

That means that even at the same depth within the cross section, the stresses in the concrete vary with the casting sequence and therefore the SLS check has to be performed at different location in the cross section. Furthermore, the differential creep and shrinkage among cross section zones tend to equalize the stresses with time. As a result, the position of the cables and the stress sequence has to be carefully analysed during the design phase, in order to optimize its design.

3 Conceptual design of cable supported concrete bridges

3.1 Introduction

Cable stayed bridges, are nowadays the most used solution for medium spans ranging from 300 to 800m. In the case of concrete decks, the span ranges from 250 to 400m.

For spans up to 400m the deck solution usually adopted is a composite (steel deck with a concrete top slab) and over 500m spans, a full steel section with an orthotropic steel deck is frequently adopted. In general, concrete cable-stayed bridges are heavier than the bridges incorporating steel decks, however, when designing a concrete section taking into account the total load of the deck, self-weight, and permanent load and live loads, both concrete and composite decks may become quite similar, in terms of the weight of the deck.

3.2 General Concept

One of the first and critical decisions to be made in the design of a cable stayed bridge is the number and disposition of planes of cables: central plane or two laterals. The advantage and drawback of both possibilities are discussed in the following paragraphs.

3.2.1 Single plane of cables

In this case, the torsion forces caused by the asymmetric live load has to be resisted by the concrete box, for that reason, the deck's depth is larger due to the central suspension arrangement and as a result, the longitudinal bending moments increase as a stiffer cross section attracts more flexural forces.
Common values of the ratio span/depth of these types of decks are within the range of 1/80 to 1/120. Those values are far from the one of the classic slender floating deck with lateral suspension, which is in the range of 1/180 to 1/300.
In general, a central pylon is feasible. This type of mast is easier to build than other types of pylons as 'H' or 'A' shapes. The main drawback is the extra-width of the deck required to place the pylon.

Figure 2: Monotower with an extra space for the pylon: Usk River

An alternative solution that avoids the widening of the deck is to use an "A" shape's pylon, or even better a diamond-shape's tower (see figure 3). Those possibilities are only feasible in the case of big spans (more than 400 m), to limit the inclination of the legs of the pylons to values (less than 15 to 20º) in order to avoid severe bending flexure of the legs due to its own self-weight. The occurrence of a severe bending of the pylon legs could also be alleviated by introducing an A-shape type of arrangements in both directions as in the Rion-Antirion bridge in Greece (2005).

Figure 3: Single central plane with diamond shape's pylons

3.2.2 Lateral planes of cables

In this case the torsion caused by the asymmetric live load will be mainly resisted by differential forces of the stays on each side of the cross section.

Therefore in this case, the deck does not need to have significant torsion stiffness; as a consequence it is possible to increase the longitudinal slenderness of the deck, yet the pylon stabilisation is guaranteed. When the deck is suspended from its edges, the transversal flexure of the deck is becoming more important. Due to this highlighted importance of ensuring sufficient resistance to transverse bending, a ladder deck, formed by two lateral webs and a set of transverse beams is the most efficient deck system.

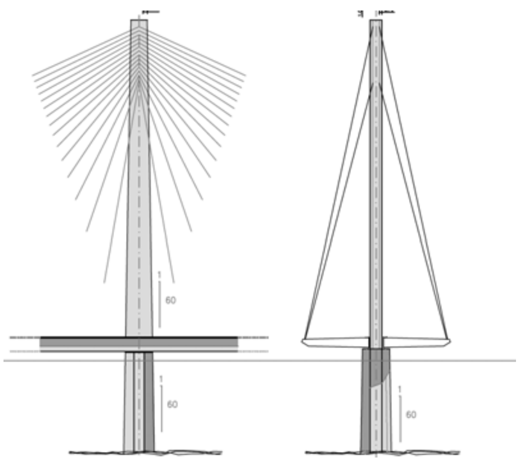


Figure 4: Central pylon with lateral suspended deck.

