Palma del Río Arch Bridge, Córdoba, Spain

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Abstract

The present paper discusses the construction of Palma del Río arch bridge, of 130 m span, recently constructed in surroundings of great landscape beauty in the south of Spain. A cable-stayed network was implemented, allowing a significant reduction in bending moments in deck and arch, which leads to structures of great slenderness and transparency. The two inclined arches are linked at the key, a very effective disposition to withstand out-of-plane buckling. The multiple crossings of the stays led to a complex geometric problem that has been solved satisfactorily with an innovative technical design of minimum visual impact.

Keywords: bowstring; tubular arch; bridge; steel; network suspension system; hangers crossing devices.

Introduction

The Network Tied Arch System

In 1926, Octavius F. Nielsen patented the development of the conventional vertical-hanger typology for bowstring arches, by means of oblique steel rods, in a V-configuration, which allowed him to turn the arch into a beam-type structure in which the rods took the shear forces caused by non-antifunicular load distributions, dramatically reducing the bending moments in the arch and the deck. The main limitation in this system comes from the compressions which may appear in some hangers when the live loads/permanent loads ratio is too high, typical in railway bridges and in light structures.

In the 1950s, the concept of network bowstring arch bridges was developed by Prof. Eng Per Tveit (Norway). In an article published in June 1966,[1] he defined it as a system which uses "inclined hangers with multiple intersections on the arch's plane." By resorting to a greater complexity and a higher amount of steel in the hanger system, it very notably reduces the risk of the hangers being subjected to compression in non-symmetrical load distributions, which renders this typology susceptible to be used in extremely light footbridges as well as road and railway bridges.

Steinkjer Bridge (*Fig. 1*) built in Norway in 1963, with a span of 80 m, was his first project using this typology, which saw a fast development in countries like Norway, Germany, United States, and Japan.

The most remarkable example is the beautiful and renowned Fehmarnsund Bridge (*Fig. 2*) in the Baltic Sea, a composite steel-and-concrete bridge for both railway and vehicles and with a span of 248 m. Built in 1963, it still holds the world record for bowstring arch bridges.

Fig. 1: Steinkjer Bridge (1963)

Fig. 2: Fehmarnsund Bridge (1963)

Structural Behavior

The vertical loads of the deck of a bowstring arch are suspended by the tensioned hangers, raising the loads to the upper arch. The vertical component of the arch's compression is transmitted to the extreme supports, and the horizontal component is resisted by the tensioned lower tie.[1]

This typology is especially useful when the soil does not bear important horizontal reactions.

The structural response against antimetric vertical loads of a bowstring with vertical hangers induces important bending moments on the arch and tie of the bridge (*Fig. 3a*).

The network system allows for a very efficient structural response which leads to a very homogeneous hanger dimensioning—the cross section is practically the same all along the structure—as well as to the minimization of bending stresses in the arch and the tie beams (*Fig. 3b*). It also improves both the in-plane and out-of-plane arch buckling conditions. Both the arch and the deck are subjected practically exclusively to axial forces, thus making it possible to attain high slenderness ratios and great material economy.[2]

Description of Palma del Río Arch Bridge

The bridge of Palma del Río, over Guadalquivir River,[3–5] constitutes a remarkable development of this typology with a bowstring that spans 130 m (*Fig. 4*), and two inclined arches that rise 25 m with a tubular cross section of 0,9 m and 50 mm of maximum thickness (*Figs. 5 and 6*). The deck consists of two simple lateral ties 0,9 m in diameter

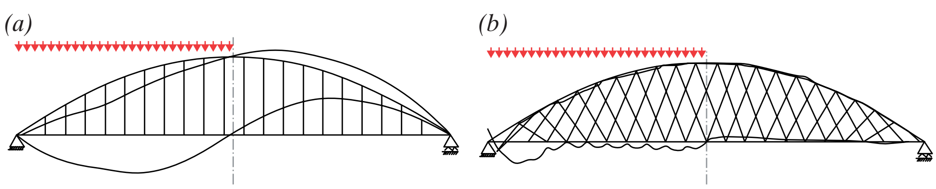


Fig. 3: (a) Structural response against antimetric vertical loads of a bowstring with vertical hangers or with a network suspension system. (b) Bending moment forces

