Structural behaviour and design criteria of

Under-deck cable-stayed bridges and Combined cable-stayed bridges.

Multi-span bridges.

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Abstract

This paper deals with the application of under-deck cable-staying systems and combined cable-staying systems to prestressed concrete road bridges with multiple spans of medium length. Schemes using under-deck cable-staying systems are not suitable for continuous bridges, since they are not efficient under traffic live load and only allow for the compensation of permanent load. However, combined cable-staying systems are very efficient for continuous bridges and enable the design of very slender decks (1/100 of span) where the amount of materials used is halved in comparison with conventional schemes without stay cables. In this paper, the substantial advantages provided by combined cable-staying systems for continuous bridges (such as high structural efficiency, varied construction possibilities, both economic and aesthetical benefits, and landscape integration) are set out. Finally, design criteria are included.

Key words:

under-deck cable-staying; combined cable-staying; cable-stayed bridges; prestressed concrete; bridges

1. Introduction

Over the last thirty years, more than twenty bridges have been built using under-deck cable-staying systems (cable-stayed bridges with the stay cables located below the deck) and combined cable-staying systems (cable-stayed bridges with the stay cables located both above and below the deck). Some of them are multi-span continuous bridges. For at least nine continuous bridges, these new types of cable-staying systems were designed in order to solve a specific problem in a certain span, such as the elimination of a particular pier or the placement of a span with a larger length. However, only on very few occasions, such as in three proposals —made by Schlaich and Menn in the 1980s— and in two built structures —Osormort viaduct (Figure 1) and Montabaur footbridge—, these new types of cable-staying systems have been used as a structural scheme for all the spans of a viaduct (Ruiz-Teran 2005; Ruiz-Teran and Aparicio 2007a).

After having established the substantial advantages offered by these cable-staying layouts applied to single-span bridges (structural efficiency, enhanced construction possibilities, and both aesthetic and economic benefits) (Ruiz Teran and Aparicio 2007c), in this paper the suitability of these bridge types for application to multi-span bridges is examined. The structural behaviour of these bridges is analyzed by means of a carefully chosen limited selection of the extensive bridge collection designed and studied by the authors in a previous research project. Lastly, a set of design criteria for multi-span bridges with under-deck cable-staying systems and combined cable-staying systems is established. Although many of the conclusions drawn in this paper are of a general nature, the study focuses on the application of under-deck cable-staying and combined cable-staying to prestressed concrete road bridges with medium-spans (80 metres).

2. Multi-span bridges with under-deck cable-staying systems

In under-deck cable-stayed bridges the stay cables have a polygonal layout under the intrados of the deck. They are self-anchored in sections of the deck which are supported over the piers or over the abutments and they are deflected by struts which, working under compression, introduce the upward deviation forces of the stay cables into the deck.

2.1. Continuous under-deck cable-stayed bridges with 2 struts

2.1.1 Detailed description of one selected bridge of this morphology

The selected bridge has 80-metre spans (Figure 2). The deck is a prestressed concrete box with a depth of 1.60 metres, giving a depth/span ratio of 1/50. The morphology of the cable-staying system was established using the same design criteria as recommended for single-span bridges (Ruiz-Teran and Aparicio 2007c), however the slenderness attained in the deck is less than that obtained for single-span bridges (1/50 against 1/80). In any event, the deck is still much more slender than conventional bridges without cable-staying (1/25). The under-deck cable-staying system, made up of 191 strands, each with a cross-sectional area of 140 mm² and an ultimate stress of 1860 MPa, is self-anchored in the deck and deviated by two struts. The struts support the deck at third-span sections by means of pins and are oriented along the bisector of the angle formed by the stay cables. The under-deck cable-staying system has an eccentricity at mid-span equal to 1/10 of the span. The characteristic strength of the concrete in the deck is 40 MPa.

2.1.2. Response to Permanent state

During permanent state, three actions exist: the dead load (self-weight of the structural elements: $g_1=191.85$ kN/m), the superimposed dead load (self-weight of the non structural elements: $g_2=43.10$ kN/m) and the prestressing. The stay cables are prestressed to compensate 100% of the permanent loads (g_1+g_2), so that the vertical component of the load introduced by the struts into the deck is equal to the reaction in a continuous beam with supports in the

sections where the deck lays over the struts. Thanks to the prestressing and the suitable layout of the struts, the span is subdivided and the bending of the deck is reduced to the local bending between struts (Figure 3). The 'efficiency of the under-deck cable-staying system', ξ (Ruiz-Teran and Aparicio 2007b, 2007c) under a uniform load g_1+g_2 , which is the portion of the external isostatic moment resisted by the cable-staying system, is very low ($\xi=0.28$, Table 1) in comparison with the efficiency achieved in single-span bridges with under-deck cable-staying systems designed using the same criteria ($\xi=0.89$) (Ruiz-Teran and Aparicio 2007c). In permanent state, the stay cables are stressed to 20.88 MN; 31% is due to the response to permanent load (g_1+g_2) and the remaining 69% is due to prestressing. Given the low efficiency of the under-deck cable-staying system, prestressing has the largest contribution in permanent state. The losses in the stay cables (11%) due to time-dependent effects (shrinkage and creep of the concrete and relaxation of the internal prestressing) are significantly higher than that (2%) found in single-span bridges with under-deck cable-staying systems (Ruiz-Teran and Aparicio 2007c). This fact is due to the larger flexural stiffness of this deck, as a result of the continuity and the larger deck depth (1/50 as against 1/80).