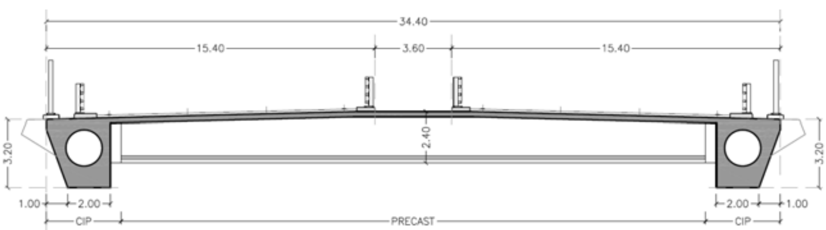


Figure 5: Ladder deck

3.3 Cross section design

As it was aforementioned, the optimization of the self-weight played a determinant role to increase the span range of the concrete decks. Therefore the refinement of the cross-section design is crucial to achieve the required span. In the following paragraphs, the governing conditions of the deck are described, as well as, the strategy to decrease the self-weight of the different structural elements.

3.3.1 Box Cross Sections

Box cross sections are formed by an upper deck slab, the concrete webs and the bottom concrete flange.

The upper deck slab has to resist directly the traffic loads. In general the design of the slab is governed by the transversal flexure due to those concentrated loads of the traffic.

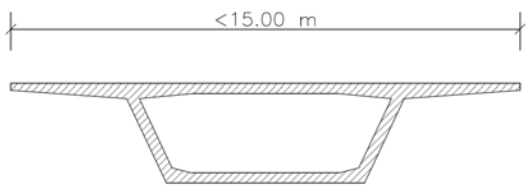


Figure 6: Narrow cross sections, without ribs or struts

For bridges where the deck width is less than 15 m wide, the slabs do not required struts or transversal cross beams to solve the lateral cantilever wings.

Shear forces are also important and haunched slab is used in the vicinity of the connection with the webs to increase the shear capacity of the webs. In the case of bridges for motorways with 4 lanes or similar, the use of struts or transversal ribs is necessary to resist the transverse bending moments of the cantilevers.

Figure 7: Wide cross section with transversal webs or with struts

In general, both alternatives: prefabricated struts or transversal ribs work well. Nevertheless, when the deck has a variable width, the struts have to be of variable length. That situation is normal where central suspension and single mast are used.

In those cases is very common to use a deck that increase its width from lateral spans to central one, in order to have enough space in the central spans to accommodate the central masts. In that situation, prestressed transversal beams are easily adapted to different widths: figure 8

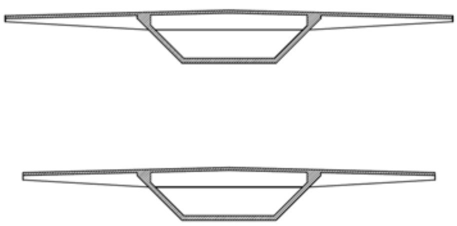


Figure 8 Cross section with different widths and transversal cross beams.

One limitation of the struts is the lack of efficiency when the angle of the struts with the horizontal is less that 20-25º. In that case, that small inclination produces also a significant tensile force in the slab which the consequent difficulty to fulfil the Service Limit State conditions.

In the case of cable-stayed bridges with longitudinally variable decks is very common that the core of the deck maintains a constant width while it is different from the total deck width. Therefore the wings have a variable length, and the struts cannot be equal, losing its efficiency as the cantilevers increase its length.

The second component of the cross sections are the webs. They have to resist the shear forces. In general the prestress does not run inside the webs as it is the normal fashion in girder decks; tendons are normally located at the top and bottom slabs and are horizontal, therefore the width of the webs could be as narrow as possible as there is no need to increase its width to allocate the sheaths of the tendons.

The third component of the cross section is the bottom slab. The thickness of the bottom slab could be streamlined to ensure a good cast of the concrete. Only in the areas in close proximity to the pylons, an increase of the thickness may be deemed to be justified.

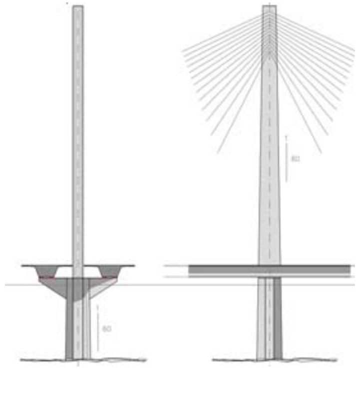
In those areas, when the deck is vertically supported, hogging moments could appear. The combination of a severe axial force with a hogging moment may require an increase of the thickness so to cope with the compression stress limit at the serviceability limit state (SLS), and to have enough compression area in ultimate limit state (ULS).

