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New trends in typology: hybrid bridges, a field for innovation in structural engineering

Nuevas tendencias en tipología: puentes híbridos, un campo para la innovación en la ingeniería estructural

José Romo[a]

[a] *Structural Engineer. CEO. FHECOR Ingenieros Consultores SA (Spain)*

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ABSTRACT

One of the fundamental characteristics of Javier Manterola's attitude towards design is innovation. His search for innovative solutions has led him to refine the canonical structural types to the limit. Furthermore, he has also contributed to the development of more complex structural solutions that could be said to constitute hybrid structures, on which this article deals.

This paper will show that hybrid bridges are not a contemporary invention, since their more or less conscious constant use in engineering through its history. For the author hybrid structure could be recognized as one of the obvious fields for creativity and innovation in structural engineering and the works of Javier Manterola are good examples of that design's approach.

KEYWORDS: Hybrid, extradosed, suspension, cable stayed, truss.

RESUMEN

Una de las características fundamentales de la actitud de Javier Manterola hacia el proyecto es la innovación. Su búsqueda de soluciones innovadoras le ha llevado a refinar los tipos estructurales canónicos hasta el límite. Además, su trabajo también incluye el desarrollo de soluciones estructurales más complejas que podrían decirse que constituyen estructuras híbridas, sobre las cuales trata este artículo.

Como se explica en el artículo, los puentes híbridos no son una invención contemporánea ya que su uso, más o menos consciente, es constante en la ingeniería a lo largo de su historia. Para el autor, la estructura híbrida podría ser reconocida como uno de los campos obvios para la creatividad y la innovación en la ingeniería estructural, siendo los trabajos de Javier Manterola el mejor paradigma de su uso.

PALABRAS CLAVE: Híbrido, extradosado, colgante, atirantado, celosía.

1. INTRODUCTION

One of the fundamental characteristics of Javier Manterola's attitude towards the design is innovation. His search for innovative solutions has led him to refine the canonical structural types to the limit. Furthermore, he has also contributed to the development of more complex structural solutions that could be said to constitute hybrid structures, on which this article deals.

This paper will show that hybrid bridges are not a contemporary invention, since their more or less conscious constant use in engineering through its history. For the author hybrid structure could be recognized as one of the obvious fields for creativity and innovation in structural engineering and the

* Persona de contacto / *Corresponding author.*
Email - Correo electrónico: José Romo: jrm@fhecor.es

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works of Javier Manterola are good examples of that design's approach.

It can be affirmed that the use of systems beyond the canonical types is common in the design of structures for buildings, because of their complexity. However, the use of combined structural systems is no so common in bridges, even though the departure from the canonical is fully justified. The aim of this paper is to contribute to the diffusion of these bridges, in which without leaving the structural rigor, several resistant systems are combined, in order to adapt to specific problems particularities.

2. DEFINITION OF HYBRID STRUCTURES

Hybrid structures are those in which two or more different structural systems which work together coexisting or overlapping. Perhaps to understand this definition better, it is necessary to understand the opposite of the hybrid, that is, the structural types we might call canonical. The canonical types correspond to the most known structural solutions. Among these solutions are: the beam, the frame, the arch, the cable stayed bridge or the suspension bridge. In all these systems the main flow of forces is well known and is easy to understand and visualize by a connoisseur of structural engineering: in this types of bridges the structural system is very clear. It could be said that the structural science is in a state that has allowed distilling these concepts or canonical solutions leading to a high degree of improvement.

The opposite of canonical systems are hybrid systems. In this case, it is complex systems in which several resistant schemes are combined. Thus, for example, in a hybrid bridge, a frame can be combined with a stayed system, or a tube with an arch. In these structures the structural behaviour is not obvious and depends, among other aspects, on the relative rigidity between the structural systems that coexist, the connections between the systems and the sequence of construction or loading the structure.

3. CONCEPTUAL DESIGN OF HYBRID BRIDGES

In a hybrid bridge, when there are two superimposed subsystems, the structural response depends on the relative rigidity between the two subsystems (figure 1). Thus each structural subsystem takes a portion of the load proportionality to its rigidity relative to the rigidity of the whole system. That concept is applicable for live load as well as for dead loads. The designer can define a construction process, more or less freely, to decide which part of the dead loads is taken by each subsystem.

A clear example of this concept is extradosed bridges [1]. In this type of structure the selfweight is partially resisted by the stays system (typically the 60%) and the rest is taken by the deck. A deeper explanation of this structural type is included in the next sections.

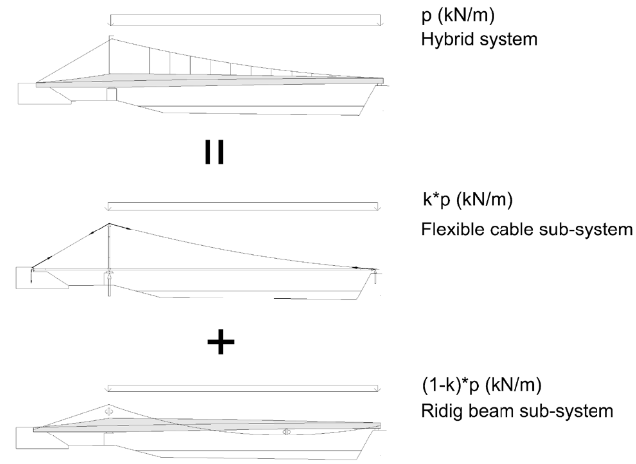

Figure 1. Structural behaviour of a hybrid structure (schematic).