2.1.3. Static response to traffic live load

The bending moment envelopes of the deck due to traffic live loads ($q=52.8$ kN/m and $Q=600$ kN in the Spanish Code (IAP 1998)) have been obtained (Figure 4). An eccentricity factor equal to 2 has been used in order to take into consideration the non uniform transverse distribution of the longitudinal bending moments due to the 600-kN vehicle. The eccentricity factor, also called distribution coefficient (Cusens and Parma, 1975), is the ratio between the maximum and the mean longitudinal bending moment per unit of transversal width due to a point load. The value of 2 is conservative and has been established on the basis of a detailed model of the bridge.

The bending moments due to traffic live load are halved in comparison with those found in conventional bridges without stay cables — a smaller reduction than the reduction to one fifth obtained for single-span bridges (Ruiz-Teran and Aparicio 2007c). In this case, the greatest bending moments occur in the support sections over piers, where the cable-staying system has no eccentricity and bending of the deck is, therefore, the only structural response available at that section.

2.1.4. Dynamic response to traffic live load

The dynamic response of the structure under two 400 kN vehicles crossing the bridge at speeds of 60 km/h —which is the dynamic test recommended in Spain (Fomento 1999) — has been analysed by means of a step-by-step time integration (with increments of 0.001 seconds). A damping factor equal to 2% has been adopted—similar values have been measured in Glacis Bridge (Schlaich and Werwigk 2001) and Takehana Bridge (Nakagawa et al. 2001), both of which are under-deck cable-stayed bridges. The maximum vertical acceleration registered is equal to only 0.06 m/s².

2.1.5. Verification of Service Limit States (SLS)

Internal prestressing in the deck made up of 400 strands, each of 140 mm², and stressed to 1450 MPa, satisfies the required limit states for concrete structures (EHE 1999; Eurocode-2-1-1 2004): the decompression SLS under the quasi-permanent action combination (permanent actions + 20% live load); the controlled cracking SLS under the frequent action combination (permanent actions + 50% live load); and the stress limitation SLS under the rare action combination (permanent actions + 100% live load). The internal prestressing has a layout that is similar to that of a beam with supports at the sections where the deck lays over the struts.

The vibration SLS is satisfied amply, since maximum accelerations are only 13% of the allowed maximum (0.45 m/s²). Vertical accelerations are limited to $0.5\sqrt{f_0}$, where f_0 is the

main frequency of vibration of the structure (BS 5400-2 1978; Eurocode 2-2 2001).

2.1.6. Verification of Ultimate Limit States (ULS)

The fatigue ULS determines the cross-sectional area of the stay cables. External prestressing anchorages allow frequent variations in tension of 80 MPa and maximum tensile stresses of 65% of the tensile strength. Stress variations due to frequent live load are 80 MPa and the maximum stress reaches 51% of the tensile strength of the stay cables. The tension ULS in the stay cables is verified amply.

The bending ULS is just satisfied at the support sections over the piers. The deck depth is restricted by this limit state and, therefore, it cannot be reduced in this section with the aim of both increasing the efficiency of the cable-staying system and reducing the bending moments in the deck due to traffic live load. The use of a variable-depth deck, reducing the depth towards the mid-span section, would increase the efficiency of the cable-staying system but would also increase the value of the hogging bending moments in the support sections due to traffic live load, and consequently this scheme has not been considered. The shear ULS is met amply.

2.2. Study of the influence of the number of struts and the continuity grade between spans

Table 2 shows the main features of four multi-span bridges with 80-metre spans. Three of them are continuous bridges: one conventional bridge without stay cables and two under-deck cable-stayed bridges with one and two struts. The fourth, that is not continuous, is an under-deck cable-stayed bridge with independent spans, similar to those designed for single-span bridges (Ruiz-Teran and Aparicio 2007c). In continuous bridges with under-deck cable-stayed systems, the larger the number of struts, the larger span subdivision, and the smaller bending moments of the deck in permanent state. However, it is important to stress that the losses in

the stay cables due to time-dependent effects and, consequently, the redistribution of internal forces are quite significant because of the high stiffness of the deck. Likewise, the larger the number of struts, the smaller the bending moments in the deck due to traffic live load and the higher the efficiency. However, it is important to stress that the efficiencies of these systems in continuous bridges are quite minor (around 30%) and, therefore, most of the external isostatic moment due to live load is resisted through the flexural response (of the deck) and not through the axial response (of the cable-staying system). Because of the magnitude of the depths (that are limited by the bending ULS at the support sections) as well as the continuity of the deck, the cable-staying system efficiencies are low regardless of the number of struts used. Consequently, in continuous bridges, under-deck cable-staying systems allow permanent load to be partially compensated but are not efficient under traffic live load.

