VIADUCT OVER RIVER ALMONTE – CONCEPTUAL DESIGN

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SUMMARY

The Viaduct over River Almonte, part of the High Speed Rail (HSR) link Madrid - Portuguese Border, means a challenge for bridge design and construction.

With its 384 m main span, it has recently become the World's largest HSR arch bridge, the largest concrete railway arch bridge, and the third largest concrete arch bridge without traffic-type distinction. In order to solve all the problems arising from a HSR crossing of this magnitude, an innovative structural scheme has been employed: a single octagonal section high-performance concrete arch diverges into two hexagonal feet at arch supports, and it is fixed to the deck at its keystone. This solution brings together structural efficiency, out of plane stability, improved response to wind effects and horizontal forces, and aesthetical values.

Keywords: *Superior deck arch bridge, high speed rail, span world record, holistic design, high-performance concrete.*

1. INTRODUCTION

High Speed Rail traffic demands linear infrastructures with important requirements, both in plan and elevation alignment, which conduct to numerous viaducts, usually of great length and sometimes high-rise. On the other hand, these structures, unavoidably flexible among the line, are submitted to significantly higher loads than those intended for other types of traffic.

Moreover, a series of severe constraints in terms of deformations and vibrations are stablished due to functional criteria: some traffic safety related (guaranteeing geometry, rail continuity, wheel and rail contact) and some dealing with users comfort. In addition, HSR bridges are subjected to important dynamic effects, are prone to suffer fatigue problems because of the intensity and repetitiveness of loads, and their total length is limited as a result of the restrained capacity of expansion devices and the interaction between track and deck.

These features make the spans of HSR viaducts tend to be lowered in comparison to those of structures designed for other traffics. Nevertheless, in some occasions the existence of important obstacles leads, inevitably, to larger spans than usual or even exceptional, as the bridge starring this article.

Fig. 1. *Render image of the bridge's environmental integration.*

The HSR link Madrid - Extremadura - Portuguese Border crosses over River Almonte in its mouth into the Alcántara Reservoir. The notable landscape and environmental value of the river, makes it mandatory not to display piers over it for the maximum water level (elevation 218 m). This fact implies a distance of 350 m between river edges which points to a viaduct with a span of about 380 m. A span of this magnitude, the largest in the very extensive Spanish HSR network (over a 100 m difference), entails additional requirements to those already reviewed for any HSR bridge. For example, the aerolastic phenomena (increasing oscillatory events caused by wind - structure interaction) can be significant for these spans and must be taken into account in the design.

Almonte Viaduct has been designed by Arenas & Asociados within the JV constituted with IDOM to draw up the whole Reservoir of Alcántara - Garrovillas section project, among the HSR link Madrid - Extremadura (with mixed traffic and a maximum speed of 300 km/h for passengers and 100 km/h for freights). The bridge, property of Spanish Rail Administrator Adif, is being constructed by contractors FCC - Conduril, and is due for completion in June 2016.

2. THE BRIDGE'S CONCEPTION

2.1. Constraints and alternatives study

The bridge design emerges from a series of imposed conditions, as the particularities of railway high speed traffic and main span (already mentioned) and the profound reflection on the problem to be solved bearing in mind multiple criteria: functionality, structural behaviour, economics, durability and maintenance, constructability and landscape integration.

In the final phase of the design process, a detailed study of alternatives was made to analyse and value the different typological options that could be adequate in this case (Fig. 2). The following alternatives were studied: four frame-type variants with V-shaped piers and lattice deck (both steel and concrete alternatives, with trains crossing over or through the truss), a superior deck arch bridge and two cable-stayed options, with single and double stays planes.

