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A New Landmark Arch Bridge in Milan

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Abstract

The search for new architectural shapes may lead to schemes of bridges which cannot be traced back to known and tested typologies. In these cases, a new aesthetics requires new static views. The novelty of the De Gasperi Bridge, located in Milan, consists of two steel arches diverging towards the lateral sides of the deck. Such a choice involved particular structural problems as regards to both the vertical loads and the lateral ones due to wind and earthquake. Another delicate issue was posed by the array of joints connecting the tubular hangers and the arches, for which cardan joints have been employed in order to avoid any flexural stresses. The paper illustrates the criteria which led to the conception of a structural system which, while respecting the shape determined by architectural choices, activates an effective and natural force path. A synthesis of the analyses and of the experimental tests performed on the cardan joint are presented.

Keywords: landmark bridge, diverging arches bridge, steel bride, cardan joints

1. Introduction

There are no particular reasons for designing a bridge with arches lying onto planes diverging towards the lateral sides. On the contrary, there are many good reasons to maintain the arches onto vertical planes or to have them converging in correspondence with their crown, and to connect them by means of transverse elements. This latter choice, in particular, makes the arches less sensitive to lateral instability phenomena, while the whole structure becomes more robust and stiffer.

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In the new De Gasperi Bridge, located at Milan Portello, the two bearing arches diverge toward the lateral sides of the deck: such a characteristic derives from an architectural choice, coherent with the recent urban requalification project, which led to the introduction of wide green areas and to the erection of few, refined and innovative tall buildings. The image of the new Portello district has to be caught in its entirety. In this context, the bridge was conceived mainly from an architectural viewpoint, as an object which is part of the surrounding landscape but, at the same time, has a character of its own.

Actually, many of the architectural intuitions were confirmed after the completion of the works. During centuries, the bridges crossing the boundaries of a city were also custom check points and could be identified as a barrier. On the contrary, the diverging shape of the arches suggests to most people the idea of opening and reception.

After some obvious and soundly based remonstrance, the structural engineer had to accept the prevailing of the architectural concept: the engineer's job became seeking a static justification to predefined shapes and giving consistency to an architectural object, thus inverting the equilibrium-oriented wisdom which wants the shape justified by the statics.

2. Geometry and Concept of the Bridge

The main structure is composed of two slightly diverging steel arches. The horizontal component of the thrust conveyed by the arches is held by the deck structure, which works like a tie. With regard to the global static, the bridge behaves like a simply supported beam, having a hinge at one side and a roller at the other. The span between the supports is 80m.

The arches are the geometrical elements of greatest significance. The arches have circular axes with radius R = 73,695m and rise f = 11,600m (Figure 1), and lie onto planes inclined at a 22.5° angle with respect to a vertical reference. Two sets of hangers, whose axes belong to a bundle of straight lines radiating from the centre of the arches, lie on the same planes.

Figure 1: The De Gasperi Bridge during loading test.

According to such a geometry, the loads are conveyed to the earth with the following path:

- the hangers carry the loads acting on the deck and they convey them to the arches;

- along the arches, starting from the crown downward, the forces conveyed by the hangers are vectorially added to one another and to the arches self-weight, so that the arches can be regarded as the funiculars of these systems of forces. This progressive build-up of forces is translated into the axial force which finally arrives at the springings, where the vertical component of this vector sum is held by the bearing supports, while the horizontal one is born by the deck.

On the whole, the deck can be seen as a cradle, hanging from the two arches: the exercise of conveying the forces according to a scheme both rational and compatible with the given geometry, has thus been solved for the vertical loads. It is worth noting that, by means of the forces transmitted by the hangers to the arches, a ballast action is exerted on these latter, which contributes in stabilizing the out of plane displacements.

On the other hand, however, with regard to the horizontal loads due to wind and earthquake, there still remained the problems deriving from the lateral flexibility of arches which are not transversally connected. The particular overall geometry of the bridge led to exclude the use of rope hangers. In fact, in addition to supporting the deck, the hangers have to exert a restraining action against the transversal displacements of the arches. In the transverse section, the elastic restrain is provided by the U-shaped frames made up of the hanger/deck-crossbeam/hanger system, working in flexure. Such a mechanism determines the distribution of stiffness and of resistance, resulting in slender tubular hangers connected to stiffer and more sturdy crossbeams by means of robust nodal joints.

At the end, the volumetric translation of these structural details resulted consistent with the imagine of the ensemble, succeeding in combining statics with aesthetics.

