Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Two new types of bridges:

under-deck cable-stayed bridges and combined cable-stayed bridges.

The state of the art.

A. M. Ruiz-Teran [a,*], A. C. Aparicio [b]

[a] Associate Professor. Department of Civil Engineering and Building. University of Castilla-La Mancha.

Academic Visitor at Imperial College London, UK

Av. Camilo José Cela s/n 13071. Ciudad Real. Spain

[b] Professor. Department of Construction Engineering. Technical University of Catalonia.

C. Jordi Girona 1-3. 08034. Barcelona. Spain.

Word count:

Title and address	72
Abstract and key words	168
Sections 1-7	5931
Acknowledgments	95
References	1146
2 Tables (2x250)	500
8 Figures (8x250)	2000
Total	**9912**

---

[*] Tel: +34 926295300 (ext. 3277) Fax: +34 926295391 E-mail: AnaMaria.Ruiz@uclm.es or aruiter@ciccp.es

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Abstract: Over the last thirty years, at least twenty cable-stayed bridges have been built that cannot be classified under existing typologies for cable-stayed bridges. These structures represent two new types of cable-stayed bridges that we herein define as "under-deck cable-stayed bridges" and "combined cable-stayed bridges". The evolution of these new bridge types is explored through consideration of the different proposals and structures that have been built throughout this period, pointing out the innovations made in each of them. In this paper we propose a new classification system for bridges prestressed by means of tendons into which these two new bridge types will fit. Studies that have been made about these structural types are also highlighted. On the basis of the aforementioned, we describe the state-of-the-art for these structural types, compiling and cataloguing information, documents and knowledge that were previously highly dispersed. Finally, we make a critical analysis of the current situation and draw some key conclusions.

Keywords: under-deck cable-staying; combined cable-staying; cable-stayed bridges; extradosed prestressing; intradosed prestressing; prestressing

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

1. Introduction

Prestressing is a powerful tool that allows structural engineers to apply internal stresses to a structure, in a desirable way, prior to it being put into use. This technique has been used on many occasions throughout the history of bridge building and it has now become a normal facet of most modern bridges. Prestressing can be applied by imposing relative displacements on the bridge supports — a technique widely used for steel bridges —, but most of the prestressing techniques, that have been extensively used in practice, involve the use of prestressing tendons (internal prestressing, external prestressing, extradosed prestressing and cable-staying). However, over recent decades, other new prestressing techniques that cannot be described using the existing terminology, or classification schemes, have been implemented on rare occasions, giving rise to two new structural types, namely under-deck cable-stayed bridges and combined cable-stayed bridges. These two new structural types are the focus of this paper.

2. Prestressing bridges with tendons

There is a conventional classification scheme for prestressed bridges using tendons that has been accepted internationally by the scientific and technical community. This scheme includes the following types of bridges: bridges with internal prestressing, bridges with external prestressing, bridges with extradosed prestressing, and cable-stayed bridges. This classification is made on the basis of the positioning of the tendons in relation to the deck cross-section. When the tendons are situated within the depth of the deck and inside the concrete cross-section, with bonded reinforcements, this case is referred to as a bridge with internal prestressing (pre-tensioned or post-tensioned reinforcement). When the tendons are situated within the depth of the deck but outside the cross-section, with non-bonded reinforcements, this case is referred to as a bridge with external prestressing. When the tendons are outside the cross-section and above the deck, this case is referred to as a cable-stayed bridge or an extradosed bridge. Many examples of each of these types have been constructed and a solid body of knowledge has been built up regarding their structural behaviour and relevant design criteria as a result.

When the tendons are located within the depth of the deck (bridges with internal or external prestressing), the tendons do not contribute in the response to traffic live load, since the stress changes in the tendons due to this action are very small and, therefore, conventional anchorages can be used for the tendons. Extradosed bridges and cable-stayed bridges may have a similar appearance at first sight (with the tendons located above the deck), but the ratio of the tower height over the span length for extradosed bridges is approximately half of that for cable-stayed bridges and therefore the stay cables make a smaller angle with the deck. This fact dictates their different structural behaviour under live load. In an extradosed bridge, the tendons have a smaller contribution in the response to traffic live loads than in a cable-stayed bridges and the stress changes in the tendons are much smaller. Hence, conventional anchorages can be used for intradosed bridges but not for cable-stayed bridges, in which anchorages with high fatigue strength are required.

Nevertheless, this classification scheme has become obsolete since it leaves out two unconventional types of cable-stayed bridges in which the stay cables occupy other positions in relation to the deck. It is consequently necessary to define these new types, and to establish names for them, since more than twenty bridges of such type have been built over the last thirty years.

For this purpose, we propose a new classification scheme for bridges with prestressing tendons (Figure 1) that includes existing definitions in addition to alternative positions of tendons in relation to the deck. Tendons may be located: (1) above the deck, i.e. over the extrados of the deck; (2) below the deck, i.e. under the intrados of the deck; or (3) both above and below the deck. Within each of these types, we define two classes, depending on the contribution of the stay cables in the response to traffic live load.

Thus, if the stay cables are located above the deck, this case is referred to as a conventional cable-stayed bridge, and within this type one can distinguish between two classes: classic cable-stayed bridges (with a high contribution of the stay cables in the response to traffic live load and consequently with high fatigue strength anchorages) and extradosed bridges (with a low contribution of the stay cables in the response to traffic live load and consequently with conventional anchorages used in external prestressing systems).

The new types of bridges defined under this new classification scheme are named by the authors as:

- Under-deck cable-stayed bridges. These are bridges in which the tendons are located below the intrados of the deck. Depending on the contribution of the stay cables in the response to traffic live load, we can distinguish two different classes: under-deck cable-stayed bridges (with a high contribution of the stay cables in the response to traffic live load), and bridges with intradosed prestressing systems (with a low contribution of the stay cables in the response to traffic live load).
- Combined cable-stayed bridges. These are bridges in which the tendons are located both above the extrados and below the intrados of the deck. Again, according to the contribution of the stay cables in the response to traffic live load, we can distinguish two different classes: combined cable-stayed bridges (with a high contribution of the stay cables in the response to traffic live load), and bridges with combined extradosed-intradosed prestressing systems (with a low contribution of the stay cables in the response to traffic live load).

The higher the contribution in the response to traffic live load, the larger the magnitude of the frequent stress changes in the tendons in the response to traffic live load and, therefore, the higher requirement for the anchorages relating to fatigue strength.

3. Structural behaviour of under-deck cable-stayed bridges and combined cable-stayed bridges

In under-deck cable-stayed bridges, the stay cables, which have a polygonal layout under the intrados of the deck, are self-anchored to the deck in the support sections over piers or abutments, and are deflected by struts which, under compression, introduce the upward deviation forces due to the cables into the deck. By prestressing the stay cables (i.e. tensing up the stay cables before putting the bridge into service), it is possible to compensate the dead load (self-weight of structural elements) and superimposed dead load (self-weight of non-structural elements), thereby greatly reducing the flexural response (reducing the permanent bending moments in the deck) and reinforcing the axial response (increasing the tensile forces in the stay cables and the compression in the struts and the deck). In addition, the under-deck cable-staying system is also efficient under traffic live load: bending in the deck due to traffic live load is reduced in comparison with systems not using stay cables, since a part of the traffic live load is resisted by the cable-stayed system working like a truss through the tension of the stay cables and the compression of both the struts and the deck.