In order to make cable-staying systems efficient under live load, only two alternatives are available: (1) either breaking the continuity between spans at the support sections over piers, by designing independent span decks, in which very high efficiency is obtained (Table 2); or (2) maintaining continuity between spans and designing other, more efficient, cable-staying layouts. If the former alternative is chosen, semi-continuous layouts that mitigate the transition between spans, ensuring the road-users' comfort, should be designed. If the latter alternative is chosen, the only way to design more efficient cable-staying systems is to increase the total eccentricity using combined cable-staying systems. Eccentricities in under-deck cable-staying systems are limited (around 1/10 of the span) by aesthetic considerations (Ruiz-Teran and Aparicio 2007b), whereas total eccentricities in combined cable-staying systems are close to the sum of the eccentricities at the support section and at the midspan section (Ruiz-Teran and Aparicio 2007c). Thus, combined cable-staying systems will allow relatively large eccentricities to be maintained while keeping within admissible ranges from an aesthetic point of view as well as increasing the total eccentricity of the cable-staying

systems.

3. Multi-span bridges with combined cable-staying systems

In this section, the question of whether or not combined cable-staying systems (Figure 5) have larger efficiencies under traffic live load is examined.

3.1. Efficiency of combined cable-staying systems in multi-span continuous bridges

Combined cable-staying systems for multi-span continuous bridges must be efficient under traffic live load even when the load is acting on alternate spans. This is a classic issue in conventional cable-stayed bridges, in which the efficiency is ensured by controlling the horizontal movements of the tower heads through various means (Gimsing 1997; Walter 1999; Manterola and Rodado 2000), such as: (1) giving the towers a large flexural stiffness; (2) making the towers triangular by splitting each pylon into two inclined legs; (3) making use of stay cables that brace each tower head from the support section of the deck on the adjacent towers; or (4) making use of horizontal stay cables that brace all the tower heads. These are the standard schemes for cable-stayed bridges with long spans, but in the case of combined cable-stayed bridges in the range of medium spans (80 metres) this set of alternatives must be reconsidered. Given the smaller dimensions of the structure, the most economic and aesthetical approach is to act on the pylons, making use of either of the first two alternatives mentioned above.

In this study, the second option was chosen (Figure 5) —splitting the pylons into two inclined legs fixed on the deck, which is in turn supported on the piers— in order to make the study independent of the pier stiffness. Choosing the first option would have led to similar structural behaviour and a slightly increased deck span.

3.2. Continuous combined cable-stayed bridges with two struts

3.2.1 Description of one selected bridge of this morphology

Once again, the bridge has 80-metre spans, with support sections at 72-metre centres (Figure 5a). The deck is a voided prestressed concrete slab (f_{ck} : 55 MPa) with a depth of 0.70 metres (depth/span ratio: 1/103) (Figure 6). The combined cable-staying system, made up of 122 strands, each of 140 mm^2 ($f_u = 1860 \text{ MPa}$), is anchored to the pylons, goes through the deck inside guide pipes (there is no connection between the stay cables and the deck in the section where both cross) and is deviated under the deck by means of two struts. The struts support the deck at third-span sections by means of pins and are oriented along the bisector of the angle formed by the stay cables. The combined cable-staying system has a maximum eccentricity of 8 metres.

3.2.2. Response to Permanent state

During permanent state, the dead load ($g_1=151.12 \text{ kN/m}$), the superimposed dead load ($g_2=43.10 \text{ kN/m}$) and the prestressing (compensating 100% of the permanent load) are acting over the structure (Figure 7). In this case, the efficiency of the under-deck cable-staying system is very high ($\xi=0.78$), tripling the efficiency of a continuous under-deck cable-stayed bridge ($\xi=0.28$) and approaching the values obtained in single-span bridges ($\xi=0.89$) (Ruiz-Teran and Aparicio 2007c). Consequently, a substantial fraction of the external isostatic moment is resisted by means of the axial response (Table 3). The increase in the efficiency of the combined cable-staying system is due to the fact that the cable-staying system has double its eccentricity (the cable-staying system is eccentric at both midspan and support sections). In the permanent state, the stay cable is stressed to 8.98 MN; 86% is due to the response to dead load (g_1+g_2) and the remaining 14% is due to the prestressing. Given the high efficiency of the combined cable-staying system, the response to permanent load has the largest contribution at the permanent state. The stress losses in the stay cables due to time-dependent

effects are less than 1%, a similar value to those obtained in single-span bridges for the same reasons described by Ruiz-Teran and Aparicio (2007c).

3.2.3. Static response to traffic live load

Figure 8 shows the bending moment envelopes of the deck due to traffic live loads ($q=52.8$ kN/m and $Q=600$ kN). Bending moments due to traffic live load are reduced to one quarter of those for conventional bridges without stay cables, double the reduction achieved with under-deck cable-staying systems. It is worthy emphasising the very substantial reduction in the hogging bending moments in the support sections over piers by making the cable-staying systems eccentric in these sections.