A delicate issue was posed by the array of joints connecting the tubular hangers and the arches. A direct connection, tube on tube, would have involved contact lines shaped according to conical sections, difficult to obtain. The nodes would have been subjected to mainly tensile forces, but accompanied by relevant secondary flexural components and by local stress peaks whose intensity would have made the satisfaction of fatigue verifications very demanding. Finally, the welding processes, that should have been carried out on-site, would have been difficult both to perform and to check. The most natural solution seemed to adopt a joint capable of conveying axial forces only, without blocking others freedom degrees. Since no joints compatible with the loads involved were available on the market, a special Cardan suspension, capable of rotation on two axes, was specifically designed. Negligible torque moments arise from the remaining rotational degree of freedom, around the longitudinal axis of the hanger, which remains locked. The use of Cardan joints introduced an element of separation between the bundle of hangers and the arches, emphasizing the continuity of the arches and, at the same time, marking the different static roles of the two systems.

3. General Characteristics and Structural Components

In its entirety, the load-bearing structure is made up of a tied-arch bridge, having a 80 m span between the springing (Figure 2). The deck, whose overall width is 13.50 m, comprises of three lane, two lateral shoulders, and a 1.50 m wide sidewalk. The structure lies on two abutments that also serve as retaining walls for the approaching embankments.

3.1. Foundations and abutments

By means of 17.00 x 9.20 x 1.20 m plinths, the foundations rest on 15 piles, having a diameter of 100 cm, and driven to a depth of 24 m. In elevation, a 1.20 m thick transverse wall rises from the plinth. The bearing supports rest on the top of such wall. At a 2.40 m distance at the back of it, a second wall, 0.60 m thick, act as retaining wall for the approaching embankment. The two walls are connected by three 0.80 m wide buttresses. The space between the two walls was left empty. Together with the lateral diaphragms which serve as wing walls for the approaching embankments, the two transverse walls form a stiff box system.