In combined cable-stayed bridges, the stay cables are located both above the extrados, and below the intrados of the deck. Where the stay cables are above the extrados, they are deflected by the pylons that take the cable downward deviation forces directly to the supports; whereas, where the stay cables are below the intrados of the deck, they have a polygonal layout and are deflected by struts that, under compression, introduce the cable upward deviation forces into the deck. As in the preceding scheme, by prestressing the stay cables, the permanent loads of self-weight and superimposed dead load are compensated, thereby reducing flexural response (reducing the bending moments in the deck) and reinforcing axial response (increasing the tensile forces in the stay cables and the compression in the struts, the pylons and the deck). In addition, the combined cable-staying system is also efficient in the presence of live load: bending in the deck due to live load is reduced in comparison with a bridge lacking stay cables, since a part of the traffic live load is resisted by the cable-stayed system working like a truss through the tension of the stay cables and the compression of the struts, the pylons, and the deck.

4. Historical development of bridges with unconventional cable-staying

4.1 First steps (1978-1991)

In 1978, the construction of the Weitingen Viaduct (Figure 2) was completed. This is a highway bridge over the Neckar River in Germany designed by Fritz Leonhardt (Civil Engineering 1978; Leonhardt 1982), and was the first bridge built with an under-deck cable-staying system. Due to the presence of significant creeping in the soil slopes of the valley, laying the foundations for the nearest piers to the abutments would have been very complicated and expensive. The end piers were therefore replaced by an under-deck cable staying system that introduced, by means of struts, an upward deviation force into the deck equal to the vertical reaction that would have been provided by the eliminated piers under the permanent loads of self-weight and superimposed dead load (ENR 1978). The viaduct is 900 metres in length, with five spans of 233.8 + 134.3 + 134.3 + 134.3 + 263.2 metres. Therefore, the length of the end spans is similar to the length of one standard 134.3-metre span plus one conventional-length end span. In fact, the struts are not placed under the midspan section of the end spans, but located slightly towards the abutments, so that the end section between the support over the abutment and the support over the strut behaves as an ‘end span’. In this case, the length of this end section is approximately 90% of the adjacent section (i.e. the section between the support over the strut and the first pier) which clearly exceeds the conventional 75-80%. However, with this proportion Leonhardt was able to make a compromise between both structural and aesthetic considerations, attaining a certain degree of balancing without making it visually obvious that the strut was not located at midspan.

In 1982, Jörg Schlaich submitted a preliminary sketched proposal for a new rail bridge in Munich, Germany, proposing an approach using an under-deck cable-staying system. That proposal got no further, but at the time Schlaich was convinced that designs using under-deck cable-staying systems were much more efficient from a structural point of view than other conventional solutions using external prestressing, since they have more eccentricity and a greater lever arm to respond to bending moments acting on the deck (Holgate 1997).

In addition, Schlaich believed in the need for having a wider range of possibilities for the design of highway overpasses and thought that designs using under-deck cable-staying systems should be taken into account (Holgate 1997). Consequently, he approached experts in the German government with the request for an opportunity to design at least one structure of this type. In 1987 he was offered the chance of doing just that in the Kirchheim overpass, that was to placed in a cutting area with more than enough vertical clearance. He then planned a portal bridge with a 45-metre span using a concrete slab with a depth of only 40 centimetres, giving rise to a depth-span ratio of 1/113 (Schlaich and Schober 1994). Problems arose when it came time to build the bridge, since the engineers who were to assume responsibility for directing the work were concerned about the difficult access to, and maintenance of, the cable-staying system as well as the possible collapse of the structure in the event of an accidental breakage of the stay cables. In view of the circumstances, Schlaich had to modify the proposed solution substantially, increasing the depth of the deck so that the initially proposed under-deck stay cables were embedded in the concrete cross-section (Holgate 1997).

The result was a portal bridge (Figure 3) where the main span has a fish-belly variable depth.

In 1987 Christian Menn and Paul Gauvreau began experimental research into the behaviour of two-span slabs with an under-deck cable-staying system (Menn and Gauvreau 1987). Therefore, the stay cables had no eccentricity in the support section over the central pier. With such a shape, the under-deck cable-staying system plays only a very small part in reducing the hogging bending moment in the deck in the support section over the pier. After their tests, Menn and Gauvreau suspected that their proposed cable-staying system could be improved upon in the section supported over the piers. In subsequent research they planned to use elements working in compression, placed between the lower part of the closest strut and the shaft of the central pier (Menn and Gauvreau 1990). However, the solution to this problem is much simpler: in order to obtain a greater contribution from the cable-staying system in the structural response to live load, and consequently to reduce the bending moments in this section, the stay cables need to be eccentric above the deck in the support section over piers, so that a portion of the bending moment due to traffic live load can be resisted by means of a force couple that tenses the stay cables and compresses the deck. However, at that time the repercussions of designing a layout with under-deck cable-staying systems for continuous bridges were unknown, and a solution such as that just detailed had not yet been conceived of. In fact, Menn designed an under-deck cable-staying system with two struts for continuous bridges with 36-metre main spans (Lemaitre and Kobler 2005).

In 1987, Schlaich succeeded in putting his ideas into practice and had three footbridges built according to his designs using under-deck cable-staying systems at the Gut Marienhof sewage treatment plant in Dietersheim, near Munich (Holgate 1997; SBP 2004). Construction of these structures proved under-deck cable-staying systems to be highly efficient for single-span bridges, since they can reduce the depth of the deck to a mere 1/85 of the span (Table 1).

In 1989, Schlaich extrapolated under-deck cable-staying systems from single-span bridges to continuous bridges and designed two proposals for Schornbachtal viaduct— with a layout similar to the one proposed by Menn for continuous bridges— and Kämpfelbach viaduct, but neither of them were built (Holgate 1997).

However, his perseverance eventually paid off. The major advance in conceptual terms was achieved with the design and construction, in 1991, of the Obere Argen viaduct (Figure 4), also designed by Jörg Schlaich (WTB and Dywidag 1991; Cazet 1992). This was the first bridge built using a combined cable-staying system (with stay cables above and below the deck). Once again, the reason for implementing such a scheme was due to the presence of creeping of soil deposits on the valley slopes, as in the case of Weitingen viaduct. During the design phase, Schlaich considered a wide range of conventional structural types (arches, trusses, conventional cable-staying systems), as well as under-deck cable-stayed, and combined cable-stayed bridges (Schlaich 1999). He eventually chose the most efficient design, namely a bridge with a combined cable-staying system, since the stay cables have high eccentricity in the critical sections precisely on the side where tension arises due to bending, i.e. above the deck in the support sections and below the deck in the midspan sections. The construction of this bridge signified the end of the first period during which under-deck cable-stayed bridges and combined cable-stayed bridges sought to establish, and were successful in gaining, a place for themselves among the different bridge types, progressing from ideas and plans on paper to real structures.