3.2.4. Dynamic response to traffic live load

The reduction of the flexural response under traffic live load, in comparison with the under-deck cable-stayed bridge, has allowed the depth of the deck to be halved. Vertical accelerations in the deck are very sensitive to depth variations and, consequently, the maximum vertical accelerations rise to 0.52 m/s^2 .

3.2.5. Verification of SLSs

The internal prestressing in the deck, consisting of 214 strands, each of 140 mm^2 stressed to 1450 MPa, amply satisfies the decompression, controlled cracking and stress limitation SLSs. The internal prestressing, once again, has a layout that is similar to that of a beam with supports at the sections where the deck lays over the struts.

The vibration SLS is just satisfied and the maximum vertical accelerations equal the maximum allowed. The design of an efficient cable-staying layout has allowed a significant reduction of the depth that is ultimately governed by the vibration SLS.

3.2.6. Verification of ULSs

Once again, the fatigue SLS determines the cross-sectional area of the stay cables, whereas the tension ULS is met amply. External prestressing anchorages are disposed. The stress variations due to frequent live load are equal to 80 MPa, while the maximum stress reaches 37% of the tensile strength of the stay cables.

The bending ULS is just satisfied in the support section over piers and, therefore, the deck depth is also limited by this ULS. The shear ULS is met amply.

3.3. Comparative study of multi-span bridges with different combined cable-staying layouts

After having proved the significant structural efficiency of combined cable-staying systems for continuous bridges, the objective of this section is now to find the optimal configuration. Three alternative combined cable-staying systems, with 2 struts, are considered (Figure 5): a) the stay cables have no connection with the deck in the sections where they cross from the extrados to the intrados of the deck — they pass inside guide pipes at the points where they go through the deck cross-section — and, therefore, a span subdivision of $1/3$ is achieved in permanent state; b) the stay cables are anchored to the deck in the section where they cross through it and, therefore, a span subdivision of $1/5$ is achieved in permanent state; and c) the intradosed stay cables (below the deck) and the extradosed stay cables (above the deck) are anchored in different sections and the span subdivision of $1/5$ is also achieved in permanent state. In these three cases, the same cross-section for the deck has been used (Figure 6). Table 4 gathers the main features of these three bridges as well as the under-deck cable-stayed bridge described in Section 2.1.

Comparing the preceding cases a) and b) in Table 4, it is shown that anchoring the stay-cables to the deck in continuous bridges produce several advantages: (1) a greater span subdivision in permanent state ($1/5$ against $1/3$); (2) a higher efficiency of the cable-staying system (0.86

against 0.78); (3) smaller hogging bending moments due to traffic live load; (4) a reduction in the amount of internal prestressing by half; (5) a reduction in the total amount of active steel by 25%; and (6) a lower concrete characteristic strength (35 against 55 MPa). The key point that produces all these advantages is the increase in the response of the extradosed stay cables when they are anchored to the deck. Comparing Tables 3 and 5, that justify the efficiencies in cases a) and b) respectively, it is seen how the component provided by the extradosed stay cables at the support section over piers is doubled, significantly increasing the efficiency of the cable-staying system. Therefore, scheme b), using stay cables anchored to the deck, is very appropriate from both structural and economical points of view. Comparing it with a conventional bridge (without stay cables), the deck depth is reduced to 25%, the self-weight and the concrete amount to 60%, and the total amount of active steel to 40%. In addition, these reductions are achieved using conventional anchorages of external prestressing and concrete with a conventional strength. The greatest drawback of this scheme is that all the stay cables (intradosed and extradosed stay cables) must be anchored in the same section, this constitutes an extra intricacy in both design and construction stages. In order to avoid this disadvantage, case c) has been considered, using the same cross section for the deck (Figure 6). However, there is one limit state that is not satisfied, the vibration SLS, since the maximum vertical accelerations in the deck rise beyond the limit following an increase of over 40%. In order to satisfy this SLS, it is necessary to increase the depth of the deck, but this leads to both reducing the efficiency of the cable-staying system and increasing the cost in materials.

4. Comparative analysis of under-deck cable-staying systems and combined cable-staying systems for multi-span continuous bridges

Under-deck cable-staying systems allow permanent load to be compensated by means of the stay cable prestressing, giving rise to the span subdivision in permanent state. However, these

cable-staying layouts are not efficient under traffic live load as long as their eccentricities are suitable from an aesthetic point of view. The contribution of the cable-staying system to resisting external hogging bending moments due to traffic live load at the critical support section over piers is very small and, consequently, the bending ULS at these sections determines the depth of the deck. In comparison with conventional bridges without stay cables, the depth of the deck is reduced by half and the self-weight by 25%, but the total amount of active steel is similar and a greater concrete characteristic strength is required. The cost in materials of these schemes is very similar to that of conventional bridges and additional structural elements (struts) must be employed.

