Infant Henrique Bridge over the River Douro, Porto

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Summary

The river Douro at Porto provides the splendid setting for several world renowned bridges. The last one built consists of a shallow and extremely thin arch spanning a distance of 280 m under a stiff box-beam deck. This “Maillart” type of arch bridge sets a world record. The deck is the stabilizing element of the slender arch. The bridge was built by setting up rigid triangular structural systems requiring temporary struts and diagonals to complement those bars provided by the arch and the deck. The equilibrium of the two bridge halves cantilevering over the river at a height of more than 70 m was achieved by cables anchored into the granite slopes, together with reinforced concrete struts built on the ground forming rigid triangular structural systems with the deck and temporary diagonals. The construction of this bridge was foreseen to be extremely difficult. Therefore, state-of-the-art monitoring equipment was installed on the bridge and its foundation elements for on-line follow up of the construction method and the several imposed settlements, upwards and downwards, introduced into the structure. The bridge is affected by the maritime climate of Porto, and thus a variety of environmental monitoring systems were installed on the bridge. The structural behaviour of the bridge is controlled and supervised on-line from the design office. A direct follow up on actual conditions ensures timely structural interventions for the rehabilitation of the bridge, if required.

Fig. 1: Arial view of the Maria Pia, Infant Henrique and Luis I bridges

Introduction

The public call for tenders for the Design-Build contract of the Infant Henrique Bridge, connecting the cities of Porto and Gaia and located halfway between the Luiz I Bridge and the Maria Pia Bridge, demanded a solution that would have to match the technical and aesthetic qualities of those two bridges, which are both considered great works of structural engineering *(Fig. 1)*. The responsibility in designing such a bridge was raised further by naming the bridge after Infant Henrique, who is one of the most distinguished figures of the city of Porto and Portugal and who led Europe on the adventure to meet other civilisations.

The project designers understood that these qualities would have to appear in a discrete manner, without fanfare and embellishment. A bridge that, without supports on the riverbed, without supports even on the banks of the river, would fly as if it were a bird over the noble waters of the river Douro, with great transparency and expressing itself in the purest possible way. This bridge does not contain any decoration. It does not contain anything that does not comply with the functional requirements. Everything in the bridge has a purpose that is both structural and functional. For this reason, it has the virtue of simplicity, structural purity, and geometric regularity.

Description of Structure

The Infant Henrique Bridge is composed of two mutually interacting fundamental elements: a very rigid prestressed reinforced concrete box beam, 4,50 m in height, supported on a very flexible reinforced concrete arch, 1,50 m thick, as shown in the elevation and cross-sections in *Fig. 2*. The span between abutments of the arch is 280 m and the rise until the crown of the arch is 25 m, thus with a shallowness ratio greater than 11/1.

In the 70 m central segment of the bridge, the arch combines with the deck to form a box section that is 6 m in height. The lateral faces of this section are recessed to give the impression of continuity of both the deck and the arch. The arch has a constant thickness and a width that increases linearly from 10 m at the central span segment up to 20 m at the abutments.

Structural Behaviour

The structural behaviour of the flexible arch – rigid deck combination has the following basic features:

- Absence of important bending moments in the arch except at its fixed ends
- Axial force variations carried by the arch are relatively moderate; the tendency of the arch rise to decrease due to thermal actions and creep and shrinkage deformations is hindered by the rigidity of the deck

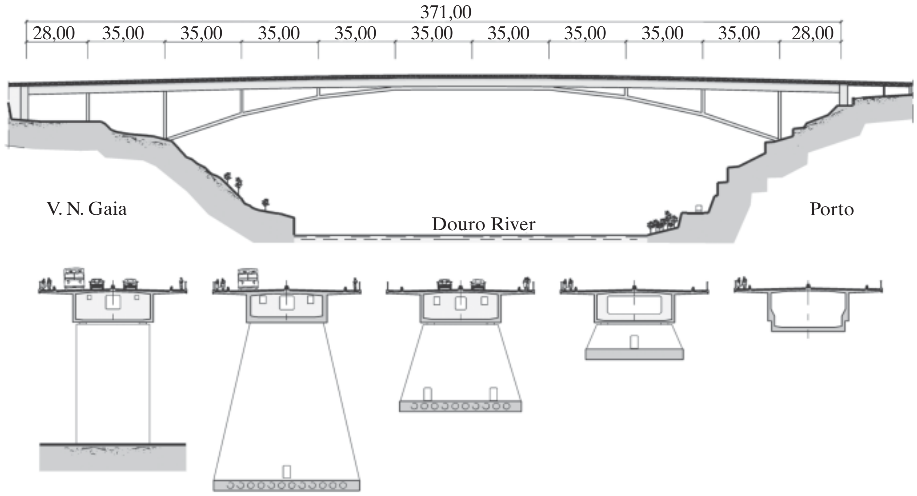

Fig. 2: Elevation and cross-sections of the bridge

- The deck behaves as if it were a continuous beam on elastic supports provided by columns spaced 35 m apart (in fact, the contribution of the deck towards resisting the applied vertical loads is around 15% for permanent actions and symmetrical live loads; this percentage increases to 20% in the case of asymmetrical live loads, which means that the usual high bending moments in the arch under live loads with a pressure line not matching the arch shape are avoided)
- Where the arch and deck combine to form the 70 m long central span segment, the eccentricity between the centroid of the arch and the centroid of the box-beam of the deck lets the high compression force arising from the arch to generate localised high negative bending moments that eliminate the positive bending moments along that central span; thus, a convex curvature in that span that counteracts the deformations that occur in the rest of the structure is guaranteed; however, there is an increase of positive bending moments in the spans preceding the central span segment
- The high compression force introduced by the arch in the central span segment of the deck allows that no prestressing is required in that span after the bridge is finished

The option for a single box-beam in the 70 m central span, where the arch and deck combine into one single element, was also an important factor in the optimisation of the structure. In effect, the dead weight of the structure per metre length in this span is close to half of the weight per metre of the structure anywhere else on the bridge, where the arch and deck are separated.

