7th INTERNATIONAL CONFERENCE ON STEEL BRIDGES

PROJECT OF TWO METAL ARCH BRIDGES WITH TUBULAR ELEMENTS AND NETWORK SUSPENSION SYSTEM

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Abstract: The present paper shows the project and construction of two arch bridges longer than 100 m span, recently constructed in surroundings of great landscape beauty. 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 inclined arches are linked at the key, a very effective disposition to withstand out-of-plane buckling. The multiple crossings of the stays generate a complex geometric problem that has been solved satisfactorily with an innovative technical design of minimum visual impact, both for the case of prestressed bars (bridge over Deba river) and for closed cables (bridge in Palma del Río over Guadalquivir river).

1. INTRODUCTION: THE NETWORK TIED ARCH SYSTEM

The most relevant feature of the network tied arch system lies in its structural and aesthetic efficiency, resorting to oblique hangers in a network arrangement.

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 1950's Professor Eng. Per Tveit (Norway) developed the concept of network bowstring arch bridge. In an article published in the June 1966 issue of The Structural Engineer, 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 Nimega in 1963, with a span of 80 m, was his first project using this typology, which attained 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 a span of 248 m. Built in 1963 it still holds the world record for this typology.

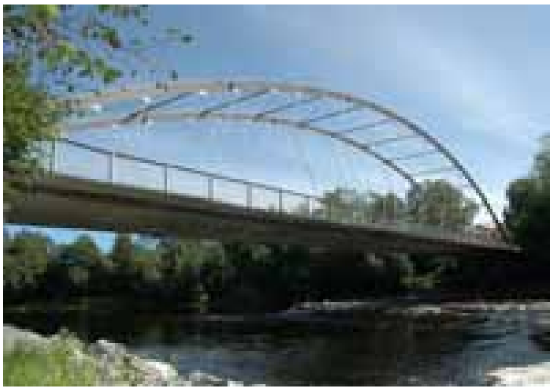

Fig. 1: Steinkjer Bridge (1963)

Fig. 2: Fehrmarnsund Bridge (1963)

2. STRUCTURAL BEHAVIOUR

Figure 3 shows the parabolic law of the bending moment forces in a simply supported span, and figure 4 shows the typical antifunicular geometry of a bowstring arch.

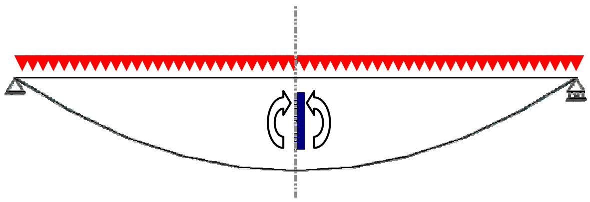

Fig. 3: Bending moments in a simply supported span

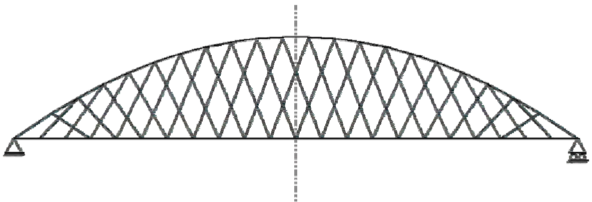

Fig. 4: Bowstrig. antifunicular geometry of the arch

The structural response to vertical loads in a bowstring with a network suspension system is shown in figure 5: the vertical loads of the deck 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.

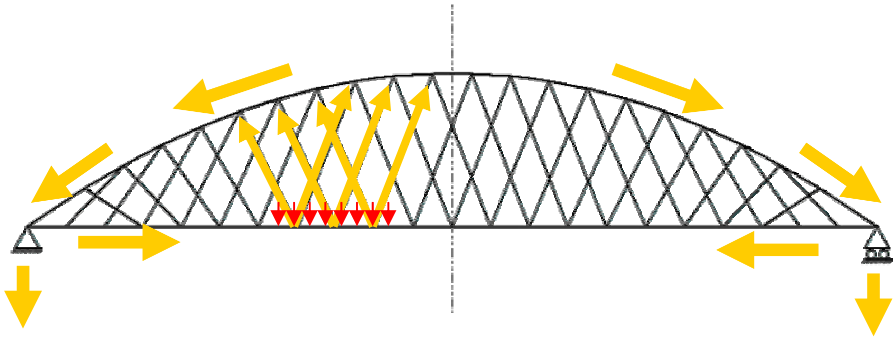

Fig. 5: Structural response of a bowstring with network supension system.

This typology is especially useful when the soil doesn't 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. 6).