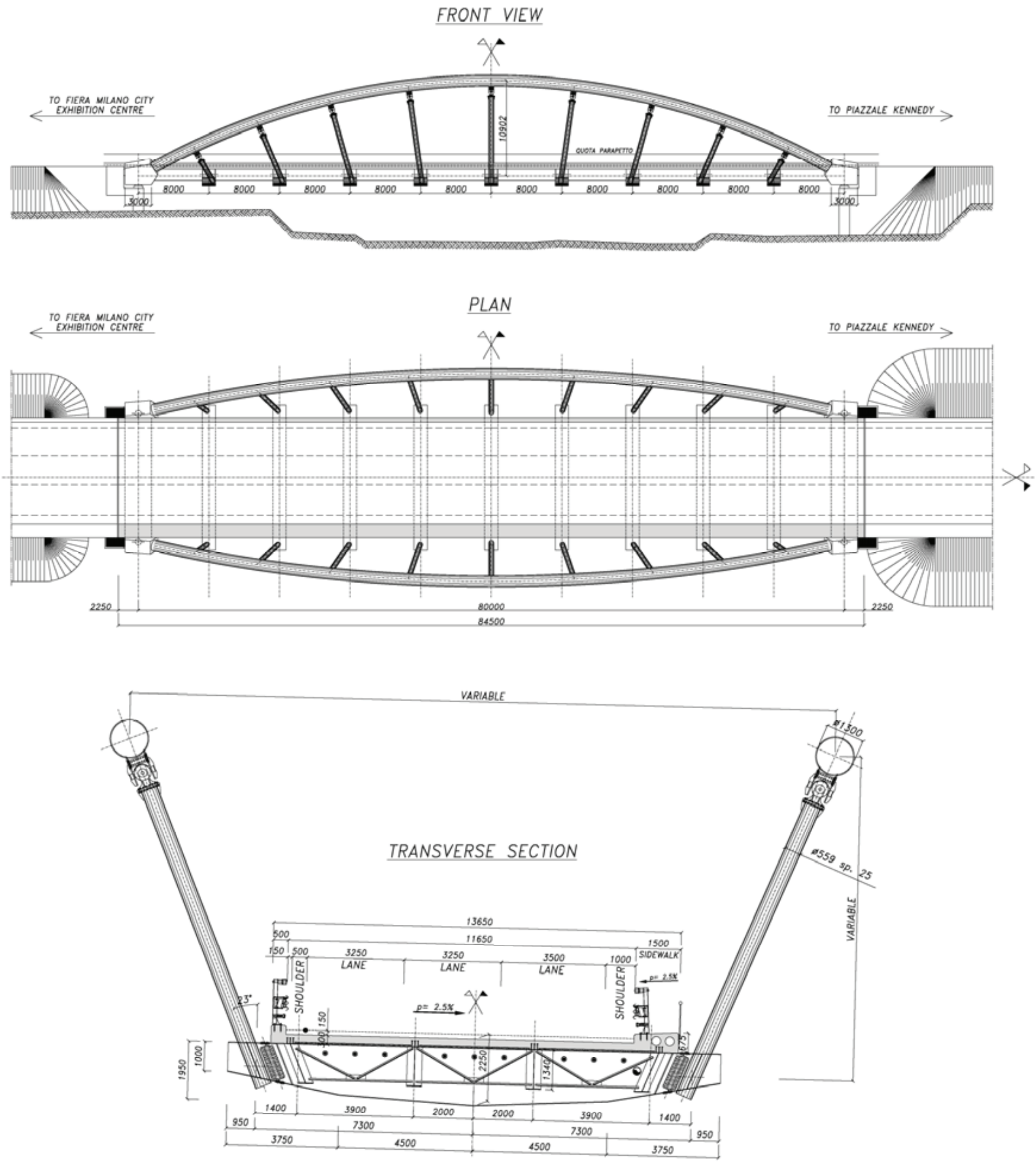


Figure 2: The De Gasperi bridge: front view, plan and transverse section.

3.2. The arches

The steel arches lie on planes with a 22.5° tilt with respect to a vertical reference, and have a mean radius R = 73,695 m and a rise f = 11,600 m. The opening of the arches at springings is 65.75°. The comprehensive length of the arches is 85 m and the rise/span ratio is f/l = 1/6.9. At design stage, the arches were conceived as tubular sections with a diameter of 1300 mm and a thickness of 30 mm. The curvature was to be obtained by calandering arch chunks having an average length of 28.3 m, which would subsequently be assembled. During construction, however, finding structural sections having the exact combination of diameter, thickness and steel type considered during the design stages, proved very difficult. Therefore, the arches were manufactured from straight stretches, having an average length of 2.98 m, shaped into tubular sections by calandering plane slabs of 30 mm thickness. Each arch was thus obtained by the assembly of three subsets, each one made up of nine straight pieces, jointed by means of complete penetration butt welds. The segmentation criterion was attentively studied, comparing different solutions, in order to minimize the perception of angular points. The maximum offset between the arch circular axis and the axes of the straight segments was about 7 mm. The result confirms the accuracy of the solution adopted.

3.3. The deck

The deck is a mixed structure, having steel girders and crossbeams, and a concrete slab. The longitudinal girders are 1340 mm high H-shaped composite sections, made from flat plates. The central girders have vertical webs, while the webs of the lateral ones are tilted at a 22.5° angle, thus recalling the inclination of the arches and making the lateral view of the deck less impacting (Figure 2).