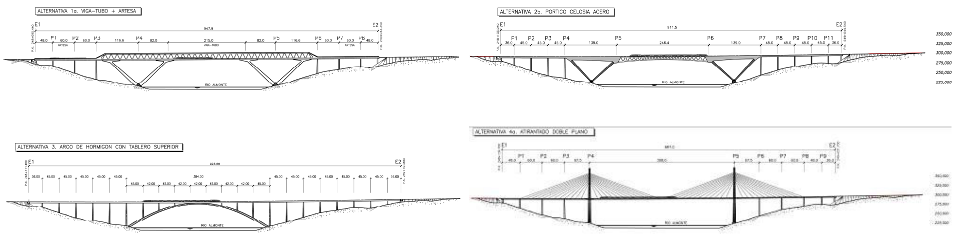

Fig. 2. *Some of the different typologies considered in the alternatives study.*

For the concrete arch solution, as no intermediate provisory supports could be located over the reservoir during its erection, three construction procedures were also analysed: arch executed by cantilever method of two half arches hanged from a temporary steel tower (Fig. 3a), arch erected by cantilever method as lower chord of two large lattice corbels, being the proper deck the superior chord (Fig. 3b), and this same alternative setting up the superior chord with provisional stays that would be removed once the arch closure is reached (Fig. 3c). For the three precedent procedures, the alternative of hoisting an auxiliary truss to execute the central part of the arch was also studied (Fig. 3d). Among all these erection sequences, all viable and successfully employed in large span arch bridges previously, the cantilever method using a provisory stay tower was considered slightly more advantageous in this case (despite having a lower use of the own bridge elements during its construction and requiring an auxiliary tower and large cable lengths). A better geometric control capacity and the allowance of preloading the arch so that its elastic deformations under permanent loads can be compensated were key facts in the election. This method makes unnecessary the introduction of a horizontal force with hydraulic jacks in the arch's crown after its closure, inevitable in the other cases to put all forces into play.

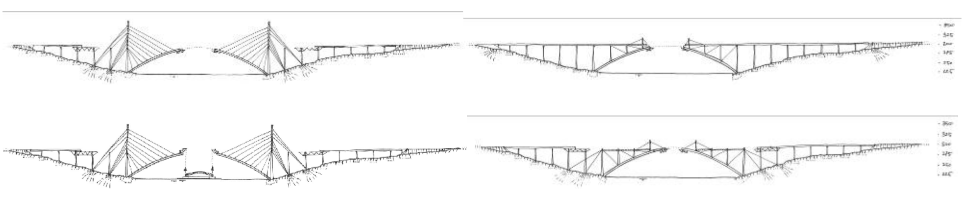

Fig. 3. *(a, b, c, d, from top left, clockwise) some of the arch's erection procedures analysed.*

As a result of the multi-criteria analysis that completed this alternatives study, it was concluded that the most suitable solution was an almost 1000 m long viaduct, with a main span constituted by a great 384 m long superior deck concrete arch. It should be erected by cantilever method with the aid of temporary cable-stay towers.

2.2. The scale of the challenge

The viaduct resulting from this analysis will become record-breaker in terms of main span:

- Largest railway bridge (and obviously HSR) in Spain.
- 4th largest bridge in Spain without traffic distinction.
- World largest High Speed Railway arch bridge, surpassing Dashengguan Bridge in China (336 m).
- World largest railway concrete arch bridge (unrestricted to HSR) with 100 m over Froschgrund Lake Bridge in the Nürnberg - Erfurt rail link, Germany (270 m).
- 3rd largest concrete arch bridge in the World with no traffic distinction, only behind Wanxian Bridge in China (420 m) and close to the larger of the two bridges between Krk and Sveti Marko islands in Croatia (390 m).

These figures give an idea of the challenge's magnitude of designing, managing and building this bridge.