4. HYBRID BRIDGES IN CONSTRUCTION HISTORY

Hybrid structures are nothing new in the world of engineering. In some periods of the history of construction, a large number of hybrid structures were used. One of these periods coincides with the development of the railway, during that period a huge number of new bridges were built. Many of those structures do not follow what it could be called canonical types. That was a period of exploration where trial and error system were extremely used. In fact many of the bridges built during that period were what it could be named as hybrid structures. In many cases the engineers used more than one structural system at a time creating safer and redundant bridges. In the figure 2, an example of those early designs is shown.

Those structures were designed without any structural analysis that could support or explain the structural behaviour of the bridge. At that time, there were no tools to design such complex and redundant structures. After that initial period, the bridges built were closer to it could be called the canonical types. Probably the tools available at that time based on the equilibrium equations led to a kind of structurally more simple systems. In a way the structural solutions used were those which could be calculated

5. CONTEMPORARY HYBRID BRIDGES

5.1 Introduction

Nowadays, the situation is rather opposite to the one explained above. Our contemporary conceptual and analytical tools allow the use of complex systems thanks to its sound comprehension. In a way today it is possible to use hybrid systems because of the evolution of the structural analysis

Figure 2. Early hybrid structures XIXth Century. Source: Structurae. Image-ID: 6316.

methods and tools. That is why, the very initial historical iron or steel structures from the XIXth Century are a good source of inspiration to the contemporary engineer. The modern techniques allow them to explore the fascinating and promising word of the hybrid structures, as it can be seen in the next chapters.

5.2 Extradosed bridges

The extradosed bridge is a good example of hybrid structure. In this type of bridges a deck with an "intermediate" rigidity is superimposed, with a flatter cable stayed system (figure 3).

During construction, it is usual to not completely compensate the permanent loads with the tightening. This percentage usually ranges between 50 to 60% [1].

The live load acts on the composite system deck and stays. By lowering the inclination of the stays, its effectiveness against live loads is low. As a consequence, only a very small fraction of the live load is resisted by the cables. Consequently, the oscillation of the tension in service conditions of the stays is very small and therefore the effect of the fatigue in them is negligible.

The extradosed bridge is the paradigm of hybrid structure. In it two systems are superimposed, the deck and the cables,

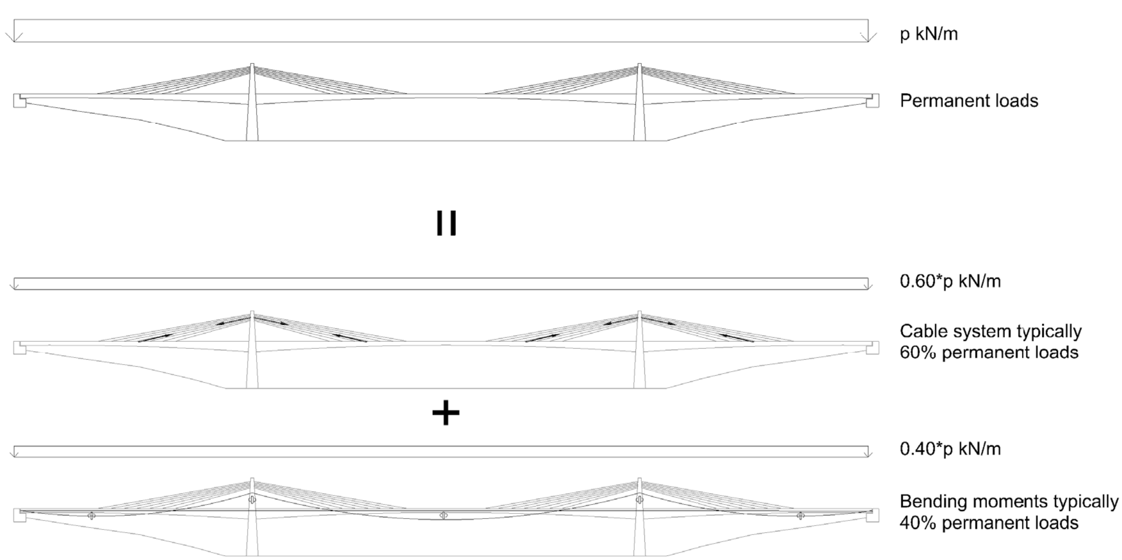

Figure 3. Structural behaviour of an extradosed bridge.

Figure 4. Brooklyn Bridge (John A. Roebling).