4.2 Development of new structural types (1992-2006)

After the construction of the Obere Argen viaduct, a significant number of engineers of considerable international prestige became interested in these types of bridges.

In 1993, work was completed on the Truc de la Fare overpass (Figure 5) in France, designed by Michael Virlogeux (Ouvrages d'art 1993a; Ouvrages d'art 1993b). This is an overpass with one single span crossing a highway in a cutting area with sufficient height clearance to allow the use of an under-deck cable-stayed scheme. Virlogeux studied alternatives using one, two and three struts and ultimately chose this last alternative, which offered the greatest efficiency of the under-deck stay cables when subjected to traffic live loads, as well as an aesthetically pleasing appearance (Virlogeux et al. 1994). Virlogeux divided the span into four equal parts through the placing of the three struts, with the outer two struts inclined in order to ensure that in the permanent state the struts would be working exclusively under compression and that the stay cables would be working under constant tension throughout their full length.

Around that same time, SETRA, under the direction of Virlogeux, was working on five alternatives for the Millau viaduct —which has recently been opened to traffic— one of which was an under-deck cable-stayed bridge.

In 1995, work was completed on the Osormort Viaduct (Figure 6) in Spain, designed by Javier Manterola (Lluch et al. 2001). This viaduct has 40-metre spans with under-deck cable-staying systems using just one strut. This scheme was chosen with the aim of making the deck as light as possible to allow the use of a self-launching form carrier designed for much smaller spans (González 1997). The deck was designed with a triangular voided section with a depth of 1.60 metres (1/25 of the span). Therefore, the weight reduction was the result of the selected cross-sectional shape, not through a major reduction in the depth of the deck. Depth reduction was only minor due to the fact that under-deck cable-staying systems are not particularly efficient in the response to traffic live load in continuous bridges, as previously mentioned. What was noted in the construction of this bridge is that the joints that must be used in span-by-span construction are not placed at the same point as in a conventional bridge, but instead in a section that is much closer to the support sections over the piers

(González 1997).

In 1997, work was completed on the footbridge providing access to the Miho Museum in the Shigaraki Hills, near Kyoto, in Japan (Watanabe 2002). Leslie Robertson designed this combined cable-stayed bridge after looking for a scheme that did not disturb, even during construction, the scenic beauty of its surroundings.

In 1998, four under-deck cable-stayed bridges and two combined cable-stayed bridges were built: Jumet footbridge (Figure 7) (Forno and Cremer 2001), Losa del Obispo bridge (Argüelles 2001), Waschhaussteg footbridge (Landesbaupreis 1998), Tobu Recreation Resort footbridge, Glacis bridge and Hiyoshi footbridge. The design of these last three introduced many innovations.

The Tobu Recreation Resort footbridge, in Japan, was the first under-deck cable-stayed footbridge to use multiple struts (Figure 8). The designers chose this scheme because they desired a structure with a weight approximately half that of a conventional scheme, since the foundations were to be placed in a soil with low strength (Tsunomoto and Ohnuma 2002). For the purpose of tensing up the stay cables, the middle strut located at the centre of the span was fixed in its final position and clamps were then placed on all the strut deviators in such a way that once the cables were tensed the struts would be located in their final positions. Consequently, since tensing was performed from the abutments, each of the strut deviators had to be positioned with a certain displacement towards the centre of the span relative to its final location (Tsunomoto and Ohnuma 2002).

The Glacis bridge (Hines and Billington 1998; Schlaich et al. 1999; Schlaich and Werwigk 2001; Schlaich and Bergermann 2004) was built over the river Danube in the city of Ingolstadt, Germany. It is a portal bridge with an under-deck cable-staying system in the middle span and was designed by Schlaich. This is a structural configuration similar to the one planned for the Kirchheim overpass, although in this case the structure was actually built. With the construction of this bridge, which has almost double the span of the Kirchheim overpass, Schlaich demonstrated that the proposal that he had made eleven years earlier had been fully thought out. In addition, this bridge is remarkable due to the fact that no falsework was required for the main span during construction. Instead of falsework, the stay cables were used as true bearing cables on which the deck of the bridge was built. In order to tense the stay cables before the construction of the deck — and thereby avoid substantial, undesirable cable deformations during construction — vertical tensor cables anchored temporarily to the river bed were used.

From an aesthetic point of view, the Hiyoshi footbridge (Takenouchi and Manabu 2002) designed by the engineers Shimura and Tanase is also noteworthy. This structure has a combined cable-staying system where the stay cables are situated in a vertical plane skewed in relation to the deck. This asymmetry creates an innovative configuration.

In 1999 and 2000, three more bridges were built: the Weil am Rhein viewpoint footbridge (Kratz 2000) in Germany, as well as the Ayumi (Uchimura et al. 2002) and Takehana bridges (Mochizuki et al. 2000; Nakagawa et al. 2001) in Japan.

In 2001, work was completed on the Morino-wakuwaku-hashi footbridge, in Japan. This footbridge consists of a stress ribbon with an under-deck cable-staying system. In a conventional stress ribbon, both the bearing cables and the prestressing tendons are placed within the concrete cross-section. However, in this stress ribbon, part of the prestressing tendons are located outside the concrete cross-section below the deck, a feature that provides several advantages: the slope of the deck at the abutments can be reduced, the horizontal anchorage force required at the abutments is reduced, the aerodynamic stability of the structure is increased, and the prestressing can be more easily replaced, since it is located outside the concrete cross-section (Kumagai et al. 2002).

Subsequently, the playing field for unconventional cable-staying systems was further broadened. Until that time only decks made of concrete, steel, or a combination of both, were used. However, between 2002 and 2004, these systems were also applied to decks made of timber — the footbridge over the Numedalslagen River —, galvanised steel — Montabaur footbridge (Galvanización 2004) —, and steel-aluminium combinations — Spinningfields footbridge.

Recently, work was finished on the Meaux viaduct in France (Placidi et al. 2004; Ouvrages d'art 2003). In this viaduct there is a span much longer than the rest that has been designed with an under-deck cable-staying system with three struts, a similar scheme to that proposed by Schlaich for the Kämpfelbach viaduct. In 2006, two new under-deck cable-stayed bridges, the Seiryuu and Fureai footbridges, have been constructed in Japan.

After having reviewed the historical development of these structural types, it is clear that great strides have been made in this field thanks to the innovative efforts of leading structural engineers, including pioneers such as Leonhardt and Schlaich as well as those following in their footsteps.

5. Research

Despite the efforts that have been made in design and construction, there remains a great deal to be accomplished in the area of research.

In 2001, the authors of this paper started up a new line of research focussed on bridges with unconventional cable-staying systems with the aims of both achieving a deep knowledge of their structural response as well as defining design criteria that could be applied directly at the planning stage. That work has already produced results, including the doctoral thesis of the first author (Ruiz-Teran 2005) — the first thesis to focus on these types of structures and to set out design criteria.