2.3. An appropriate design

2.3.1. Adequacy of typology and material to the crossing problem

The superior deck arch bridge as it has been brought up, with spans of 45 m between piers and 42 m between arch spandrel columns, is the most economical of those analysed referred to execution costs. Two of the reasons that lead to this fact are the orographic and geotechnical conditions of the zone. The presence of healthy bedrock (slate) at shallow depth and the valley's geometry made the pure arch solution (deck not hanged) very competitive. Furthermore, the deck has been posed with a conventional single cell box section along the entire viaduct. Thanks to an appropriate span distribution between piers or pilasters, it can be casted with a movable scaffolding system (Fig. 4). It is also the best alternative from the durability and maintenance point of view, so future costs are optimized by this concept.

Another favourable aspect of this alternative is its behaviour against dynamic effects. The use of concrete throughout all the structure makes its mass and damping imply a better response to vibratory phenomena in comparison to other solutions.

The bridge is also more advantageous from the environmental point of view. Not just as a landscape for its integration in the surroundings (which we consider quite appropriate), but because of the fact of disposing fewer structural elements, highly concentrated, minimizing birds deaths for impact on them. A really important aspect in a valley defined as a birdlife corridor.

2.3.2. Specific design aspects which improve the basic typological scheme

In addition to all the features already mentioned that make a superior deck concrete arch bridge an accurate crossing solution by itself, the developed viaduct incorporates a series of specific design aspects which directly respond to this case's span, location and HSR traffic. These aspects improve significantly the basic solution.

On one hand, the deck is linked to the arch at its keystone, not only working as vertical loads supporting element, but taking advantage of its capacity of transmitting braking and acceleration forces to the foundations. Stablishing the deck's fix point next to the junction, makes it necessary to place track expansion devices just in abutments, in an almost 1 km long viaduct (Fig. 4 and 6).

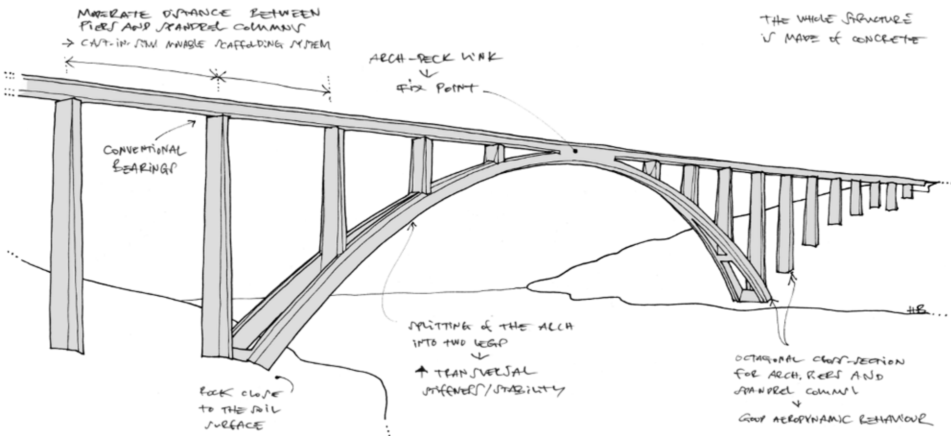

Fig. 4. *Some characteristics that convert the design in appropriate to the problem.*

Moreover, the arch splits into two legs at springers, ameliorating the bridge's transversal behaviour and its response against *hors plan* instability phenomena. These improvements are of great importance in a structure of such span and a reduce deck width (14 m) due to its railroad character. The transverse split of the arch's axis (Fig. 4 and 6) and the horizontal inertia variation at springers (maximal) and midspan (minimal) increases the arch's stiffness maintaining its mass, leading to a better functioning against dynamic effects (both vertical or horizontal) whether caused by wind or trains itself, compared to solutions with constant depth and width.

Having a solution with a good response to dynamic effects in accordance to its mass, stiffness and damping, we have also sought to reduce one load type that can cause these effects, wind. It arises an octagonal shape for arch, piers and spandrel columns. Thus, a better aerodynamic performance is achieved, really important in large span structures like this. Boundary layer wind tunnel tests confirmed these facts for both final and temporary situations during construction.

