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RESEARCH ACHIEVEMENTS IN UNDER-DECK AND COMBINED CABLE-STAYED BRIDGES

Ana M. Ruiz-Teran[1], Angel C. Aparicio[2]
[1] *Principal Lecturer in Structural Engineering. University of East London (UEL), UK*
[2] *Professor in Bridge Engineering. Technical University of Catalonia (UPC), Spain*
e-mails: a.m.ruiz-teran@uel.ac.uk; angel.carlos.aparicio@upc.es

Abstract: Under-deck cable-stayed bridges and combined cable-stayed bridges constitute two innovative bridge types that have been designed and built on only a few occasions over the last thirty years by outstanding structural engineers, such as Leonhardt, Schlaich, Menn, Virlogeux, Manterola, and Cremer. In these bridge types, the stay cables have unconventional layouts: below the deck, in the case of under-deck cable-stayed bridges, and above and below the deck, in the case of combined cable-stayed bridges. Over the last few years, major research advances related to these bridge types have been made to the point that now research dictates the development of these new bridge typologies. In this communication, a general overview of the current state-of-art will be set out; addressing issues related to built bridges, research developments, structural behaviour, design criteria and potential applications for these innovative bridge types. Major attention will be paid to their highly-efficient structural behaviour, that allows a significant reduction in the amounts of materials in comparison with conventional bridges, leading to sustainable design. Other advantages of these structural types, such as the numerous construction possibilities, aesthetical properties, and broad range of potential applications, will also be stressed.

Keywords: under-deck cable-stayed bridges; combined cable-stayed bridges; bridge design.

1. Introduction:

Under deck and combined cable-stayed bridges are two relatively new types of cable-stayed bridges that have been developed over the last thirty years. Stay cables are usually assumed to be above the deck in cable-stayed bridges, but this is not always the case. In under-deck cable stayed bridges, the stay cables are located below the deck and deviated by means of struts that, working under compression, introduce the cable upward deviation force in the deck. In combined cable-stayed bridges, the cables are located above and below the deck, and deviated by means of both pylons located above the deck and struts located below the deck.

Around thirty bridges with these structural types have been constructed over the world over this period. Most of them are located in Germany, Japan, France and Spain (Ruiz Teran and Aparicio 2007a).

2. Historical development of under-deck and combined cable-stayed bridges:

The first under deck cable stayed bridge was Weitingen viaduct (Figure 1), designed by Fritz Leonhardt. It was completed in 1978. The first combined cable-stayed bridge was Obere Argen viaduct (Figure 2), designed by Jorg Schlaich. It was completed in 1991. In both cases, the unconventional cable stayed layouts were introduced in order to avoid the construction of the end piers of both viaducts. In both cases, the soil creeping in the slopes of the valleys would have made very difficult the design and expensive the construction of the end piers of both viaducts.

Figure 1. Weitingen viaduct (photograph courtesy of Holger Svensson, Leonhardt, Andra und Partner)

Figure 2. Obere Argen Viaduct (photograph courtesy of Jorg Schlaich, copyright Elsner, Gert, Stuttgart).

By prestressing the stay cables, it was possible to eliminate the end piers of the viaduct. The stay cables were prestressed in a way in which the bending moment diagrams in permanent state, under dead load and the superimposed dead load, were exactly the same as those in the bridges in which the end piers had not been eliminated. These stay cables are also active and efficient under traffic live load (Ruiz-Teran and Aparicio 2007b). This efficiency allows the design of deck with higher slenderness than those in conventional bridges without stay cables. A few excellent design proposals using these schemes were rejected, since the high slenderness achieved were received with trepidation rather than with approval (Ruiz-Teran and Aparicio 2007a).

After this uncertain initial period, in the nineteen-nineties, several worldwide renowned structural engineers, such as Virlogeux (Figure 3), Manterola (Figure 4) and Cremer (Figure 5), design bridges with these types.

Figure 3. Truc de la Fare fauna overpass (photograph courtesy of Nicholas Janberg, www.structurae.de)

Figure 4. Osormort viaduct (photograph courtesy of Javier Manterola)

Figure 5. Jumet footbridge (photograph courtesy of Jean Marie Cremer).