At that time, the studies made about these structural types were few in number and focussed on very particular aspects. None of them went so far as to define design criteria. In addition, very few articles had been published in international journals, and those that had were mainly about the design and construction of built structures rather than about research results — as can be appreciated by checking the references section of this paper. Furthermore, there was a lack of a consolidated body of knowledge on these structural types, and therefore a consistent naming or classification system did not exist. Given that the information and knowledge that had been generated was both very scarce and very scattered, the current authors thought it necessary to publish a paper defining the state-of-the-art for these structural types, gathering the scattered information and ordering, classifying, and naming these very unconventional structures.

The research carried out by other authors had been concentrated in five centres, namely the Institut für Baustatik und Konstruktion (IBK, linked to ETH) in Switzerland, the Institut für Leichtbau Entwerfen und Konstruieren (ILEK, linked to the University of Stuttgart) in Germany, the Swiss Federal Institute of Technology in Lausanne, Switzerland, as well as the Nihon and Saitama universities in Japan.

The first research work on this subject, mentioned previously, was undertaken by Christian Menn and Paul Gauvreau in 1987 at ETH. They arrived at under-deck cable-staying systems as an extrapolation of external prestressing and thought about the possibility of applying these systems to continuous bridges with voided slabs and spans of between 25 and 40 metres, thus broadening the range of spans for slab bridges. They performed laboratory tests on a slab with two 10-metre spans and a depth of 27 centimetres (1/37) and checked the behaviour due to permanent loads considering time-dependent effects (concrete creep and shrinkage) as well as the static and dynamic behaviour under live loads (Menn and Gauvreau 1990).

In 1998, the results of a research project carried out jointly by the University of Nihon and the company Sumitomo Construction were published (Umezu et al. 1998). This was a theoretical study of six bridges with three spans and external prestressing, in which eccentricities were increased and pylons and struts were used to achieve combined cable-stayed schemes. The decks studied had 75-metre spans and depths of 1/23 of the span. It was noted that as the eccentricity of the tendons is increased, the efficiency of the tendons is enhanced and the amount of the active steel required is reduced.

At the same university, Professor Masao Saitoh and his team carried out substantial work on the subject of structures with under-deck cable-staying systems. Their work did not focus on bridges, but instead analysed structures using cables, in an attempt to order and classify them on the basis of their behaviour (Saitoh and Okada 1999). One of the classes that they define is that of ‘beam string structures’, which simply consist of beams with under-deck cable-staying systems, and they examine the use of such structures for different purposes like large-span roofs, bridges and lightweight façades. Theirs was the first attempt at ordering these types of structures, which have their own identity and consequently have their own design criteria rather than being an extrapolation of bridges with external prestressing.

Aurelio Muttoni, of the Swiss Federal Institute of Technology in Lausanne, also studied under-deck cable-stayed bridges. His research began by studying the response to live load of single-span bridges using different layouts of under-deck cable-staying systems (Muttoni 2002). However, in trying to increase the stiffness of the under-deck stay cables, his research became focussed upon bridges where the bare steel of the under-deck stay cables is replaced by prestressed concrete, i.e. the stay cables are embedded in prestressed concrete. He applied this scheme to the design and construction of several bridges, namely the Breno bridge, the bridge over the Capriasca River and the bridge over the Tessina River (Muttoni 1997). Since 1997, he has been pursuing a line of research into the concrete used for the prestressed-concrete stays of these bridges (Jungwirth and Muttoni 2002).

Likewise, Peter Marti, at ETH, has also studied aspects of under-deck cable-stayed bridges. In 1999, Armand Fürst and Peter Marti published the results of an experimental project (Fürst and Marti 1999) on 12-metre beams with under-deck prestressing systems embedded in concrete, using structural schemes similar to those that Aurelio Muttoni had used in his bridges. He also supervised Massimo Laffanchi's doctoral thesis (Laffanchi 1999) on structural types of curved bridges, in which he briefly deals with under-deck cable-stayed bridges of single-spans.

At Saitama University, in Japan, Aravinthan, Witchukreangkrai and Mutsuyoshi have made studies of beams with one and two 5-metre spans, with both under-deck cable-staying systems and combined cable-staying systems. They obtained these schemes on the basis of external prestressing, attempting to increase the ultimate bending capacity of beams with this type of prestressing (Aravinthan et al. 2005).

Jörg Schlaich, who continues his academic work as professor emeritus at ILEK — a German institute for the research on light structures —, has recently co-authored a book (Schlaich and Bergermann 2004) focussed on lightweight structures, in which he also deals with bridges with unconventional cable-staying systems.

A doctoral thesis defended recently at ILEK (Ploch 2004) examines the safety factors for prestressing in bridges using prestressed tendons, including under-deck cable-stayed bridges. This institute has also analysed the basic behaviour of structures with under-deck cable-staying systems, and, in fact, the studies carried out to date are included as part of the class handouts for one of the subjects taught by ILEK lecturers at the University of Stuttgart

(Lemaitre and Kobler 2005).

Recently, Strasky (2005) has written a book about stress ribbon and cable-supported pedestrian bridges in which four examples of unconventional cable-stayed bridges are included.

6. A critical analysis of the current situation

As previously mentioned, the first structure built using an under-deck cable staying system dates back to 1978. Since then at least seventeen bridges, viaducts and footbridges have been built using under-deck cable-staying systems and seven have been built with combined cable-staying systems. Thirteen of these structures have either steel or composite decks, nine have prestressed concrete decks and one has a timber deck. Most of these structures are located in Germany, Japan, France and Spain, all of which are countries with cutting-edge bridge-building industries. Table 2 gives a summary of the built structures fitting into these two bridge categories.

If we examine the reasons for building bridges using under-deck cable-staying and combined cable-staying systems, we find four trends:

(1) Elimination of piers in viaducts. The cable-staying systems used have allowed end piers (Weitingen viaduct, Obere Argen viaduct and Losa del Obispo bridge) and central piers (Schlaich’s proposal for Kämpfelbach and the Meaux viaduct) to be eliminated.

(2) “Help” for decks by means of systems with stay cables to attain lighter deck cross-sections and consequently reduce the self-weight of decks. The aim here is to reduce the cost of foundations (Tobu Recreation Resort footbridge), to use lighter self-launching form carriers (Osormort viaduct), or to mitigate against seismic actions — proposal for the Vinalopó River bridge (Rui-Wamba et al. 1991) and Torizaki footbridge (Kamazawa et al. 2002).

(3) Design of structures to reinforce their aesthetic appeal through the use of cable-staying systems (Jumet footbridge, Miho Museum footbridge, Waschhaussteg footbridge, Hiyoshi footbridge).