Fig. 4: Aerial view of Palma del Río Bridge over Guadalquivir River

Fig. 6: Aerial view of the bridge

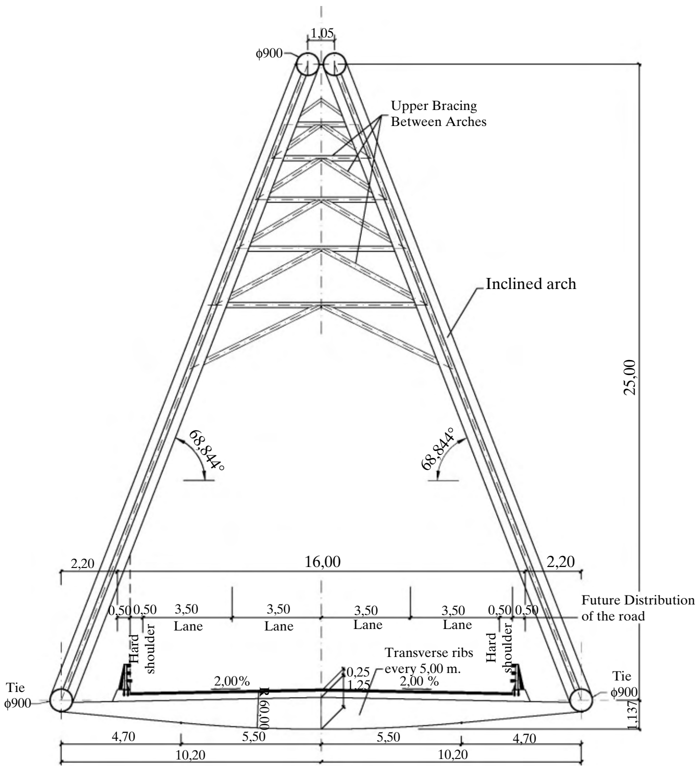


Fig. 5: Cross section (Units: m)

and 40 mm in maximum thickness, and one intermediate platform supported by transverse composite concrete–steel beams of variable height spaced every 5,0 m (*Figs. 5 and 6*).

The extreme slenderness of the arches and ties (H/L = 1/144,4) is obtained thanks to closed cable network suspension system (*Figs. 4 and 6*), which drastically minimizes the bending moments on the arches and ties, and reduces the buckling effects on the arches, as has been described before.

The deck's platform is 16 m wide, and the deck consists of an upper slab of 0,25 m thickness. This slab is composed of the inferior precast slabs supported on the transverse steel beams of the deck placed every 5 m, and the upper reinforcement and cast-in-place concrete which completes the total thickness of the slab.

The transverse beams that form the deck span 20,4 m between the tubular lateral ties of the bridge (*Fig. 7*). The hanger's anchorages are located right where the transverse beams meet the lateral ties (*Fig. 9*). This way the lateral ties are not subjected to the effect of the punctual loads that act on the deck.

The deck's transverse composite steel–concrete beams have variable height, and the beam's lower plate follows a circular curve with 60 m radius in the central part, and a linear variation in the rest. The maximum height is 1,25 m and the cross section is an "I" beam (*Fig. 7*).

The steel used in both arches, ties, and the deck is S-355-J2G3.

The aim of the lateral ties of the bridge, which are tubes of 0,9 mm diameter, is mainly to equilibrate the horizontal component of the arches in the extremes, avoiding the transmission of the horizontal reaction to the foundations, as well as to provide the previously mentioned lateral support for the transverse beams of the deck.

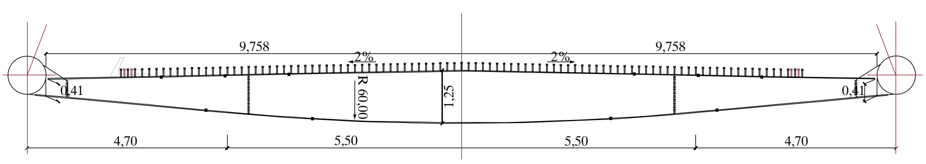


Fig. 7: Detail of a typical transverse beam placed every 5 m (Units: m)

The hangers act as the linking element between the deck and the arches, and transmit the vertical loads from the former to the latter. The hangers were designed in an inclined network suspension system linking the ties to the arches, with spaces of 5 m between their extreme anchorages (*Figs. 8 and 9*).

Furthermore, as the number of hangers increases, it allows the use of small units that are easy to fit.

The main bearing structure of the bridge includes the two arches, which are inclined at 21,20° with respect to a vertical plane; they arise from the extremes of the lower part of the deck converging with the lateral ties. Both arches meet at the crown of the bridge and rise to 25,0 m, with a rise/span ratio of 1/5,2.

All along the arches, and at every 5 m, are arranged the upper extreme anchorages of the hangers. Bracing the inclined arches, the authors designed a K truss with tubular elements, as can be seen in *Fig. 10*, which reduces the out-of-plane buckling length of the arches.