As it was aforementioned, in the rest of the deck away from the pylons support areas, the required bottom thickness ranges from 0.20 to 0.25m. In those areas the sagging moments create tensile forces in the bottom part of the section which are resisted by the tendons.

Bearing in mind the aforementioned considerations, the sections can be designed extremely shallow, with an equivalent thickness of less than 0.50m, which means a self-weight in the range of 12.5kN/m^2, being the total load in the range of 18kN/m^2, which is not far from the 16.0kN/m^2 typical of the composite solutions.

3.3.2 Double Box Sections

Only in extremely wide cross sections (as in the range of 40 m), a double concrete box section could be a feasible solution: figure 9



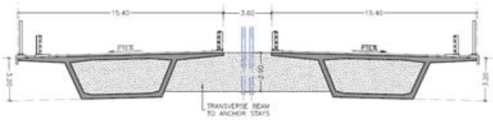


Figure 9: Double concrete box

4 Prestress layout

In concrete cable stayed bridges, the prestress forces need to be controlled, first in the area close to the pylon, where hogging bending moment have to be resisted, in particular in the first construction stages where the deck is working as a balanced cantilever.

The other critical area is the central part of the deck, where there is no axial compression force due to the stays. There the governing sagging moments would attract tensile stresses to the concrete.

Another important aspect is that in flexible decks, the secondary prestressed bending moments due to the redundancy of the structure, became just opposite to the primary ones, resulting in an axil load. [3]

It is important therefore to recognize during the design stage the global effect of the prestress force including the primary and secondary bending moments caused by its eccentricity from the center of gravity of the cross section, and its influence in the redistribution of forces due to creep and shrinkage at the long term stages.

One critical point in prestressed concrete decks is the severe requirement regarding tensile stresses in the concrete in the vicinity of the tendons. This problem could be sorted out by using external prestress. In this case, the cracking conditions are less demanding, as they are the same as in reinforced concrete decks.

3.4 Continuous Cable Stayed Bridges

Modern demands and technology are leading to the design of long crossings, where classic three spans cable stayed bridges are not feasible.

Long continuous cable stayed bridges, are the right solution, but the lack of back stays anchored to a fix point introduce strong implications in the design

Figure 10: Example of a continuous cable stayed bridge [4]

In continuous cable stayed bridges, the importance of the relative stiffness between pylons and deck and their connections (bridge articulation) and the cable arrangement are the key variables in the design. [5]

3.5 Main span versus approach spans design

One of the advantages of using concrete decks in cable-stayed bridges is the easy integration between the cable stayed sections and the approach spans. With the use of concrete decks, it is possible to provide a clean transition, ensuring uniformity regarding construction, structural efficiency and a high quality visual appearance.

Figure 11: Usk River Crossing, UK. FHECOR]

3.5 Construction

The construction of medium and long span cable-stayed bridges is normally achieved by balanced cantilever construction techniques. In those cases, the balance of the construction of both sides of the pylons is necessary, in order to not overdesign pylon and foundation at the temporary stage design situations.

In those cases, the casting of the deck is done in one stage by means of travellers that transfer the self-weight of the casting segment to the previous constructed structure.

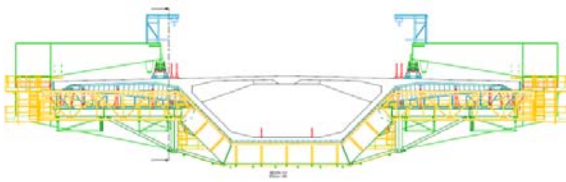



Figure 12: Mersey Cable Stayed Bridge: Flint and Neill and FHECOR: Travellers for the construction of the main spans [6]

6. References

1 Leonhardt F. (1987) Cable Stayed Bridges with Prestressed Concrete. Special Report PTI

2 ENV 1992-1-1 (2004) Eurocode 2 Design of Concrete Structures

3. Svenson H.(2012) Cable Stayed Bridges. Ernst&Sohn

4. Romo J. (2015) Four Spans contiuous cable stayed bridge without extra cables. Multispan Large Bridges Conference. Porto

5 Virloguex M. (2001). Bridges with Multiple Cable-Stayed Spans. SEI IABSE.

6. Sanders P, Brennan G, Wood H, et al (2016) Mersey Gateway Bridge - Design for Construction. IABSE Stockholm 2016