(4) Construction of bridges over deep valleys (Takehana bridge) or over wide rivers (Glacis bridge) without requiring falsework. This goal has been attained both by means of under-deck cable-staying systems using tendons that are either exposed or embedded in concrete as well as by means of stress ribbons with an upper deck — San José bridge (Lin and Kulka 1973), Taojin bridge, Ganmon enchi enro bridge, Seiun bridge (FIB 2006), Mozomi bridge (FIB 2006).

What is clear after studying these different proposals and structures is that these types of cable-stayed schemes are poorly known because they are unconventional, and this circumstance is confirmed by several facts:

- Proposals are sometimes made for cable-staying layouts that are not efficient in the presence of traffic live load and that are only effective for compensating permanent loads. This is the case with the application of under-deck cable-staying systems to continuous bridges.
- Sometimes the designers who choose these highly innovative approaches encounter serious problems in having their designs built: since their proposals are novel and highly unconventional, the authorities tend to be rather reluctant to approve and build them.
- When these cable-stayed schemes are designed and built, no specific scientific and technical references are available. To date, there is no consolidated body of knowledge dealing with these types of structures, or, at least, none that has been clearly set out or presented. This is confirmed by the fact that no books or studies have been published on the subject of the structural behaviour and design criteria of these types of bridges (with

the exception of the first author's doctoral thesis) and that very few research papers exist.

Nevertheless, it is important to note that the structural and aesthetic potential offered by these new types is attracting a growing number of structural engineers of great international prestige, including Fritz Leonhardt, Jörg Schlaich, Christian Menn, Michael Virlogeux, Javier Manterola, Leslie Robertson and Jean Marie Cremer. The aesthetic potential of these bridges has also proven to be of interest to architects who have taken part in the design of such structures. Many of these bridges have been awarded prizes, both for their structural features and their aesthetic appeal, such as the Osormort viaduct, the Glacis bridge, and the Gut Marienhof (Constructa-Preis 1990), Morino-wakuwaku-hashi, Miho Museum, Waschhaussteg (Landesbaupreis 1998), and Hiyoshi footbridges.

7. Conclusions

(1) Beside the classical types of cable-stayed bridges, there are two other types of unconventional cable-stayed bridges: "under-deck cable-stayed bridges" and "combined cable-stayed bridges".

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

(3) In combined cable-stayed bridges, the stay cables are located both above the extrados and below the intrados of the deck. Where the cable-stays are above the extrados, they are deflected by the pylons that carry the downward deviation forces directly to the supports; whereas, where the stay cables are below the intrados of the deck they have a polygonal layout and are deflected by struts that, working under compression, introduce the cable upward deviation forces into the deck.

(4) In both types the axial response (with the stay cables in tension, and the pylons, deck, and struts in compression) is enhanced, whereas the flexural response (deck in bending) is reduced. Because of this fact, lighter structures are designed and the amounts of materials required are reduced.

(5) There are only a few bridges built with these structural types but most of them have been designed by structural engineers of great international prestige (Leonhardt, Schlaich, Menn, Virlogeux, Manterola, Robertson, Cremer, etc). In particular Schlaich's mastery has been fundamental for the development of these structural types.

(6) In the different examples of these structural types that have been presented, the cable-staying system has been developed in order to achieve the following objectives: (1) elimination of piers in viaducts, (2) self-weight reduction in decks, (3) aesthetic purposes, and (4) development of construction methods without falsework.

(7) These structural types were not well known up to now: some highly unsuitable structural schemes have been proposed, there is practically no scientific and technical literature on the subject and some authorities are reluctant to build such unconventional structures. In order to fill this gap in knowledge, it is necessary to analyze their structural behaviour, determine the circumstances in which they are suitable, establish appropriate design criteria, and make all of this information available to the international scientific and technical community. The authors of this paper have already worked in this direction developing a doctoral thesis and a research project. Before publishing further results, it was recognised that there was a need to define the state-of-the-art by compiling all the widely scattered work produced up until now, as well as defining and naming these new structural types.

Acknowledgments

The authors would like to express their sincere gratitude to the engineers and companies that have provided us with both the pictures included in this paper and their publishing permission; in particular, Jean Marie Cremer (Bureau Greisch, Belgium), Nicolas Janberg (www.structurae.de, Germany), Javier Manterola (Carlos Fernández Casado S.L., Spain), Jörg Schlaich (Schlaich, Bergermann und Partner, Germany), Holger Svensson (Leonhardt Andrä und Partner, Germany), and Meguru Tsunomoto (Oriental Construction Co, Japan). The authors would also like to express their gratitude to the Spanish Ministry of Education for the post-doctoral fellowship received by the first author.

References

Aravinthan, T., Witchukreangkrai, E., and Mutsuyoshi, H. 2005. Flexural behaviour of two-span continuous prestressed concrete girders with highly eccentric external tendons. ACI Structural Journal, **102**(3): 402-411.

Argüelles, R. 2001. Steel structures. Joinings and structural systems (Estructuras de acero. Uniones y sistemas estructurales). Volume 2. Bellisco, Madrid (in Spanish).

Cazet, P. 1992. The steel Obere Argen viaduct (Le viaduc métallique sur l'Oberargen). Bulletin Ponts Metalliques (OTUA), **15**: 97-114 (in French).

Civil Engineering. 1978. Cable-stayed bridge with cables below the deck level in Germany. Civil Engineering (ASCE): 18-19.

Constructa-Preis.1990. Industrial architecture in Europe. Vincentz Verlag, Hannover.

ENR. 1978. Inverted stayed-girder bridges soil problems. Engineering News Record, **23**: 18-19.

Gonzalez, A. 1997. Transverse axis of Catalonia. Section: Calldetenes-Sant Juliá de Vilatorta-Sant Sadurni d'Osormort (Eje transversal de Cataluña. Tramo: Calldetenes-Sant Juliá de Vilatorta-Sant Sadurni d'Osormort). Revista de Obras Públicas, **3364**: 61-66 (in Spanish).

FIB. 2006. 2006 fib awards for outstanding concrete structures. Winner, special mentions and nominees. Bulletin 36. Laussane.

Forno, J.Y., and Cremer, J.M. 2001. Steel bridges and composite bridges designed in Greisch Office (Puentes metálicos y mixtos diseñados por el Estudio Greisch). Puentes Mixtos. Estado actual de su tecnología y análisis. Comunicaciones y Mesas Redondas de las III Jornadas Internacionales, Madrid, pp. 721-742 (in Spanish).

Fürst, A., and Marti, P. 1999. Experimental tests of precast beams with prestressing below the deck (Versuche an trägern mit unterspannung aus vorfabrizierten, vorgespannten betonzuggliedern). IBK, ETH, Zürich, Switzerland. (in German).

Galvanización. 2004. Montabaur Bridge (El puente de Montabaur). Galvanización, **14**(2): 7 (in Spanish).

Hines, E., and Billington, D. 1998. Case study of bridge design competition. Journal of Bridge Engineering, **3**(3): 93-102.

Holgate, A. 1997. The art of structural engineering. The work of Jörg Schlaich and his team. Edition Alex Menges, Stuttgart.