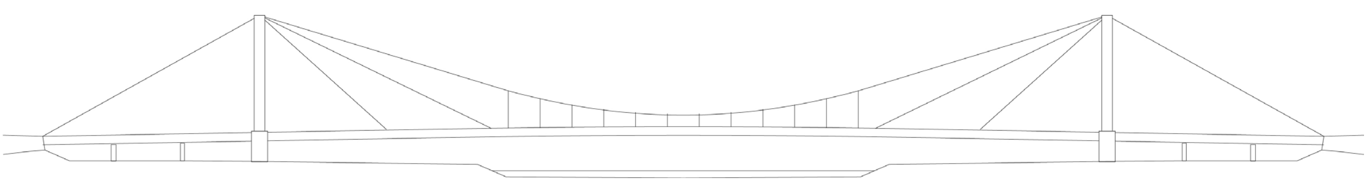

Figure 5. Köln-Mülheim Bridge across the Rhine, proposed by Dischinger in 1949.

combining their way of working at the designer's will. To do this, the angle of the stays can be varied with the horizontal, as well as the rigidity of the deck, to graduate the part of overload that each subsystem will take.

In this case, the fundamental objective is to reduce the variation of loads in the stays so that the fatigue oscillation is minimal. In this way the cables can be designed working at a higher stress than in the case of the canonical cable stayed systems, with the consequent savings.

5.3 *Suspension and cable stayed combined systems*

Besides de extradosed bridges there are other structural solutions used nowadays which could be considered as a hybrid structure. For instance, the combination of a cable stayed system with a suspension system in the same structure is a good example of that.

The superposition of both systems could be found as far ago as the John A. Roebling Bridge in Cincinnati, opened in 1867 with its 317 m world record span length at its time [2]. This bridge is the predecessor of Roebling's masterwork, the Brooklyn Bridge in New York.

In both bridges, Roebling used stays close to the pylons and superimposed with the global suspension system to increase the stiffness of the bridge. The hangers are located on the entire superstructure. That is why we could talk about a suspension bridge with a certain rigidity or stiffness.

Other example is the proposal for the reconstruction of the Köln-Mülheim Bridge across the Rhine, proposed by Dischinger in 1949 [3]. In this case, the bridge had the two systems, stayed and suspended, but in different zones of the bridge. Here in the area closer to the pylons the deck is just stayed meanwhile the central part of the deck is suspended from the main cables.

In this sense, the bridge is a perfectly hybrid bridge since the author has decided to differentiate two areas in which the subsistence system is different.

A recent example of the application of this kind of hybrid system is the "Third Bosphorus Bridge" designed by M. Virloguex and J.F. Klein with 1408 m of span [4]. Here the system

Figure 6. Third Bosphorus Bridge (M. Virlogueux and J.F. Klein).
Source: https://commons.wikimedia.org/wiki/File:Yavuz_Sultan_Selim_Bridge_IMG_3080.jpg

Figure 7. Orio Bridge. (FHECOR).

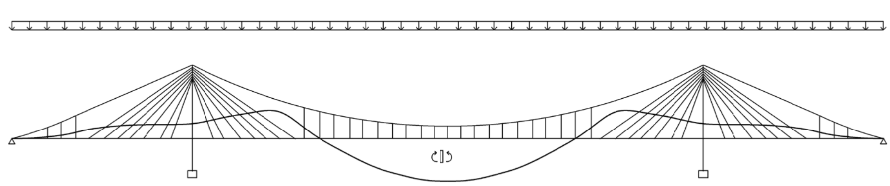

Figure 8. Orio Bridge: bending moments in the deck for a uniform live load applied to the whole deck. (FHECOR).

is conceptually similar to the Dischinger's proposal. However, while in the case of the Rhine Bridge, the cable stayed area and the suspended part do not overlap, in the case of the Bosphorus Bridge (figure 6), both areas overlap for an important magnitude, although not completely on the whole deck as on the Brooklyn Bridge . Again we can see in this example, how the designer can play with both the relative rigidities of the systems, and with their geometric configuration to achieve the desired structural behaviour.

A similar solution but with a central suspension system is the Orio Bridge [5] designed by the author. In this case the hybrid system was used for having low towers that blended into the horizontal landscape of the river Oria estuary. The bridge has only a central plane of cables, and the deck has a box steel cross section with a torsional rigidity enough to span from the torsional point the distance between the abutments.

One issue interesting to highlight is the greater rigidity of the hybrid bridge with respect to the traditional suspension bridge. Figure 8, shows for example the bending moments when a uniform vertical load acts on the whole deck. As it can be seen, there is an important reduction of the effective span length for the deck bending moments, compared with

Figure 9. Infante Dom Henrique Bridge. Adao da Fonseca & IDEAM.