Fig. 8: Frontal view of the arches and the upper bracing

Fig. 9: Anchorages every 5 m

The distance between anchorages for the network suspension system is reduced to 5 m, fulfilling multiple objectives:

- reducing the buckling length of the arches (*Fig. 10*)
- reducing the bending moments of the deck
- simplifying the arches–hangers and deck–hangers anchorages, because of the use of small units of hangers
- achieving a great efficiency in the distribution of punctual loads on the deck.

At the initial point of the arches and lateral ties of the deck is arranged a transverse rib (*Fig. 11*), similar to the normal transverse beams of the deck, which has to resist the horizontal transverse forces due to the inclination of the arches. These ribs have two intermediate bearings so as to coerce the torsional turn of the ties and constrain the out-of-plane buckling of the arches in their beginning.

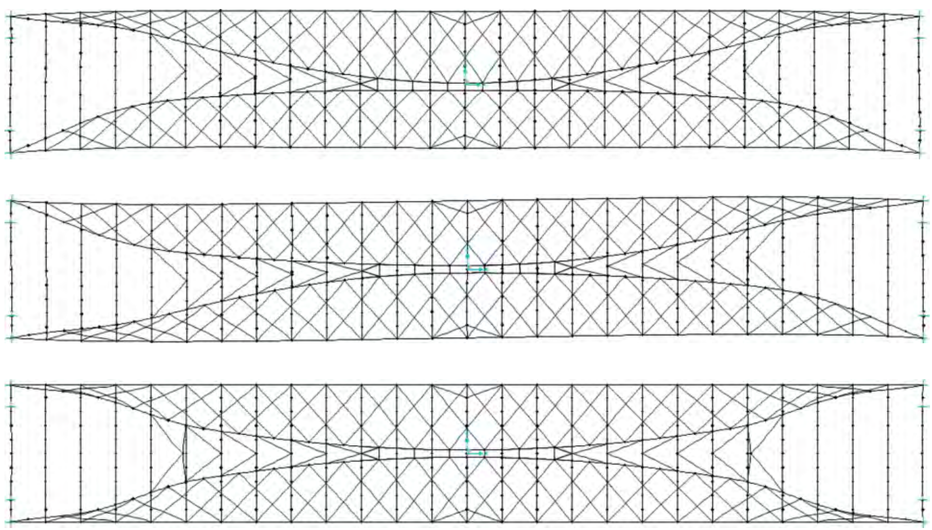


Fig. 10: Plan view of the first three out-of-plane buckling modes

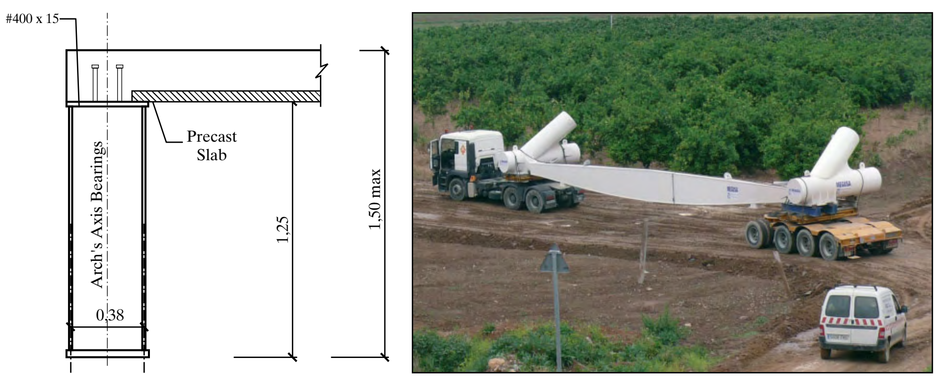


Fig. 11: Cross section and view of the transverse rib placed at the initial point of the arches

Constructive Process

The material used for the construction of the arches was steel. It was thought that concrete would be the ideal material for the compressed arches, but analysis of the construction process revealed that steel has great advantages: the execution can be carried out by dividing the whole length of the arches in shorter pieces that are easily transportable and can be welded on site with simple auxiliary elements, reducing the duration of construction.

The use of steel as the predominant structural material also permits reducing the vertical reactions transmitted to the foundations, optimizing their cost.

The first stage of the construction involved erection of the piles, with 1,50 m diameter, then the cap piles of the two piers of the arch bridge, and after that, the two piers. The foundations of the temporary supports were also on deep piles so as to avoid trouble with eventual river flood.