Kamazawa, H., Hojo, M., Shionozaki, H., and Matsui, T. 2002. An innovative two span continuous PC bridge using large eccentric external tendons. Torizaki River park bridge. National Report. FIB Congress 2002, Osaka, Japan. pp 189-192.

Kratz, A. 2000. Footbridge in Weil am Rhein (Fuβgängerrucke in Weil am Rheim). Steel structures in Stuttgart (Stahlbauten in und um Stuttgart). Bauen mit Stahl, **610**: 83-84 (in

German)

Kumagai, T., Tsunomoto, M., and Machi, T. 2002. Stress-ribbon bridge with external tendons. Morino-Wakuwaku Bridge. National Report. FIB Congress 2002, Osaka, Japan. pp 169-172.

Laffanchi, M. 1999. Conception of curved bridges (Zur konzeption gekrümmter brücken). Doctoral thesis supervised by Peter Marti. IBK, ETH, Zürich. (in German).

Landesbaupreis 1998. National building awards (Landesbaupreis). Ministerium für Bau, Landesentwicklung und umwelt, Germany. (in German).

Leonhardt, F. 1982. Bridges (Ponts, Puentes). Presses polytechniques romandes, Lausanne. (in French and Spanish).

Lemaitre, C., and Kobler, M. 2005. Course on sketching and designing civil engineering (Entwerfen und konstruieren von ingenieurbauten). University of Stuttgart. (in German)

Lin, T.Y., and Kulka, F. 1973. Construction of rio Colorado bridge. Prestressed Concrete Institute Journal, November-December, pp. 92-101.

Lluch, A., Loran, G., and Plaja, A. 2001. Transverse axis of Catalonia. Bridges and tunnels: dialogue between technical and landscape (L’eix Transversal de Catalunya. Ponts i túnels: diàleg de la tècnica amb el paisatge). Generalitat de Catalunya, Catalonia. (in Catalan and Spanish).

Menn C., and Gauvreau P. 1987. Scale model study of an externally prestressed concrete slab bridge. International Conference on cable-stayed bridges. Bangkok, pp. 919-926.

Menn C., and Gauvreau P. 1990. Externally prestressed concrete slab bridges: model test results. ACI SP, **120**: 289-304

Mochizuki, H., Hanada, K., Nakagawa, T., Hanawa, Y., Yamagiwa, I., Yasuda, K., Fujino, Y., and Nagai, M. 2000. Design and construction of a cable-trussed girder bridge. Fifth International Bridge Engineering Conference. Transportation Research Record, Vols. 1 and 2, pp. 293-298.

Muttoni, A. 1997. Bridges with an innovative static system (Brücken mit einem innovativen statischen system). Schweizer Ingenieur und Architekten, **26**:28-31(in German)

Muttoni, A. 2002. Bridges with under-deck cable staying systems (Brücken mit vorgespannter stahlunterspannung). Stahlbau, pp. 592-597. (in German)

Nakagawa, T., Okada, T., Hamazaki, Y., Okada, N., Mochiduki, H., and Nagai, M. 2001. Structural characteristics of a cable-trussed bridge. IABSE Conference, Seoul.

Ouvrages d'art .1993 a. Under-deck cable-staying systems. Design of the bridge nº 13 at A75. (Dalle précontrainte sous-bandée. Étude de l'ouvrage dárt nº 13 sur A75). Ouvrages d'Art, **15**: 2-4 (in French).

Ouvrages d'art. 1993 b. Under-deck cable-staying systems. Construction of the bridge nº 13 at A75 (Dalle précontrainte sous-bandée. Exécution de l'ouvrage dárt nº 13 sur A75). Ouvrages d'Art, **16**: 16-18 (in French).

Ouvrages d'art .2003. An innovative composite structure: the viaduct crossing Marne valley in Meaux (Une structure mixte innovante: le viaduc de franchissement de la vallée de la Marne à Meaux). Ouvrages d'Art, **42**: 13-21 (in French).

Placidi, M., Commun, J.P., Lecointre, D., and Sablon, J.Y. 2004. An innovative composite structure: the viaduct crossing the Marne valley in Meaux. FIB Symposium, Avignon.

Ploch, J. 2004. Definition of the concept of security in prestressing (Zur definition und zum sicherheitskonzept der vorspannung).Doctoral thesis supervised by Kurt Schafer. ILEK, Stuttgart (in German).

Rui-Wamba, Barragan, P., Cirici, E., Bellod, J.L., Prieto, R., and Cobian, I. 1991. Zubi. Obras Públicas (OP), **19**: 144-145.

Ruiz-Teran A.M. 2005. Unconventional cable-stayed bridges. Structural behaviour and design criteria. Doctoral Thesis. Supervised by A.C. Aparicio. University of Cantabria, Spain (in Spanish).

Saitoh, M., and Okada, A. 1999. The role of string in hybrid string structure. Engineering Structures, **21**: 756-769.

SBP. 2004. Sewege plant München II (Kläwerk München II). Schlaich Bergermann und Partner, Stuttgart. (in German).

Schlaich, J., Schlaich, M., and Werwigk, M. 1999. New Glacis bridge in Ingolstadt (Die neue Glacisbrücke Ingolstadt). Beton und Stahlbetonbau, **94**(11): 466-475 (in German).

Schlaich, J. 1999. Cable-stayed bridges with special features. IABSE Conference, Malmö

Schlaich, J., and Bergermann R. 2004. Light structures. Prestel.

Schlaich, J., and Schober, H. 1994. Highway overpass in Kirchheim (Steg über die autobahn bei Kirchheim). Beton und Stahlbetonbau, **89**(2): 40-44 (in German).

Schlaich, M., and Werwigk, M. 2001. The Glacis bridge in Ingolstadt, Germany. IABSE Conference, Seoul

Strasky, J. 2005. Stress ribbon and cable-supported pedestrian bridges. Thomas Telford, London.

Takenouchi, K., and Manabu, I. 2002. Function and development of pedestrian bridges in Japan. Footbridge 2002. AFGC and OTUA International Conference, Paris.

Tsunomoto, M., and Ohnuma, K. 2002. Self-anchored suspended deck bridge. Pedestrian bridge of the Tobu recreation resort. National report. FIB Congress 2002. Osaka, Japan, pp.

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

181-184

Uchimura, T., Miyazaki, M., Kondoh, S., and Okumura, K. 2002. Prestressed concrete deck bridge supported from bellow by cables. Ayumi bridge. National Report. FIB Congress 2002, Osaka, Japan. pp 177-180.

Umezu, K., Fujita, M., and Yamazaki, J. 1998. Study of a new structural type for prestressed concrete bridges. IABSE Symposium, Kobe.

Virlogeux, M., Bouchon, E., Lefevre, J., Resplendino, J., Crocherie, A., Ageron, C., Bourjot, A., Clement, M., Million, P., Gudefin, C., and Valence, M. 1994. A Prestressed concrete slab supported from below: The Truc de la Fare bridge. XII Congres de la FIP, Washington.