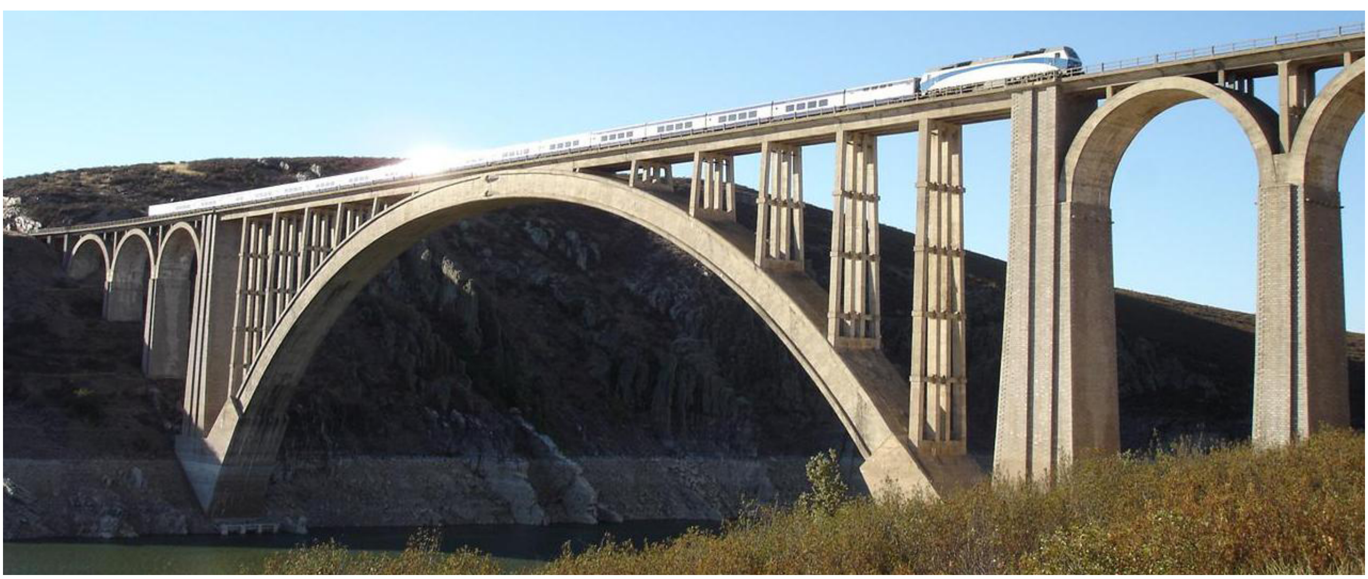

Figure 10. Martin Vigil Viaduct.
Source: Luis Cortés, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=18329848

the case of the classic suspension bridge. Here the stay system are quite stiffer than the suspension system and therefore the general bending moment in the deck and the deflection in the center of the span are smaller than the one corresponding to a suspension bridge.

As seen through those examples, this hybrid solution has its own field of use. In many cases the combined stayed and suspended system improves the stiffness and therefore the performance of the bridge when is compared with a classic suspension bridge, which makes the solution applicable in the cases that the deformations can be critical, as it happens for example in the case of railway bridges.

5.4 Arches with rigid deck

This is again not a new idea, the combination of a rigid arch and a slender deck, or vice versa, a slender arch with a rigid deck, is present in the structural engineering from the XIXth Century.

The example of the figure 9 of Porto, is an example of the combination of a slender arch with a stiff deck.

As an opposite example, the Martin Vigil Viaduct by E. Torroja (1939) [6], is a paradigm of a stiff arch with a slender deck.

In both cases, the designer could define the way of live loads are shared between deck and arches as a consequence of their relative bending stiffness.

Figure 11. Obhur Bridge. (FHECOR).

It is obvious that the possible combinations are huge. One further idea could be the combination of a tubular truss deck with a more slender arch. This was the proposal for the Obhur bridge (Saudi Arabia) developed by the author. Here there was a limitation of the maximum height of the crown of the arch, because of the structure was closed to an airport. The conceptual design led to a shallow arch, with a relationship rise/length of the arch close to 1/10, to compensate that the deck was designed with a high stiffness. Therefore in this case the bulk of the moments caused by the uneven live loads are resisted by the deck.

5.5 *Extradosed and frame systems*

This section presents two examples of combined hybrid bridges designed by J. Manterola, the Andalusia Bridge [7] and the Viana's Prince Bridge [8]. Both structures are extradosed bridges where there is a combination of a stiff deck with a system of cables with a low inclination. But beside that, J, Manterola introduces inclined struts to reduce the flexure of the deck adding a frame system to the structure. The bridges are therefore a combination of an extradosed and a frame structural system.

In both bridges the innovative and the smart engineering solution is also complemented with a typical flair for designing nice and elegant structures, which is a constant in the works of J. Manterola.

5.6 *Arches and stressed ribbons*

Another master in the use of combined systems is Jiri Strasky [9]. Some of his most important contributions to hybrid struc-

Figure 12. Andalusia Bridge (Córdoba) J. Manterola. Source: Carlos Fernández Casado S.L.

Figure 13. Viana's Prince Bridge (Lérida). J. Manterola. Source: Carlos Fernández Casado S.L.