Construction Method

A shallow and slender arch can only function structurally if in conjunction with the deck. The construction method was to progress by cantilevering the deck and the arch from each side of the river, as shown in *Fig. 3*. Two temporary pillars were built first in order to reduce the span from 280 m to 210 m, during construction, and trusses were created by adding tensile diagonal bars (provided by temporary stays) and vertical compression bars (provided by the reinforced concrete columns and temporary steel struts) between the arch and the deck. Therefore, two cantilever trusses of considerable height were constructed until the deck and arch met. The 70 m central span was built by typical cast-in-place segmental box-beam construction methods.

Trusses were created similarly in the slopes outside the arch. They were defined by the deck, abutments, column P1 (on the Gaia side of the river, reinforced concrete struts built on the ground and working integrally with the rock foundation, and diagonals provided by temporary stays. These diagonals worked as backstays and ensured that the two bridge halves were tied back to the deck abutments until they were united at the centre. Tensile forces in all diagonals were applied and regulated in a predefined order to control the structural response of the two cantilever trusses.

Equilibrium of the advancing cantilevers was secured by inclined ground anchorages and by footings connected together by reinforced concrete struts. Geometry of these footings was optimized in order to mobilize the rock foundations in resisting the horizontal components of the construction forces, which meant that forces generated in footing struts were kept under control and stability of the rock slopes was ensured. After the two bridge halves were united by the crown segment *(Fig. 4)*, backstays, diagonals, temporary struts and pillars

Fig. 3: Construction method

Fig. 4: View of the bridge before temporary elements were dismantled

were all dismantled following to a very detailed sequence.

Several techniques and procedures used in the construction of the Infant Henrique Bridge were highly innovative. Moreover, to build a large bridge subject to a geometrical precision criteria never before demanded was, in itself, an enormous challenge for the contractor. Also, the erection of an extremely slender and shallow arch over the distance of 280 m lead to the construction of the deck ahead of the “suspended” arch, which is a method that had been used only once before, with the Nakatanigawa Bridge in Japan, where the arch spans 100 m and rises 19 m.

The generalised use of computer controlled and aided systems are mentioned. From the construction of the Infant Henrique Bridge, the following application examples are noted:

- The positioning of the support platform for the arch formwork was adjusted to the millimetre, before the concrete of each segment of the arch was poured, and was carried out using two automatic and computerized hydraulic systems
- The monitoring of the structural behaviour of the bridge during construction was carried out by centralized computer systems that collected data from relevant structural elements of the bridge and that automatically stored, managed, and processed these data in order to interpret readings supplied by the internal monitoring devices
- The special operations of upwards and downwards settlements on top of the temporary pillars, as well as the release of the bridge from those temporary pillars, were controlled by those computer systems, with on-line follow up of readings in the internal monitoring devices
- The removal of the temporary pillars weighing 8000 kN was achieved by means of a rotation and transfer system *(Fig. 5)* with on-line control and adjustment of forces in the hydraulic jacks that suspended the rotation axis located halfway up the pillar.

Fig. 5: Removal of the temporary pillar on the Porto side of the bridge

Control of Construction

Construction of this bridge was a major achievement requiring a highly efficient monitoring system, capable of assessing physical quantities of different types, namely support reactions, axial forces, bending moments, rotations and temperatures at particular sections of the arch, deck and temporary struts and pillars, and axial forces in the temporary stay cables (backstays and diagonals). The monitoring of the construction of the bridge was performed by three separate instrumentation systems, one for the granite slopes on each side of the river, another for the foundations and another for the concrete elements and temporary stay cables.

Conclusion

The Infant Henrique Bridge exhibits high technical and aesthetic qualities and represents an important technological advance in construction, both because of the magnitude of its dimensions and because of the following set of relevant facts:

- It is the second largest concrete arch in Europe; with a span $L = 280$ m, it is only surpassed by the Krk Bridge, in Croatia, constructed in 1979 and which, with a 390 m span, held the world record for 18 years, up to 1997
- It holds the world record for straight segmental arches; with a constant thickness of 1,50 m (approximately $L/187$), it stands out for being extremely slender in relation to the usual thicknesses used in conventional rigid arch solutions (between $L/40$ and $L/60$)
- The rise of $f = 25$ m means a shallowness ($L/f = 11{,}2$) for the arch that has no parallel in the field of large span arch bridges
- Its “static coefficient” ($L^2/f > 3000$), which is directly proportional to the axial force existing at the crown of the arch, is the largest of any concrete arch built to date.

In fact, this arch is the most loaded and the most “delicate” in the world. Notwithstanding the fact that it is a world record holder for slenderness, it possesses the greatest axial force of any arch.

Evidently, it is a bridge inspired by the works of art designed by the Swiss engineers Robert Maillart and Christian Menn. From the former, is mentioned the Bridge over the Schwandbach stream, built in 1933 and having a span of 37,4 m. From the latter, are referenced the Hinterrhine Bridge, in the Viamala Gorge, and the two bridges with a span of 112 m, built in the second half of the twentieth century, over the Moesa stream on the south slope of the San Bernardino Pass.

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SEI Data Block

Owner:
Metro do Porto, SA, Portugal

Designers:
AFAssociados, Porto, Portugal
IDEAM, Madrid, Spain

Contractors:
EDIFER, Lisbon, Portugal
NECSO, Madrid, Spain

Passive steel (t):	3800
Prestressing steel (t):	660
Concrete (m^3):	26 000
Service date:	March 2003