A few research studies considering these new bridge typologies started to be published at the latest nineteen-nineties. However, all of these studies were focussed on different topics and tangentially consider these bridge types. By the beginning of the twenty-first century, despite the number of bridges with these structural types already constructed, there was not any study available providing understanding about the structural behaviour of these bridges and proposing appropriate design criteria.

3. Recent research achievements:

In 2005, Ruiz-Teran submitted a PhD Thesis about the structural behaviour and design criteria of under-deck and combined cable-stayed bridges (Figure 6) that was supervised by professor Aparicio.

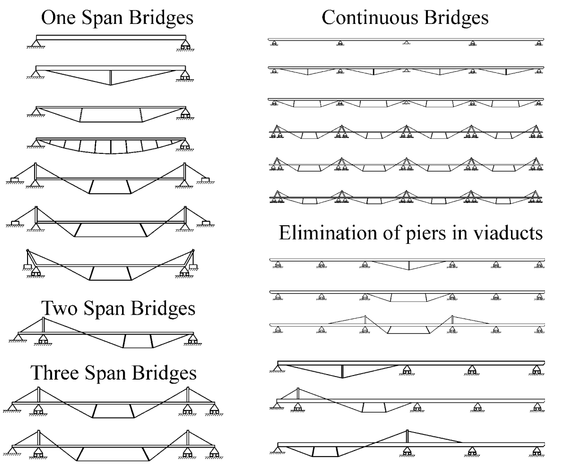

Figure 6. Different schemes of under-deck and combined cable-stayed bridges studied by the authors

Ruiz-Teran and Aparicio have outlined the state-of-art of these bridge types (Ruiz-Teran and Aparicio 2007a), have identified the parameters that govern their structural response (Ruiz-Teran and Aparicio 2007b), studied their structural behaviour and proposed design criteria for both single-span (Ruiz-Teran and Aparicio 2008a) and multi-span (Ruiz-Teran and Aparicio 2008b) bridges, studied their structural response under breakage of stay cables (Ruiz-Teran and Aparicio 2009a), proposed unconventional cable-stayed layouts for the elimination of both intermediate and end piers in viaducts, and proposed appropriate methodologies for the analysis of the dynamic response under either the breakage of stay cables (Ruiz-Teran and Aparicio 2007c) or the transit of traffic live load (Ruiz-Teran and Aparicio 2009b), since traditional procedures were demonstrated to be inappropriate. As a consequence of these research achievements, the FIB Diploma 2009 for research, awarded by the International Association of Structural Concrete (FIB), was presented to the first author of this paper (Ruiz-Teran 2009).

4. Main features:

4.1 High efficiency of the cable-staying systems:

The efficiency of the cable staying system (Ruiz-Teran and Aparicio 2007b) can be measured through a parameter β that represents the fraction of the external isostatic moment ($qL^2/8$ due to a uniform-distributed load q and QL/4 due to a point load Q, in a beam of length L) that is resisted by means of the tension of the eccentric stay cables. The efficiency of the cable-staying system is inversely proportional to the relative rigidity of the deck to the cable-staying system, χ, that is given by:

$$\chi = \frac{EI}{E_{SC}A_{SC}L^2}\, g_I\left(\frac{L_s}{L}, n\right) + \frac{I}{AL^2}\, g_A\left(\frac{L_s}{L}, n\right) \quad (1)$$

where E and E_{SC} are the Young´s modulii of the deck and of the stay cables respectively, A and A_{SC} are the cross-sectional area of the deck and of the stay cables respectively, I is the moment of inertia of the deck, L_S is the length of the strut at mid-span section, n is the number of struts. g_I and g_A are two functions that are defined on the basis of the geometry of the cable-staying system and are inversely proportional to L_S/L and n. The smaller the relative rigidity of the deck to the cable-staying system, the larger the efficiency of the cable-staying system.