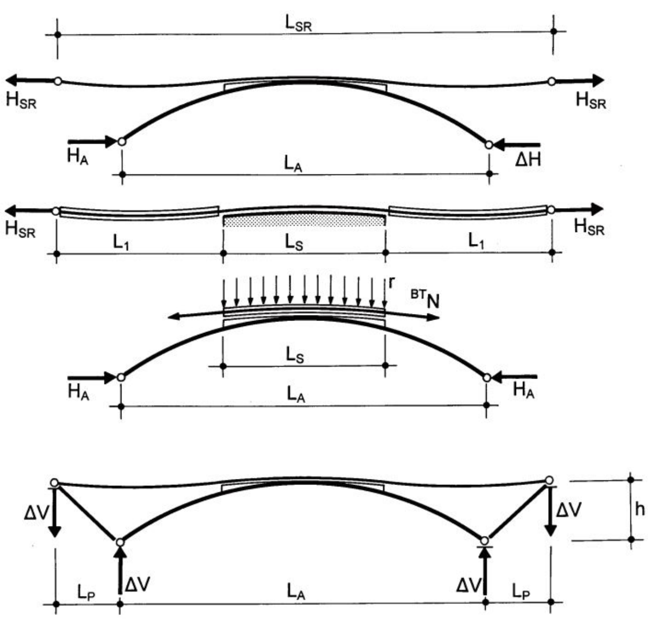

Figure 14. Stress ribbon supported by arch.
(Conceptual ideas by Jiri Strasky [10]).

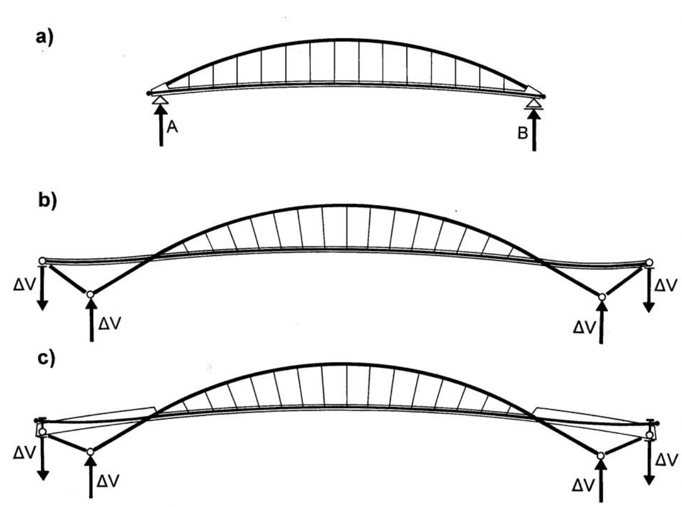

Figure 15. Stress ribbon suspended by arch.
(Conceptual ideas by Jiri Strasky [10]).

tures are those in which he combines an arch with a stress ribbon structure. Using that combination he achieves a self-anchoring system where the horizontal force from the stress-ribbon is transferred by inclined concrete struts to the foundation, where it is balanced against the horizontal component of the arch. With that disposition, there is no need to resist very large horizontal forces at the abutments, which determines the economy of that solution in many cases. In figures 14 and 15 the conceptual development stages of the solution are shown.

These two examples show that two canonical systems: the arch bridge and the stressed ribbon can be combined to achieve a hybrid structure that effectively solves one of the problems that are critical for both types, its dependence on the ability to transmit horizontal actions to the ground.

5.7 *Longitudinal adjacent combined systems*

A completely different way to conceive hybrid bridges is by combining two structural systems longitudinally to solve the same span. It is quite normal to have different structural sys-

Figure 16. Franjo Tudjman Bridge. Source: Structurae, photographer Bernd Kramarczik [11].

tems longitudinal to solve different spans, for instance combining a main span with a cable stayed or an arch bridges with continuous approach viaducts designed as a continuous deck. What is quite unique is having two adjacent structural systems to solve the same span. Probably the most known example of that possibility is the Franjo Tudman Bridge in Dubrovnik, Croatia. Here in order to solve a main span of 304.05 m, a stayed system is combined with a cantilever concrete box-girder. The connexion of the two systems is hinged, and probably the asymmetry of the crossing led to that special structure.

This unique design is perhaps one of the few examples of the use of two different structural types combined longitudinally, in an exceptional hybrid bridge.

5.8 Summary

As seen through the above examples, there are nowadays, in real practice, some good examples of hybrid bridges that show the potentiality of this kind of concepts. A field of innovation in which more examples will be seen in the future, following for example, the ideas presented in the next section.

Many of the examples presented here were designed as a consequence of special requirements such as the need of stiffening in the case of cable supported bridges. In that opportunity the combination of a suspension and a stayed system gives the required rigidity to the system. In the case of the stress ribbon structures, the combination of the ribbon with an arch system makes the structure self-anchored and therefore the horizontal forces transmitted to the ground are successfully eliminated.

6.
HYBRID BRIDGES POSSIBILITIES

6.1 Introduction

As described above, there are several types of hybrid bridges which have a clear field of application. It is obvious that it society will build more Extradosed Bridges or combination of Stayed and Suspended Bridges.