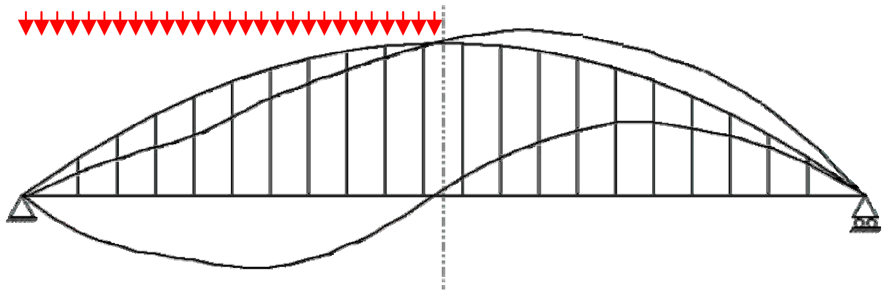

Fig. 6: Structural response against antimetric vertical loads of a bowstring with vertical hangers. Bending moment forces.

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 minimisation of bending stresses in the arch and the tie beams (Fig. 7). 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.

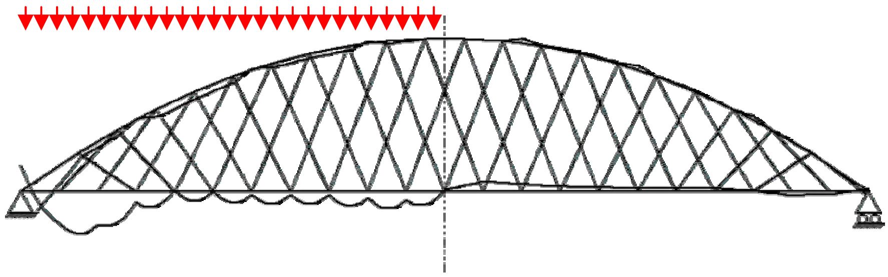

Fig. 7: Structural response against antimetric vertical loads of a bowstring with a network suspension system. Bending moment forces.

3. DESCRIPTION OF THE BRIDGES

We have had the occasion to design and construct the first big two arch bridges of this typology in Spain, Deba and Palma del Río, of extreme slenderness. Special care was placed on the design of those elements with a greater visual and aesthetic impact: geometrical order of the two leaning families of hangers on each plane, arch and tie beam anchorage details and, especially, the specific design of anti-friction devices at the crossing of hangers as described later.

3.1 Bridge over Deba River.

The arch bridge over Deba River, with a 110 m span (Figs. 8, and 9), was designed with two inclined steel arches with 800 mm of diameter and 45 mm of maximum thickness near the supports, and 25 mm of minimum thickness at mid span. The arches are inclined 17,3º with respect to a vertical plane.

It could be thought to use concrete as the ideal material for the compressed arches, but analyzing the constructing process, 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 schedule of construction.

Fig. 8: Elevation view of the brige over Deba River

Fig. 9: Front view of the brige over Deba River

The deck consists of a double composite steel-concrete box girder (Figs. 10 and 11) of 1.30 m of total height, and great lateral ribs, with 5,0 m span supporting wide sidewalks in cantilever, beside the plane of the arches. The steel quality in the arches and the deck is S-355-J2G3.

The double box girder of the deck works as a tie mainly tensioned because of the work of the arch. The upper slab materializes the platform for the vehicles.

The deck is suspended every 5 m by the crossed hangers in a network suspension system. The hangers-deck connection is achieved by means of the lateral cantilever beams placed every 5 m, which bear the lateral sidewalks placed at their ends (Fig. 10).

The inclined arches are doubly symmetrical, and they are linked together at the key with a simple plate. With this solution, the out of plane bucking length of each arch is reduced (Fig. 12) minimizing transverse bracing between the arches.

The structural response of these arches is similar to a vertical arch, with an additional effect in the extremes, where the horizontal component of the transverse force has to be equilibrated by a transverse beam placed at the supports.