It can be said that the design of Almonte Viaduct has made improvements to the basic type of superior deck concrete arch bridge, to address the specific problems of a large span HSR crossing such as: high horizontal reactions transmission to the ground together with a limited longitudinal displacement of the deck, the need of an appropriate dynamic effects behaviour caused by wind or vehicles, the need of ensuring transversal stiffness with a narrow deck typical of this traffic.

Furthermore, the spans' distribution between piers (founded directly to ground) or spandrel columns (leaning over the arch) has sought the disposal of a sufficient number of supports over the arch in order to reach an anti-funicular behaviour with curved pressure line (not polygonised). On the other hand, the employment of the same deck's cross-section along the entire length eases its execution and the subsequent maintenance of the viaduct. Therefore, the resulting structure becomes quite similar to a PSC continuous span bridge (materials, technology, employed cross-sections, bearings typology…) in terms of maintenance. In fact, it is not difficult to assimilate the viaduct elevation to a concrete box girder bridge with conventional spans, where the ground has been replaced by a solid arch at its crossing area over the reservoir. We also believe this solution produces an aesthetically balanced, harmonious and orderly image (Figs. 1, 5 and 6).

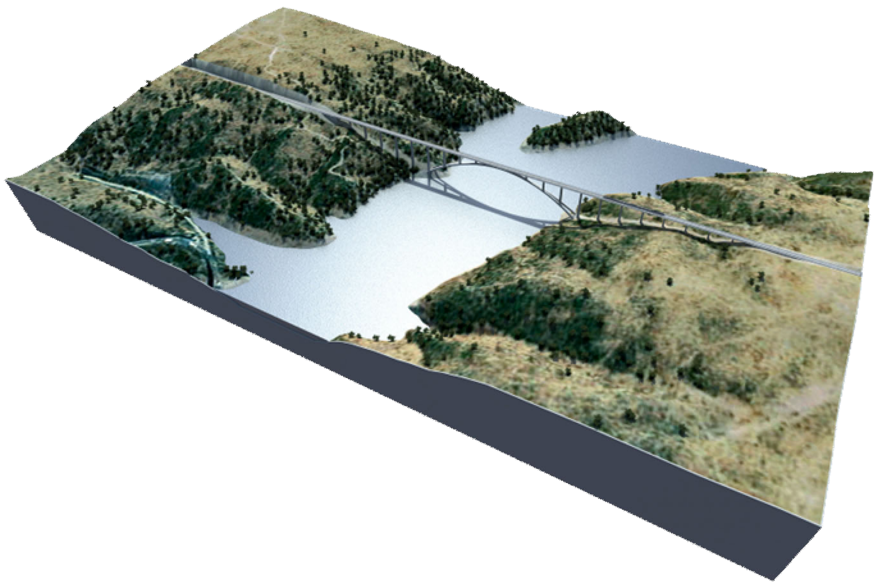

Fig. 5. *Aerial render view of the viaduct.*

3. THE DESIGNED BRIDGE

The viaduct is constituted by three different zones (Fig. 5 and 6). An approach viaduct (Madrid side) with a series of span 36 m + 6·45 m; the main span over the river with a 384 m long great arch, upon which leans the deck (45 m + 6·42 m + 45 m span distribution); and finally, another series of access spans (Cáceres side, 7·45 m + 36 m).

3.1. Deck

The deck is a hyperstatic posttensioned concrete box girder executed in-situ, with a constant depth of 3.10 m and a total width of 14 m (accommodating Adif's conventional high speed double track). Arch's unavoidable flexibility, although the spans' reduction between columns, causes a higher need of prestressing and better concrete (HP-60 instead of HP-40) in this section.