The extradosed bridges described in previous chapters are good examples of the possibility of a hybrid structure. Its range of application of 150 to 250 m lies between the classic continuous concrete box-girder deck built by cantilevering and the canonical cable stayed bridges. The extradosed bridges is an unbeatable solution in multi-span structures, which solves the problems of flexibility of continuous cable stayed bridges. Other hybrid solutions, such as the combination of suspended and stayed bridges are also of interest when the pure suspension system has not enough stiffness against live loads, which could be the case of railway bridges. This kind of structural hybrid system could also be necessary for stabilising long span bridges.

Beside those two types of hybrid bridges already presented, it is possible to foresee a wide range of other possible bridges.

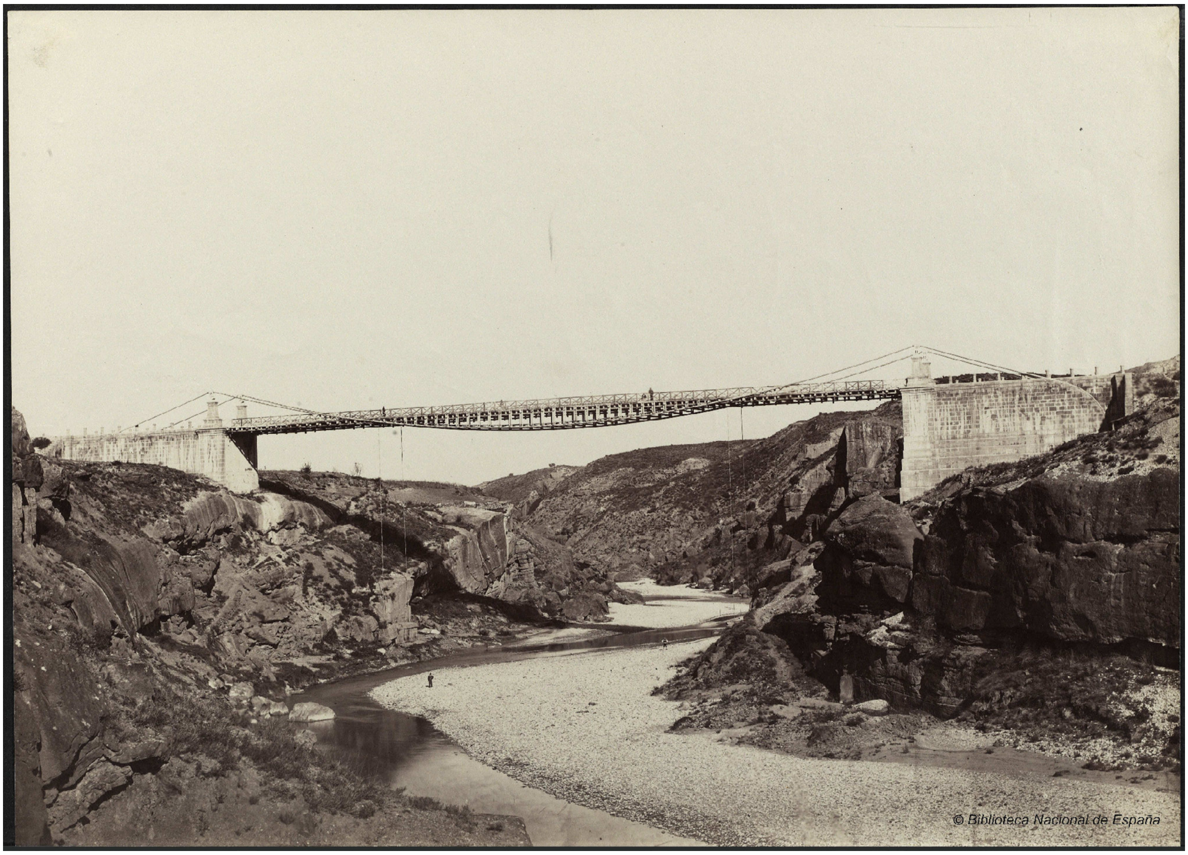

Figure 17. Lascellas Bridge Spain. Source.: Biblioteca Nacional de España.