4.2 Span subdivision:

The span subdivision (Ruiz-Teran and Aparicio 2008a,b) is easily achieved in these bridges by prestressing the stay cables in a way that the vertical components of either the anchor forces of the stay cables in the deck or the cable deviation forces introduced in the deck by means of the struts are equal to the vertical reactions in a continuous beam with supports in the sections of the deck in which either the stay cables are anchored in or the struts are connected to (Figure 7c). The larger the efficiency of the cable-staying system, the smaller the component in the stay cable loads in permanent state due to the active prestressing of the cables and the larger the component due to the passive response due to the self-weight and the superimposed dead load. In addition, the smaller the flexural stiffness of the deck, the larger the efficiency of the cable staying system, the smaller the losses in the cables and consequently the smaller the redistribution of internal forces due to time-dependent effects. In under deck and combined cable-stayed bridges, the span subdivision is almost maintained over time owing to the small redistribution of internal forces due to time-dependent effects (Figure 7d).

4.3 Efficiency under traffic live load:

In order to design cable-staying systems that are efficient under live load it is necessary: (1) to design stay cable layouts with large eccentricities at the critical sections of the deck, locating them beyond the side of the deck in which tensile stresses are introduced due to the existing bending moments, and (2) to design the bridge with a small relative rigidity of the deck to the cable-staying system. The satisfaction of both conditions leads to cable-stayed bridges that resist the traffic live load mainly by axial response rather than by flexural response. The bending moment envelopes due to traffic load (Figure 7e,f) are significantly different to those in conventional bridges without stay cables. High efficiencies (β=0.9) can be easily achieved in these types of bridges.

4.4 High sensitivity to vibrations due to traffic live load:

The reduction of the flexural response allows a large reduction in the deck depth that leads to a significant increase of the accelerations in the deck due to the transit of heavy vehicles (Figure 7g). In fact, the deck of the deck in road bridges of these structural types with short and medium spans is governed by the SLS of vibrations. This SLS must be verified following an acceleration-based approach, since the traditional deflection-based approach considered by many codes leads either to unsafe design or to overdesign (Ruiz-Teran and Aparicio 2009b). For example, the maximum vertical accelerations in the under-deck cable-staying road bridge included in Figure 7g are equal to 0.41 m/s^2, i.e.14 times larger than that in a road bridge with the same length without stay cables.