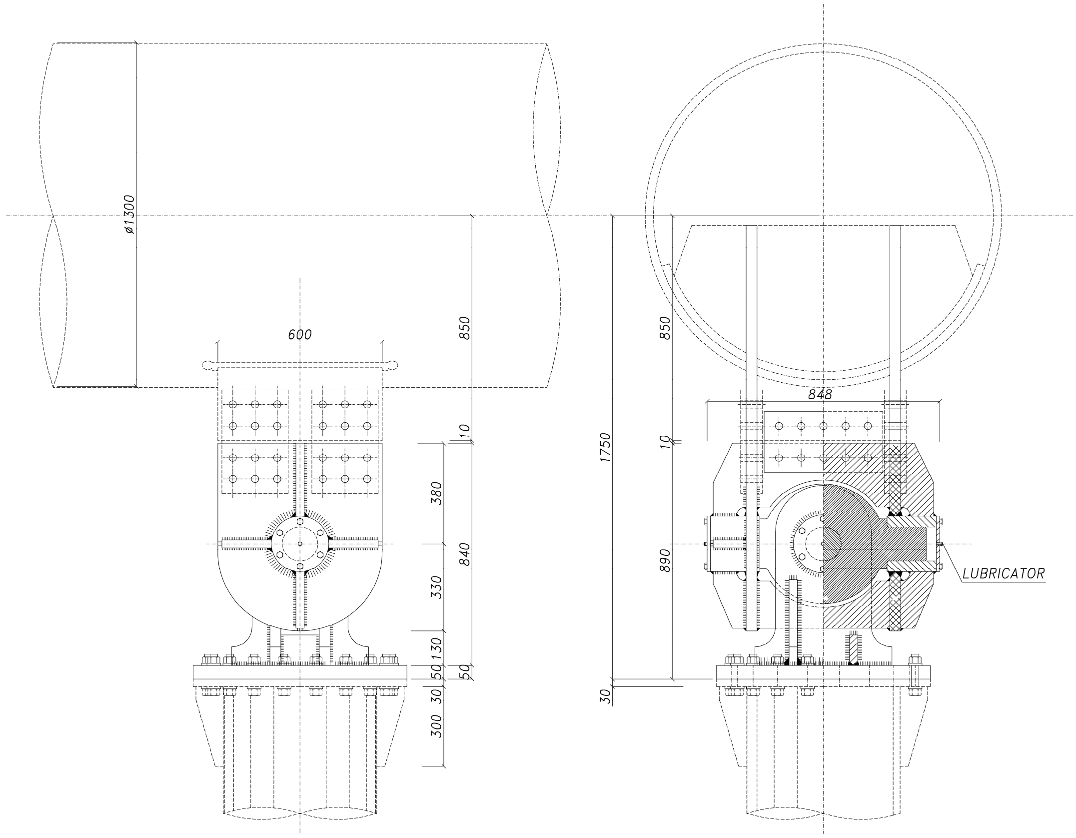
The reinforced concrete slab is 250+50 mm thick, and is connected to the steel girders by means of Nelson studs. The connection between the longitudinal beams and the arches is obtained thanks to nine transverse box girders, slightly tapered at the two ends (minimum height is 1000 mm, maximum height is 1950 mm), which stretch outside the deck width and are connected to the tubular hangers. Three manholes were left in the crossbeams, so as to allow internal inspections.

The deck is stiffened at the intrados and at the extrados by two sets of bracing crosses, laid out at a constant 4 m pitch in the longitudinal direction, and at a 3.25 m pitch in the transverse direction.

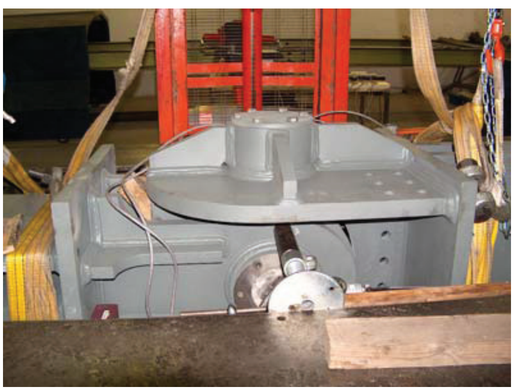
The upper bracing system is necessary only in the transient assembling phase, before the casting of the slab. The lower bracing system is made up of 90x9 L sections: its contribution allows the deck to behave like a box girder, improving both stiffness and torsional resistance. The slab collaborates with the steel substructure of the deck in bearing part of the tension which contrasts the thrust conveyed by the arches. Some areas of the slab, in correspondence with the crossbeams, are also subjected to negative flexural moments. Finally, in case of asymmetric load conditions, the zones situated at about one quarter of the span are affected by a further contribution to negative bending moments. In order to reduce tensile stresses, the usual construction requirements (section and geometry of the reinforcements, concrete of adequate resistance, cast progressively and possibly enriched with steel fibers in the most sensitive areas) have been integrated by a prestressing action. To this aim, nine prestressing cables, made of 20/0,6"strands, run straight immediately underneath the slab, at a barycentic level inside the contour of the deck.

3.4. The tubular hangers

The two sets of nine hangers that connect the tips of the crossbeams to the arches, are made up of tubular profiles, having a diameter of 620 mm and a thickness of 23.8 mm (Figure 2). The connection between hangers and crossbeams is stiffened internally by plates arranged so as to form a cross, and, externally, by four triangular fins.



a)



b)

c)

Figure 3: The Cardan joint: a) view and cross-section; b) the lab tests; c) the assembled joint.