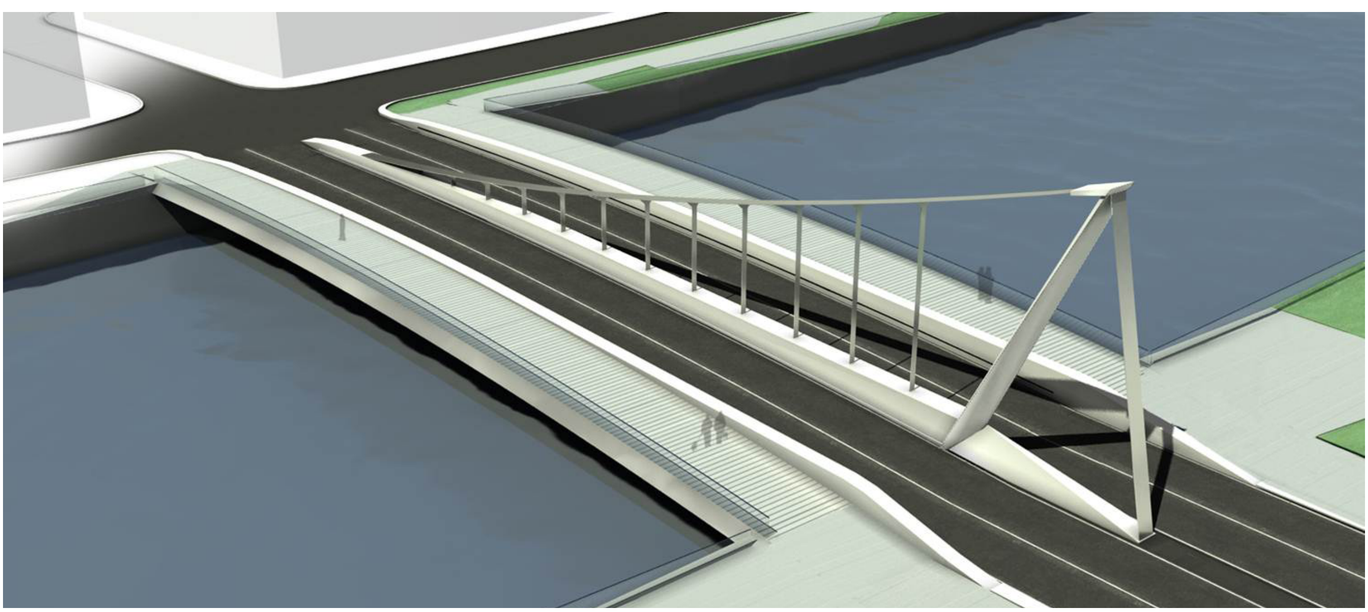

Figure 18. Zorrozaurre bridge. (FHECOR).

The following sections will present just a few examples, as a brief set of the enormous variety of combinations.

6.2 Suspension systems with a rigid deck

The combination of a rigid deck suspended by cables is not a new idea. Some of the early suspension bridges combined a rigid deck, usually a truss beam, with a suspension system.

The bridge of Lascellas built in 1867 in Spain is an example of the early design of a suspension bridge with a low sag/span ratio.

Here again, the designer could modify the main parameter to stablish which part of the dead and live load will be resisted for the deck or the cable.

Figure 19. Arga bridge. (FHECOR).

Figure 20. Dvorecky bridge. (FHECOR).

In general, the stiffness of the deck could be achieved by using a solid beam or by a truss structure.

An example of the first type is the proposal of the author for the first Zorrozaurre Bridge in Bilbao. The bridge has a stiff deck and a shallow suspension system. In this case, the stiffness of the deck was achieved by using two solid elevated steel box beams, which also divides the sidewalks for pedestrians, and the central zone for traffic. The distribution of the permanent load between the two systems can be selected as the designer can modify the forces taken by the hangers, while the distribution of the live loads between main cable and deck depends only of the relative stiffness of the two systems.

Other example of that is the proposal of the author for the Arga Bridge. The structure is a combination of a rigid truss deck with a shallow cable suspension system (figure 19). As in the Zorrozaurre Bridge, the distribution of the permanent forces between deck and cable can be selected by the designer meanwhile the distribution of the life load depends only on the relative vertical stiffness of both systems.

The following example is a proposal for the Dvorecky Bridge in Prague. Here a combination of a suspension system and a framed deck was used to reduce the height of the pylon more suitable with the landscape.

All those examples are just a short set of solutions, which show the field of application of that variety of hybrid bridges.

6.3 The hollow beam

The concept of the hollow beam tries to take full advantage of the resistant capabilities of a beam working at bending, reducing its own weight by lightening the beam wherever possible.

A beam, simply supported, working at bending has two different zones related to its structural behaviour. On one hand there is the mid-span where we have the maximum bending moments and the minimum shear forces, and on the other hand the support area in which the situation is reversed, with the minimum bending moments and the maximum shear forces.

At mid-span, it is sufficient to have an upper compressed chord and a lower tensioned chord to resist the existing forces. That is why in that area it is possible to lighten the section removing much of the web of the beam.

Figure 21. Cork Footbridge. (FHECOR).

Figure 22. New Danube. (FHECOR).