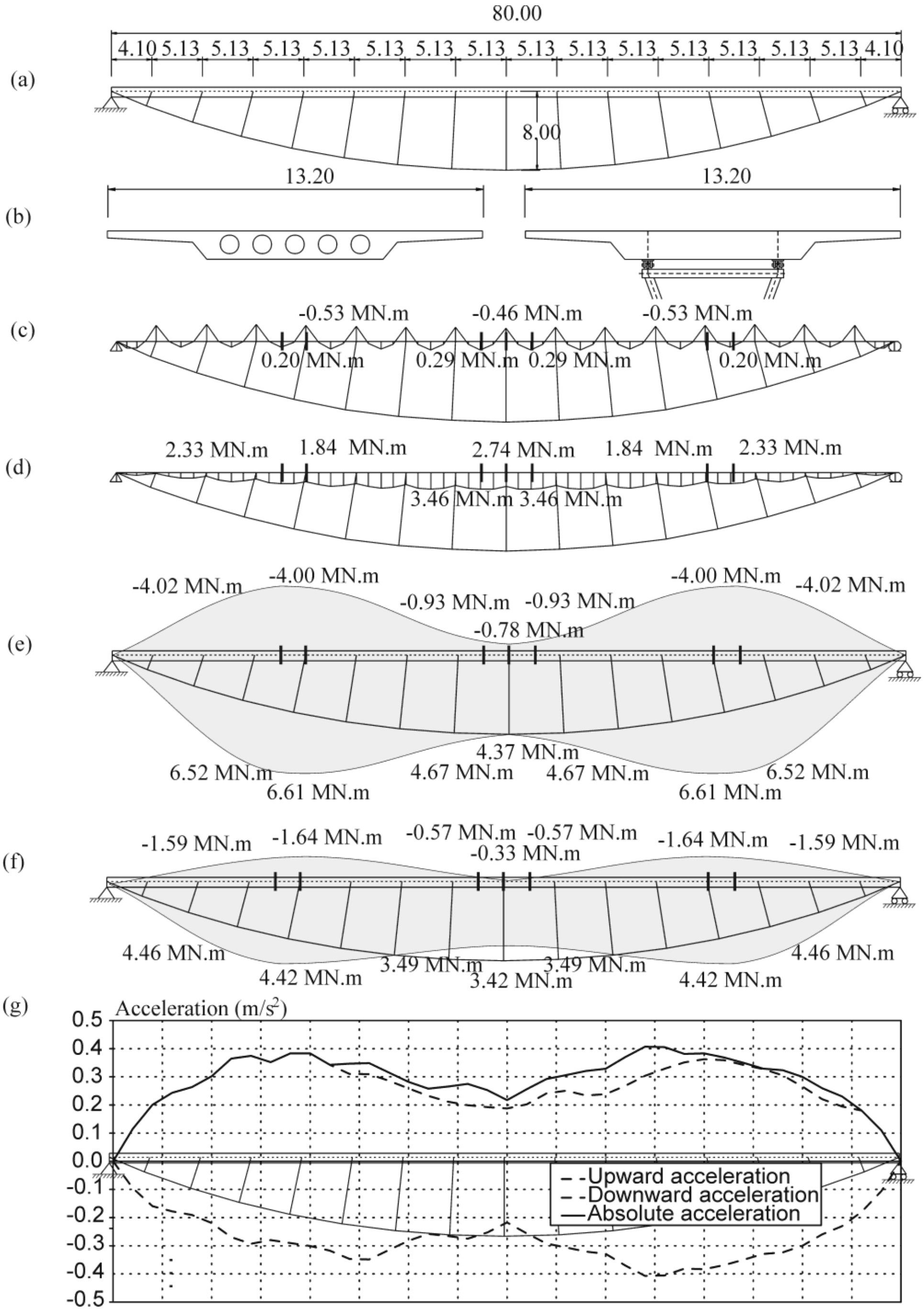

Figure 7. Diagrams in an 80 m span under-deck cable-stayed bridge with multiple struts: (a) Elevation of the bridge; (b) cross-sections of the deck; (c) bending moment diagram in permanent state due to self-weight (184.86 kN/m), superimposed dead load (43.10 kN/m) and prestressing of stay cables; (d) bending moment diagram in permanent state due to due to self-weight, superimposed dead load, prestressing of stay cables, concrete shrinkage, concrete creep and relaxation of the internal prestressing; (e) bending moment envelope due to a uniformed distributed traffic live load equal to 52.8 kN/m (4 kN/m2); (f) bending moment envelope due to a point traffic live load equal to 600 kN; (g) envelope of vertical accelerations due to the passage, from the left to the right abutment, of two vehicles of 400 kN at 60 km/h

4.5 Sustainable design due to small amount of conventional materials:

The reduction of the flexural response leads to a significant reduction in the amount of materials required for the deck, in comparison with conventional bridges without stay cables. These new structural types are therefore compliant with sustainable design considerations. For bridges with prestressed concrete decks and main spans of 80 m, in single-span bridges, the depth of the deck is reduced to 20% (with slenderness equal to 1/80), the self weight to 30% and the amount of active steel to 30% (Ruiz-Teran and Aparicio 2008a); whereas, in continuous bridges, the depth of the deck is reduced to 25% (with slenderness equal to 1/100), the self weight to 60% and the active steel to 40% (Ruiz-Teran and Aparicio 2008b).

4.6 Great construction possibilities:

These structural types offer a wide range of possibilities from the point of view of construction. In fact the use of these bridge types would allow the extension of the span range of certain construction methods, such as the bridge construction by means of longitudinal precast prestressed elements (with joints over the struts, and assembled on site) (Ruiz-Teran and Aparicio 2007a) and the construction of viaducts by means of self launching gantries (Ruiz-Teran and Aparicio 2007b) (due to the large reduction in the self-weight). In addition, these systems allow the construction of bridges over deep valleys or wide rivers without using falsework, since the under-deck cable staying system can be used as a temporary bearing system.