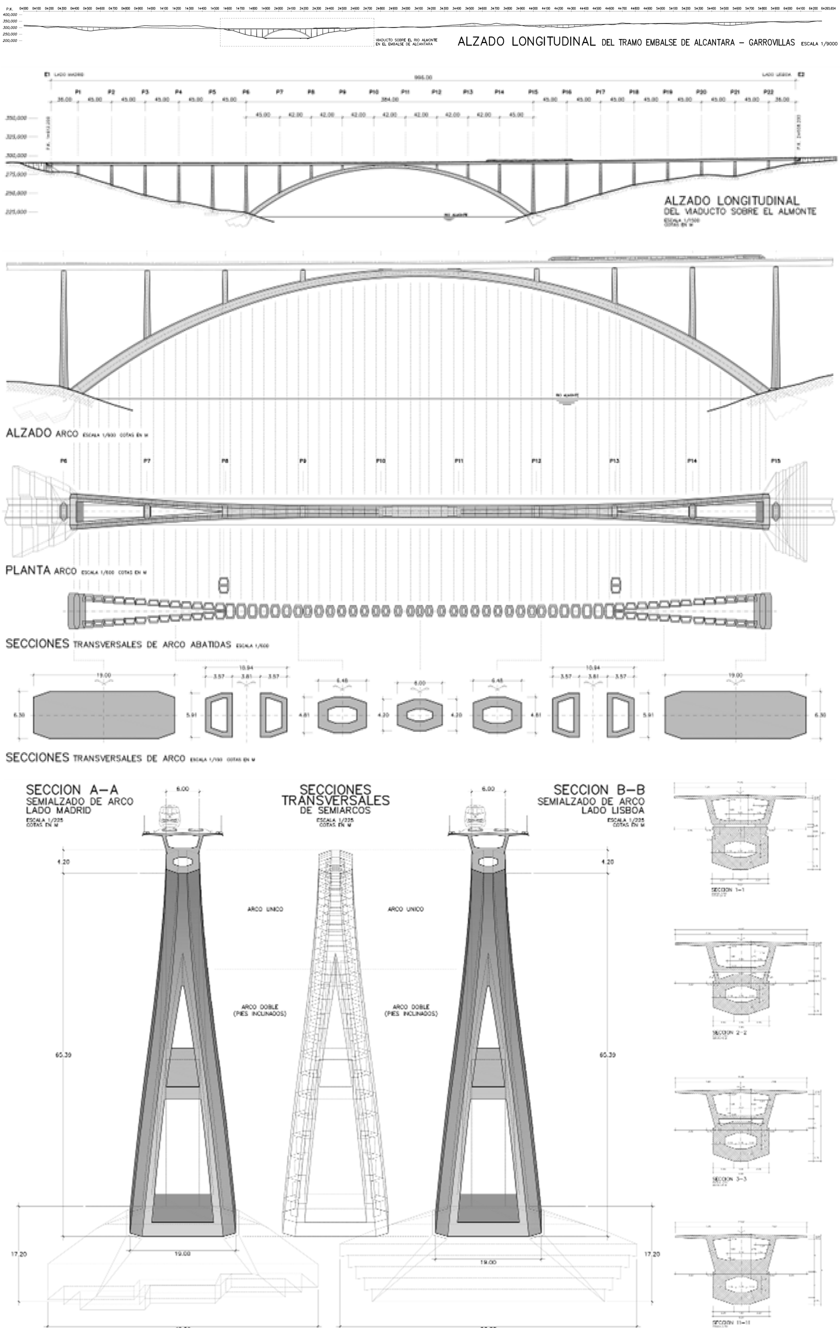

__Fig. 6.__ General elevations, arch's geometry and arch-deck linking detail.

3.2. Arch

The arch is conceived in high performance self-compacting concrete (HAC-80). It has a hollow octagonal section with variable depths in its 210 central meters, splitting into two variable hexagonal section legs until reaching their springing points. Both legs, get braced to each other beneath pilasters 7 and 14 (Fig. 4 and 6).

At springers, the arch has a depth of 6.90 m, with a distance between legs external surfaces of 19 m. At keystone, the depth decreases to 4.80 m and the width to 6.00 m, coincident with the deck's inferior width, to which gets linked shaping a unique concrete section along 30 m (Fig. 6).