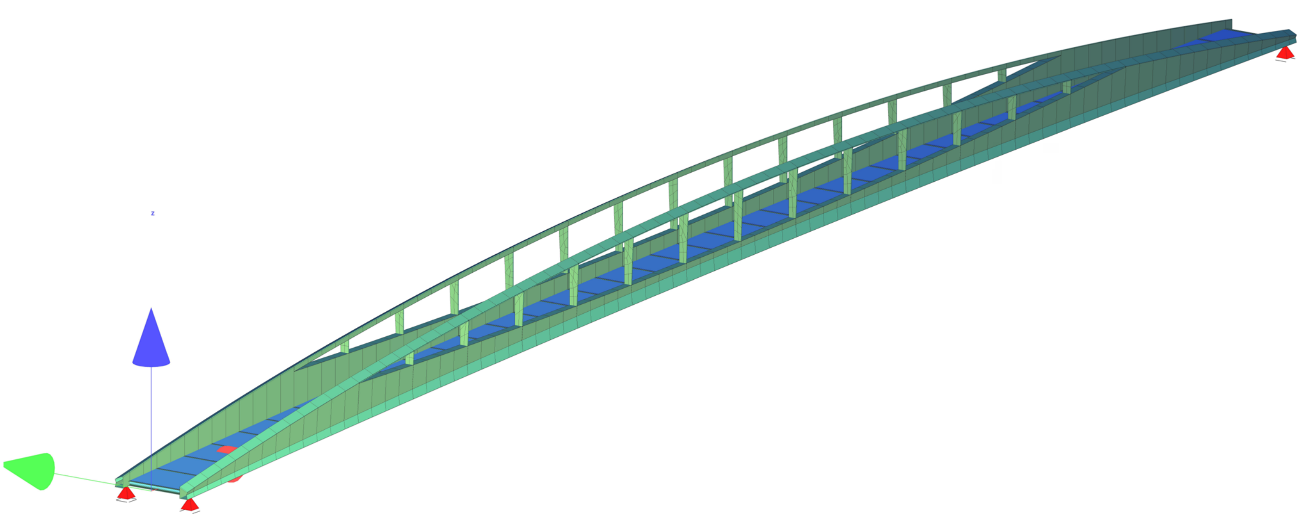

Figure 23. Eibar footbridges. (FHECOR).

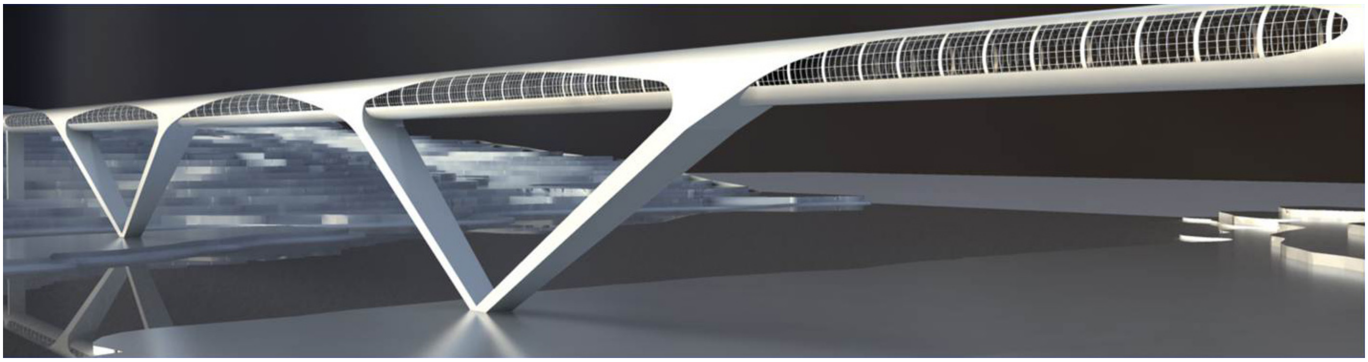

Figure 24. Ulla Bridge. (FHECOR).

On the contrary, in the support zone it will be necessary to have a solid web, since it is necessary to resist high shear forces, while the bending moments are not important, so it is possible to have a smaller depth than at mid-span.

An example of this hybrid concept, as an intermediate type between a pure beam and a shallow arch, is the proposal for a footbridge in Cork (Ireland) designed by the author. There a central beam built with an important voided central area, which emphasizess the slenderness of the structure.

The same concept was used for the New Danube Bridge competition in Budapest. In that case the structure had a span in the range of 500 m and the concept was developed together with Dissing and Weitling architects.

Other examples of that type of hybrid structure are the two footbridges in Eibar (Spain), currently under construction. There, the system is formed by two lateral beams with the same concept (figure 23).

6.4 Frames and tubes

As simple example of other hybrid structures is the proposal for the Ulla Bridge designed by the author [12]. Here a truss tubular deck cross section is combined with a frame supporting system. The frame with is inclined struts reduces the flexure of the deck, improving its deformational behaviour, which is critical due to the use of the bridge for a high speed railway line.

The struts of the frame have a precise inclination at each side to compensate the horizontal forces due to the permanent loads in the foundation.

It is also obvious from the former examples, that the combination of tubular decks with other structural systems such as arches, frames, stays or suspension systems opens another world of possibilities.

7
CONCLUSIONS

It is clear that the canonical structural types, such as: beams, frames, arches, cable stayed or suspension bridges, are very well developed, and in a sense structural engineering has been able to refine those solutions to their limits. In many cases, the canonical types are the right and more suitable solutions. Nevertheless, in some cases, the functional requirements or just the context where the bridge has to be built, led to what it could be called hybrid bridges.

As it could be seen through the examples previously presented, the Hybrid solutions have a wide field of application. That is the case, for instance, of the extradosed bridges; that type of bridges is in between the concrete box bridges and the cable stayed bridges, but that is only one possibility out of the universe of possible combinations.

As part of the tradition developed by our masters, such as Javier Manterola, the hybrid structures are a field of developing news ideas or concepts, and therefore a vast space for innovation in structural engineering.

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