It was necessary to create embankments on both sides of the river near the piers so as to install the works platform to assemble the steel framing for the deck (*Fig. 12*) and arches, prior to lifting each piece.

Fig. 12: View of the embankments of both sides of the river and the first segments of the steel framing for the deck

The assembly of the segments of the deck was done by welding on site the transverse beams to the lateral tubular ties; each completed module is kept them ready to be lifted using cranes (*Fig. 13a and b*).

Figure 13a shows the lifting of the central segment of the deck, with the use of two big cranes placed on each side of the river and one more auxiliary crane.

Once the complete steel framing, propped on four temporary double supports, was finished (*Fig. 13b*) the arches could be erected.

First of all, it was necessary to place four temporary double props over the deck to support the different segments of the arches (*Fig. 14a*).

(a)

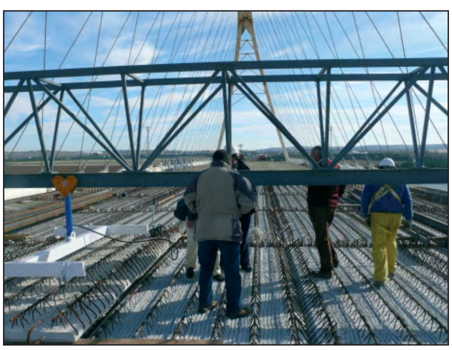
(b)

Fig. 13: (a) Erection of the central segment of the deck (b) Concluded view of the deck propped

(a)

(b)

Fig. 14: (a) Erection view of the two inclined arches (b) Close operation



(a)

(b)

Fig. 15: (a) View of the positioning of the upper precast slabs. (b) The reinforcement of the deck

Figure 14a and b shows two different views of the bridge while placing the two side portions of both arches.

Meanwhile, in the three central segments, the bracing between arches was welded on site. Once these operations concluded, each modulus of the double arches was lifted using cranes in a manner similar to that on the deck, leaving the arches propped up (*Fig. 14a and b*).

Figure 14b shows how the arches' crown was closed by lifting and adjusting the central segment in place.

Finally, all the welding between the different segments of the arches and the connection of the arches to the lateral ties was completed.

With the complete steel-structure finished, the arches' temporary props could be removed, enabling the arches to be functional.

With the deck framing still propped, the hangers of the bridge were fitted and tensioned following the tension sequence designed in the project. Once this stage was completed, the props of the deck were removed.

With the deck suspended by the hangers, the precast slabs on the upper platform were placed on site. *Figure 15a* shows the auxiliary transverse truss beam used for placing the precast slabs. These precast slabs span 5 m between the transverse beams of the deck.

Once all the precast slabs were positioned, the deck was ready for placement of the upper reinforcement and the pouring of concrete on the slab. *Fig. 15b* shows the slab after the reinforcement was finished.

Once the construction of the deck was completed, the final adjustment of the tension of the hangers, the finishing tasks, and the load test were carried out.

Hangers Crossing Devices

The multiple crossing between hangers were resolved with an original device that minimizes the visual impact of these crossings.

The hangers are closed cables with a diameter of 45, 40, or 37 mm, which compose the network suspension system of each inclined arch, located on two different parallel planes, each one of them with a slight eccentricity of 50 mm with respect to the arch's plane (*Fig. 16*); that is the reason why