On the other hand, combined cable-staying systems with the stay-cables anchored to the deck allow the span subdivision in permanent state (even after accounting for time-dependent effects) and have a high efficiency under traffic live load. The reduction in the self-weight of the deck leads us to consider the possible increase of the span range of construction by means of self-launching gantries. Furthermore, the reduction in the amounts of all the materials of the deck leads us to think about these structural types as competitive schemes even from an economical point of view. For instance, the cost of materials of the deck of a combined cable-stayed bridge with 80-metre spans is similar to that of a conventional bridge (without stay cables) with 40-metre spans. This statement is based on a simple economic analysis in which the main deck components (such as concrete, formwork, internal prestressing, stay cables, and passive reinforcement) have been assessed using the current prices in the Spanish market. Additionally, in comparison with the conventional bridge, although the total construction budget of the combined cable-stayed bridge would include some extra elements, such as pylons and struts, many others would be removed, such as half of the piers and their respective foundations. Therefore, this is a suitable scheme for viaducts crossing wide valleys since, beside of being appropriate from various (structural, constructive, economical and

architectural) points of view, it can be justified by taking into account considerations related to landscape integration (the 'barrier effect' is reduced by eliminating half the piers).

5. Continuous combined cable-stayed bridges with two and three spans

The application of unconventional cable-staying systems to bridges with two and three spans has also been studied. As for multi-span continuous bridges, in bridges with two or three spans, under-deck cable-staying schemes are not efficient under traffic live load as long as their eccentricities are appropriate from an aesthetic point of view. Therefore, two-span bridges and three-span bridges with combined cable-staying systems were designed, using similar amounts of materials to those used in multi-span continuous bridges.

6. Design criteria

The analysis of the results and conclusions of the parametric study that has been conducted has allowed us propose the design guidelines set out below.

6.1. Morphology

1) *Structural elements*. Decks of under-deck cable-stayed bridges require struts and under-deck stay cables. Decks of combined cable-stayed bridges require struts, combined stay cables, pylons, and, in the particular case of the end spans, back stay cables and anchorage counterweights.

2) *Types of cable-staying systems*. There are three possible layouts for multi-span bridges with unconventional cable-staying systems: (1) continuous bridges with combined cable-staying systems, (2) semi-continuous bridges with under-deck cable-staying systems, with independent spans joined by means of continuity slabs to ensure road-users' comfort, and (3) continuous bridges with under-deck cable-staying systems. In the first two schemes the cable-staying system is very efficient under traffic live load, making it possible to design very

slender and economical structures. In the third scheme, the cable-staying system is very inefficient under traffic live load—if the eccentricity of the cable-staying system is limited by aesthetic considerations—, and even the span subdivision achieved after prestressing the stay cables does not remain indefinitely due to time-dependent effects, making this scheme not particularly attractive from structural and economical points of view. For the design of under-deck cable-stayed bridges with independent spans, the design criteria for single-span bridges with under-deck cable-staying systems will be applicable (Ruiz-Teran and Aparicio 2007c). For the design of continuous bridges with unconventional cable-staying systems, the following criteria set out below will be applicable.

3) ***Layout of cable-staying systems.*** In the case of multi-span continuous bridges with combined cable-staying systems, the layouts must be designed in order to ensure the efficiency of the cable-staying systems even if traffic live load acts on alternate spans. The standard schemes for classic cable-stayed bridges with multiple spans, that control the movement of the tower heads, are valid although two of them are the most appropriate: (1) the use of towers with large flexural stiffness and (2) splitting of the pylon into two inclined legs doubling the supports of the deck over the piers.

4) ***Connection of the stay cables to the deck.*** In combined cable-stayed bridges it is possible to choose between two different connections at the section where the stay cables cross through the deck: (1) stay cables anchored to the deck or (2) stay cables not connected to the deck, but rather passing through guide pipes where they go through the deck cross-section. When the stay cables are anchored to the deck, a greater span subdivision is achieved, along with a larger efficiency of the cable-staying system and a reduction of the amount of materials used for the deck. However, the need to anchor all the extradosed and intradosed stay cables in the same section introduces an extra intricacy in both design and construction stages. In continuous bridges with under-deck cable-staying systems, the stay cables will be self-

anchored in the support sections of the deck over piers and abutments.

5) ***Span Subdivision. Location of the connection points of the cable-staying system to the deck.*** Span subdivision is achieved thanks to the prestressing of the stay cables, compensating 100% of the permanent load (dead load and superimposed dead load). When the span is subdivided, the bending of the deck in permanent state is reduced to the local bending between the sections of the deck which are connected to the cable-staying system (the sections where the deck lays over the struts and the sections where the stay cables are anchored to the deck) and the supports sections of the deck over piers. These sections must be uniformly distributed over the length of the deck.

6) ***Depth of the deck.*** In order to make the cable-staying system more efficient under live load, the smallest depth that satisfies both the bending ULS and the vibration SLS will be specified. For continuous bridges with 80-metre spans, the depth/span ratio can be equal to 1/100 if a combined cable-staying system is disposed and 1/50 in the case of an under-deck cable-staying system.