4.7 Large capacity for withstanding the sudden breakage of stay cables:

These bridges are able to overcome scenarios that are far more severe than that demanded by the codes in relation to the accidental breakage and sudden loss of stay cables (Ruiz-Teran and Aparicio 2009a). The analysis of this accidental situation must be performed through a proper dynamic analysis and not through the simple traditional approach based on dynamic amplification factors (that is suggested by many codes and guidelines), since this approach have been shown to be unsafe.

4.8 Linear behaviour:

These bridge types can be safely analysed through linear analyses (Ruiz-Teran 2005). The consideration of the mechanical non-linearity of the prestressed concrete sections for ultimate limit states implies the reduction of the flexural stiffness of the deck and the reduction of the non-dimensional parameter χ (see Eq. 1), and, consequently, the increase of the efficiency of the cable-staying system. This redistribution of internal forces is favourable for the design of the deck and does not affect the design of the stay cables, since their design is governed by the ULS of fatigue rather than by the ULS of normal stresses. The small geometrical non-linearity of the bridge does not affect the design of the deck, although it must be considered for the design of the struts.

5. Applications:

5.1 Single-span bridges:

Both under-deck and combined cable-staying systems are very appropriate for single-span bridges (Ruiz-Teran and

Aparicio 2008a) (see Figure 6). Nevertheless, there are certain differences between the two systems that significantly affect the design. Combined cable-staying bridges required about half the cross-sectional area for the cables than under-deck cable-staying systems, due to the higher effective eccentricity of the combine cable-staying systems – approximately equivalent to the sum of eccentricities in mid-span and support sections. However, the need for back stays leads to a similar amount of active steel. In addition, the required counterweights for anchoring the back stays significantly affect the cost in materials per square metre of the structure.

5.2 Multi-span bridges:

For continuous bridges, only combined cable-staying systems have a high efficiency under traffic live load (Ruiz-Teran and Aparicio 2008b) (see Figure 6). Under-deck cable-staying systems are appropriate for achieving span subdivision, although the losses in the stay-cables due to time-dependent effects are significant. However, they are not efficient enough under live load when the eccentricities are admissible from an aesthetic point-of-view (Ruiz-Teran and Aparicio 2007b). Under-deck cable-staying systems are suitable for multi-span bridges when the spans are independent, only creating a semi-continuous slab by means when the road users' comfort must be guaranteed.

5.3 Elimination of piers and viaducts with unbalanced span distribution:

The implementation of under-deck and combined cable-staying systems in viaducts allows the elimination of certain piers. By the implementation of under deck and combined cable-staying systems, the main characteristics of the deck (such as depth, concrete strength, amount of reinforcement, amount of active steel, etc) can be maintained, despite the existence of a particular span in the viaduct being double the length of the other spans (Ruiz-Teran and Aparicio 2008c). These schemes are therefore very appropriate when due to non-structural conditions it necessary to have one span in a viaduct of significantly larger length than the rest. In addition, it could be considered as an alternative option when a pier in a built bridge has to be shifted. In these cases, the span subdivision can be achieved in permanent state prior to time-dependent effects, although the losses due to time-dependent effects are not negligible. However, the hogging bending moments in the larger span due to traffic live load would double those in other spans, since the efficiencies of the cable-staying systems are not large enough due to the fact that the slenderness of the deck is not high enough. The design strategy must be to counteract the increase in the bending moments due to traffic live load with the reduction of the bending moments in permanent state resulting from the span subdivision.

6. Conclusions:

This paper has presented a general overview of the recent research achievements in under-deck and combined cable-stayed bridges. In addition, the main features and field of application for these types of bridges have been highlighted. In summary, these bridges, that have been introduced and developed by outstanding structural engineers (such as Leonhardt, Schlaich, Virlogeux, Manterola, Robertson and Cremer) and constructed mainly in Germany, Japan, France and Spain, have a very efficient structural behaviour, require a small amount of materials for the deck (in comparison with conventional bridges without stay cables), allow sustainable design, have great possibilities, and posses strong aesthetic characteristics.

The work presented in this paper for the 13th School Conference in Advances in Computing and Technology, held at the School of Computing, IT and Engineering of the Univeristy of East London is a summary of a journal publication submitted by Ruiz-Teran and Aparicio (2010).

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