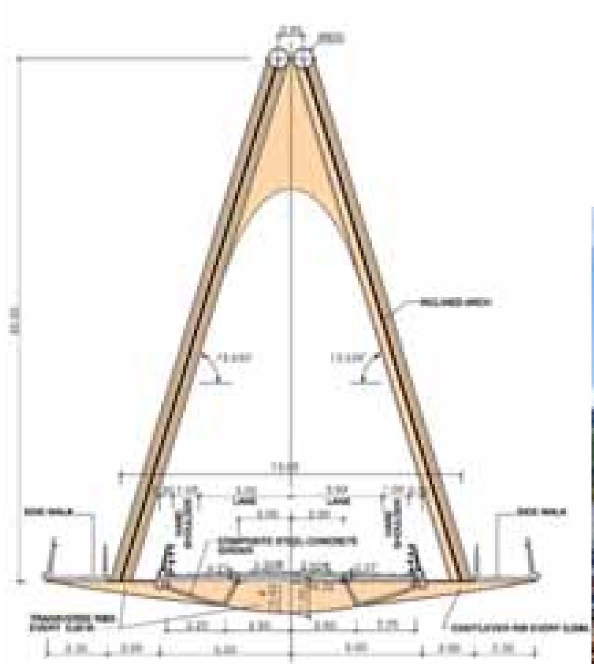

Fig. 10: Deba Bridge cross section

Fig. 11: View of the deck while erection

The tubular cross section of the arches is easy to find among standard suppliers, and only needS to be curved to get the final design geometry, reducing the number of operations, and minimizing the welding length.

The parabolic geometry of the arches follows the antifunicular law of vertical loads, with a rise of 20 m, and a rise/span ratio of 1/5,5.

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. 12).
- 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.

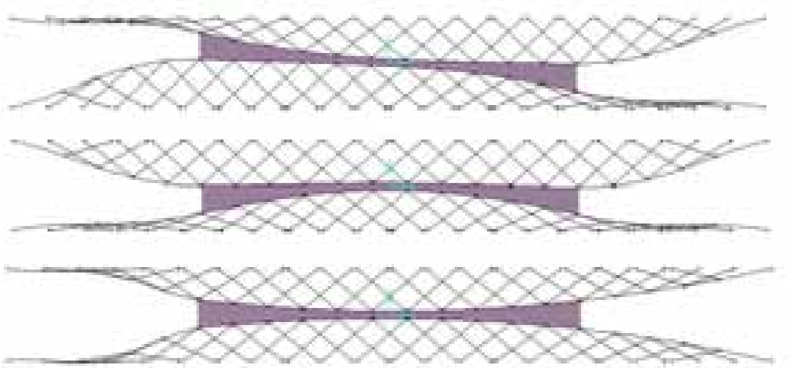

Fig. 12: Plan view of the first three out of plane buckling modes

3.2 Bridge of "Palma del Río" over Guadalquivir River

The bridge of Palma del Río, over Guadalquivir River spans 130 m (Fig. 13), and the two inclined arches rise 25.0 m with a tubular cross section of 900 mm of diameter and 50 mm of maximum thickness (Fig. 14 and 15). The deck consists of two simple lateral ties of 900 mm of diameter 40 mm of maximum thickness, and one intermediate platform supported by transverse composite concrete-steel beams of variable height spaced every 5,0 m (Figs. 14 and 15).

Fig. 13: Aereal View of "Palma del Río" Bridge over Gualdalquiver River

The extreme slenderness of the arches and ties (H/L=1/144,4) is obtained thanks to closed cable network suspension system (Fig. 13 and 15), which drastically minimizes the bending moments on the arches and ties, and reduces the buckling effects on the arches, as it has been described before.

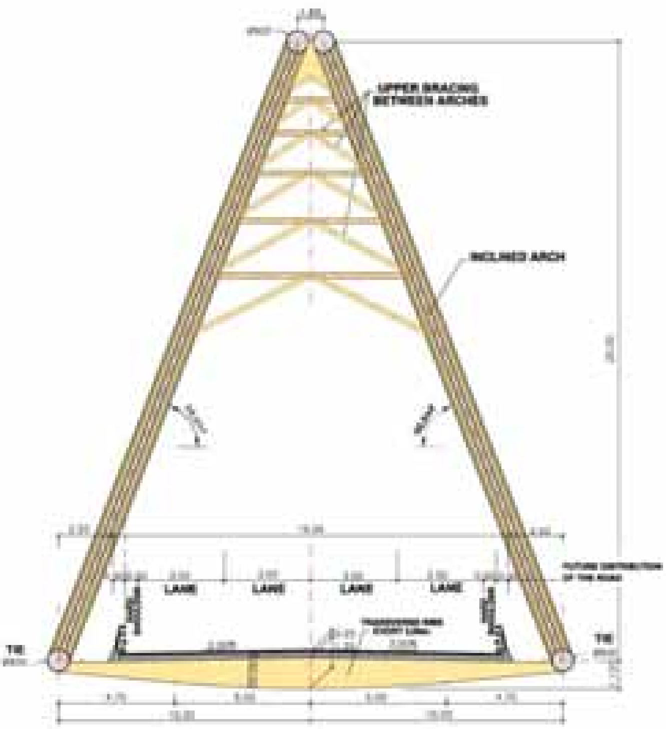

Fig. 14: Cross section

Fig. 15: Aereal view of the bridge

The deck's platform is 16 m wide, and the deck consists of an upper slab of 0,25 m in thickness. This slab is materialized by the inferior precast slabs supported on the tranverse 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 materialize the deck span 20,4 m between the tubular lateral ties of the bridge (Fig. 14). The hanger's anchorages are located right where the transverse beams meet the lateral ties (Fig. 17). This way the lateral ties aren't subject 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 of radius in the central part, and with a linear variation in the rest. The maximum height is 1,25 m, and the cross section is an "I" beam.