7) ***Connection between the deck and the struts.*** The struts should be connected to the deck by means of pins in order to avoid the introduction of concentrated bending moments into the slender decks and struts as well as to strengthen the axial response. Diaphragms should be employed in these sections. For stressing the intradosed stay cables, temporary props are used to immobilise the struts during the stressing process.

8) ***Orientation of the struts.*** The struts are placed along the bisector of the angle formed by the stay cables in order to ensure that the stress is constant all along the stay cable, allowing the optimum design of the stay cables.

9) ***Eccentricity of the cable-staying systems.*** Eccentricities at mid-span sections and support sections on the order of 1/10 of the span are appropriate for these types of structures.

Although larger eccentricities increase structural efficiency, they are unsuitable from an aesthetic point of view (Ruiz-Teran and Aparicio 2007b). The eccentricity used should be a compromise between structural and aesthetic considerations.

10) ***Layout of the cable-staying systems.*** Once both the points where the deck lays over the struts and the eccentricity of the cable-staying system at critical sections have been established, the layout of the stay cables is determined by means of three conditions: (1) eccentricity at the critical sections must be as established; (2) all the struts are placed along the bisector of the angle formed by the stay cables; and (3) the vertical component of the deviation forces introduced through the struts into the deck must be uniform, in order to compensate the permanent load, which is also uniform.

11) ***Layout of the internal prestressing.*** The layout will be similar to that of a bridge with supports at the points where the cable-staying system is connected to the deck (the sections where the deck lays over the struts and the sections where stay cables are anchored to the deck), in addition to the supports of the deck over piers.

12) ***Sections of the deck.*** Voided slabs are appropriate, since the efficiency of the cable-staying system increases with the reduction of the radius of gyration of the deck (Ruiz-Teran and Aparicio 2007b). The space between voids will be established by the placement of the internal prestressing and by construction requirements, but not by the verification of the shear ULS which will be amply satisfied.

6.2. Limit states that govern the dimensions of the different structural elements

1) ***Cross-section of the stay cables.*** The cross-section of the stay cables is determined by the ULS of fatigue that is linked to the anchorage technology used: stay-cable anchorages ($\sigma_{\max} \leq 0.45f_{pu}$ and $\Delta\sigma_{\max} \leq 200$ MPa) or conventional external-prestressing anchorages ($\sigma_{\max} \leq 0.65f_{pu}$ and $\Delta\sigma_{\max} \leq 80$ MPa). This limit state requires a double verification: (1) the

maximum stress must be less than $\sigma_{\max}$ and (2) the variation in stress due to frequent live load must be less than $\Delta\sigma_{\max}$. Stress changes due to rotation of the anchorages of the stay cables as well as the wind effects should be considered if they are not negligible. If the cable-staying systems have a high efficiency, as in the case of continuous combined cable-stayed bridges, the critical verification is that associated with the variation in stress. If the cable-staying systems have a low efficiency, as in the case of continuous with under-deck cable-stayed bridges, the critical verification is that related to the maximum stress.

2) ***Depth of the deck.*** For medium spans (80 metres), the depth of the deck in continuous combined cable-stayed bridges is governed by the vibration SLS, whereas in continuous under-deck cable-stayed bridges it is governed by the bending ULS.

3) ***Characteristic strength of the concrete of the deck.*** It is advisable to use the minimum strength that both ensures the verification of the stress limitation SLS and the durability of the structure.

4) ***Amount of internal prestressing.*** In contrast with conventional bridges, the amount of prestressing is conditioned by the controlled cracking SLS and even by the bending ULS. Attempting to satisfy these limit states through the increase of the passive reinforcement (using only the internal prestressing required to satisfy the decompression SLS) gives rise to sections that are so highly reinforced that they are not very recommendable from both construction and durability points of view.

5) ***Amount of internal reinforcement.*** Because of the large reduction of the flexural response of the deck and in order to avoid a brittle failure, it is necessary to verify the bending ULS taking into consideration the hogging and sagging cracking bending moments if they are larger than the design bending moments.

7. Conclusions

A complete and systematic parametric study of multi-span continuous bridges with two innovative structural types (under-deck cable-stayed bridges and combined cable-stayed bridges) has been undertaken. Their structural response has been analysed and a set of design criteria has been established (Section 6). Although many of the conclusions are of a generic nature, the study focuses on road bridges with medium spans (80 m) and prestressed concrete decks. In view of the structural behaviour, Conclusions must be split in three different sections:

7.1. Multi-span continuous bridges with under-deck cable-staying systems

- 1) For this type of bridge, the axial response is not clearly enhanced, since cable-staying systems without eccentricities at the support sections are not appropriate for continuous bridges. The span subdivision attained after stressing the stay cables is partially lost due to time-dependent effects. In addition, the efficiencies of these cable-staying systems under traffic live load are very low as long as the eccentricities of the stay cables are admissible from an aesthetical point of view.
- 2) The depth of the deck can be smaller than that in conventional schemes without stay cables, but savings are not significant due to the type of materials required (concrete with a higher characteristic strength, and external prestressing anchorages with higher fatigue strength).
- 3) Consequently, the use of under-deck cable-staying systems for continuous bridges is not justified from both structural and economical points of view.