The upper connection between hangers and arches is provided by Cardan joints, connected to the hangers tip by flange joints, which in turn are stiffened by triangular fins (Figure 3). The upper part of the joint is held by grippers, fitted inside the arches and emerging from especially provided slots, so that all other parts of the joint are left hidden. Considering its peculiarity, after an attentive theoretical modelling, lab tests on a 1:1 prototype of the joint were performed, before proceeding with the final stages of the design process.

3.5. Bearings supports and expansion joints

Pot bearings supports, produced by Alga S.p.A., have been employed. Their bearing capacities are: in the vertical direction V_{max} = 9750 kN; in both transverse directions H_{max} = 1500 kN. The maximum longitudinal movement capability is $\delta = \pm$ 100 mm. The expansion joints are of the Algaflex T200S type, with a maximum movement capability of ± 100 mm.

4. Structural Analyses and Experimental Tests

4.1. Structural Analyses

The bridge has been modelled as a spatial frame having 213 nodes and 472 elements, of which 416 were employed for the modelling of the deck. Each arch was modelled with 20 elements, and the hangers with a total of 36 elements.

Static analyses were performed in order to evaluate the stress characteristics and for the verification of the main structural elements. Stability analyses for the evaluation of the critical Eulerian load of the entire structure were carried out, with particular attention paid to the behaviour of the arch in a direction normal to the plane onto which the arch lies.

Dynamic analyses and response spectrum analyses were used to identify the dynamic and seismic behaviour of the bridge. For the seismic analyses, the structure was considered as comprised in Zone 4, on an A class soil (according to the Italian building codes), which correspond to a max horizontal acceleration of 0.156 g, and max acceleration of 0.135 g on a C class soil.

A special study was dedicated to the Cardan joint, whose central plate was modelled by means of three-dimensional finite elements. A prototype of the same joint was tested at the Material Testing Lab of the Department of Structural Engineering at the Politecnico di Milano. The tests were coordinated by Prof. Eng. Carlo Poggi. Electrical strain gauges were applied to the model's pin, making it possible to draw comparisons between actual and theoretical stresses.

5. Workshop Activities. Building. Erection Stages. Load Tests

5.1. Workshop activities. Building and erection stages

All primary works were carried out in the steelwork manufacturer workshop, together with the assembly of arches and deck substructures of transportable dimensions. The arches were preassembled into three stretches, approximately 28m long, each composed of nine straight segments. During the preassembling stages the dimensional characteristics and the effectiveness of the temporary lifting systems were checked. The nine deck crossbeams were also assembled in the workshop. The two crossbeams placed in correspondence with the springings, more cumbersome and remarkably heavier (900kN) than the other parts, were subdivided into two halves. The four half-crossbeams were the only elements which required special transportations.

The building stages can be summarized as follows: a) construction of foundation piles, plinths and reinforced concrete abutments; b) assembly of the steel substructures; c) casting of the reinforced concrete deck slab; d) finishing works. The manufacturing of the steel parts took about six months.

5.2. Controls and Load Tests

Row materials, cutting and working tolerances were systematically controlled at the workshop. All the welded connections were checked with ultrasonic and X-ray tests. The geometric attitude during assemblage at the construction site was controlled by topographic surveys. The pre-commissioning load tests took place on July 15th 2009. The main deflection under the load exerted by six 440kN lorries was 36mm. The expected theoretical value was 44mm.

6. Conclusions

This paper presents the criteria followed in designing the new De Gasperi Bridge, located at Milan Portello. The main structure is composed of two steel arches, having a 80 m span and laying into planes which are slightly tilted with respect to the vertical reference. The paper describes the structural concept and the static role of the different parts composing the bridge. The Cardan joints, which connect the hangers to the arches, not only mark the different static roles of the two systems, but also provide an element of peculiarity to the overall image of the bridge.

7. Design Staff

The design staff of the new structure was composed as follows:

- Project managing and general design: Metropolitana Milanese S.p.A., under the supervision of e. Arini, A. Cavagna, M. Recalcati, Merlanti and M. Chiorboli;
- Urban planning and architectural design: L. Forges Davanzati and F. Colombo;
- Structural project: P. G. Malerba, P. Galli, M. di Domizio.
- Chief site engineer: M. Saibene (MM S.p.A.).
- Engineer in charge of pre-commissioning load testing: P. Piacentini.
- Main Contractor: Claudio Salini Grandi Lavori S.p.A., Rome – Milan.
- Steelworks manufacturer: BIT S.p.A, Cordignano, Italy.
- The F.E. structural analyses on the main components of the Cardan joints were performed in cooperation with M. Sartori.