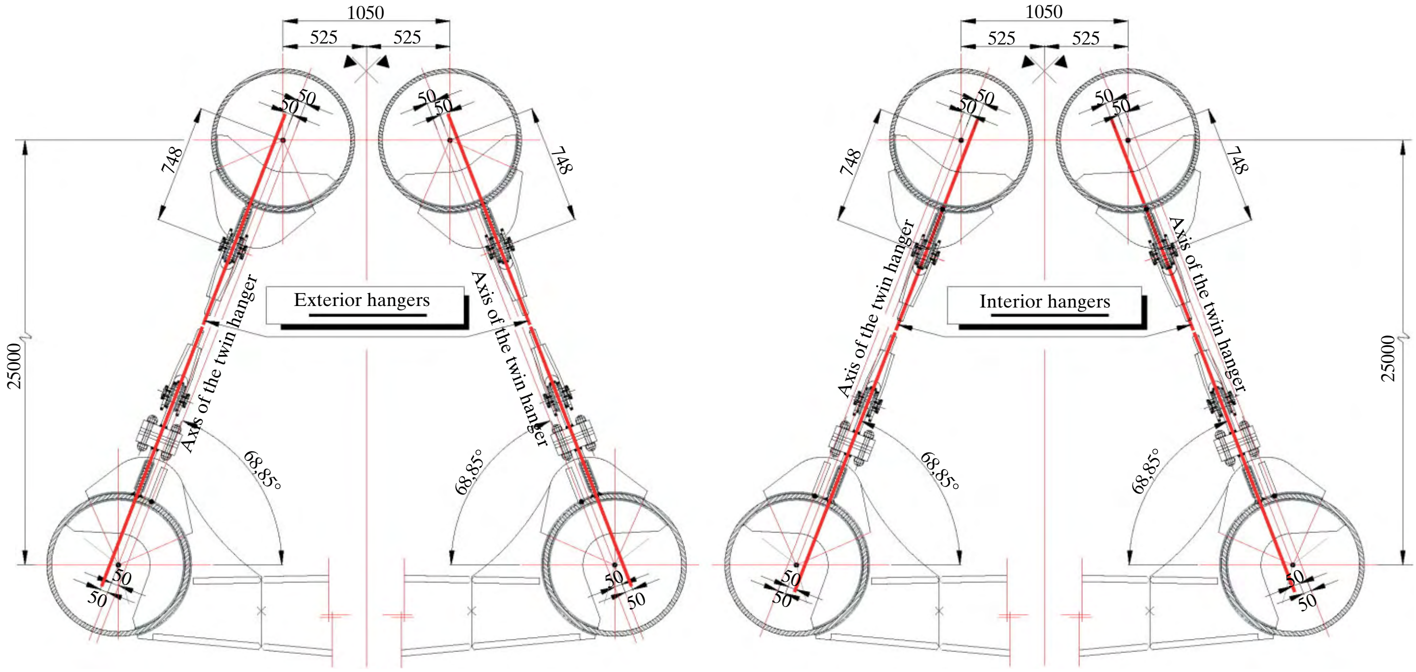
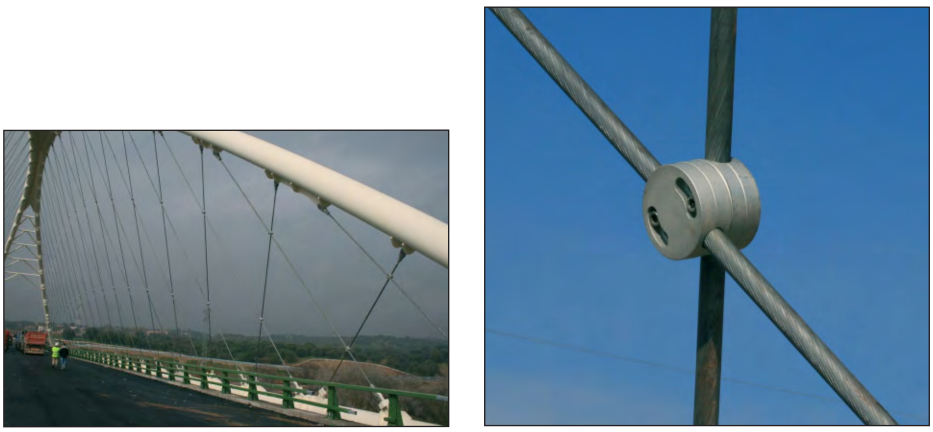


Fig. 16: Two different parallel planes of the hangers of the bridge with a slight eccentricity of 50 mm with respect to the arch plane (Units: mm)



(a) *(b)*

Fig. 17: (a and b) Palma del Río's cable hanger crossing device

the hangers cross but do not cut one another. A device placed at the place of the crossing hangers allows the fastening of the cables as well as the free turn of one cable with respect to the other (*Fig. 17a and b*).

Conclusion

This paper describes the main advantages of the bowstring arches with hangers in a network suspension system typology, remarking the reduction of the bending moments in deck and arch, which leads to structures of great slenderness and transparency.

A good example of this typology is Palma del Río Bridge, a bowstring steel arch bridge with tubular elements and network suspensions system.

This system, added to the inclined arches linked at the key, and the upper bracing between arches, with a K truss with tubular cross-sections, reduces the out-of-plane bucking length of the arches.

The multiple crossings of the stays have been resolved satisfactorily with an innovative technical design of minimum visual impact for the closed cables.

References

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SEI Data Block

Owner:
GIASA

Designers:
IDEAM, S.A., Madrid, Spain.

Contractor:
FCC Construcción, S.A.

Structural steel (t—kg/m2):	671,6—322,8
In situ concrete (deck) (m^3):	546
Passive Steel (bridge deck) (t):	69,6
Total Cost (EUR millions):	3,323
Service date:	January, 2008