Watanabe Y. 2002. Miho museum bridge, Shigaraki, Japan. Structural Engineering International, **12**(2): 245-247

WTB and Dywidag. 1991. Bridge over Obere Argen valley (Talbrücke Obere Argen). Walter-Thosti-Boswau & Dywidag (in German)

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Table 1: Under-deck cable-stayed bridges and combined cable-stayed bridges. Main dimensions.

Bridge	Deck material	Main span (m)	Platform width (m)	h/L	Ls/L	hp/L	Amount of active steel (kg/m^2)/span (m)
Weitingen viaduct	Steel	263	31	1/43	1/9	-	0,13
Gut Marienhof footbridge	Steel	22	6	1/85	1/7	-	0,29
Obere Argen viaduct	Steel	258	29	1/69	1/9	1/5	0,13
Truc de la Fare overpass	Prestressed concrete	53	8	1/33	1/11	-	0,26
Osormort viaduct	Prestressed concrete	40	12	1/25	1/8	-	0,13
Miho Musseum footbridge	Steel	114	7	1/57	?	1/7	?
Jumet footbridge	Steel	37	3	1/116	1/12	-	?
Losa del Obispo bridge	Composite	62	11	1/41	1/8	-	0,19
Tobu recreation resort footbridge	Prestressed concrete	40	3	1/98	1/17	-	?
Glacis bridge	Prestressed concrete	76	12	1/109	1/22	-	0,74
Wacshhaussteg footbridge	Steel	?	?	?	?	?	?
Hiyoshi footbridge	Steel	90	5	1/53	?	?	?
Weil am Rhein viewpoint	Steel	14	?	?	1/8	-	?
Ayumi bridge	Prestressed concrete	79	7	1/88	1/16	1/4	?
Takehana bridge	Composite	74	10	1/28	1/5	-	0,24
Morino-wakuwaku-hashi footbridge	Prestressed concrete	128	4	1/427	1/24	-	0,12
Torizaki river park footbridge	Prestressed concrete	33	6	1/47	1/14	1/19	?
Numedalslagen footbridge	Timber	90	?	?	?	-	?
Montabaur footbridge	Galvanised steel	26	3	?	1/11	1/7	?
Spinningfields footbridge	Steel and aluminium	45	?	?	?	-	?
Meaux viaduct	Composite	93	31	1/21	?	-	0,06
Seiryuu footbridge	Prestressed concrete	37	3	1/106	1/18	-	?
Fureai footbridge	Prestressed concrete	39	3	1/112	1/16	-	?
Bercy-Tolbiac footbridge	?	?	?	?	?	-	?

h/L: deck depth / Length of the span

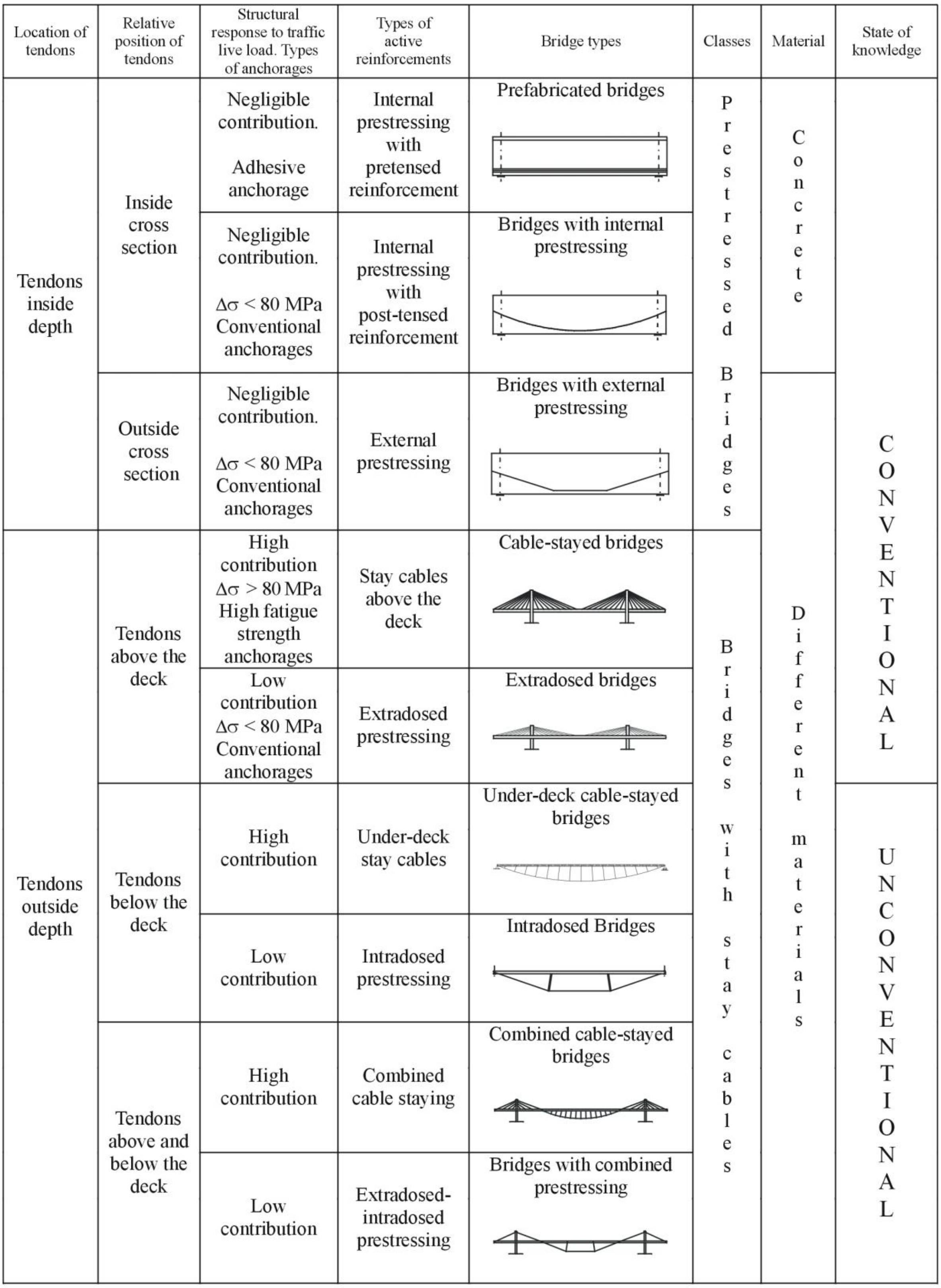
Ls/L: strut Length / Span length

hp/L: pier height / Span Length

Table 2: Under-deck cable-stayed bridges (UCSB) and combined cable-stayed bridges (CCSB) in chronological order.