3.3. Piers and spandrel columns and abutments

Both piers and columns have variable octagonal shape. Their heights vary from 12 m (pier 22) to the 66.30 m of pier 15. Piers 6 and 15, due to their height and their function as support of the temporary cable-stay tower during the erection procedure, are made of HA-50 concrete (instead of HA-40 used in the other ones).

Abutments are U-shaped and made of reinforced concrete.

3.4. Foundations

Foundations (arch, piers and abutments) are all direct to rock layer, as it appears close to soil surface. The arch's foundations, which also comprise their adjacent piers (Fig. 4, 5 and 6), have an irregular and terraced polyhedrical shape. Their geometry is conditioned by the direction of the resultant efforts transmitted by the ensemble arch - pier, and the need of adapting to the healthy rock layer position; where they should be embed at least 2.00 m.

The temporary cable-stay system during construction, demands anchored footings to the ground at each side of the arch foundation.

3.5. Bearings and bird protection barrier

Each of the deck bearings is carried out by conventional POT type bearings made of confined elastomer (all with a maximum capacity of 20000 kN, except those on abutments (8000 kN) and beside the deck-arch link (16000 kN)). It is placed a free bearing and a longitudinally guided one in each pier or abutment. Temporary exceptional fixed bearings (83000 kN) are required beneath the cable - stay towers (piers 6 and 15), being replaced once de arch closure is reached and the steel towers removed.

To avoid birds' collision with coaches in the most transparent way, the common 3.00 m opaque barriers have been replaced by a discrete protection barrier made of tubular profiles of the same height.

4. STRUCTURAL BEHAVIOUR

As brief summary, because the complete calculation process will be described in other article, an evolving calculation model has been made including all the erection stages (Fig. 7). The analysis has taken into account the geometrical imperfections in each phase, the effects of creep and shrinkage on concrete, and the non-linearity both for steel and concrete. In order to assure a good durability and avoid dynamic amplifications by stiffness' loss, as design criteria it has been stablished that the arch must not suffer cracking during its construction neither its lifetime under serviceability loads.

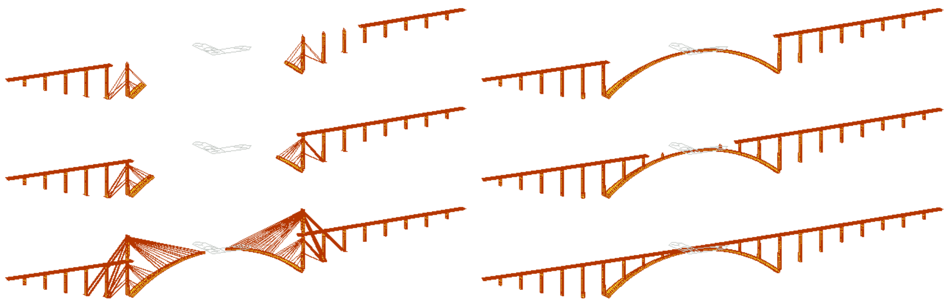

***Fig.** 7. Images of the evolving calculation model.*

5. WIND TUNNEL TESTS

The span of the viaduct exceeds widely the 200 m stablished in the IAPF-2007 as limit from which it is necessary to consider aeroelastic effects due to wind. Apart from this regulation, in the preliminary phases of the project we realized that the span length led to natural vibration frequencies which indicated that the bridge could be sensitive to these effects (below 0.30 Hz in its first modes).