7.2. Semi-continuous decks with under-deck cable-staying systems

- 1) Under-deck cable-staying systems applied to multi-span bridges have high efficiencies only if semi-continuous schemes with independent spans are designed. Design criteria for single-span bridges (Ruiz-Teran and Aparicio 2007c) are applicable to these bridges and

road users' comfort is ensured by means of flexible continuity slabs between adjacent decks.

- 2) In comparison with conventional schemes without stay cables, a 30% reduction in the amount of the materials used in the decks is achieved.
- 3) These types of bridges can be justified from structural, economical and aesthetical points of view.

7.3. Multi-span continuous bridges with combined cable-staying systems

- 1) In permanent state, the span subdivision is achieved through the prestressing of the stay cables (compensating 100% of dead load and superimposed dead load), the placement of intermediate struts and the possible anchorage of the stay cables to the deck. The axial response (tension of the stay cables and compression of the deck, the struts and the pylons) is enhanced whereas the flexural response is reduced to the local bending of the deck between the support sections, over the struts and the piers, as well as the possible anchorage sections of stay cables to the deck. The span subdivision is not affected by time-dependent effects, since the stress losses in the stay cables are very small (2%).
- 2) Under the traffic live load, the axial response is also enhanced in relation to the flexural response. The larger total eccentricity (the sum of the eccentricities at the support and mid-span sections) of these combined cable-staying systems provides a higher efficiency (80%) that can even be increased further by anchoring the stay cables to the deck (90%). This high efficiency leads to the ULS of fatigue being the critical limit state for determining the cross-sectional area of the stay cables.
- 3) The strengthening of the axial response makes it possible to design extremely slender bridges that make an efficient structural use of the materials disposed. Combine cable-staying systems applied to multi-span continuous bridges with spans of medium length

- (80 m) allow the design of much smaller deck depths (1/100 of the span). In comparison with conventional continuous schemes without stay cables, the deck depth is reduced to 25%, the amount of concrete to 60%, and the total amount of active steel (internal prestressing and stays cable) to 40%. These reductions are attained using conventional concrete (35 MPa) and conventional anchorages for external prestressing
- 4) The substantial reduction in the depth of the deck also involves a significant increase in the vertical accelerations associated with the dynamic response of the structure to traffic live load. In bridges with spans of medium length, the depth of the deck may be governed by the vibration SLS.
 - 5) These are innovative schemes that can extend the applicable range of conventional construction methods, such as the construction of viaducts by means of both self-launching gantries and longitudinal precast elements.
 - 6) These schemes can be expected to be very competitive and even more economical than conventional schemes due to the substantial reduction in both the amounts of materials used for the decks and the design actions over other structural elements (such as bearings, abutments, piers and foundations).
 - 7) These schemes can be very suitable for wide valleys. The ‘barrier effect’ of the piers can be reduced, enhancing the landscape integration, without an increase in cost.
 - 8) The fact that the stay cables are partially located above the deck, framing and bounding the space of passage over the structure, can mean an extra value, from an aesthetic point of view. This effect is achieved with smaller towers than that in cable-stayed bridges, again contributing to the landscape integration.
 - 9) Provide the presence of sufficient vertical clearance, these original and innovative schemes (as far as the authors’ knowledge, no one has yet built any continuous road

bridges of this type) are the most suitable and competitive schemes for bridges with multiple spans of medium length, due to their structural efficiency, enhanced construction methods, both economical and aesthetical considerations, as well as landscape integration possibilities.

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Table 1: Distribution of the external isostatic moment due to $g_1+g_2 = 234.95 \text{ kN/m}$ in a continuous under-deck cable-stayed bridge with 2 struts

	Support Section	Mid-span Section	Sum (Σ)
Cable-Staying System	0 MN.m	51.80 MN.m	51.80 MN.m
(Axial response)	0 %	27.56 %	27.56 %
			$\xi=0.2756$
Deck	-90.77 MN.m	45.39 MN.m	136.16 MN.m
(Flexural response)	48.29 %	24.15 %	72.44 %
Sum (Σ)	-90.77 MN.m	97.19 MN.m	187.96 MN.m
	48.29 %	51.71 %	100 %

Table 2: Comparison of Under-Deck Cable-Stayed Bridges

	Continuous schemes			Discontinuous
	at the support section over piers			scheme
	Without stay cables	1 strut	2 struts	2 struts
Depth / Span	1/25	1/50	1/50	1/80
Section type	box girder	box girder	box girder	voided slab
Self-weight (kN/m)	259	192	192	188
Total amount of active steel ^a	0.68	0.70	0.63	0.48
Amount of internal prestressing in the deck ^a	0.68	0.49	0.42	0.20
Stay cable amount ^a	0	0.21	0.21	0.28
fck (MPa)	35	50	40	40
Bending moments in permanent state				
Without time-dependent effects				
Maximum (MN.m)	80.57	15.66	6.97	10.99
Minimum (MN.m)	-161.15	-31.32	-13.93	-16.45
With time-dependent effects				
Maximum (MN.m)	80.57	15.69	13.36	13.50
Minimum (MN.m)	-161.15	-40.12	-26.71	-11.99
Bending moments due to traffic live load				
Maximum (MN.m)	44.55	20.70	22.49	16.61
Minimum (MN.m)	-46.07	-32.73	-27.65	-8.66
Efficiency of the cable-staying system (ξ)				
		0.25	0.28	0.89
Acceleration due to heavy vehicles (m/s^2)				
	0.03	0.07	0.06	0.41