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

The aim of the lateral ties of the bridge, tubes of 900 mm of 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 the previously mentioned lateral support for the transverse beams of the deck.

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 (Fig. 16 and 17).

Fig. 16: Frontal view of the inclined arches and the upper bracing.

Fig. 17: Anchorages every 5 m.

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

The main bearing structure of the bridge are the two arches, which are inclined 21,20º with respect to a vertical plane, and 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 25,0 m, with a ratio rise-span 1/5,2.

All along the arches, and every 5 m, are arranged the upper extreme anchorages of the hangers. Bracing the inclined arches, we designed a K truss with tubular elements as it can be seen on figure 16, which reduces the out-of plane buckling length of the arches.

At the initial point of the arches and lateral ties of the deck, is arranged a transverse rib, 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 bucking of the arches in their beginning.

3.2.1 Description of the constructive process

It was necessary to create embankments on both sides of the river near the piers so as to materialize the works platform to assemble the steel structure of the deck and arches, prior to rising each piece.

The assembly of the segments of the deck is done by welding on site the transverse beams to the lateral tubular ties until completing each modulus of the deck, leaving them prepared for the rising with the use of cranes (fig. 18 and 19)

Fig. 18: View of the elevation of one complete segment of the deck

Fig. 19: View of the complete deck supported on provisional piers

Once finished the deck's metallic structure, the assembly of the arches began. First of all, it is necessary to place over the deck 4 provisional props to support the different segments of the arches. Meanwhile the bracing between arches on site was welded. These operations concluded, each modulus of the arches was raised by using cranes in a similar way to that of the deck, leaving the arches propped (Figs. 20 y 21). Finally all the welding between the different segments of the arches had to be completed.

With the whole metallic structure finished, the provisional props can by removed, causing the arches to start working.

Fig. 20: View during the arches' assembly.

Fig. 21: Arches' crown clossing operation

With the deck still propped, the hangers of the bridge were fitted and tensioned (Fig. 22) following the tension sequence designed in the project. This phase completed, the props were removed.

With the deck suspended by the hangers, the precast slabs on the upper platform were placed on site (Fig. 23), leaving the deck ready for the upper reinforcement and the pouring of concrete on the slab.

Fig. 22: Fitting of the hangers

Fig. 23: Positioning of the precast slabs.

Eventually the final adjustment of the tension of the hangers, the finishing tasks, (pavement, joints, etc), and the load test were carried out.

4. DETAIL OF THE HANGERS CROSSING DEVICES

The design of both arch bridges placed especial emphasis on the simple and tidy design of the unions between hangers and the tubular sections of arches, in Deba and Palma del Río, and between hangers and tubular ties in Palma del Río, unions of great visual impact, with details that combine an easy way of construction, and resistance effectiveness.

The multiple crossings between hangers were resolved, in each case, with an original device, that enables the hangers' arrangement and minimizes the visual impact of these crossings.

Fig. 24: View of the rod hangers of Deba Bridge.

Fig. 25: Detail of the hanger crossing device

In Deba Bridge all the hangers are steel rods disposed on the same inclined plane, what requires a device similar to a yoke, as can be seen on figures 24 and 25, which lets a rod cross through the other.

In fact, the hangers of Palma del Río Bridge, that are closed cables with 45, 40, or 37 mm of diameter, which compose the network suspension system of each inclined arch, are located on two different parallel plans, each one of them with a light eccentricity of 6 cm with respect to the arch's plane, that is the reason why the hangers cross but don't cut one another. At the end of the crossing hangers there was a device that allowed the fastening of the cables as well as the free turn of one cable with respect the other (Fig. 26 and 27).

Fig. 26: View of the cable hangers in Palma del Río bridge

Fig. 27: View of the hanger crossing device.

5. CONCLUSIONS

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, as the two steel tubular arches described.

This system, added to the inclined arches linked at the key, and the upper bracing between arches, with either a simple plate, in Deba Bridge, or a K truss with tubular sections in Palma del Río Bridge, 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, both for the case of prestressed bars (Deba Bridge), and for closed cables (Palma del Río Bridge).