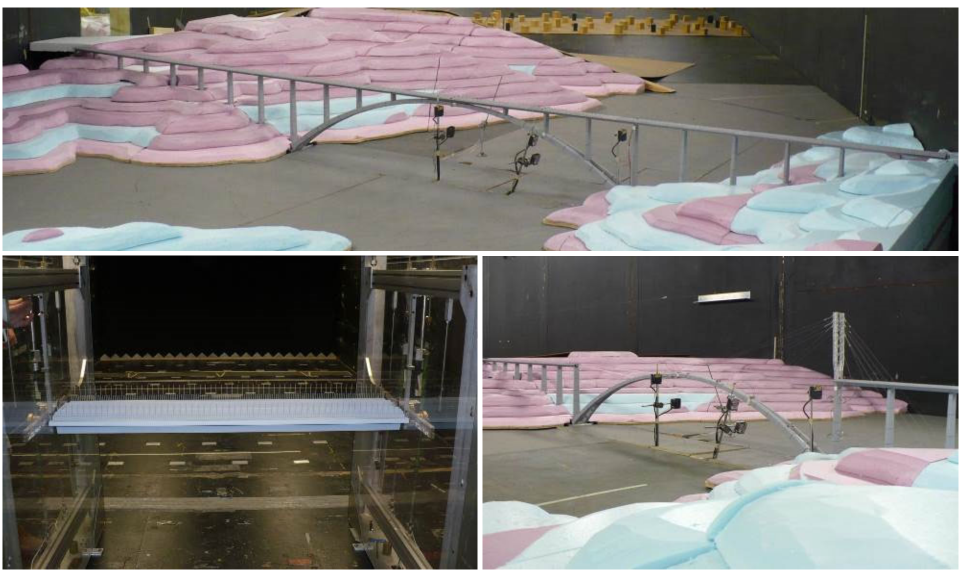

***Fig. 8.** Aerodynamic and aeroelastic wind tunnel tests.*

This fact, together with the structure's three-dimensionality and the complex orography of the surroundings, made it necessary testing complete bridge models (in addition to sectional essays) [1].

These studies enabled the determination of the specific static wind loads for this bridge. They have also validated the aerodynamic adequacy of the employed sections, and confirmed the correct behaviour of the structure.

6. CONCLUSIONS AND ACKNOWLEDGEMENTS

Almonte Viaduct is a real challenge in the design and construction of bridges, disciplines where it can turn into a milestone for diverse reasons:

- Its function as a landmark of the new HSR link between Madrid and the Portuguese Border.
- Its exceptional dimensions, which will make it the largest railway bridge in Spain and the World's largest concrete railway bridge.
- The quality of its structural design. The employment of a scheme where the single octagonal arch splits into two hexagonal legs at springing points and gets linked to the deck at keystone. These facts bring together structural efficiency, out-of-plane stability (as required by HSR deformation limits), improved response against cross wind effects (verified in boundary layer wind tunnel tests), and aesthetics.
- The use of high-performance self-compacting concrete (HAC-80) in the arch's execution.
- Its complex erection procedure. The arch has been built by cantilevering of half arches with the aid of two provisory cable-stay towers in each edge, and six auxiliary tower cranes, four of them stablished over the cantilevers.
- Its sustainable design and its convenience in terms of durability and maintenance. Within the complexity of the problem, the solution is the most similar to a PSC continuous span bridge (as for materials, technology, employed cross-sections, bearings typology…).

From its apparent simplicity, the design solves simultaneously multiple functional, structural and environmental requirements implied in the crossing problem. Solutions that seem easier, in bridge design and many disciplines, are usually the most difficult to develop.

The project of a unique structure as Almonte Viaduct has required great effort. It has been possible thank to the participation and good work of many people besides the article authors: Héctor Beade, Emilio Merino, Javier Martínez, Santiago Guerra, Pablo Alfonso, Miguel Sacristán, Javier Fernández, Ysabel Guil, Marianela García, Juan Ruiz, etc.

REFERENCES

[1] TERRÉS J.M., MANS C., KING P.J.C., CAPELLÁN G. and BEADE H., Estudio experimental del efecto del viento en un Puente Arco de 384 m de luz en fases de servicio y constructiva, *V ACHE Congress, Barcelona,* pp. 650.