^a Amounts of active steel given in kg/m^2 / span (m)

Table 3: Distribution of external isostatic moment due to $g_1+g_2 = 194.22 \text{ kN/m}$ in a continuous combined cable-stayed bridge with 2 struts

	Support Section	Mid-span Section	Sum (Σ)
Cable-Staying System (Axial response)	-36.21 MN.m 28.77 %	61.92 MN.m 49.20 %	98.13 MN.m 77.97 % $\xi=0.7797$
Deck (Flexural response)	-17.63 MN.m 14.01 %	10.09 MN.m 8.02 %	27.72 MN.m 22.03 %
Sum (Σ)	-53.84 MN.m 42.78 %	72.01 MN.m 57.22 %	125.85 MN.m 100 %

Table 4: Comparison of under-over-deck cable-stayed bridges

	Under-deck cable-stayed bridge	Combined cable-stayed bridges		
		Stay cables without deck connection (inside guide pipes) (case a)	Stay-cables anchored at the same section (case b)	Stay-cables anchored at different sections (case c)
Depth / Span	1/50	1/103	1/103	1/103
Number of strands (extradosed stay cables)		122	186	140
Number of strands (intradosed stay cables)	191	122	110	137
Total amount of active- steel ^a	0.63	0.36	0.27	0.31
Amount of internal prestressing in the deck ^a	0.42	0.22	0.11	0.12
Amount of stay cables ^a	0.21	0.14	0.16	0.19
fck (MPa)	40	55	35	35
Bending moments in permanent state				
Maximum (MN.m)	13.36	5.32	3.14	3.22
Minimum (MN.m)	-26.71	-9.66	-4.55	-4.54
Bending moments due to traffic live load				
Maximum (MN.m)	22.49	8.94	7.23	8.47
Minimum (MN.m)	-27.65	-12.58	-6.33	-5.86
Efficiency of the cable-staying system (ξ)				
	0.28	0.78	0.86	0.85
Acceleration due to heavy vehicles (m/s^2)				
	0.06	0.52	0.46	0.65
Maximum allowed acceleration (m/s^2)				
	0.45	0.52	0.54	0.49

^a Amounts of active steel given in kg/m^2 / span(m)

Table 5: Distribution of the external isostatic moment due to $g_1+g_2 = 194.22$ k/Nm in a continuous combined cable-stayed bridge with two struts and with the stay-cables anchored to the deck

	Support Section	Mid-span Section	Sum (Σ)
Cable-Staying System (Axial response)	-56.41 MN.m 44.82 %	51.78 MN.m 41.15 %	108.19 MN.m 85.97 % $\xi=0.8597$
Deck (Flexural response)	-11.82 MN.m 9.39 %	5.84 MN.m 4.64 %	17.66 MN.m 14.03 %
Sum (Σ)	68.23 MN.m 54.21 %	57.62 MN.m 45.79 %	125.85 MN.m 100 %

Figure captions

Figure 1: Osormort Viaduct, Spain (courtesy of Javier Manterola, Carlos Fernandez Casado S.L.).

Figure 2: Continuous under-deck cable-stayed bridge: a) elevation, b) scheme and c) cross-section.

Figure 3: Bending moment diagrams in permanent state: a) due to g_1 (dead load) + g_2 (superimposed dead load) + prestressing of the stay cables; b) due to g_1 + g_2 + prestressing of the stay cables + shrinkage + creep + relaxation (internal prestressing).

Figure 4: Bending moment envelopes due to traffic live load: a) $q=52.8$ kN/m (4 kN/m²); b) $Q=600$ kN ($M_{Q\text{ TOTAL}} = 2M_{Q\text{ GRAPH}}$).

Figure 5: Elevation and schemes of combined cable-stayed bridges: a) with stay-cables passing through the deck (not connected to the deck); b) with stay cables anchored to the deck; c) with stay cables anchored to the deck in different sections.

Figure 6: Combined cable-stayed bridges. Cross-sections: a) calculation cross-section and b) real cross section and c) section showing the connection with a strut

Figure 7: Bending moment diagrams in permanent state: a) due to g_1 (dead load) + g_2 (superimposed dead load) + prestressing of the stay cables; b) due to $g_1 + g_2$ + prestressing of the stay cables + shrinkage + creep + relaxation (internal prestressing).

Figure 8: Bending moment envelopes due to traffic live load: a) $q=52.8 \text{ kN/m}$ (4 kN/m^2); b) $Q=600 \text{ kN}$ ($M_{Q \text{ TOTAL}} = 2M_{Q \text{ GRAPH}}$).