Bridge	Designer	Year	Country	Type
Weitingen viaduct	Fritz Leonhardt	1978	Germany	UCSB
Gut Marienhof footbridge	Schlaich, Berermann und Partner	1987	Germany	UCSB
Obere Argen viaduct	Schlaich, Berermann und Partner	1991	Germany	CCSB
Truc de la Fare overpass	Michael Virlogeux	1993	France	UCSB
Osormort viaduct	Javier Manterola	1995	Spain	UCSB
Miho Musseum footbridge	Leslie E. Robertson	1997	Japan	CCSB
Jumet footbridge	Jean Marie Cremer	1998	Belgium	UCSB
Losa of the Obispo bridge	José Ramón Atienza	1998	Spain	UCSB
Tobu Recreation Resort footbridge	Toyo Ito & Associates	1998	Japan	UCSB
Glacis bridge	Schlaich, Berermann und Partner	1998	Germany	UCSB
Wacshhaussteg footbridge	Schlaich, Berermann und Partner	1998	Germany	CCSB
Hiyoshi footbridge	Simura & Tanase	1998	Japan	CCSB
Weil am Rheim Viewpoint	Schlaich, Berermann und Partner	1999	Germany	UCSB
Ayumi bridge	CTI Engineering	1999	Japan	CCSB
Takehana bridge	-	2000	Japan	UCSB
Morino-wakuwaku-hashi footbridge	Yosuki Kojima	2001	Japan	UCSB
Torizaki river park footbridge	Civil Engineering Services	2001	Japan	CCSB
Numedalslagen footbridge	Kristoffer Apeland	2002	Norway	UCSB
Montabaur footbridge	Ludwig Müller Offenburg	2003	Germany	CCSB
Spinningfields footbridge	Whitby Bird	2004	United Kingdom	UCSB
Meaux viaduct	Michael Placidi	2004	France	UCSB
Seiryuu footbridge	Asahi Development Consultants Ltd and Oriental Construction Co. Ltd	2006	Japan	UCSB
Fureai footbridge	Taiyo Consultants Co. Ltd and Oriental Construction Co. Ltd	2006	Japan	UCSB
Simone-de-Beauvoir footbridge	RFR Ingenieurs	2006	France	UCSB

List of Figures



Location of tendons	Relative position of tendons	Structural response to traffic live load. Types of anchorages	Types of active reinforcements	Bridge types	Classes	Material	State of knowledge
Tendons inside depth	Inside cross section	Negligible contribution. Adhesive anchorage	Internal prestressing with pretensed reinforcement	Prefabricated bridges	Prestressed Bridges	Concrete	CONVENTIONAL
		Negligible contribution. $\Delta\sigma < 80$ MPa Conventional anchorages	Internal prestressing with post-tensed reinforcement	Bridges with internal prestressing			
	Outside cross section	Negligible contribution. $\Delta\sigma < 80$ MPa Conventional anchorages	External prestressing	Bridges with external prestressing		Different materials	
Tendons outside depth	Tendons above the deck	High contribution $\Delta\sigma > 80$ MPa High fatigue strength anchorages	Stay cables above the deck	Cable-stayed bridges	Bridges with stay cables		
		Low contribution $\Delta\sigma < 80$ MPa Conventional anchorages	Extradosed prestressing	Extradosed bridges			
	Tendons below the deck	High contribution	Under-deck stay cables	Under-deck cable-stayed bridges			UNCONVENTIONAL
		Low contribution	Intradosed prestressing	Intradosed Bridges			
	Tendons above and below the deck	High contribution	Combined cable staying	Combined cable-stayed bridges			
		Low contribution	Extradosed-intradosed prestressing	Bridges with combined prestressing			

Figure 1: Classification of bridges with prestressing by tendons

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Figure 2: Weitingen viaduct (courtesy of Holger Svensson, Leonhardt Andrä und Partner)

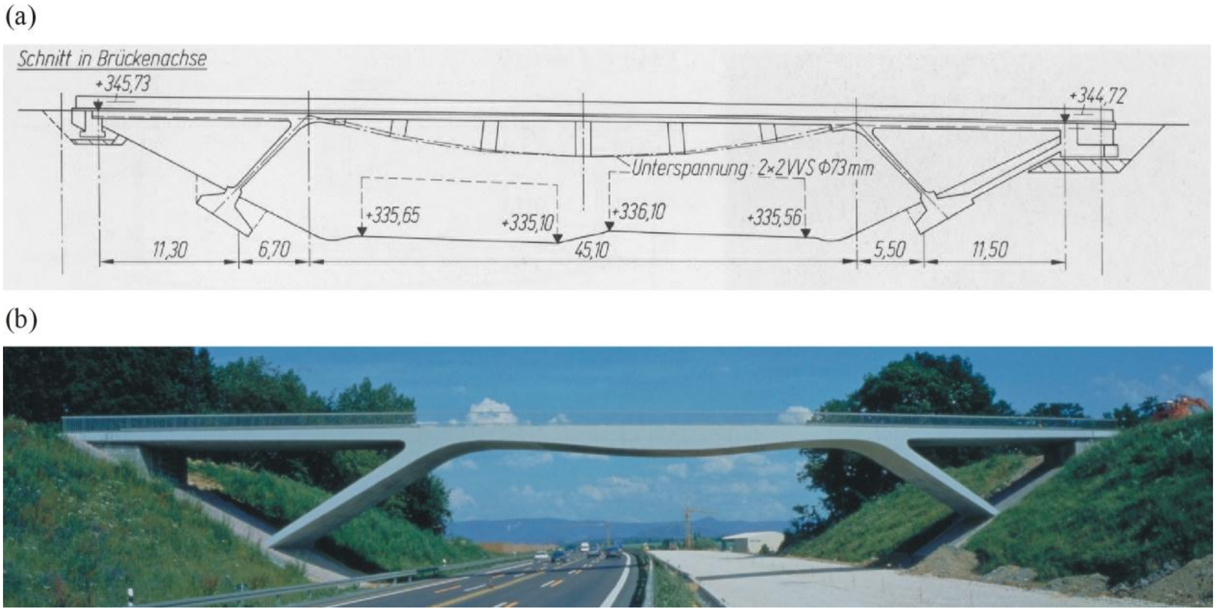


Figure 3: Kirchheim overpass, (a) proposal (courtesy of Jörg Schlaich, ©Schlaich, Bergermann und Partner)and (b) built structure (courtesy of Jörg Schlaich, ©Elsner Gert, Stuttgart)

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Figure 4: Obere Argen viaduct (courtesy of Jörg Schlaich, ©Elsner Gert, Stuttgart)

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Figure 5: Truc de la Fare overpass (courtesy of Nicolas Janberg, www.structurae.de)

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Figure 6: Osormort viaduct (courtesy of Javier Manterola, Carlos Fernández Casado S.L.)

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Figure 7: Jumet footbridge (courtesy of Jean Marie Cremer, Bureau Greisch)

Cite this paper as: Ruiz-Teran AM, Aparicio AC, 2007, Two new types of bridges: under-deck cable-stayed bridges and combined cable-stayed bridges - the state of the art, *Canadian Journal of Civil Engineering*, Vol:34, ISSN:0315-1468, Pages:1003-1015 [doi: 10.1139/L07-017]

Figure 8: Tobu recreation resort footbridge (courtesy of Meguru Tsunomoto, Oriental Construction Co)